Failure Management Policies

Module 2.5en

What must be done to **mitigate the consequences** of the failure modes identified in RCM Question 5?

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RCM

A process used to
determine what must be done
to ensure that a physical asset continues to do what
its users require it to do in its operating context:

What do its users require it do (Functions)?
What specific performance losses can occur (Failures)?
What event causes the failure (Failure mode)?
What happens when it fails (Effects)?
Why does it matter (Consequences)?

Failure Management policies

Can you predict, prevent or mitigate the failure consequences (Maintenance task)?
What if no mitigating task can be found (Default action)?

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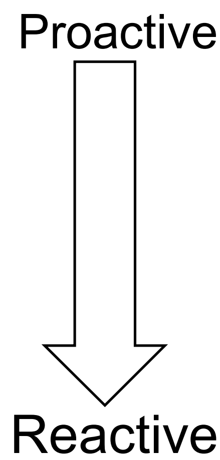
Failure Management Policies

1. CBM = Condition Based Maintenance
2. TBM = Time Based Maintenance
3. FF = Failure Finding
4. Redesign
5. NSM = No schedule maintenance



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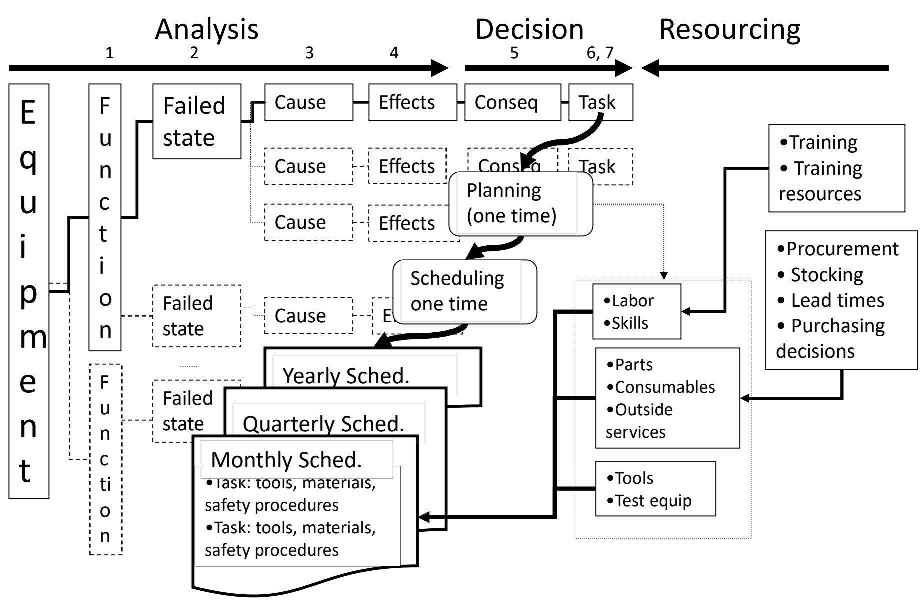
RCM line of sight



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Time Based Maintenance (TBM)

"Time" can be calendar time but more often it is the **"working age"** of the asset measured in a convenient unit proportional to the accumulated **stress** on the asset.

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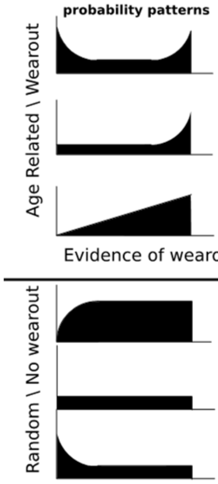
The RCM Curves. What do they mean?



The six conditional failure probability patterns	UAL 1978	Broberg 1973	MSDP Studies 1983	SSMD 1993
A.	4%	3%	3%	6%
B.	2%	1%	17%	0%
C.	5%	4%	3%	0%
Evidence of wearout	11%	8%	23%	6%
D.	7%	11%	6%	0%
E.	14%	15%	42%	60%
F.	68%	66%	29%	33%
No evidence of wearout	89%	92%	77%	93%

Intrinsic or actual failure behavior?

- Answer: Intrinsic or true behavior regardless of PM
- How is this possible?

It's a Paradox!

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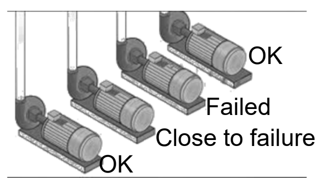
The answer lies in the observed data

At the moment of maintenance, we observed that:

1. Some items failed
2. Some were in excellent condition but were renewed anyway
3. Some were about to fail

- We report the above findings to our manager. And,
- **What does he ask?**



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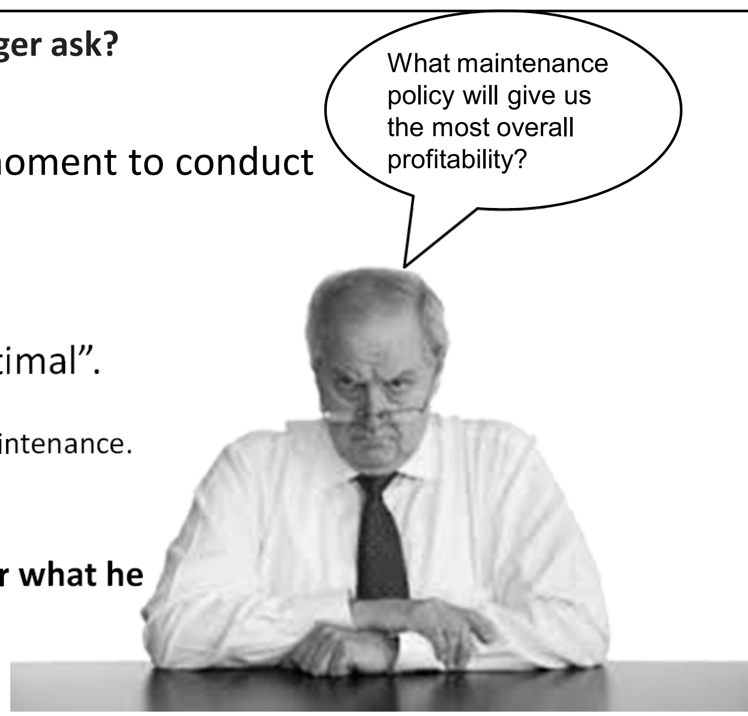
What does the astute manager ask?



“What is the "**optimal**" moment to conduct maintenance?”

He wants a PM policy…
The policy should be “optimal”.

- Not too many failures.
- Not too much ~~unnecessary~~ maintenance.

How do we give our manager what he wants?

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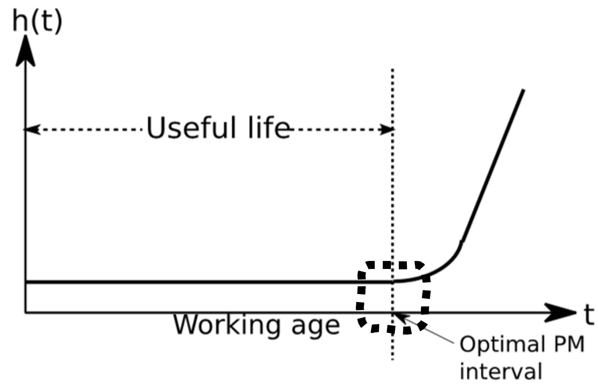
Assume the "true" failure behavior is "B"



So what is the answer to the question: Do the RCM curves represent the true or PM modified failure behavior?

Given that we have "real world" data – **how do we draw these true behavior curves?**

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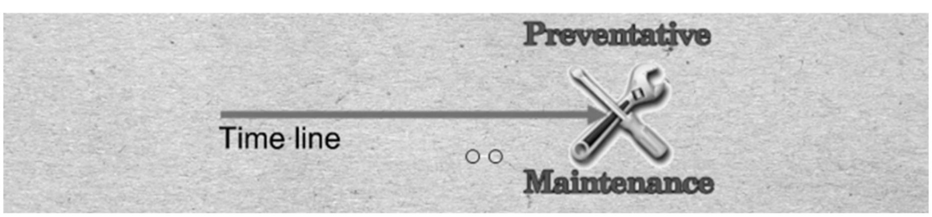
Suspended data



Suspended lifetimes are those that end by an act of prevention <u>without</u> having failed

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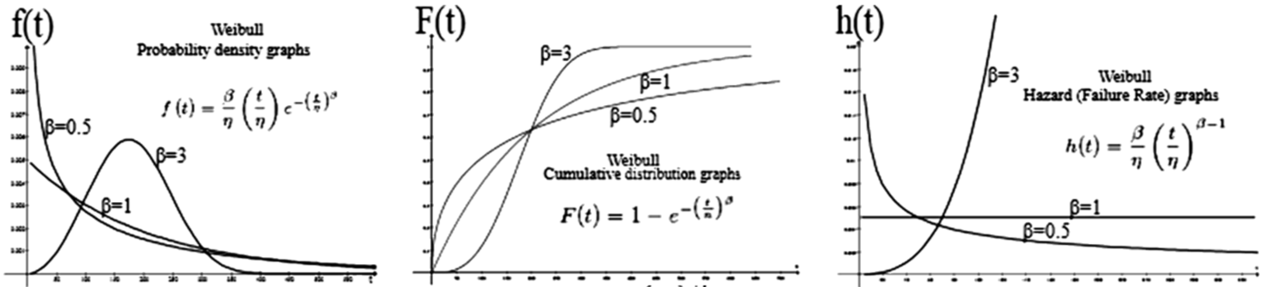
The most popular way of drawing the intrinsic reliability curves: Weibull analysis

Three of the forms of the Weibull equation



1. Probability density $f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right) e^{-\left(\frac{t}{\eta}\right)^{\beta}}$ (Eqn. 1)
2. Cumulative distribution $F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$ (Eqn. 2a), and

   Reliability (aka Survival Probability) $R(t) = 1 - F(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$ (Eqn. 2b)
3. Failure Rate $h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$ (Eqn. 3)

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Therefore to draw the RCM Curves…

We need to “solve” the Weibull equation to “estimate” the values of:

- The shape parameter β, and
- The scale parameter η

$$\boxed{h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}}$$

There are several ways to perform the estimation. Let’s have a look at one of them in the following example …

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Observations at maintenance

Item	Failure age	The part's life ending event
A	84	Failed (**F**)
B	91	Suspended (**S**)
C	122	Failed (**F**)
D	274	About to fail (**F**)

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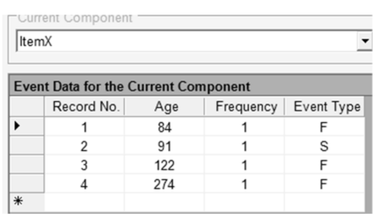
Enter the data and fit the Weibull to the data

1



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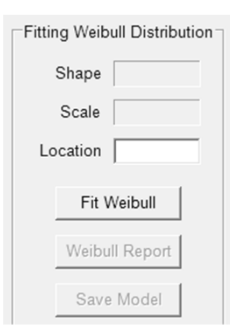

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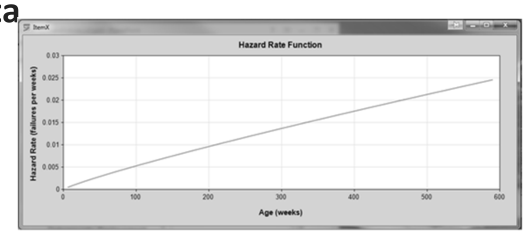

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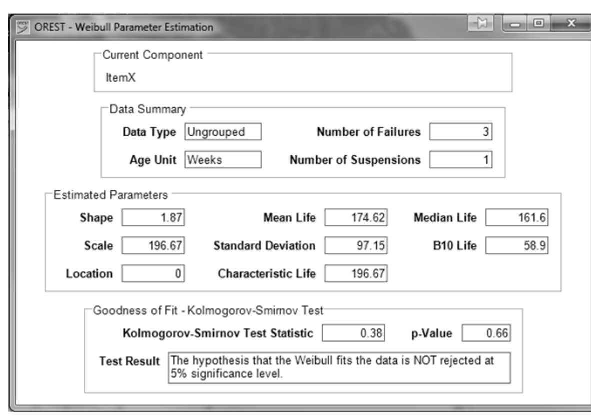

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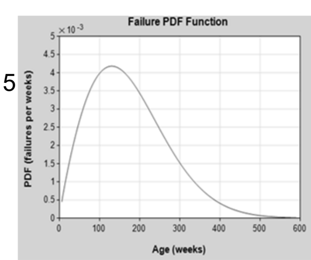

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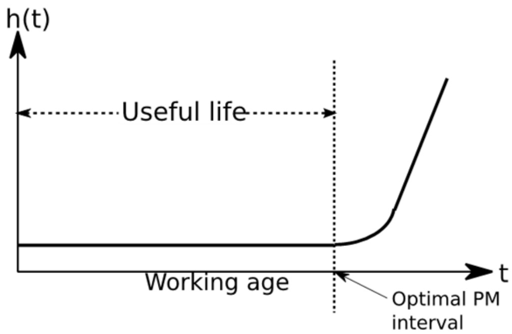
Now that we can draw the curve we still need to know how to select the optimal age point

$$\mathrm{h}(t) = \frac{f(t)}{1 \quad \int_0^t f(t)\,dt}$$



We do this by focusing on the "probability density" form of the Weibull curve…

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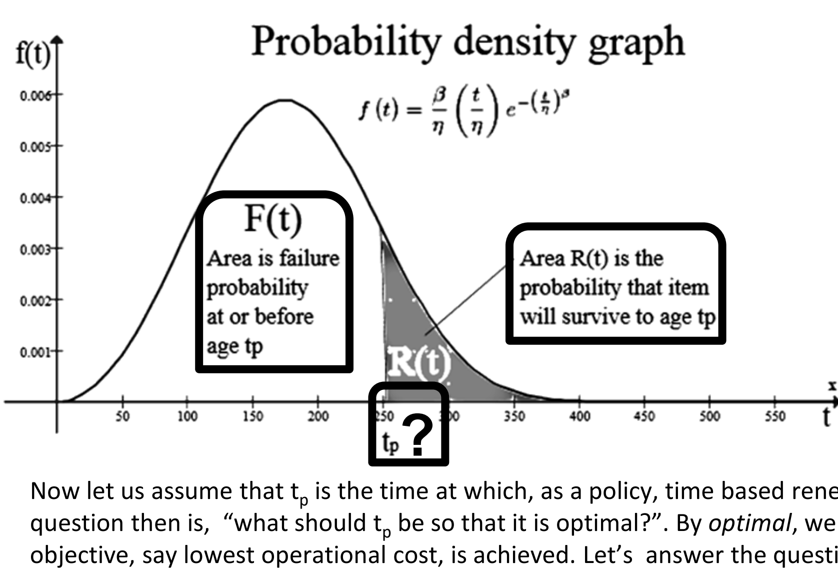
The Probability Density graph has some revealing characteristics…



$$C_t = C_R R(t_p) + C_F\left(1 \quad R(t_p)\right)$$

$$t_t = t_p R(t_p) + t_F\left(1 \quad R(t_p)\right)$$

$$\frac{C_t}{t_t} = \frac{C_R R(t_p) + C_F\left(1 \quad R(t_p)\right)}{t_p R(t_p) + \int_0^{t_p} t f(t)\,dt}$$

Now let us assume that t_p is the time at which, as a policy, time based renewal, is carried out. The obvious question then is, "what should t_p be so that it is optimal?". By *optimal*, we mean that the organizational objective, say lowest operational cost, is achieved. Let's answer the question…

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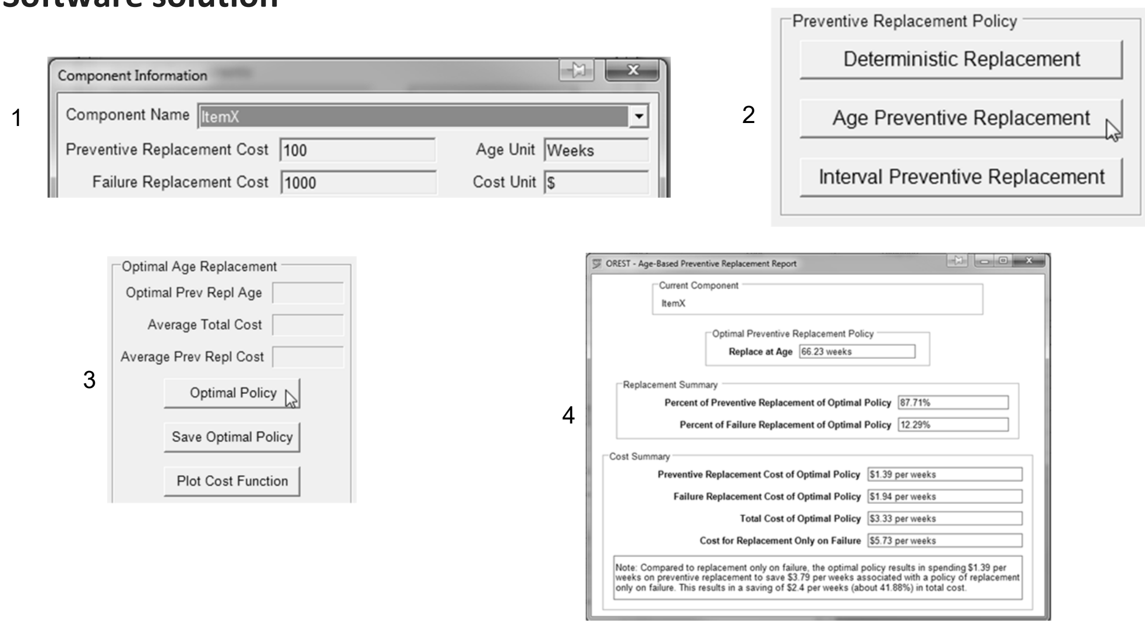
Software solution



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2.5.1 Quiz 1 Policies

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1. One may consider the first 4 questions in the RCM process as the "analysis" phase of RCM. And the last three questions as the "what to do about it?" decision phase. True or False? * (1 point)

- True
- False

2. A FF (failure finding) task may be considered proactive because * (1 point)

- 1. The inspection is performed routinely according to the preventive maintenance schedule in the EAM.
- 2. The inspection and its frequency are designed to reduce the probability of a multiple failure to an acceptable level.
- 3. The RCM analysis establishes a maintenance plan and schedule. RCM can also guide training and procurement functions. True or false?

3. The RCM analysis establishes a maintenance plan and schedule. RCM can also guide training and procurement functions. True or false? * (1 point)

- True
- False

4. A PM work order is issued by the EAM every 3 months to verify the condition of an electrical panel. The technician is required to report hot spots, dirt, clogged ventilation and to take appropriate remedial action. Would this activity be an example of TBM or CBM? * (1 point)

- TBM
- CBM

5. TBM or time based maintenance can be based on calendar time or another variable that increases in proportion to the accumulated stress on the asset. Which of the following would not be appropriate for scheduling TBM? * (1 point)

- Fuel consumed?
- Hour meter?
- Odometer?
- Raw material input?
- Product output?
- Number of failures?

6. The RCM curves represent * (1 point)

- the designed in reliability of a component independent of the maintenance performed.
- the reliability behavior of a component as a result of adhering to the manufacturers recommended maintenance program.

7. An "Optimal" maintenance policy is designed to achieve * (1 point)

- The lowest cost of maintenance
- The highest availability
- Either of the above or a desired balance among high reliability, low cost, high yield, and safety.

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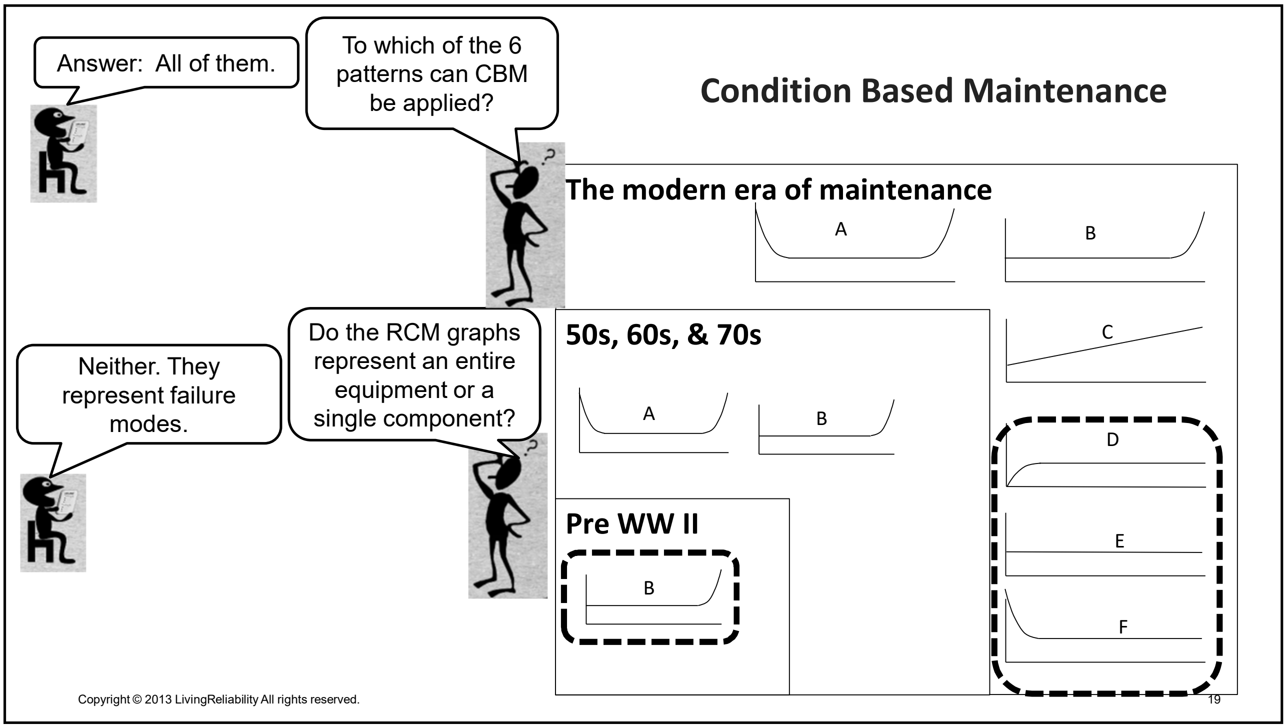
Answer: All of them.
To which of the 6 patterns can CBM be applied?
Condition Based Maintenance
The modern era of maintenance
A
B
C
D
E
F
50s, 60s, & 70s
A
B
Pre WW II
B
Neither. They represent failure modes.
Do the RCM graphs represent an entire equipment or a single component?
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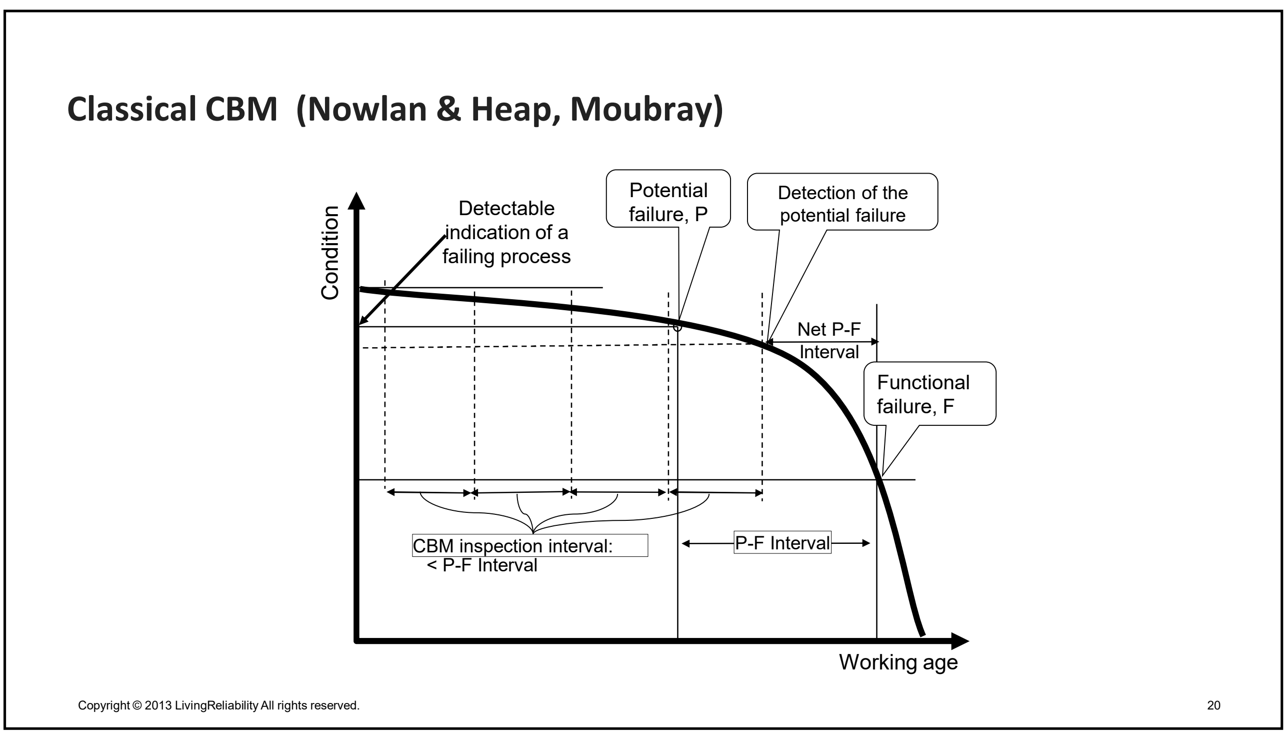
Classical CBM (Nowlan & Heap, Moubray)
Condition
Detectable indication of a failing process
Potential failure, P
Detection of the potential failure
Net P-F Interval
Functional failure, F
CBM inspection interval: < P-F Interval
P-F Interval
Working age
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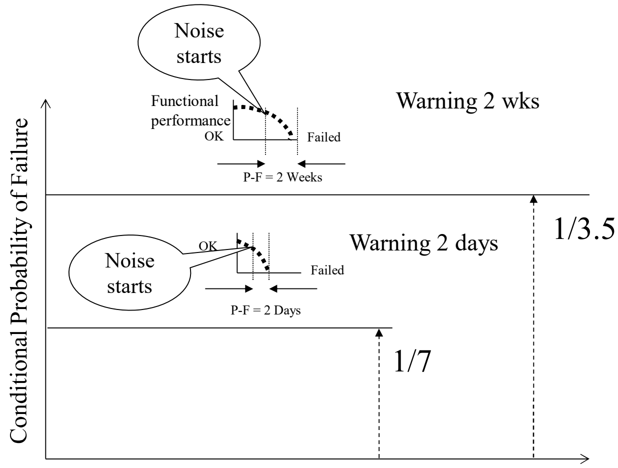
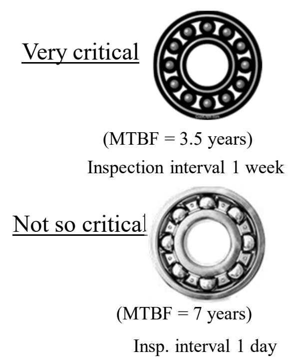
Two Bearings





CBM Inspection Frequency Assertions:

1. The lower the Mean Time Between Failure (MTBF), the more frequently you monitor?
2. The more critical, the more frequently you monitor?

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The P-F Interval limitations

Assumes that:

1. The potential failure set point, P, of an identifiable condition is known, and that
2. The P-F interval can be found and is reasonably consistent (or its range of variation can be estimated), and that
3. It is practical to monitor the item at intervals short enough to provide adequate maintenance reaction time within the net P-F interval

*In most maintenance departments these assumptions are unsubstantiated. **CBM Performance is unverified**.*

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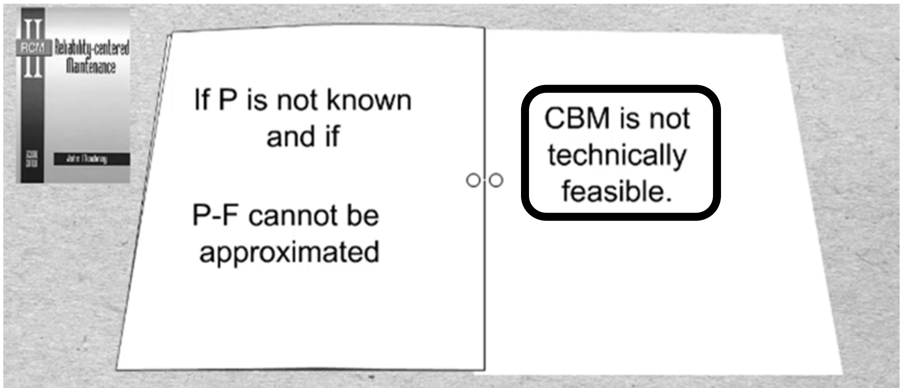

For this reason, before addressing the P-F interval, we must first discover **when and how** to declare a potential failure **P**.

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Conclusions

1. The P-F Interval is a reasonable **first approximation** towards the establishing a CBM inspection interval
2. The P-F is often developed during an RCM analysis in the **absence of data**
3. It is usually **subjective** based on (a consensus) recollections of potential and functional failures.
4. Analysis, called "Age exploration" by N&H, should be used in a continuous improvement process to
    1. **confirm** inspection frequencies and
    2. **refine** predictive models (more confidence in CBM decisions)

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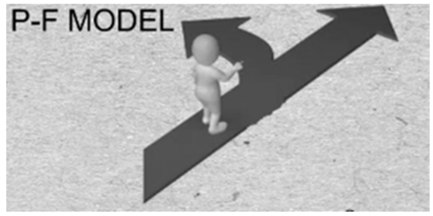
An alternative CBM policy (called "RULE" can…

1. estimate Remaining Useful Life, and
2. issue a confidence level for that estimate.

RULE

Remaining Useful Life Estimation



To attain these goals we will begin by revisiting the MTTF (Mean Time Between / To Failure

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What is the MTTF (Mean Time to Failure)?

Mathema $t\ t{=}0\ t{=}\infty\ tf\ t\ dt{=}\ t{=}0\ t{=}\infty\ R\ t\ dt$

=0 $t{=}\infty\ tf\ t\ dt$= t=0 $t{=}\infty\ R\ t\ dt$ =0 $t{=}\infty\ R\ t\ dt$ $t{=}\infty\ R\ t\ dt$ $t{=}\infty\ R\ t\ dt$ $t{=}\infty\ R\ t\ dt$ =∞ $tf\ t\ dt$= t=0 $t{=}\infty\ R\ t\ dt$ $t{=}\infty\ tf\ t\ dt$= t=0 $t{=}\infty\ R\ t\ dt$ $t{=}\infty\ tf\ t\ dt$= t=0 $t{=}\infty\ R\ t\ dt$ cally it is "Expected" life:

$$E\ t == \int_{t=0}^{t=\infty} tf(t)dt = \int_{t=0}^{t=\infty} R(t)dt$$

- Approximately: It is the "average" life of a group of similar items:

	A	B
1		Failed at week
2	Item A	13
3	Item B	15
4	Item C	25
5	Item D	18
6	Item E	4
7	**MTTF=AVG(B2:B6)**	**15**

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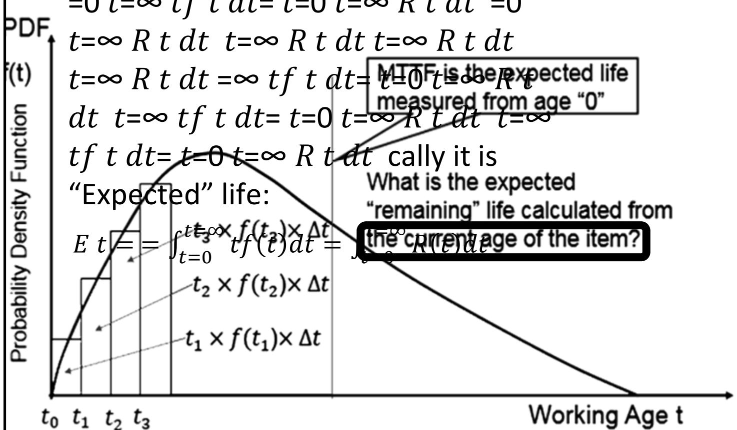
What is the MTTF (Mean Time to Failure)?

Mathemat t t=0 t=∞ tf t dt= t=0 t=∞ R t dt

=0 t=∞ tf t dt= t=0 t=∞ R t dt =0 t=∞ R t dt t=∞ R t dt t=∞ R t dt t=∞ R t dt =∞ tf t dt= t=0 t=∞ R t dt t=∞ tf t dt= t=0 t=∞ R t dt t=∞ tf t dt= t=0 t=∞ R t dt cally it is "Expected" life:

$E\ t = \int_{t=0}^{t=\infty} tf(t)dt = \int_0^{\infty} R(t)dt$

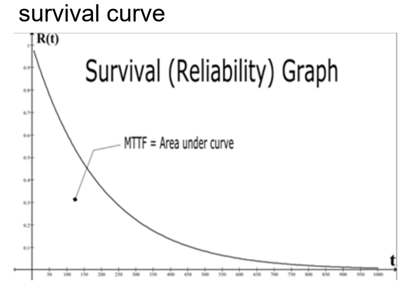


$$\sum t_i \times f(t_i) \times \Delta t = E(t) = MTTF = \int_{t=0}^{t=\infty} tf(t)dt$$

- Approximately: It is the "average" life of a group of similar items:

	A	B
1		Failed at week
2	Item A	13
3	Item B	15
4	Item C	25
5	Item D	18
6	Item E	4
7	**MTTF=AVG(B2:B6)**	**15**

- Graphically it is the area under the survival curve



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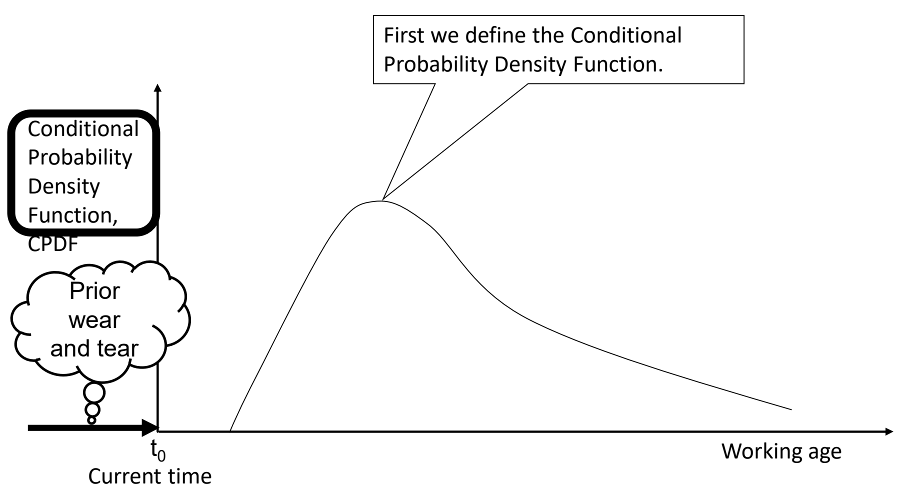
What is the expected life measured from the current age?



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Conditional (Probability) Density Function

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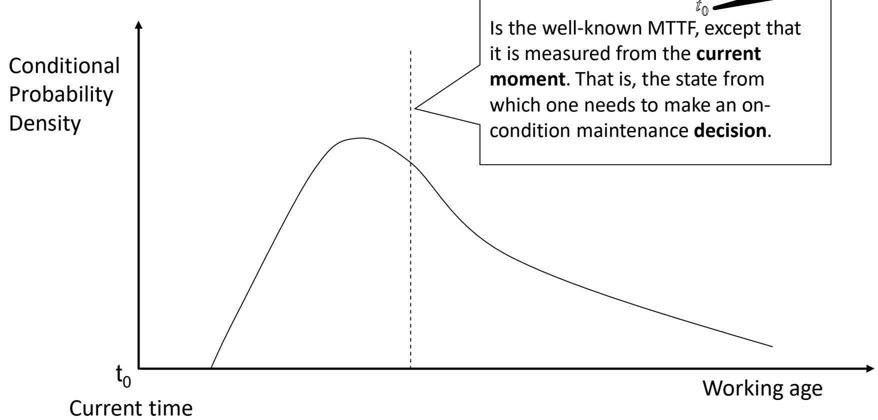
Next we define the Conditional MTTF

Conditional MTTF $= \int_{t_0}^{\infty} t f(t) dt$

Current time

Is the well-known MTTF, except that it is measured from the **current moment**. That is, the state from which one needs to make an on-condition maintenance **decision**.



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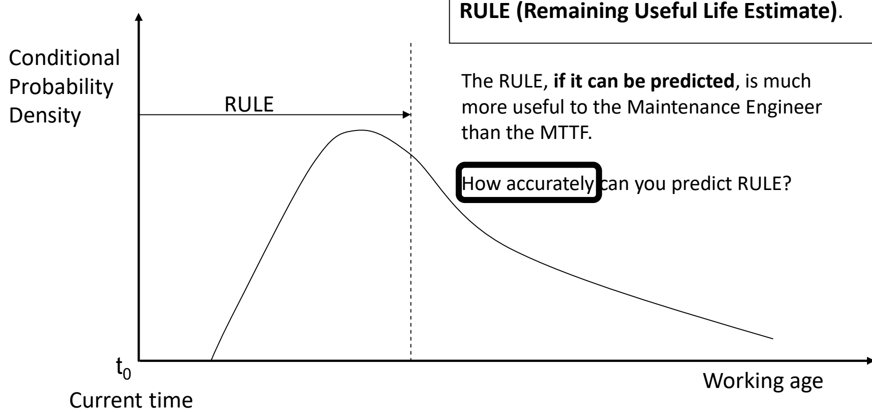
Remaining Useful Life Estimate (RULE) is the conditional MTTF



The Conditional MTTF is known as the **RULE (Remaining Useful Life Estimate)**.

The RULE, **if it can be predicted**, is much more useful to the Maintenance Engineer than the MTTF.

How accurately can you predict RULE?

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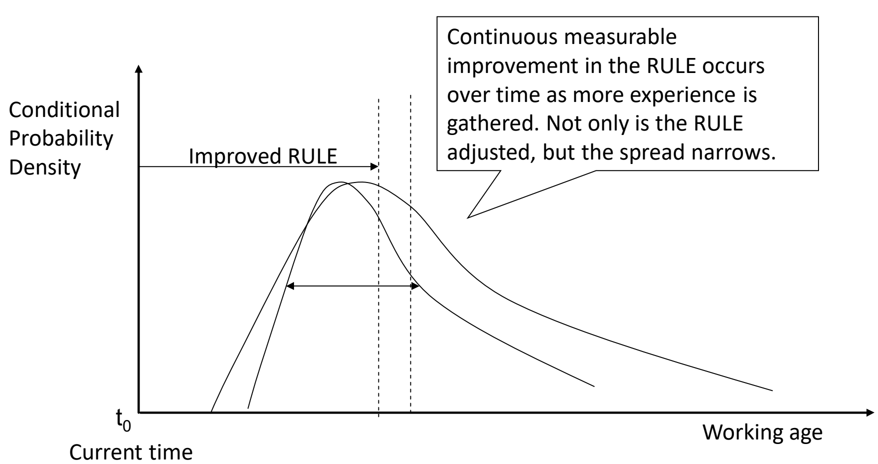
Continuous improvement in predictive maintenance



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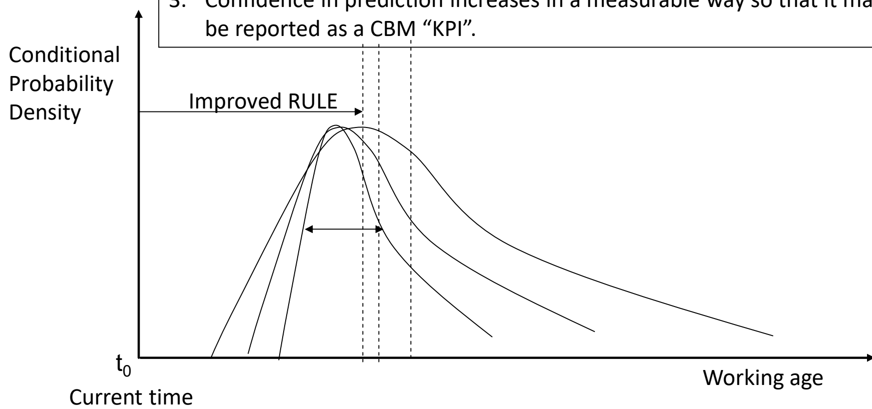
Measuring improvement in predictive maintenance

As we improve our work order reporting skills:
1. The graph narrows
2. The RULE improves.
3. Confidence in prediction increases in a measurable way so that it may be reported as a CBM "KPI".



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RULE (EXAKT™) Workshop

1 Determine the **influential** CBM variables.

2 Find the **relationship** among age, influential CBM variables, and failure probability.

3 Set up a model for **predicting** the state of the influential monitored variables.

4 Incorporate **business data** into the decision process

5 Build the decision model

6 Set up an **automatic** agent that will monitor new data as it arrives in a database and report an item's RULE and the recommended CBM decision.

7 Monitor CBM performance (**confidence**) in terms of standard deviation.

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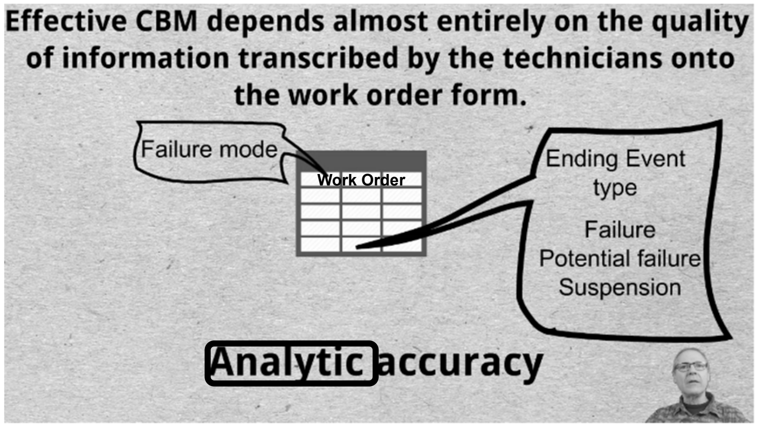

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How do we improve confidence in Predictive Maintenance?

1. By reporting both **failures and suspensions** when closing work orders.
2. By continuously improving the RCM **knowledge base** when closing work orders.
3. By ensuring EAM catalogs **reflect** the RCM reality.
4. By generating **samples** from the CMMS/EAM.
5. By applying **reliability analysis** techniques to build CBM decision models from high quality data in the EAM.

These steps describe the Living RCM process.

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2.5.1 Quiz 2 Policies

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1. The P-F interval is a model that (select the INCORRECT answer): * 1 point

- describes a strategy for the design of a CBM program.
- describes an approach for estimating the CBM inspection interval.
- describes the logic for determining how to declare a potential failure.
- is based on a judgment or first approximation of P-F interval.

2. CBM applies to all six RCM failure behavior patterns because (select the INCORRECT statement): * 1 point

- The age dimension is a "stand-in" for relevant yet unmonitored condition data.
- The RCM study by Nowlan and Heap proved that most failure modes are age dependent.
- The RCM graphs represent only the age based failure behavior of a component, part, or failure mode.

3. The MTTF is generally useful for predicting failure. True of False. * 1 point

- True
- False

4. Which of the following, concerning, conditional MTTF is INCORRECT? * 1 point

- The conditional mean time to failure is a more useful concept in the maintenance department than the MTTF.
- The conditional MTTF is, by definition, an estimate of the remaining useful life (or RUL).
- The conditional MTTF assists in determining the inherent age based reliability behavior of an item.

5. The standard deviation is a useful way to monitor CBM performance. It is highly influenced by the quality of work order data entered by the technician. True or False? * 1 point

- True
- False

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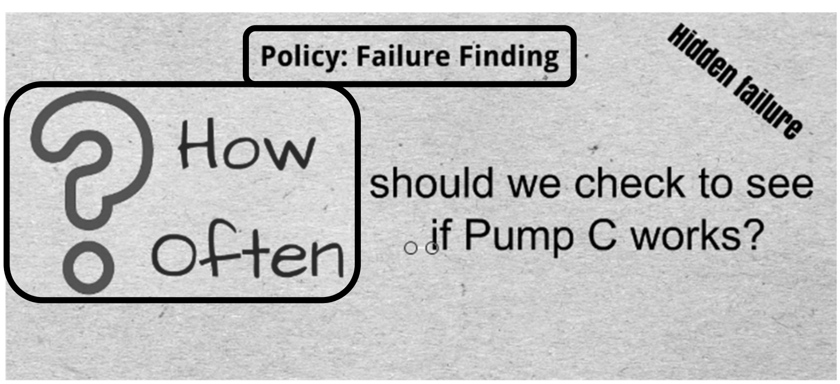
Failure finding interval



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Maintenance policy Failure Finding
FFI = Failure Finding Interval

How often should we check to see if Pump C works?

The FFI would depend on

1. The reliability of the Protector $\mathbf{M_{prot}}$
2. The tolerated unavailability of the Protector $\mathbf{U_{prot}}$*

$$FFI \ \alpha \ M_{prot} \times U_{prot}$$

$$FFI = K \times M_{prot} \times \boxed{U_{prot}} \quad \textit{(Eq. 1)}$$

* U_{prot} is called (in SIS standard) the required "Probability of Failure on Demand (PFD)"

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Tail light failures

	Joe	Henri	Leon	Jed	Mark	Zelda
2010						
2011						X
2012	X					
2013			X			
2014					X	
2015						

5 years x 6 devices = 30 device years
M_{prot} = 30 device years / 4 failures = 7.5 years

Since failure could have occurred any time during the year, on average the devices would have been unavailable half the time:

Uprot = 1/2yr x 4dev / 30dev-yr = 1/15

Use these results to determine K.
FFI = K x M_{prot} x U_{prot} **(Eq. 1)**
1 = K x 7.5 x 1/15
K=2
Now user wants device 99.99% available or .01 % unavailable. So U_{prot} = .0001
FFI = 2 x 7.5 x .0001 = .55 days. Twice a day.

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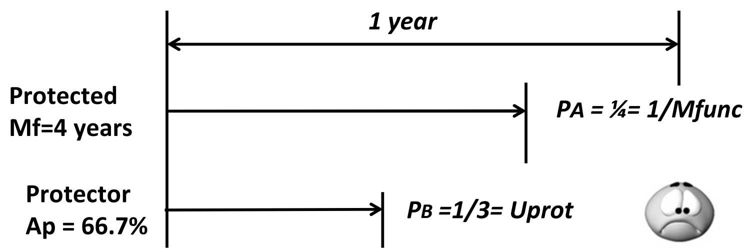
We found in the "Consequences" module that:



Probability Multiple Failure = PA * PB = 1/4*1/3 = 1/12

1/Mfunc | Uprot | 1/Mmf

Uprot = Mfunc/ Mmf (Eq. 2)

Where:
Uprot = Required Unavailability of Protector
Mfunc= MTBF of main function.
Mmf = Mean time between multiple failures

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General formula for FFI
(based on linear approximation that assumes Uprot < .05)

Combining equations 1 and 2

$$FFI = 2 \times Uprot \times Mprot \ \ (\boldsymbol{Eq.1})$$

$$Uprot = \frac{Mfunc}{Mmf} \ (\boldsymbol{Eq.2})$$

Substituting 2 into 1 gives:

$$FFI = \frac{2 \times Mfunc \times Mprot}{Mmf} \ (\boldsymbol{Eq.3})$$

Where:
FFI = Failure-finding task interval
U_{prot} = Unavailability of the protective device
M_{prot} = MTBF of protective device
M_{func} = MTBF of protected function
M_{mf} = Tolerable mean time between multiple failures

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More than one failure mode in the device

$$FFI = \frac{2 \times Mfunc}{Mmf \times (\frac{1}{M_1} + \frac{1}{M_2} + \quad)} \ (\boldsymbol{Eq. 3})$$

Valid if

- each failure mode on its own knocks out the protective device
- one task can detect any of the failure modes
- the failure modes are all independent of each other
- the total unavailability is small (less than 0.05)

Redundant protective devices

$$FFI = M_{prot} \times \left\{ \frac{(n+1)M_{func}}{M_{MF}} \right\}^{1/n}$$

Where:

FFI = Failure-finding task interval

M_{prot} = MTBF of protective device

M_{func} = MTBF of protected function

M_{MF} = Tolerable mean time between multiple failures

n = Number of fully redundant protective devices

Voting systems

$$FFI = M_{prot} \times \left\{ \frac{(n-r)!\, r!\, (r+1) \times M_{func}}{n!\, M_{mf}} \right\}^{\frac{1}{r}}$$

Voting systems are usually called k out of n systems, where:

n = number of units in parallel

k = number of units needed to activate the safety function (To reduce probability of false or nuisance alarms at least k of the n devices need to trigger.)

r = number of units which must be failed for the

system to fail

so: r = n - k + 1

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The FF test can itself induce a (hidden) failure

$$FFI = \frac{2 \times M_{ExclInd}}{(1 - p_{Ind})} \times \left\{ \frac{M_{func}}{M_{MF}} - p_{Ind} \right\}$$

Where:

FFI = Failure-finding task interval

p_{Ind} = Probability that the FF test will induce a hidden failure

$M_{Exclind}$ = MTBF of the device excluding test induced failure

M_{func} = Demand rate of protected function

M_{MF} = Tolerable mean time between multiple failures

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If multiple failure has only monetary consequences, then an <u>optimized</u> FFI can be calculated

$$FFI = \left\{ \frac{2M_{prot}M_{func}C_{ff}}{C_{mf}} \right\}^{\frac{1}{2}}$$

For single protective device

$$FFI = \left\{ \frac{(M_{tive})^{n}(n+1))M_{ted}C_{ff}}{nC_{mf}} \right\}^{\frac{1}{n+1}}$$

For redundant protective devices

Where:

C_{ff} = cost of FF task

C_{mf} = cost of multiple failure

n = Number of fully redundant protective devices

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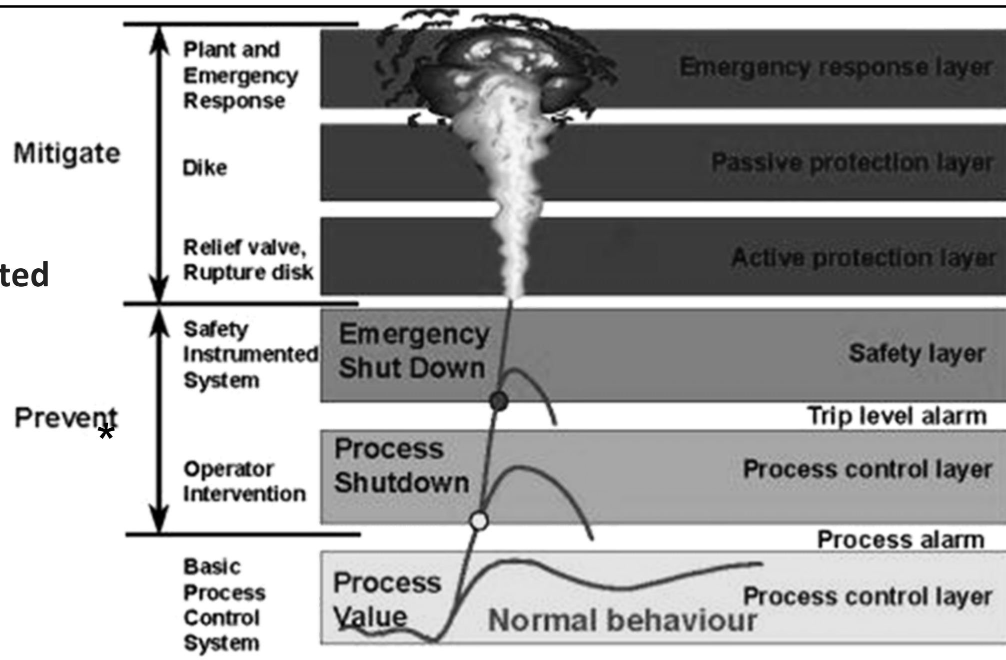
Safety instrumented systems*



Source Emerson SIS Course 1: Depiction of Layers of Protection

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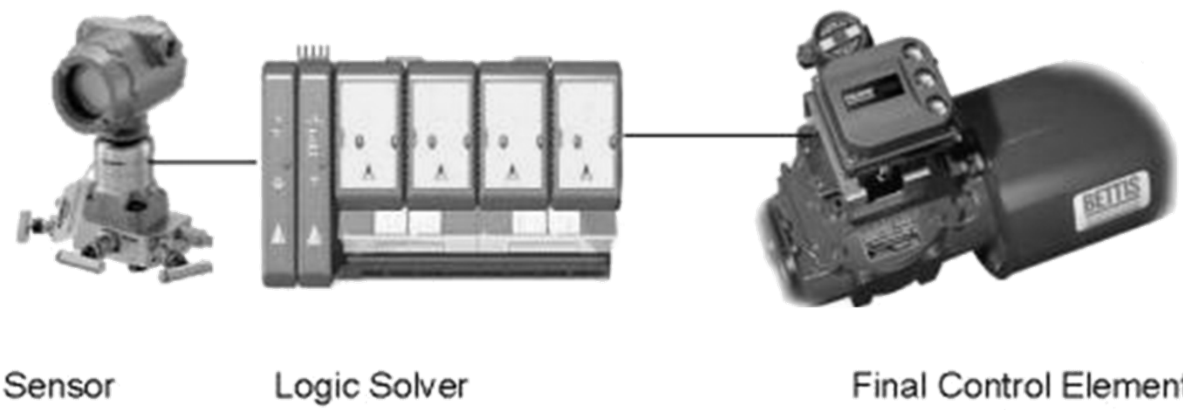
Consists of three elements



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Standards

General standard:

IEC Standard 61508 (Functional Safety of Electric, Electronic and Programmable Electronic Systems)

Specific to process industries:

IEC Standard 61511 and **ISA 84.00.01-2004**

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Safety Integrity Levels

SAFETY INTEGRITY LEVEL (SIL)	REQUIRED SAFETY AVAILABILITY (RSA)	AVERAGE PROBABILITY OF FAILURE ON DEMAND (PFD) =1-RSA = U_{prot} = tolerated device unavailability.
1	90 99%	0.01 to 0.1
2	99 99.9%	0.001 to 0.01
3	99.9 99.99%	0.0001 to 0.001
4	99.99% 99.999%	0.00001 to 0.0001

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Multiple Failure Risk = Probability x Severity

Probability

PROBABILITY LEVEL	DESCRIPTIVE WORD	FREQUENCY OF OCCURRENCE
5	Frequent	One per year
4	Probable	One per 10 years
3	Occasional	One per 100 years
2	Remote	One per 1,000 years
1	Improbable	One per 10,000 years

Severity

SEVERITY LEVEL	DESCRIPTIVE WORD	POTENTIAL CONSEQUENCES TO PERSONNEL
5	Catastrophic	Multiple deaths
4	Severe	Death
3	Serious	Lost time accident
2	Minor	Medical treatment
1	Negligible	No injury

Risk	Possible required SIL
25	4
15 to 25	3
6 to 14	2
1 to 5	1

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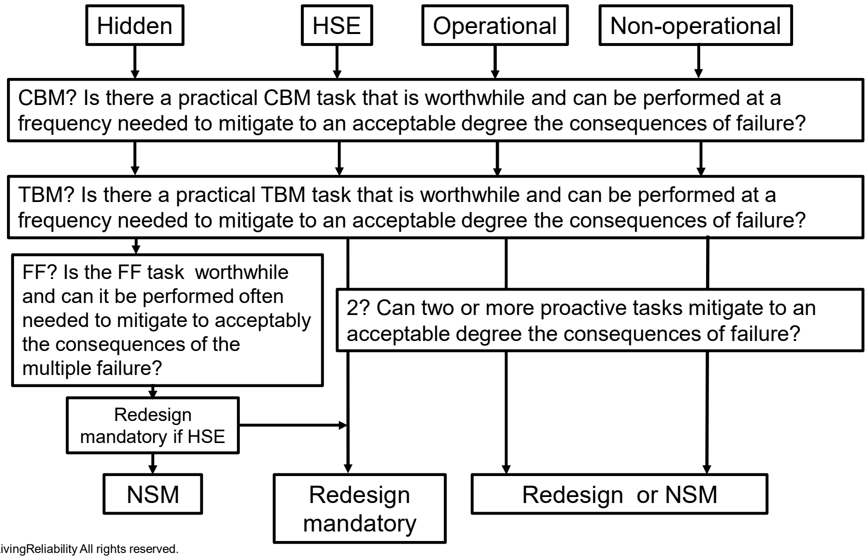
If proaction not applicable nor effective a default task may be mandatory



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No scheduled maintenance NSM

HSE branch of the RCM decision tree

- NSM not available as a choice in the decision tree.

Operational and non operational branches

- NSM is accepted only if a cost-effective task cannot be found.

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Redesign – Purpose is to lower the risk.

Hidden

If HSE impact redesign is compulsory

1. Make hidden failure evident (fail safe) by replacing or modifying it.
2. Modify so that a FF task is technically feasible.
3. Add another layer of redundancy to the hidden function
4. Increase the availability of the hidden function.
5. Increase reliability of the protected function

HSE	**Operational**	**Non-operational**
Redesign is compulsory	Redesign may be desirable	Redesign may be desirable

1. Increase the reliability of the asset.
2. Add a protective function
3. Modify so that CBM or TBM task is applicable and effective
4. Modify for a lower HSE impact
5. Modify for a less costly and less disruptive repair

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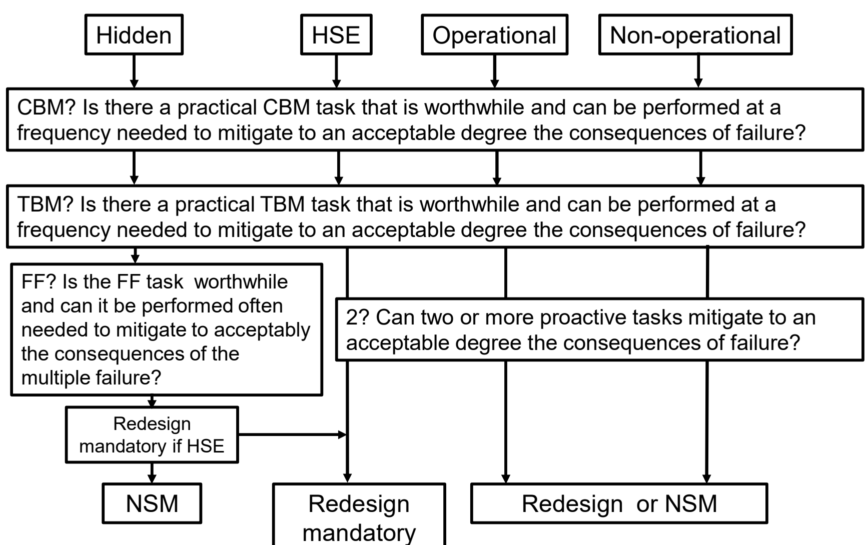
A note on the decision tree – SAE JA1011 – 1999 & Military RCM

GUIDELINES FOR THE NAVAL AVIATION RELIABILITY-CENTERED MAINTENANCE PROCESS

NAVAIR



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2.5.1 Quiz 3 Policies

https://forms.gle/m9RChqLcjW9uCLfJ6

1. The failure finding interval applies usually to failures whose consequences are hidden. True for False? * 1 point

- True
- False

2. The failure finding interval depends on: * 1 point

- The reliability of the protector.
- The unavailability of the protector.
- The accepted mean time between multiple failures.
- The consequences of the multiple failure.
- Environmental, health, and safety regulations.
- All of the above.

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