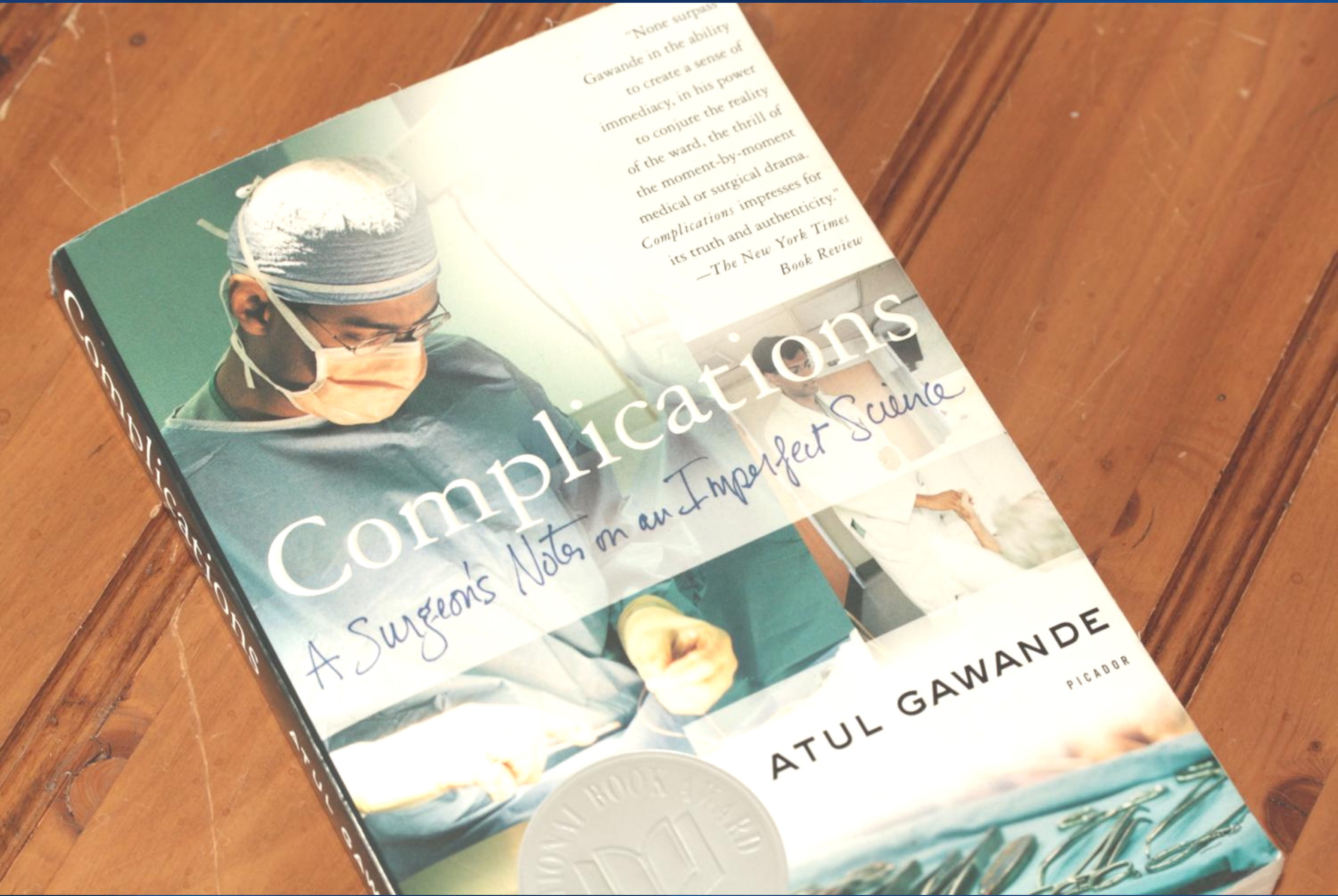
Root Cause (Failure) Analysis

Eugene T. Cottle
Reliability Engineer


"None surpass Gawande in the ability to create a sense of immediacy, in his power to conjure the reality of the ward, the thrill of the moment-by-moment medical or surgical drama. Complications impresses for its truth and authenticity."
—The New York Times Book Review
Complications
A Surgeon's Notes on an Imperfect Science
ATUL GAWANDE
PICADOR

Root

Cause

“ Cause ”

A confluence of events, factors and conditions which conspire to produce an outcome.

"Root"

Event(s), factor(s) or condition(s) which are under your control and which, if corrected or eliminated, will prevent recurrence of the undesirable outcome.

Cause

A confluence of events, factors and conditions which conspire to produce an (undesirable) outcome.

More terminology…

- RCA (Root Cause Analysis)
  - A disciplined process for focusing ideas to identify root cause(s). A class of problem solving methods
- RCFA (Root Cause Failure Analysis)
  - Reactive, in response to a failure
- RCCA (Root Cause and Corrective Action)
  - Incorporates preventive corrective action into the process (i.e., elimination of special causes)

Root Cause Analysis

- Safety-based RCA
  - accident analysis and
  - occupational safety and health
- Production-based RCA
  - quality control for industrial manufacturing
- Process-based RCA
  - Expanded scope to include business processes
- Failure-based RCA
  - Based on failure analysis
  - employed in engineering and maintenance.
- Systems-based RCA
  - amalgamation of the all the others, and includes
    - change management,
    - risk management, and
    - systems analysis

Objectives

- Prevent recurrence
- Responsibility
  - “Hand-off” the investigation
    - Begins with an assumption of “cause”
  - Liability
  - Blame

Deming's 14 points

1. Create constancy of purpose toward improvement of product and service, with the aim to become competitive and stay in business, and to provide jobs.
2. Adopt the new philosophy. We are in a new economic age. Western management must awaken to the challenge, must learn their responsibilities, and take on leadership for change.
3. Cease dependence on inspection to achieve quality. Eliminate the need for inspection on a mass basis by building quality into the product in the first place.
4. End the practice of awarding business on the basis of price tag. Instead, minimize total cost. Move towards a single supplier for any one item, on a long-term relationship of loyalty and trust.
5. Improve constantly and forever the system of production and service, to improve quality and productivity, and thus constantly decrease cost.
6. Institute training on the job.
7. Institute leadership (see Point 12 and Ch. 8 of "Out of the Crisis"). The aim of supervision should be to help people and machines and gadgets to do a better job. Supervision of management is in need of overhaul, as well as supervision of production workers.
8. Drive out fear, so that everyone may work effectively for the company. (See Ch. 3 of "Out of the Crisis")
9. Break down barriers between departments. People in research, design, sales, and production must work as a team, to foresee problems of production and in use that may be encountered with the product or service.
10. Eliminate slogans, exhortations, and targets for the work force asking for zero defects and new levels of productivity. Such exhortations only create adversarial relationships, as the bulk of the causes of low quality and low productivity belong to the system and thus lie beyond the power of the work force.
11. a. Eliminate work standards (quotas) on the factory floor. Substitute leadership.
    b. Eliminate management by objective. Eliminate management by numbers, numerical goals. Substitute workmanship.
12. a. Remove barriers that rob the hourly worker of his right to pride of workmanship. The responsibility of supervisors must be changed from sheer numbers to quality.
    b. Remove barriers that rob people in management and in engineering of their right to pride of workmanship. This means, inter alia, abolishment of the annual or merit rating and of management by objective (See CH. 3 of "Out of the Crisis").
13. Institute a vigorous program of education and self-improvement.
14. Put everyone in the company to work to accomplish the transformation. The transformation is everyone's work.

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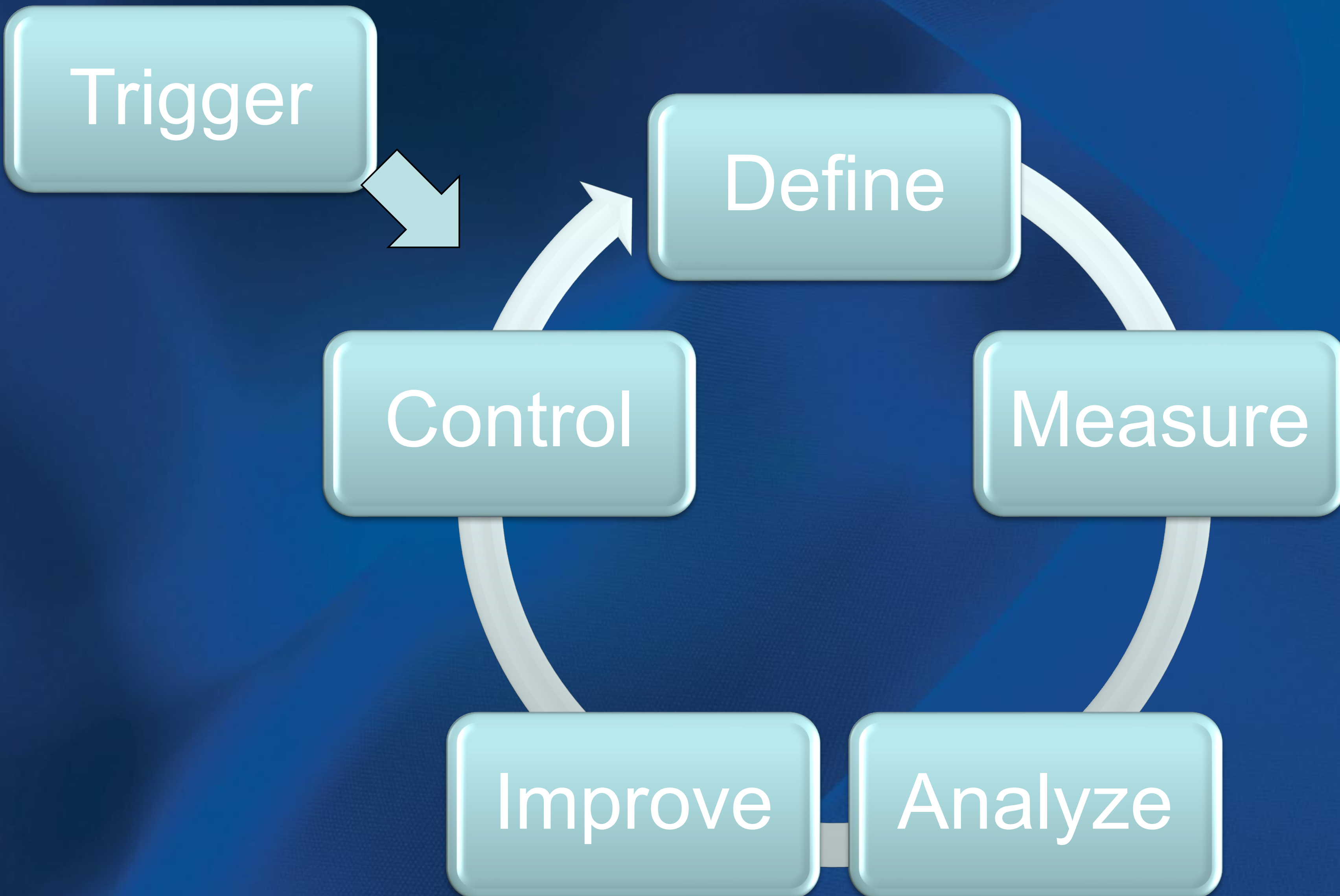
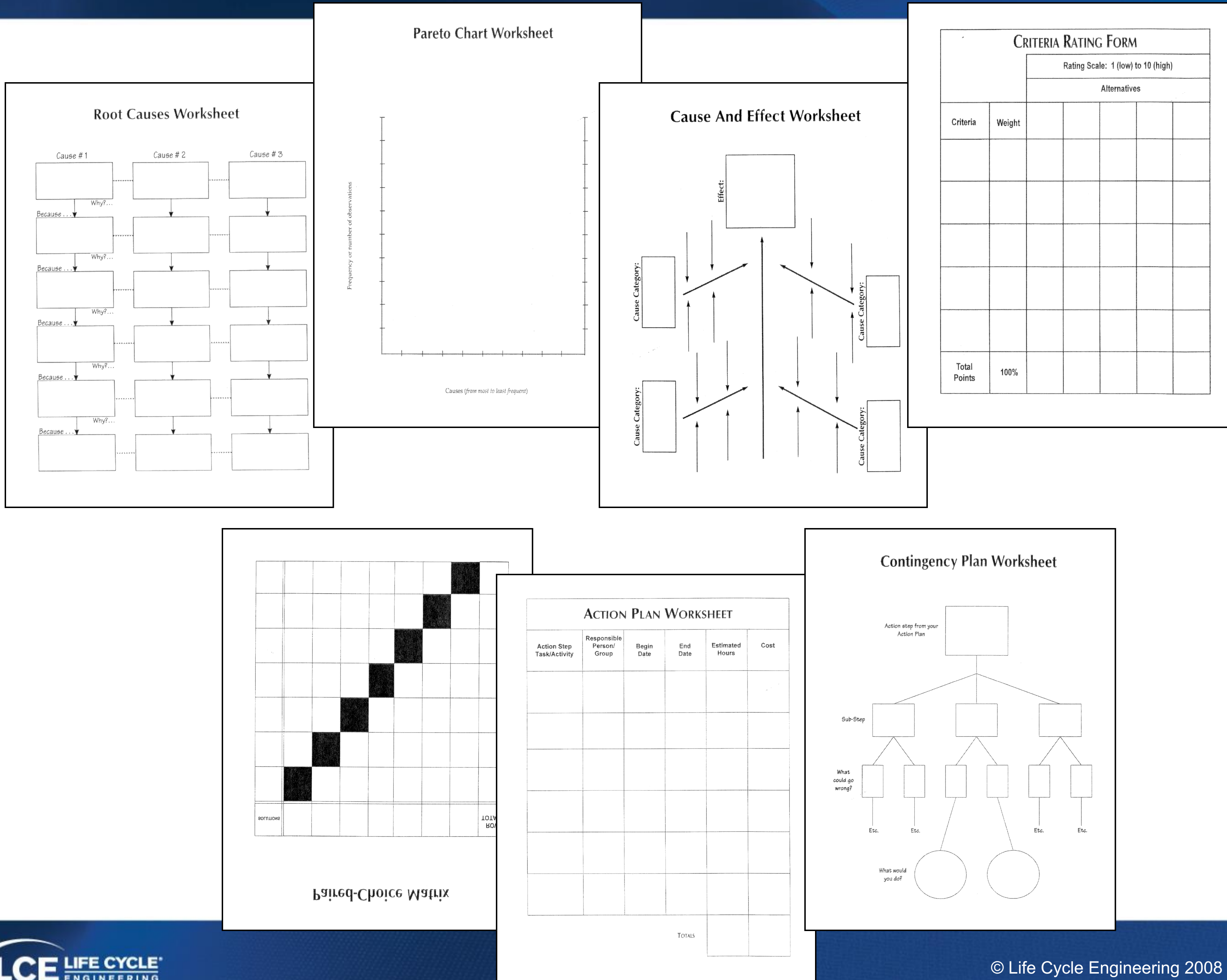
DMAIC





Pareto Chart Worksheet
Frequency or number of observations
Causes (from most to least frequent)
Criteria Rating Form
Rating Scale: 1 (low) to 10 (high)
Alternatives
Criteria
Weight
Total Points
100%
Root Causes Worksheet
Cause # 1
Cause # 2
Cause # 3
Why?...
Because...
Cause And Effect Worksheet
Effect:
Cause Category:
Paired-Choice Matrix
Action Plan Worksheet
Action Step Task/Activity
Responsible Person/ Group
Begin Date
End Date
Estimated Hours
Cost
Totals
Contingency Plan Worksheet
Action step from your Action Plan
Sub-Step
What could go wrong?
Etc.
What would you do?

5 Whys

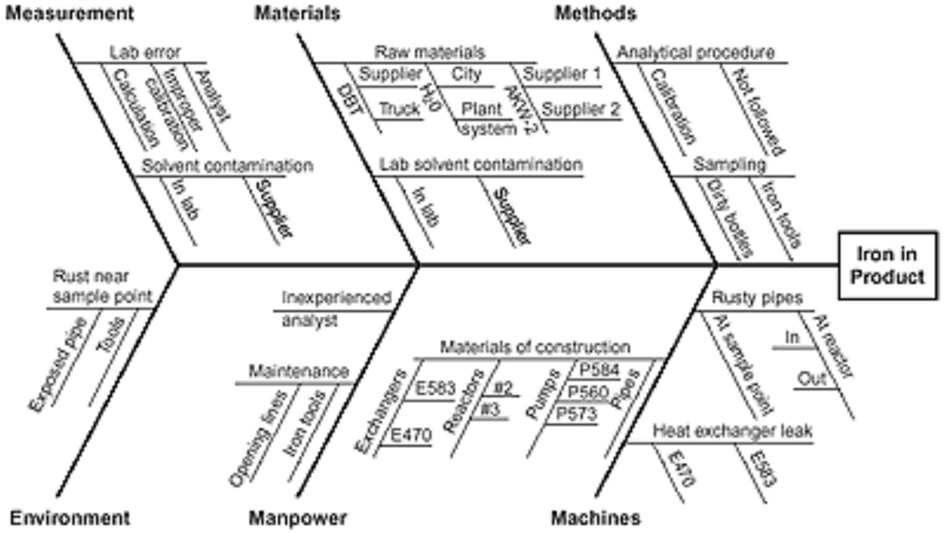
- 5 Whys
  1. *Why?* - The battery is dead. (first why)
  2. *Why?* - The alternator is not functioning. (second why)
  3. *Why?* - The alternator belt has broken. (third why)
  4. *Why?* - The alternator belt was well beyond its useful service life and has never been replaced. (fourth why)
  5. *Why?* - I have not been maintaining my car according to the recommended service schedule. (fifth why, root cause)

Sakichi Toyoda
(豊田 佐吉 *Toyoda Sakichi*, February 14, 1867 – October 30, 1930)

5 why's continued

- Why 5?
  - Nothing magic about the number 5
  - After about 5 it can get absurd or go out of scope
  - Do we have control over this cause?
  - Will eliminating this cause prevent recurrence?
- Shortcomings
  - Oversimplifies cause and effect relationships
    - Multiple causal and contributing factors
    - Confluence of events
  - Not a structured method for effective investigations
    - Other methods help identify possible factors
- Fundamental idea underlying all RCA's (Cause ⇨Effect)

Ishikawa Diagram
(also "fish-bone" diagram)



- Can come at any point in the process
- Helps direct activities
- Brainstorming tool
- Followed by data collection, verification, tests, etc.

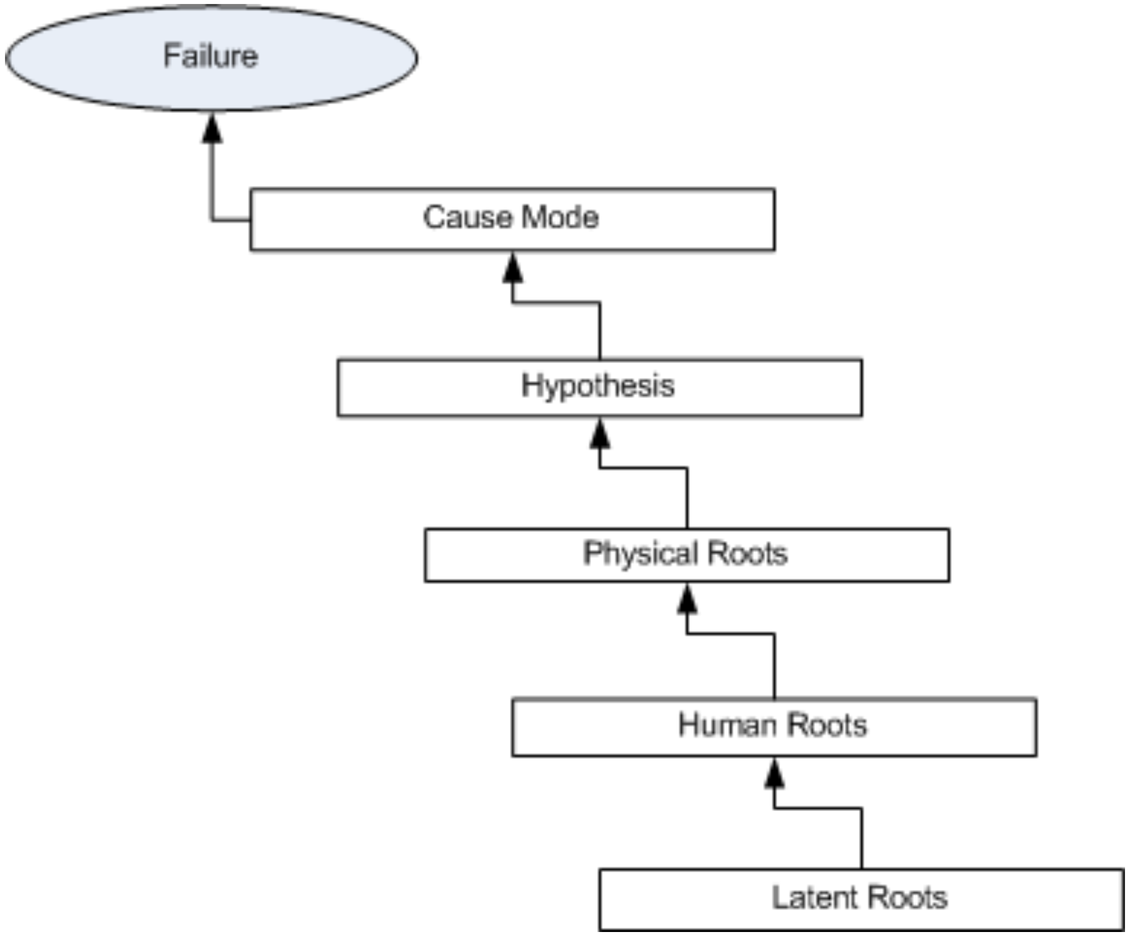
Tague's, Nancy R. *The Quality Toolbox*, Second Edition, ASQ Quality Press, 2004, pages 247-249

Ishikawa diagrams

- The 6 "M"s
  1. Machine,
  2. Method,
  3. Materials,
  4. Maintenance,
  5. Man and
  6. Mother Nature (Environment)
- The 8 "P"s
  1. Price,
  2. Promotion,
  3. People,
  4. Processes,
  5. Place / Plant,
  6. Policies,
  7. Procedures, and
  8. Product (or Service)
- The 4 "S"s
  1. Surroundings,
  2. Suppliers,
  3. Systems,
  4. Skills

Failure Model

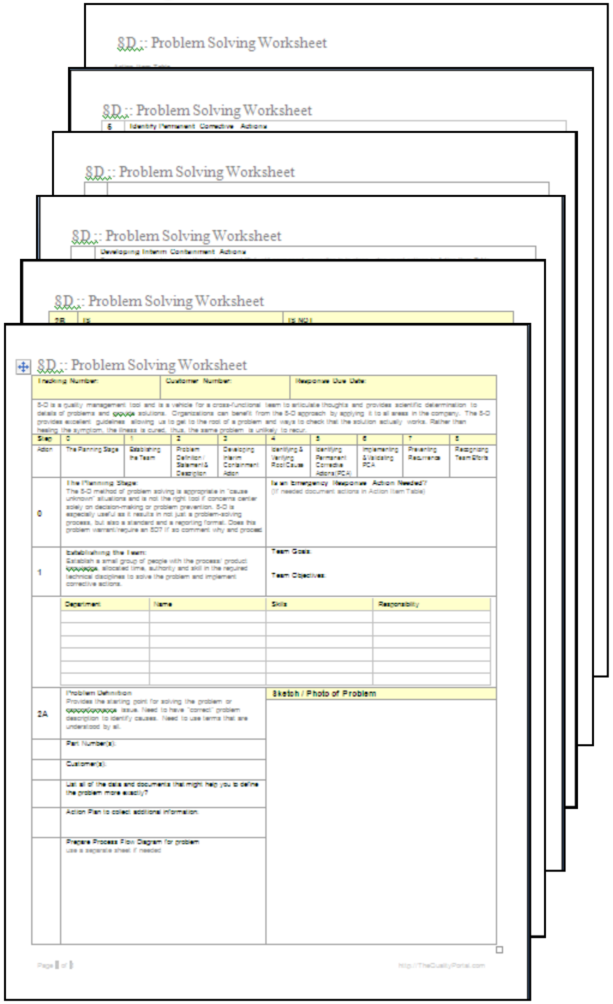
- The level at which any root cause should be identified is the level at which it is possible to identify an appropriate failure management policy



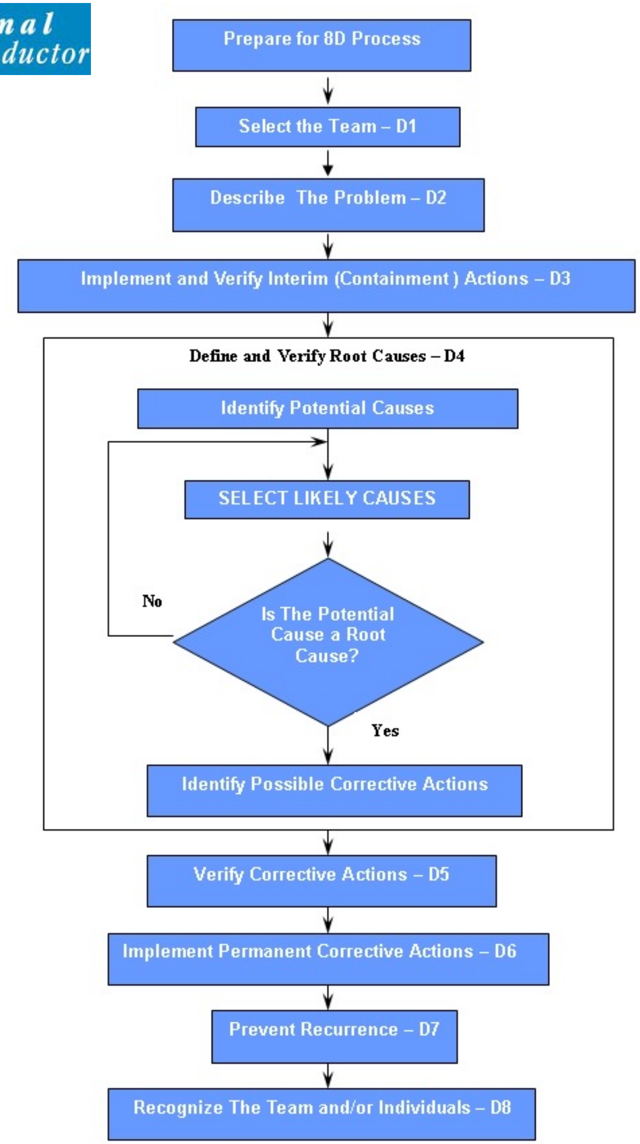
"8 Disciplines" or "8D"

- The 8 Disciplines
  1. Use Team Approach
  2. Describe the Problem
  3. Implement and Verify Short-Term Corrective Actions
  4. Define and Verify Root Causes
  5. Verify Corrective Actions
  6. Implement Permanent Corrective Actions
  7. Prevent Recurrence
  8. Congratulate Your Team
- Other tools can be incorporated into the steps of an 8D

TheQualityPortal.com



National Semiconductor



8D :: Problem Solving Worksheet

2B	IS	IS NOT
Who	Who is affected by the problem? Who first observed the problem? To whom was the problem reported?	Who is not affected by the problem? Who did not find the problem?
What	What type of problem is it? What has the problem (part id, lot #s, What is happening with the process & Do we have physical evidence of the	
Why	W Is	
ere	W	

Kepner-Tregoe (KT) analysis

Pioneered in early 1960's

USAF and NASA

"built on the premise that people can be taught to think critically"

- Invite someone from a different area as a "fresh set of eyes"
  - "Could you please explain…?"
  - "How do you know…?
  - "Do you have any data to show that…"

Wh	When has it been noticed since?	
ow Much/ Many	Quantity of problem (ppm)? How much is the problem costing in dollars, people, & time?	How many could have the problem but don't? How big could the problem be but is not?

- Also, "failure probability distribution" – Answers simultaneously
  - "How many as a portion of the population?" and
  - At what point in their life (age, cycles, etc.)
- You need good data to answer these questions

What is acceptable?

What do you expect?

Everything fails …

If you push it hard enough

If you run it long enough

If it gets hot enough

Etc.

It will fail.

Statistical Analysis

- Important to understand…
  - Coincidence
  - Correlation
  - Cause

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Statistical Analysis

- Important to understand…
  - Coincidence
  - Correlation
  - Cause
- Tools…
  - Design of Experiments (DOE)
  - Analysis of Variance (ANOVA)
  - Correlation analyses
  - Hypothesis testing

"Smoking is one of the leading causes of statistics."

-- Fletcher Knebel

Selecting and prioritizing actions

- Requires some knowledge of probability of occurrence - *Data*

Probability Range From	Probability Range To	Definition	SEVERITY / Probability	Catastrophic	Critical	Marginal	Negligible
~1	8×10^{-2}	Likely to occur frequently	Frequent	**1**	**3**	**6**	**10**
8×10^{-2}	8×10^{-3}	Will occur several times in life of an item	Probable	**2**	**5**	**9**	**14**
8×10^{-3}	8×10^{-4}	Likely to occur sometime in life of an item	Occasional	**4**	**8**	**13**	**17**
8×10^{-4}	8×10^{-5}	Unlikely but possible to occur in the life of an item	Remote	**7**	**12**	**16**	**19**
8×10^{-5}	~0	So unlikely it may be assumed that it won't occur	Improbable	**11**	**15**	**18**	**20**

	Customer Notification	Containment	Corrective Action
1~5	**Immediate**	**Restrict field use. Purge existing stock.**	**Complete field retrofit as quickly as possible.**
6~10	Immediate	Warn customer to avoid conditions leading to the failure. Hold shipments till design change is incorporated.	Complete paced field retrofit at earliest opportunity.
11~15	Service Bulletin	No containment required	Change design, offer upgrade to customer.
16~20	Revision notes	No containment required	Change design at next opportunity, or correct the problem in the next generation product.

Selecting and prioritizing actions

- FMEA (Failure Modes and Effects Analysis
- Requires some knowledge of probabilities

CLIENT LOGO HERE

SIMPLIFIED FAILURE MODES AND EFFECTS ANALYSIS (SFMEA)

Plant: ______
System: ______
Subsystem: ______
Analysts: ______

SEV = Severity
OCC = Occurrence
DET = Detection
RPN = Risk Priority Number

SUBSYSTEM FUNCTION	FUNCTIONAL FAILURE	COMPONENT	POTENTIAL FAILURE MODE(S)	POTENTIAL EFFECT(S) OF FAILURE	POTENTIAL CAUSE(S) OF FAILURE	CURRENT CONTROLS	CURRENT PROCESS KNOWN FREQUENCY	RISK ASSESSMENT (AS IS)			
								SEV	OCC	DET	RPN
											0
											0
											0
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Keys for Success

- You aren’t the expert
  - Challenge everything
  - Speak with data, act on fact
- ***Have the data*** – and use it
- Don’t let motivations drive conclusions
- Resources
  - Always resource-constrained
  - Depends on risk and criticality
- Finish the job - verification

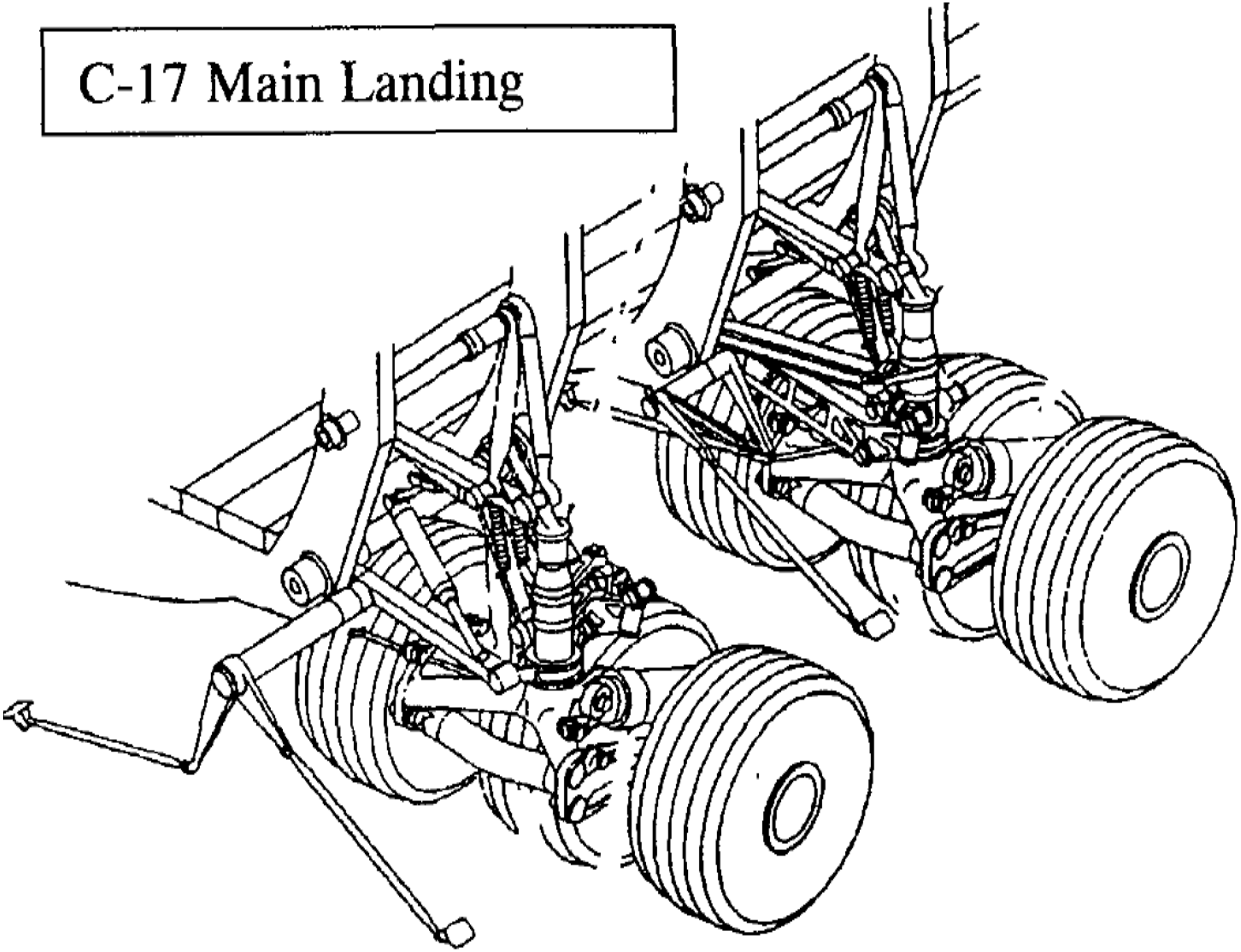
Case Studies

"In theory, there is no difference between theory and practice; In practice, there is."

-- Chuck Reid


YIELD TO AIRCRAFT
4
5

C-17 Main Landing



Department of Defense Inspector General Auditing Report 99-193, C-17 Landing Gear Durability and Parts Support, June 24, 1999

- Designed for and subjected to 600 hour durability test, vibration and thermal (Specification requirement)
- A couple of redesigns already
  - Identified location and mechanism of failure
  - Made it more robust both times
- Discarding 10-13 sensors per month
- Problem: Solve the high failure rate.

- ***Discarding*** 10-13 sensors per month
- A couple of redesigns already
- Problem: Solve the ***high failure rate***.
- Although each redesign had made the sensor stronger, there was never clear definition of the requirement
- Initial problem was an inadequate specification
- Most of the sensors currently being discarded had not failed
  - "Swaptronics"
- Resolution: Improve troubleshooting

Blue Screen of Death (BSOD)

BSOD continued…

Bug Check 0x77: KERNEL_STACK_INPAGE_ERROR

The KERNEL_STACK_INPAGE_ERROR bug check has a value of 0x00000077. This indicates that the requested page of kernel data from the paging file could not be read into memory.

Parameters

The four parameters listed in the message can have two possible meanings.

If the first parameter is 0, 1, or 2, the parameters have the following meaning.

Parameter	Description
1	**0:** Indicates that the page was retrieved from page cache **1:** Indicates that the page was retrieved from a disk **2:** Indicates that the page was retrieved from a disk, the storage stack returned SUCCESS, but **Status.Information** is not equal to PAGE_SIZE
2	Value actually found in the stack where the signature should be
3	0
4	Address of the signature on the kernel stack

If the first parameter is any other value, the parameters have the following meaning.

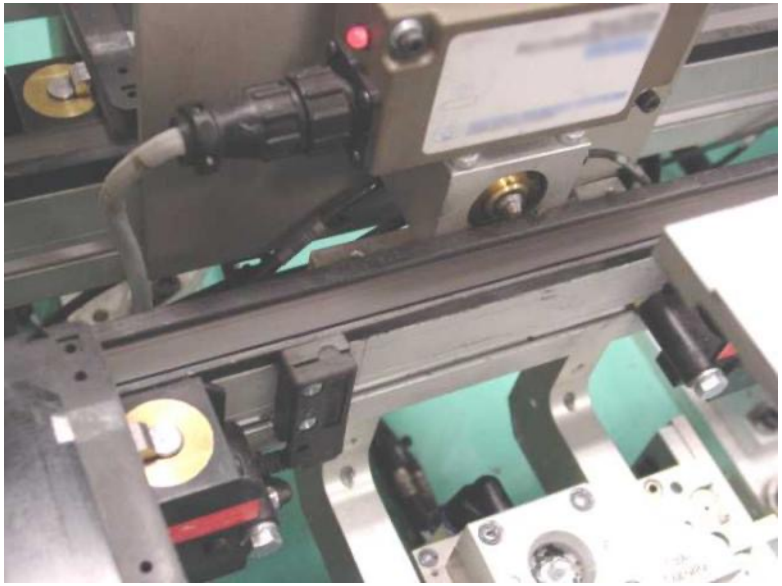
Parameter	Description
1	Status code
2	I/O status code
3	Page file number
4	Offset into page file

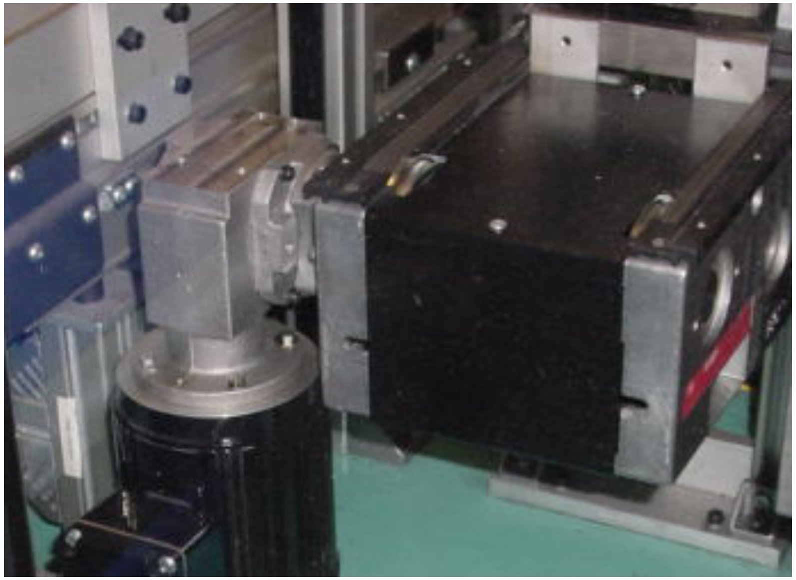
Key take-aways

- Conclusion
  - Micro-bubbles forming on the disk drives
  - Only happens if the (computer) is left on all the time
  - Corrective action was to turn off the computers at and restart them once every 24 hours
    - Not a true corrective action
- Lessons for RCFA
  - Took about 18 months from initiation of activity to report
  - Dedicated (and determined) engineer

Conveyor Failures

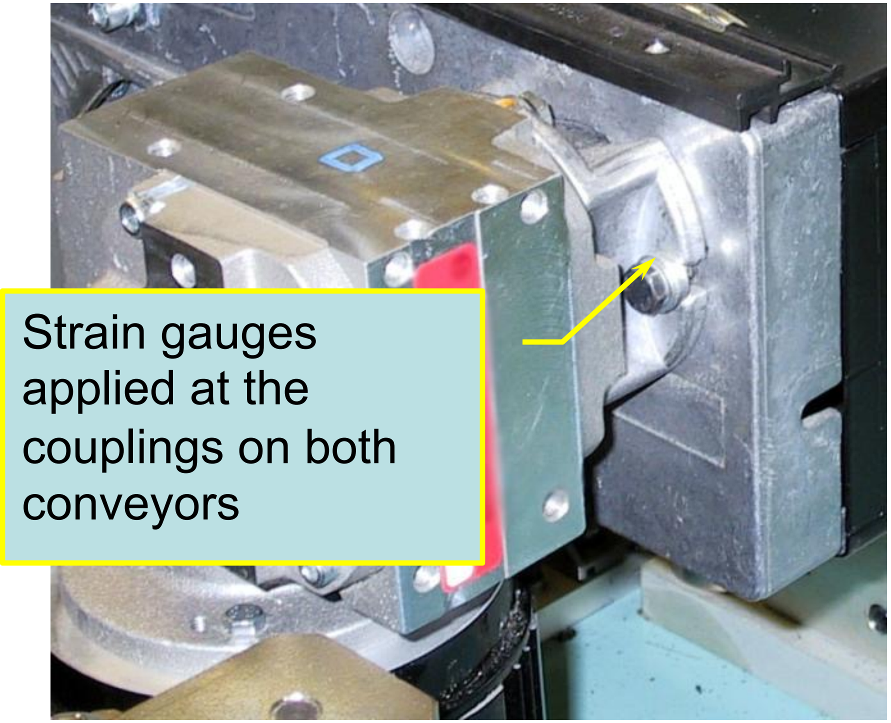
- High failure rate
  - Motors tripping
  - Gearbox failures
- Solve the high failure rate



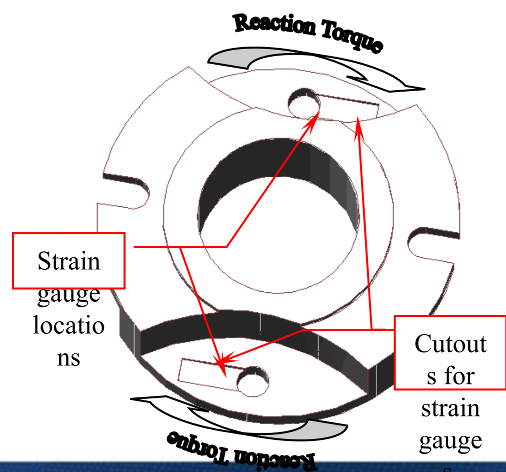


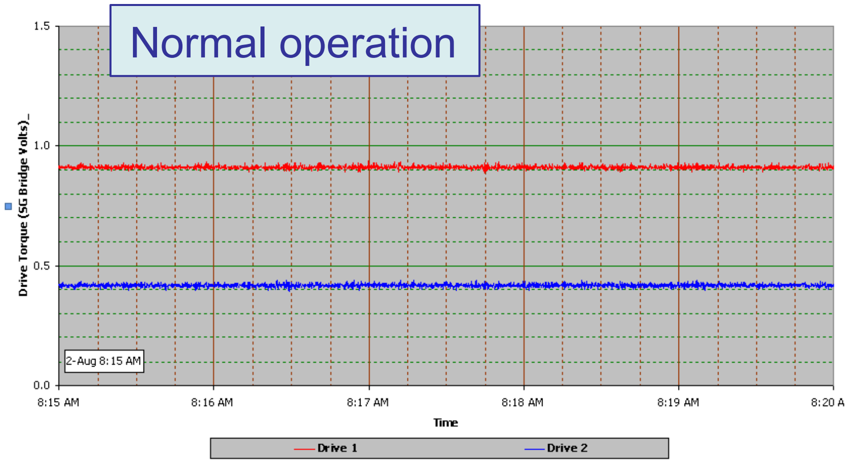
Conveyor Failures continued…

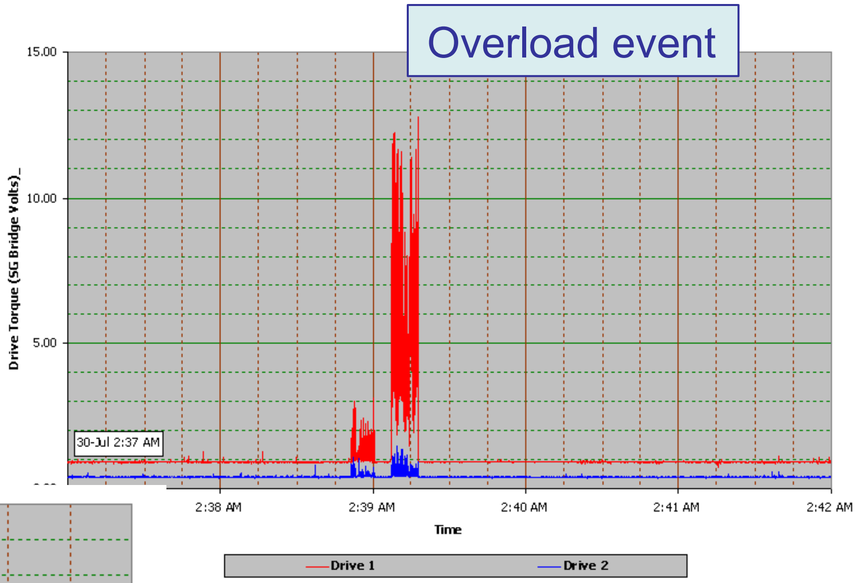
- Problem definition
  - The corrective action team determined that the failures were generally of two types,
    1. premature wear out consistent with long term, slightly elevated loading, and
    2. failures consistent with transient torque overloads.
  - One side has a higher failure rate than the other
  - Load?

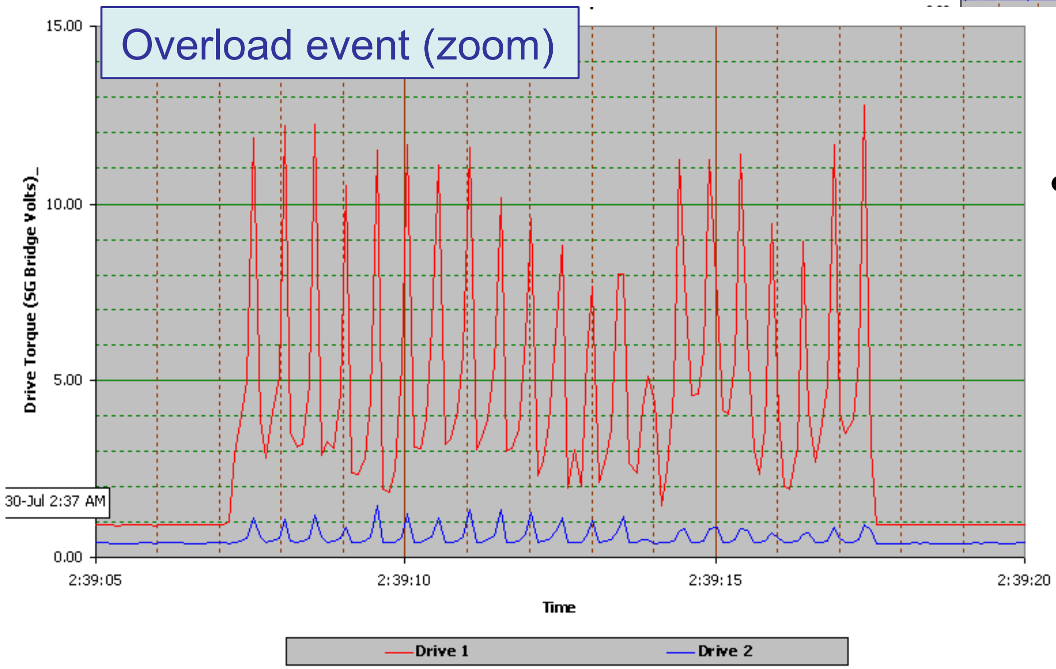


- Setup a remote data acquisition system (WebDaq)
- Began gathering long-term data
  - About 8 days of continuous data
  - Then about 137 hours of intermittent (triggered) data









- Frequency indicates coupling slipping

Conveyor Failures conclusion

- Life difference between drives is normal wear-out due to higher load during normal operation
- Premature failures due to overload events…
  - "Clamping" of the belts due to programming errors in control system
- Latent causes ***not*** addressed…
  - Development, installation and run-off process that permitted the programming errors
  - Process that failed to catch the errors

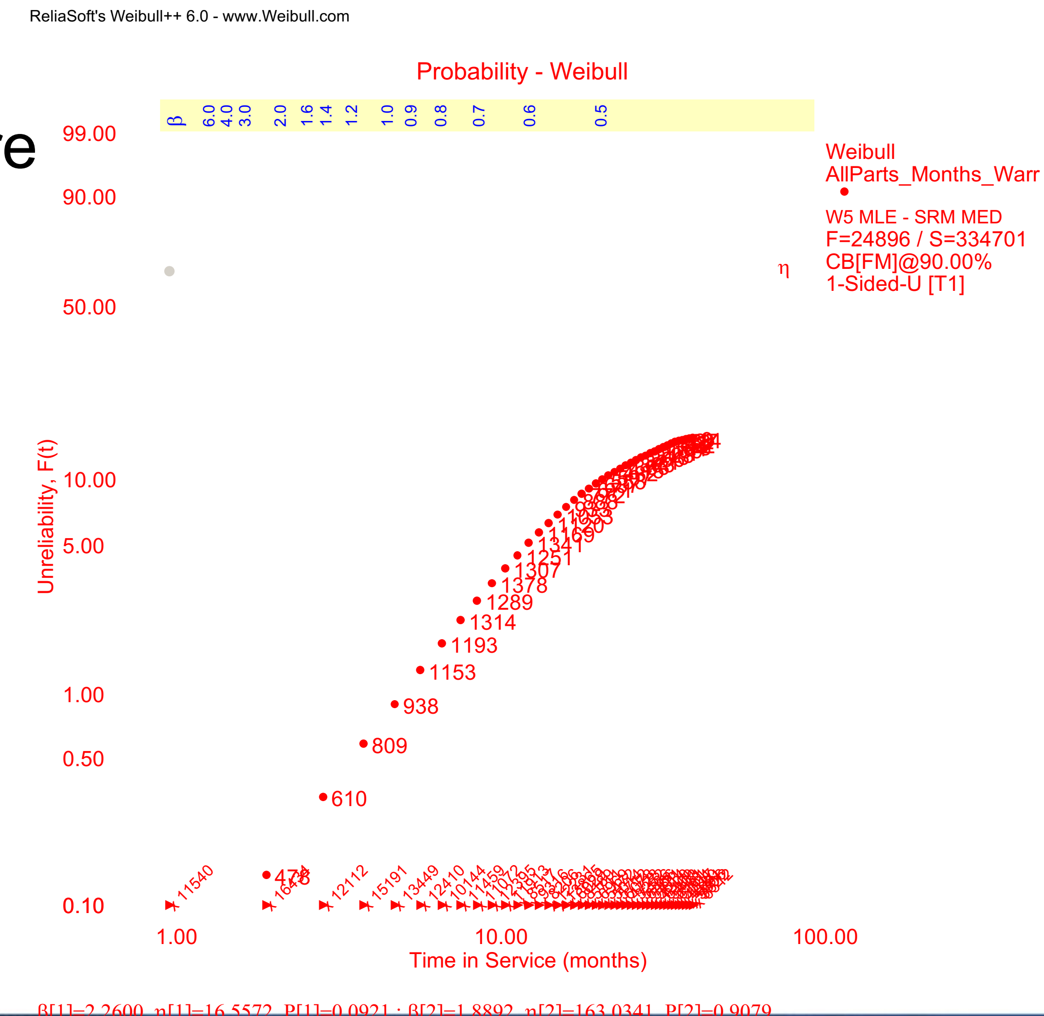
- Fundamental Principles / Lessons Learned (for Root Cause Failure Analysis…)
  - Devoted adequate resources
  - Did ***not*** do a design change based on initial "apparent" cause
  - Problem definition / Data collection
  - Time commitment
    - 10 Months from identification of failure for RCFA to final report

Mobile hydraulic pumps Truck pumps leakage

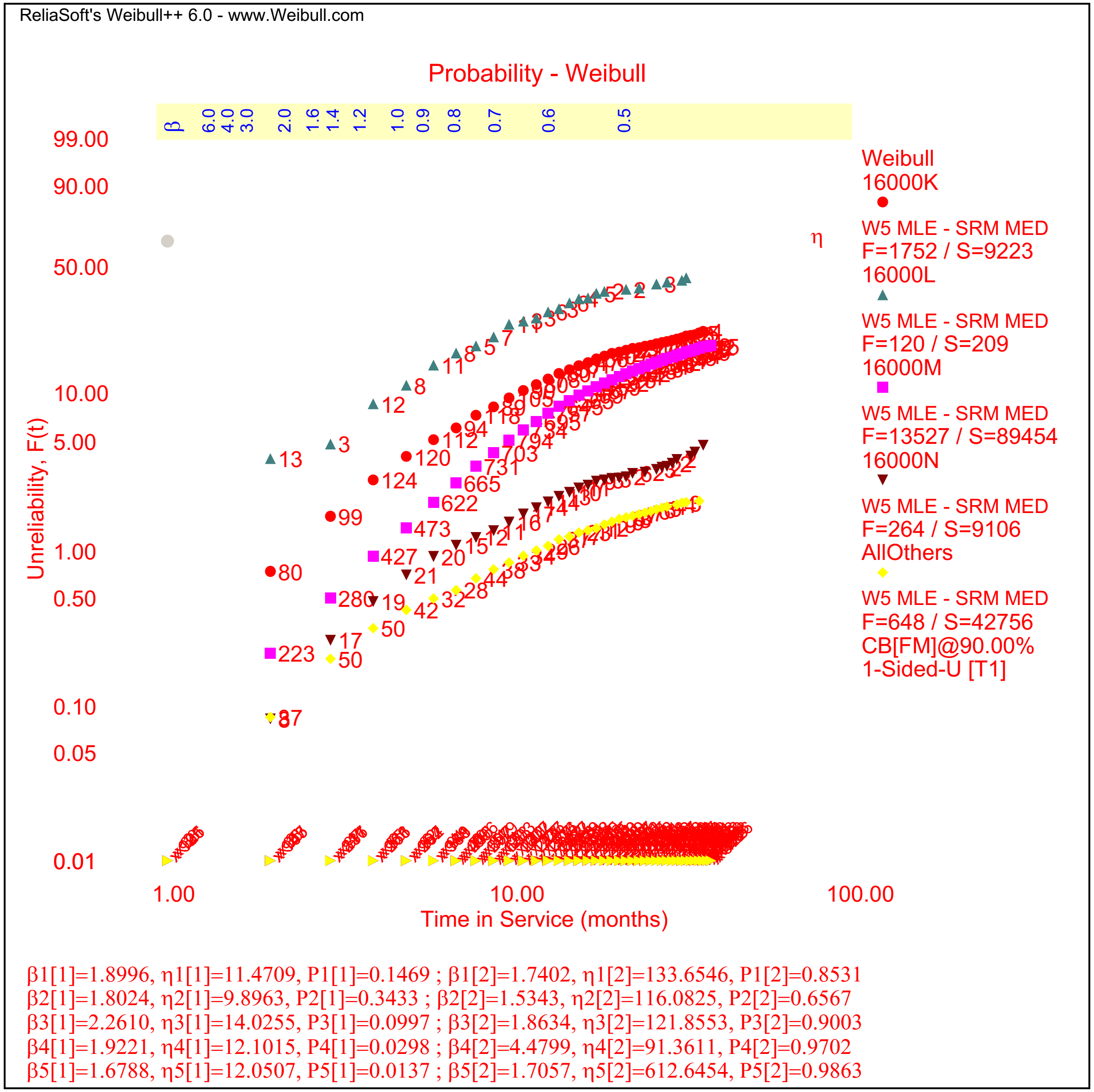
- Problem
  - Reported substantial increase in failure rate due to leakage
  - Initial conclusion (assumed) – faulty pump
  - Initiated a campaign to replace all the pumps
- Very good data
  - Extensive details on *every* failure
    - Model, serial number, application, hours in service, calendar time in service…

Mobile hydraulic pumps continued… Truck pumps leakage continued…

- Established 13 year timeline showing entire history of design and application
- Reviewed detailed removal history and failure probability distributions
- Identified 2 different failure modes…

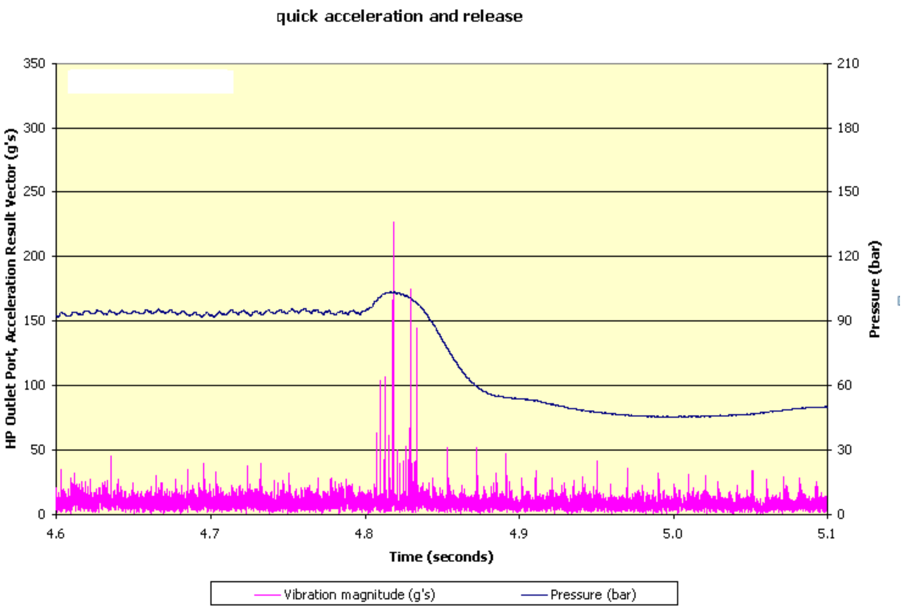


Further analysis permitted us to isolate and identify subpopulations with distinctly different failure distributions



Mobile hydraulic pumps continued…
Truck pumps leakage continued…

- Truck test results
  - 1. The highest acceleration levels are always associated with rapid pressure drops, |dP/dt| about 1800 bar per second or greater.
  - 2. Pressure drops (|dP/dt|) on Truck 2 were on average a little greater truck 1, but they never result in the impact signature.
  - 3. |dP/dt| >= about 1800 bar per second ALWAYS results in an impact signature on truck 1



Mobile hydraulic pumps continued…
Truck pumps leakage conclusions

- Have the data
- Statistical tools
- Resources
  - About 1 year

The word 'politics' is derived from the word 'poly', meaning 'many', and the word 'ticks', meaning 'blood sucking parasites'."

-- *Larry Hardiman*

Acme* Gearbox - Background

- 3-stage, 1800kW gearbox driving a rock crusher
- Late in the evening there was a vibration alarm
- Alarm was "not unusual", they continued operating
- Early the next morning there was a loud noise, and shutdown for vibration

*Some details have been changed

Background continued…

- Over the next few days they replaced the gearbox with a spare
- Vendor was consulted. They “knew exactly what went wrong”
- Insurance company requested an independent Root Cause Failure Analysis

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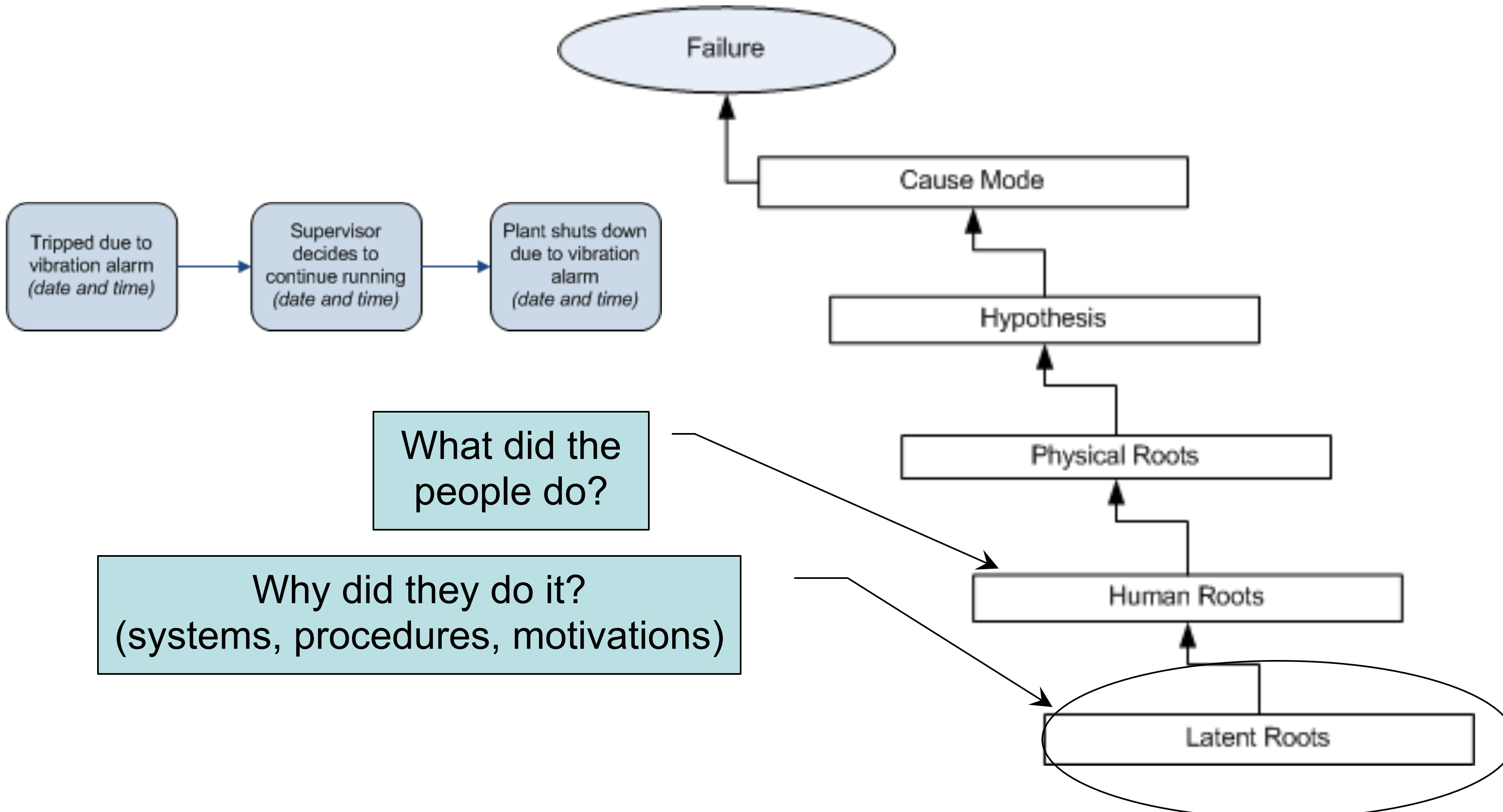
Complications

- "Independent"
  - Implies limited cooperation between experts
    - People who designed and built the equipment
    - People who maintained and operated equipment
  - Don't take everything at face value
    - Consider everyone's motivations
    - There are vested interests in different possible conclusions
- Limited access to the hardware
  - Resources

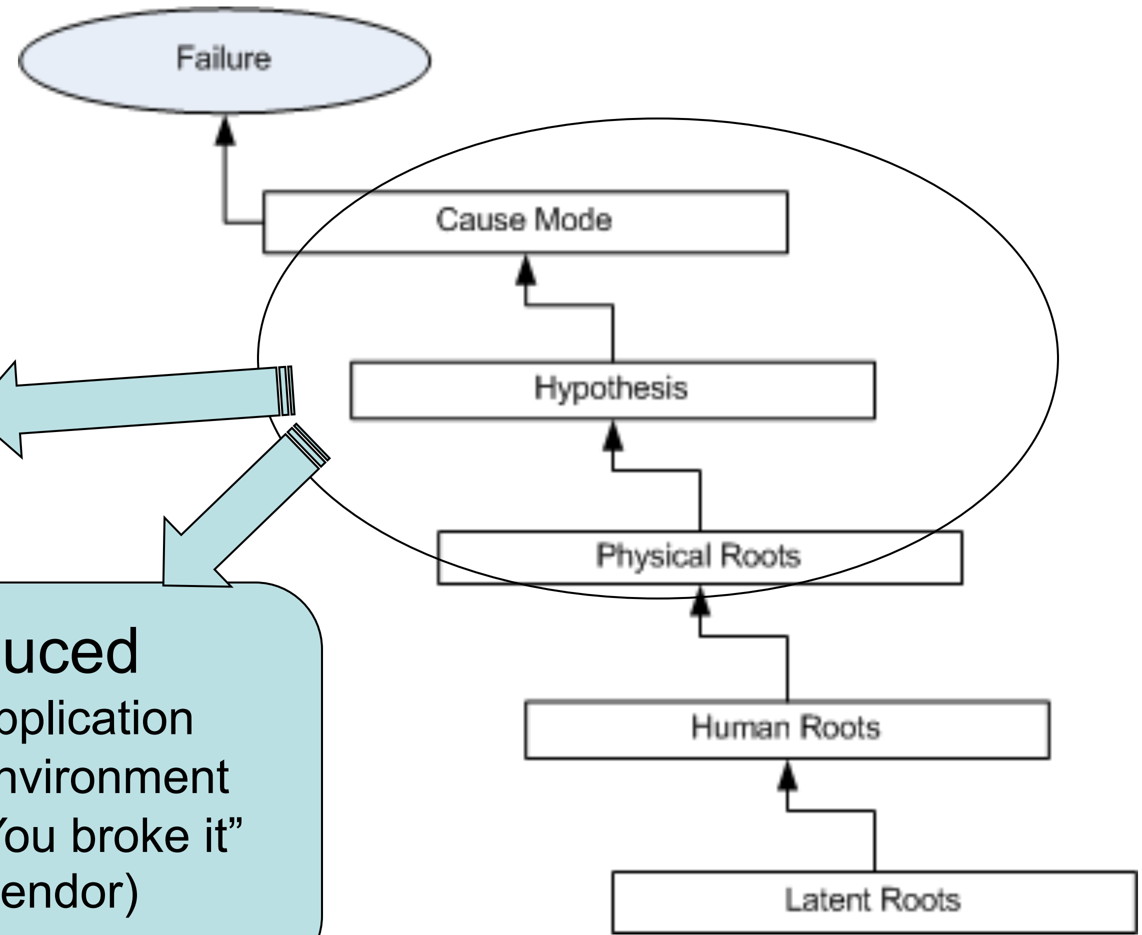
Investigation



This is where you usually find the “root” cause

Investigation

Inherent
- Design
- Materials
- “It broke” (user)



Induced
- Application
- Environment
- “You broke it” (vendor)

Answers the question “which humans?”

Data (“Describe the problem” from 8D form)

- Loading, both before the incident and historically
- Equipment design, ratings (what was it expected to do?)
- Maintenance history
- Vibration analyses / reports

Contaminant report…

Account Number		Description	Caution
Account Name		Application	
		Manufacturer	
Date		Model	
Signum Number		Registered Lubricant	

Comments: VISIBLE SEDIMENT is preventing certain testing: Some tests could not be run because the level of sediment in the sample could cause damage to precision laboratory equipment. Oil should not contain visible sediment. Carefully resample the system to insure that no outside contamination is introduced. If this is already the 2nd sample, then consider: 1. The sample was not taken from the bottom of the reservoir, 2. Use sample ports to insure that the sample is taken from the same point each time. 3. Make sure that all tank fill caps and breathers are properly secured. 4. If applicable, insure that the filter/centrifuge is working properly 5. Check non-turbulent areas for localized contamination. 6. If this was a representative sample, consider to drain and flush the system or utilize appropriate filtration to remove the sediment.

Sample ID			
Date Sampled			
Report Date			
Brand	**MOBIL**	MOBIL	MOBIL
Lubricant Tested	**SHC 634**	SHC 634	SHC 632
Equipment			
Oil Age			
Resv. Temp			
Make-up			
Oil Changed			
Filter Changed			
Lubricant Data			
Contamination Rating	**+Caution**	Normal	Normal
Equipment Rating	**Normal**	Normal	Normal
Oil Rating	**Normal**	Normal	*Alert
Viscosity @ 40C	**436.0**	444.3	*446.5
ISO Code (4/6/14)	**+**	21/19/14	
Particle Count > 4µ	**+**	17558	
Particle Count > 6µ		3754	
Particle Count >14µ		141	
PQ Index	**0**	8	
TAN (mg KOH/g)	**0.50**	0.59	0.57
Water (Hot Plate)			NotDetected
Water (Vol%)	**0.011**	0.007	

Sample ID			
Report Date			
Wear Elements (ppm)			
Al (Aluminum)	**0**	0	0
Cr (Chromium)	**0**	0	0
Cu (Copper)	**0**	0	0
Fe (Iron)	**5**	5	2
Mo (Molybdenum)	**0**	0	0
Ni (Nickel)	**0**	0	0
Pb (Lead)	**0**	0	0
Sn (Tin)	**0**	0	1
Contaminant Elements (ppm)			
B (Boron)	**1**	0	0
K (Potassium)	**0**	0	0
Na (Sodium)	**0**	0	0
Si (Silicon)	**15**	11	15
Additive Elements (ppm)			
Ba (Barium)	**0**	0	0
Ca (Calcium)	**20**	1	1
Mg (Magnesium)	**5**	0	0
P (Phosphorus)	**701**	728	676
Zn (Zinc)	**12**	1	1

Vibration

★

GEAR REDUCER

Peak vibration on the reducer is .172 in/sec occurring at 11,323 cpm; the intermediate gearmesh frequency. The motor outboard bearing continues to exhibit minor levels of higher frequency bearing defect vibration occurring at 8.2X the shaft speed. We recommend periodically checking

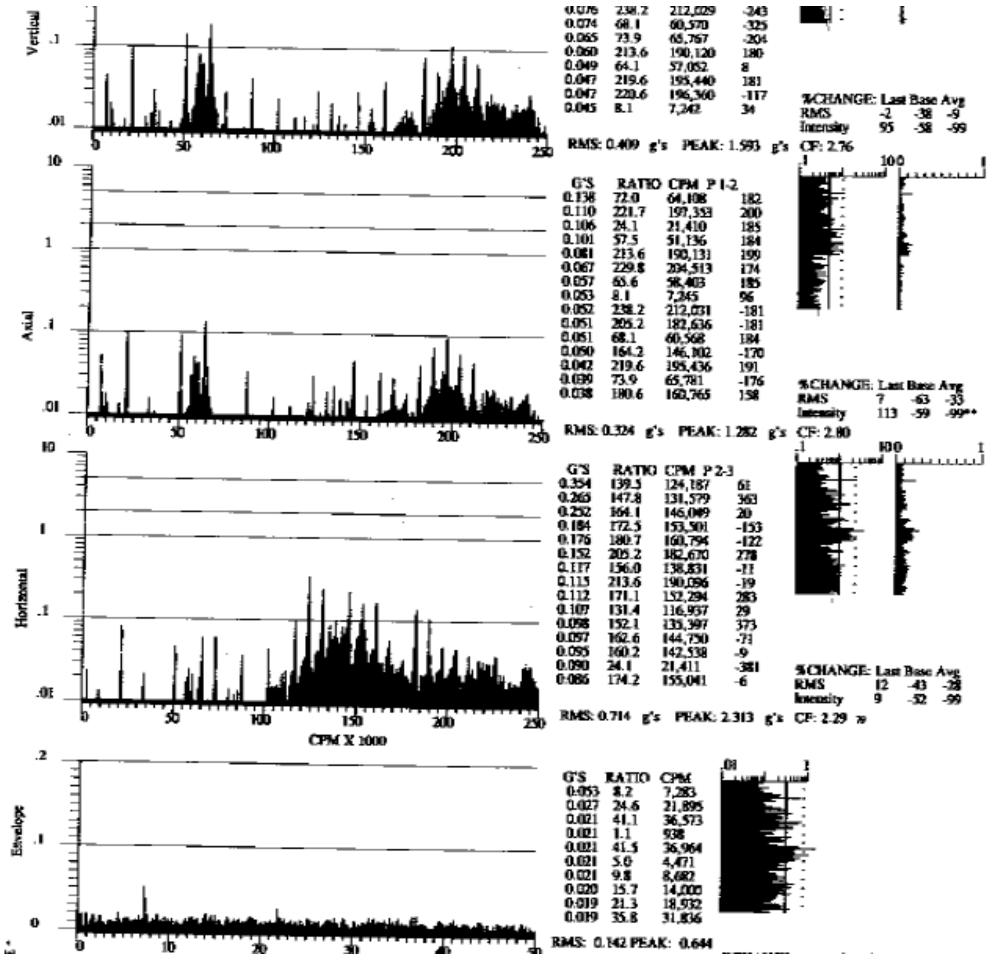
History Report

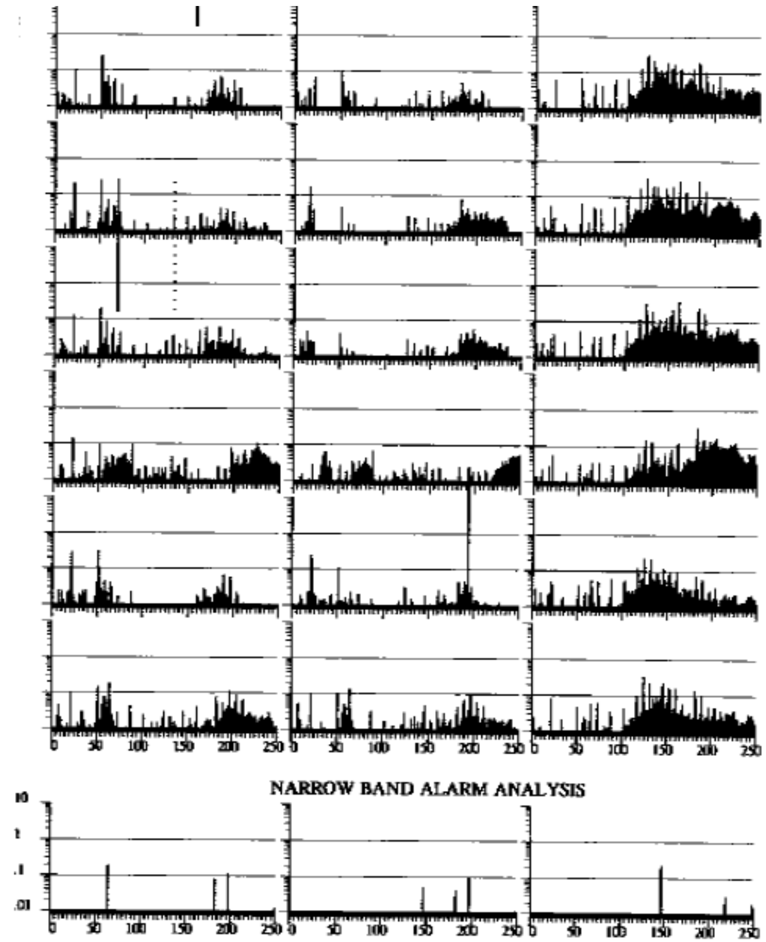
(monthly checks… one year history)

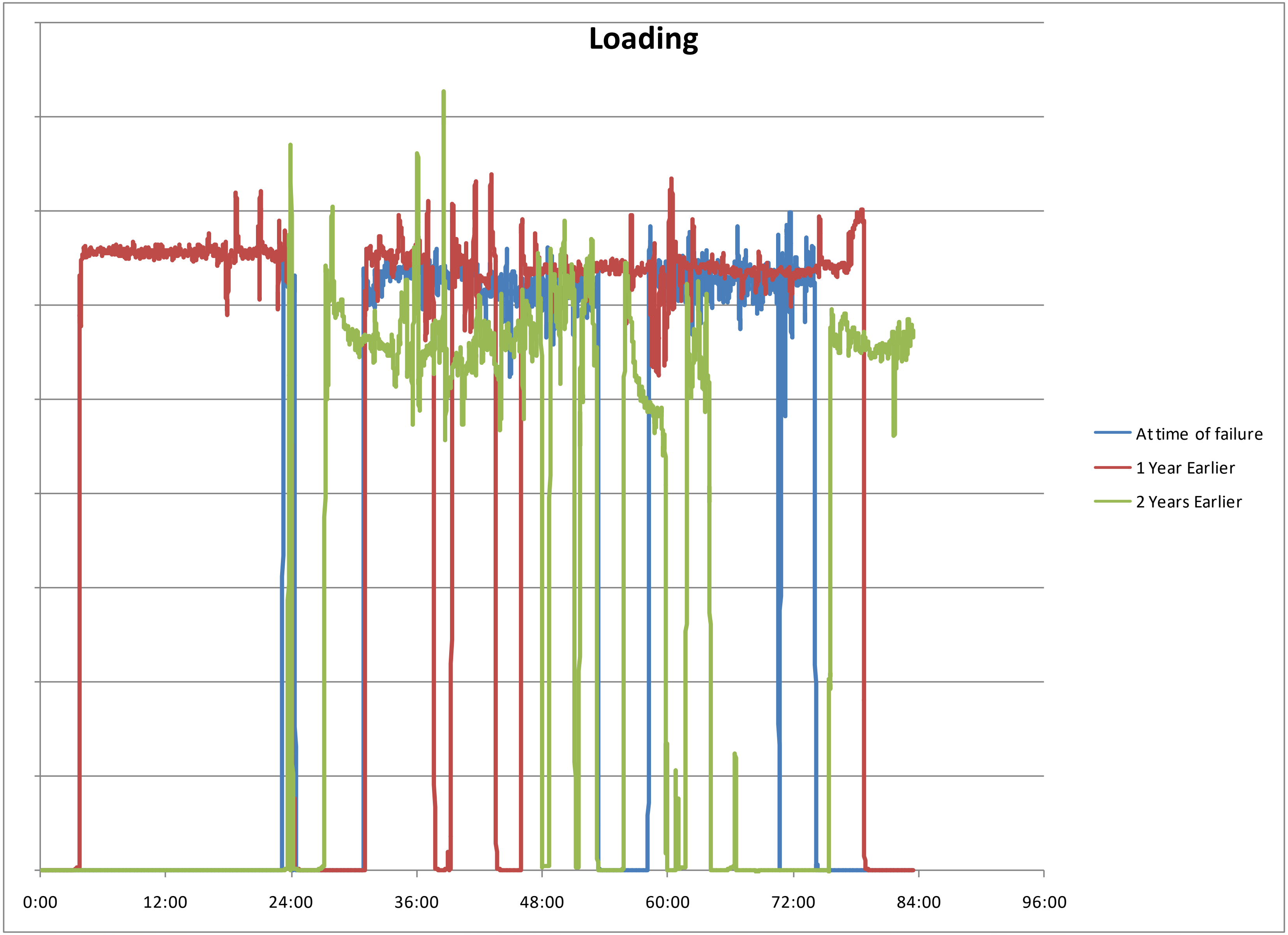
	Machine Name												
(motor bearing)	GEAR	1	1	1	1		1	1	1	1	1		

- Requested source data, FFT parameters, etc.

Vibration (source data)

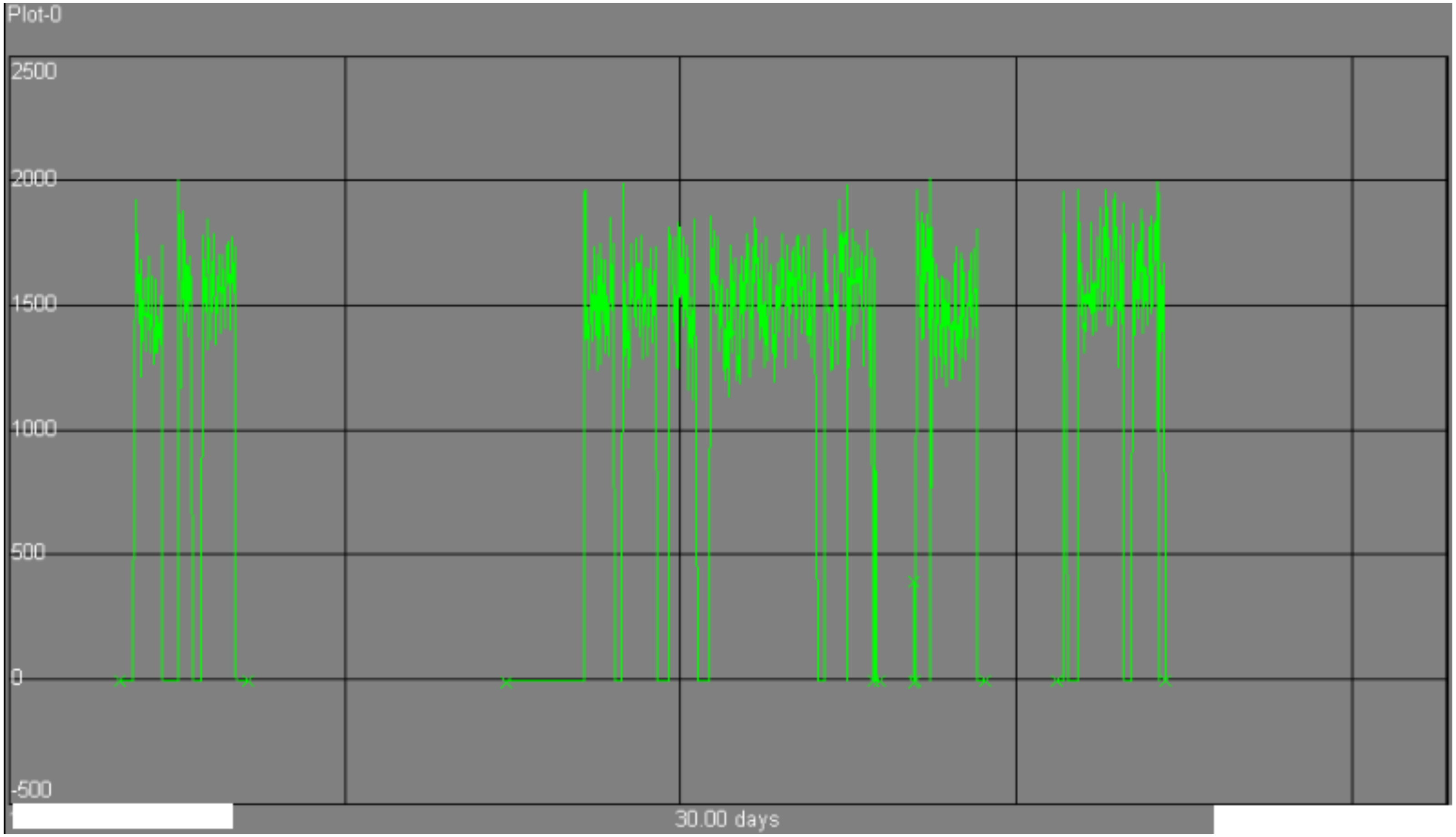




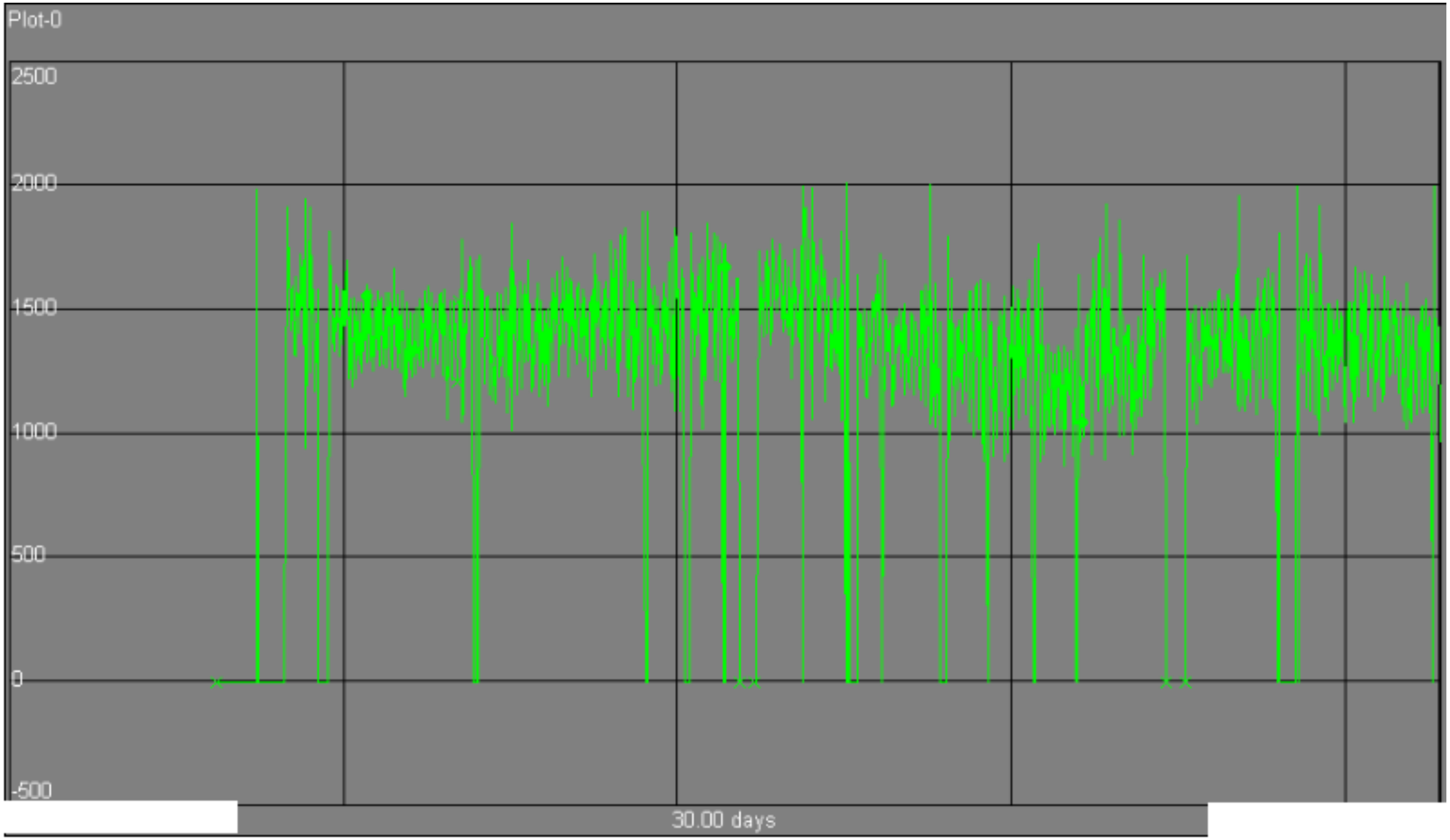


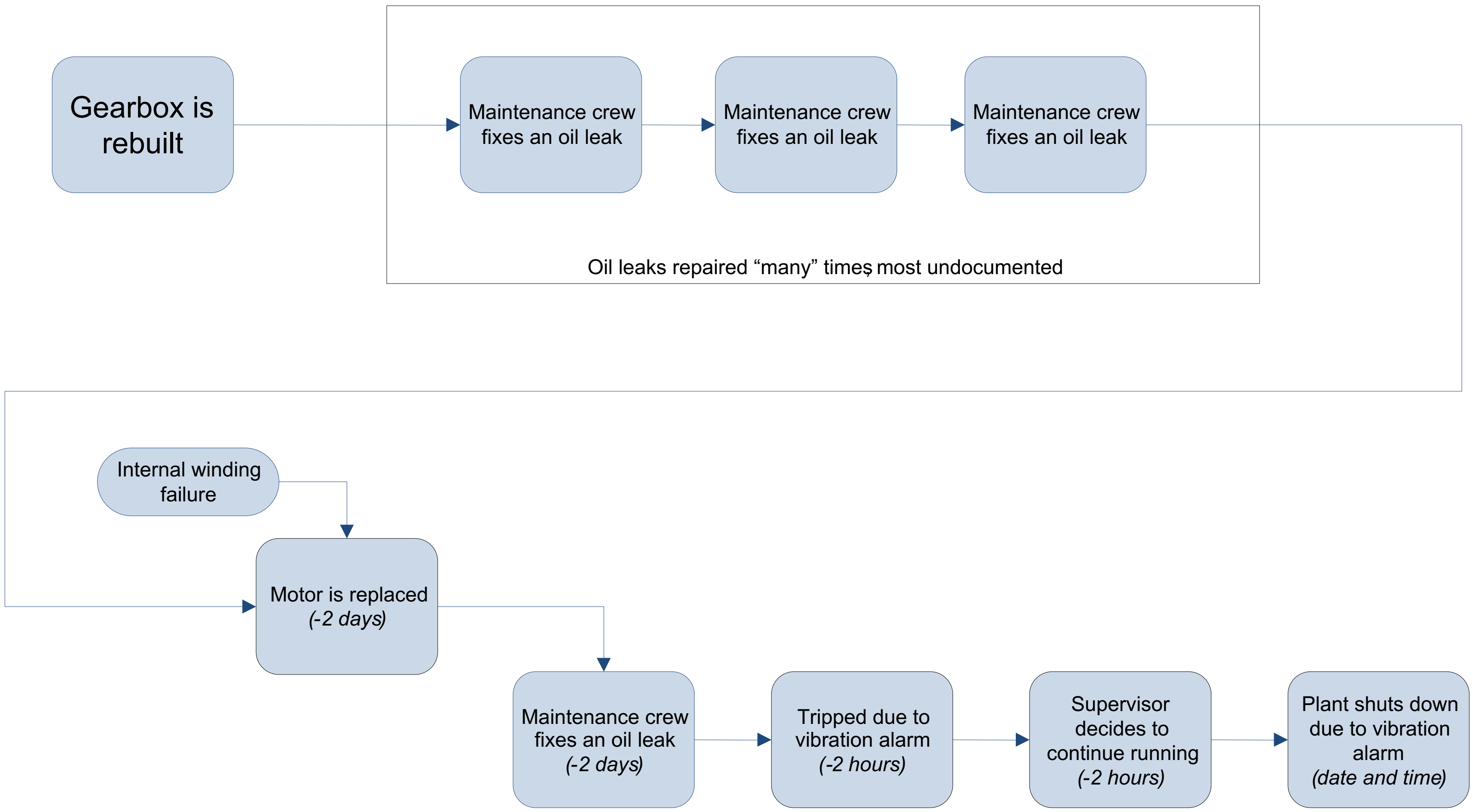
Loading
0:00
12:00
24:00
36:00
48:00
60:00
72:00
84:00
96:00
At time of failure
1 Year Earlier
2 Years Earlier

Power – 30 days leading up to failure



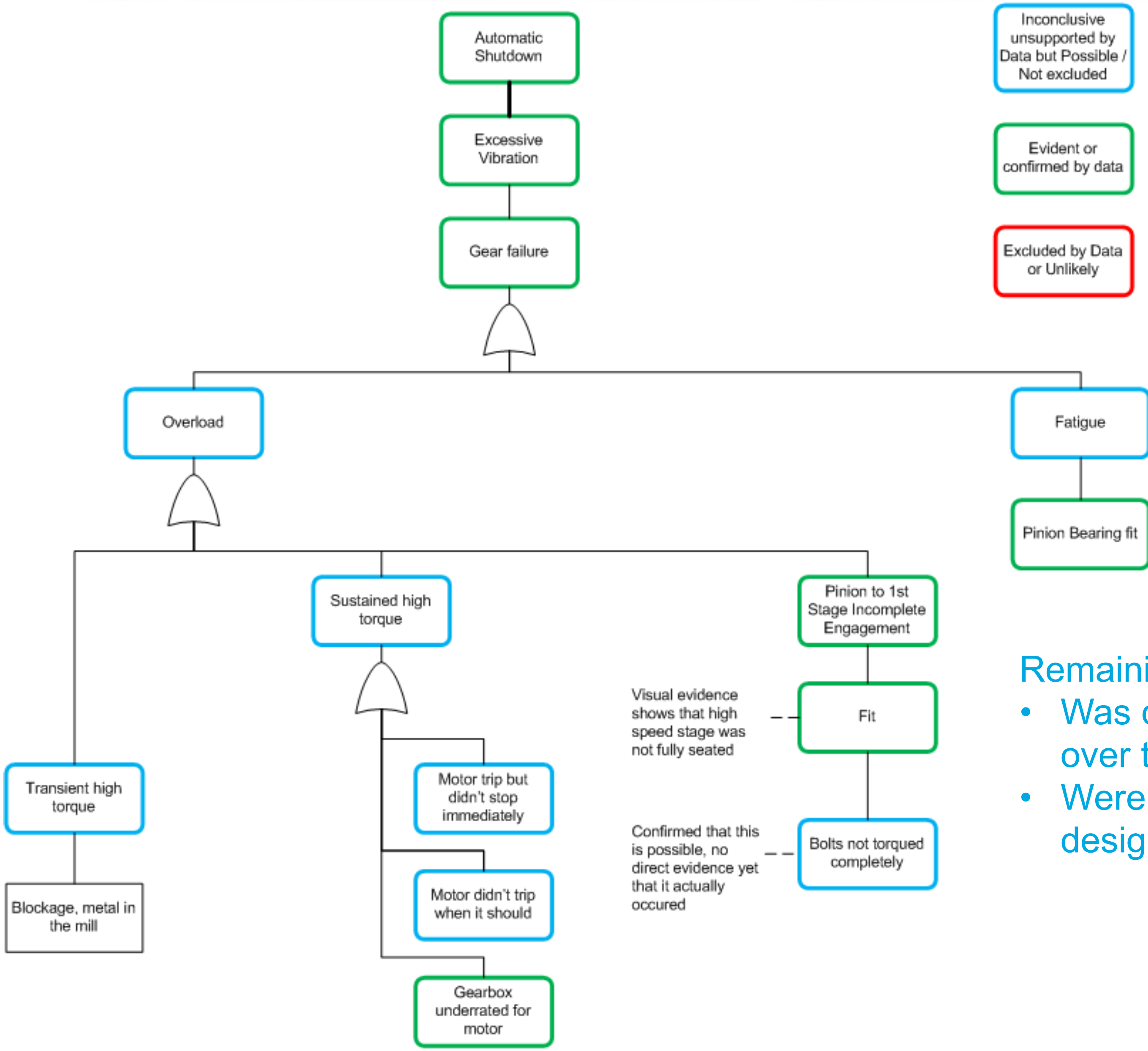
Power – 30 days 1 year earlier




Gearbox is rebuilt
Maintenance crew fixes an oil leak
Maintenance crew fixes an oil leak
Maintenance crew fixes an oil leak
Oil leaks repaired "many" times, most undocumented
Internal winding failure
Motor is replaced (-2 days)
Maintenance crew fixes an oil leak (-2 days)
Tripped due to vibration alarm (-2 hours)
Supervisor decides to continue running (-2 hours)
Plant shuts down due to vibration alarm (date and time)

Interviews – the picture that emerges

- 2 days prior – high speed shaft was not properly drawn up to engage the pinion
  - Crew did not have specs or manuals
  - No one knew where they were
- Oil leaks had been repaired "many times" since rebuild
- Could have been improperly reinstalled any of those times
- Prior to failure, crews heard "Rumble" typical of loading too much material (common occurrence)
- Other crews described the proper procedure, "tribal knowledge"
- Maintenance records were incomplete
- Vendor reported no apparent problems when new motor was installed
- Control room vibration monitoring was not helpful
- Alarms occurred "all the time" with no action taken
- There were indications a failure was imminent



Remaining questions:

- Was damage accumulating over time?
- Were there material or design contributors?

Metallurgical report

- Two contact patterns…
  - “Frosting” below the pitch line, indicating a period of normal wear
  - Obvious indications of wear near tooth tips
- Bearings indicated a severe misalignment
- Nothing anomalous in material properties (hardness, case depth, chemical and microstructure)
- Failure was due to low cycle fatigue prior to overload

Root cause conclusions

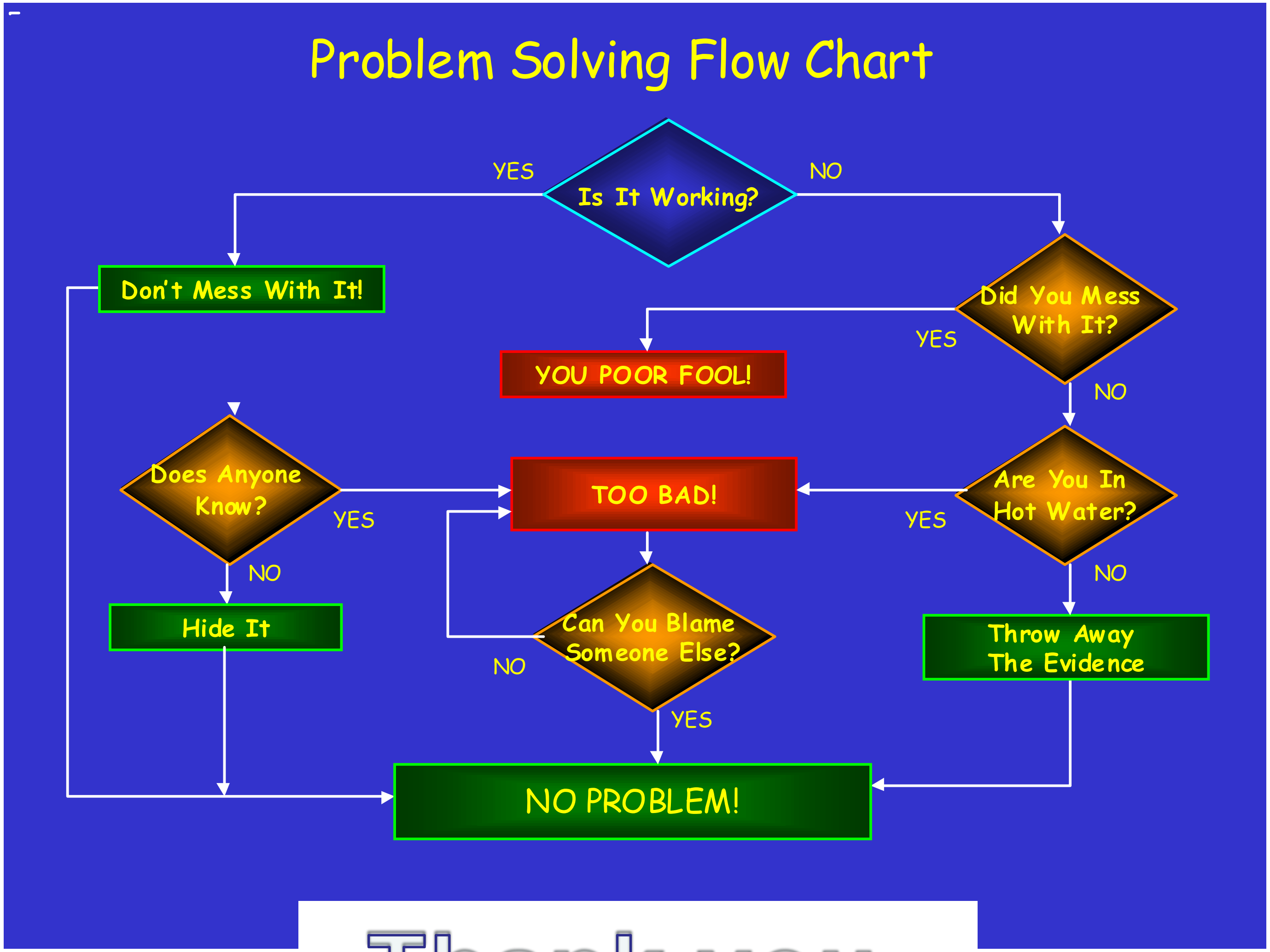
- Induced failure due to
  - improper maintenance, resulting in low cycle fatigue then overload
  - High loads due to material overloading were a likely contributor
- Latent factors:
  - Poor cooperation with supplier(s)
  - Inadequate documentation and equipment specific training
  - Ineffective warning system and propensity to ignore warnings

- Proposed corrective actions
  - Acquire up-to-date specifications, documentation and maintenance procedures for critical equipment
  - Ensure equipment specific training for maintenance personnel
  - Review adequacy of alarm system to ensure warnings are **adequate** and **meaningful**
  - Define appropriate responses
  - Instill a culture that expects response and action

Conclusions, or if you remember nothing else about Root Cause Analysis, remember this:

- **Do it**. RCA is the engine that drives continuous improvement.
- Have the data
  - Keep good records, not just of failures but of
    - All maintenance actions
    - When did it begin service? … end?
    - Operating conditions
    - If you don't have a good CMMS, get one.
    - If you do (or when you do), USE IT
- Resources. Have the right
  - People
  - Training, and
  - Tools.

The last word…



Thank you.