TOOLBOX SESIÓN

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Reliability Centered Maintenance (RCM)
A Case Study

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INTRODUCTION

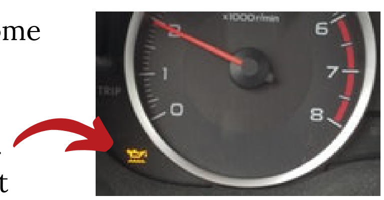
Reliability Centered Maintenance (RCM) is a powerful Reliability improvement process. RCM isn't a new process. The application of its principles spans five decades. It has been - *and is being* - applied in nearly every industry throughout the world. When it is **applied correctly**, with the **right people**, overwhelming positive results can be reaped that can transform an organization. *I've seen it first-hand.*

RCM embodies many Reliability fundamentals. Exploring, understanding, and applying these fundamentals at a basic level can help you achieve Reliability goals - *even if you never formally implement* RCM. But here's the catch. ***You have to actually apply the principles!***

THE STORY

RCM stole my technical heart and soul 26 years ago; I often apply RCM principles in my own life. But, just as it often happens in the Reliability "real world," I got busy and didn't take the time to "walk my own talk." And I suffered the **Consequences** for it.

On a recent 400-mile journey in my 2014 Subaru Forrester (coming home from speaking at a Reliability conference!), I experienced an **unanticipated failure** with my boxer engine's lubrication system that interrupted my trip. While driving on the highway, my **Low Engine Oil Light** illuminated on the dashboard, so I had to pull over at the nearest gas station to troubleshoot.



I could have completely avoided the situation if I had **proactively managed** one **Failure Mode**. But I didn't. Instead, I was thrown into full-blown **Reactive Mode** - *150 miles from my home.*

Given what I do for a living, I asked myself, *how did I let this happen*? I felt embarrassed until I realized that many organizations experience the same thing. "*Running from to fire*" 🔥 and living in Reactive Mode is (unfortunately) a common circumstance in our industry. But it is largely avoidable. So I decided to make lemonade 🍹 out of my lemons, and that's how this Case Study was born.

WHAT WE'RE GOING TO EXPLORE

I deconstructed my (unfortunate) event and created this real-life RCM Case Study. Together, we will learn and demonstrate some of RCM's most important principles at a very basic level including:

- Building a **Failure Modes and Effects Analysis** (FMEA)
- Assessing **Criticality**
- Assigning safe and cost-effective maintenance tasks by applying the **P-F Interval**.
- Discovering what **Protective Devices** are, why they are so important, and how RCM can help you to properly take care of them

WHAT YOU'LL GET FROM THIS CASE STUDY

This Case Study is *not* a comprehensive introduction to RCM. But you will leave with a **clear understanding** of what RCM is and you will have a **working knowledge** of some very **important Reliability fundamentals** because we are going to apply them - *together*!

THE RCM PROCESS

The application of *True RCM* consists of preparing an *Operating Context* and carrying out the 7 *steps of RCM*, as depicted in Figure 1.

OPERATING CONTEXT

An Operating Context is a document that includes relevant technical information such as the scope of analysis, theory of operation, equipment description, and RCM analysis notes. In essence, it is a **storybook identification** of the system to be analyzed. The Operating Context also documents notes and assumptions regarding analysis decisions. It is an important **source of reference** for Working Group and Validation Team Members.

In the interest of time, the Operating Context is typically drafted by the **RCM Facilitator** before the analysis begins and is then reviewed with the **RCM Working Group** before the first step in the RCM process (identifying Functions) is accomplished. During this time, the Working Group reviews and revises the Operating Context, as required.

The Operating Context is considered a *living document* and is edited as more is learned about the equipment and additional issues come to light during the analysis.

Prepare the Operating Context

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Step 1: Functions
Record what the asset does, not what it is. Include desired standards of performance in its present operating context.

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Step 2: Functional Failures
Document the ways in which the asset can fail to fulfill its Functions.

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Step 3: Failure Modes
Determine what causes each Functional Failure.

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Step 4: Failure Effects
Write what happens if nothing were done to predict or prevent each Failure Mode.

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Step 5: Failure Consequences
Determine how each Failure Mode matters

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Step 6: Proactive Maintenance and Intervals
Determine if On-Condition (AKA Condition Based Maintenance) or Preventive maintenance is technically appropriate and worth doing.

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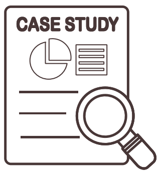
Step 7: Default Strategies
Determine if there are any other actions that are appropriate.

Figure 1: The RCM Process



Operating Context Excerpt for my 2014 Subaru Forester

Let's take a look at some Operating Context details for our Case Study.

- 2014 Subaru Forester – personal use vehicle. (I drive it almost exclusively.)
- Drive approximately 12,000 miles per year in the Southeastern United States (almost entirely in Alabama). Longest journey ~ 4 hours from home.
- I do have a "backup" car – 2004 Toyota Corolla.
- Scope of analysis is limited to Failure Modes that result in illumination of the Low Engine Oil Light and the Low Engine Oil Light circuit.
- 2.5-liter horizontally opposed four-cylinder (boxer) engine, 170 horsepower.
- Low Engine Oil Light illuminates in the event that the engine oil decreases to the low level (~ 1 quart low) as indicated on the dipstick.

STEP 1: FUNCTIONS

It's no coincidence that the first step in the RCM process is writing Functions. John Moubray taught us that Reliability isn't a "thing" on its own. Rather, **Reliability** is "sprinkled" amongst all the Functions of a piece of equipment. So, when we write Functions, we **define the Reliability we need** from our equipment. Then we can use the rest of the RCM process to identify the actions we need to take to ensure that Reliability.

Primary and Secondary Functions

There are two types of Functions - *Primary* and *Secondary*. The Primary Function is the main purpose a system exists. Other Functions of a system are called *Secondary Functions*.

Evident and Hidden Functions

Functions are classified as either *Evident* or *Hidden*. *Evident Functions* are those that, upon failure, become evident to the Operating Crew **under normal conditions**. For example, if the battery in your car cannot provide adequate electricity to start the car, failure of that Function becomes evident when the car won't start. Likewise, if the fuel pump fails and cannot deliver fuel to the engine, that becomes evident when the car stops running.

Functions are considered *Hidden* if, when the Function fails, it does not become evident to the operating crew under normal conditions. In the context of RCM, Hidden Functions are almost always **Protective Devices**.

Protective Devices

Protective Devices are devices and systems intended to protect people, the asset, and sometimes an organization **in the event that another failure occurs**. For example, an air bag in a vehicle is intended to prevent occupants from hitting the vehicle interior or objects outside the vehicle *in the event of an accident*. If the air bag in a car were in a failed state right now, without inspection, we wouldn't know it. That's what makes it a **Hidden Function**. **Without inspection**, it takes **another failure** (in this case, an accident with significant impact) to know it is in a failed state.

Multiple Failure

In the context of RCM, a *Multiple Failure* occurs when a Protective Device is in a failed state AND another failure occurs. For example, if there is a vehicle accident AND the air bag is in a failed state, that constitutes a *Multiple Failure*.

And that's why it is so important to (1) be aware of our Protective Devices and (2) to take care of them properly. Because they are intended to protect **in the event that something else goes wrong**. RCM gives us powerful tools for determining how we should properly care for Protective Devices.

Writing Evident Functions

Evident Functions are written as depicted in Figure 2.

To + Verb + Object + Performance Standard(s) + Operating Context

Figure 2: How to Write an Evident Function

Primary Function of my 2014 Subaru Forester

A common mistake when writing Functions is to write them too vague. For example, consider this Primary Function for my Forester:

To get from "Point A" to "Point B."

This obviously lacks detail. Remember, when we write Functions, we **define the Reliability we need**, so we must be specific. Following the formula for writing Functions in Figure 2, the Primary Function of my 2014 Subaru Forester is as follows. Figure 3 breaks down the various elements.

To transport up to 5 adult passengers and 3 medium-size suitcases along paved roads and highways, drive up to 360 miles without stopping, in climates that range from 0 to 115 degrees Fahrenheit, while protecting passengers from the elements, as required.

Verb	Transport
Object	Up to 5 adult passengers and 3 medium-size suitcases
Performance Standards	• Along paved roads and highways • Drive up to 360 miles without stopping • In climates that range from 0 to 115 degrees Fahrenheit • While protecting passengers from the elements
Operating Context	As required

Figure 3: Primary Function of my 2014 Subaru Forester

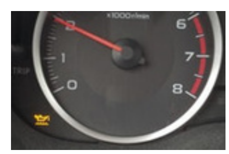
Writing Hidden Functions

A Function for a Protective Device details what the system needs to be *capable of doing* and when it is *required to operate*. It follows the model below, as depicted in Figure 4.

> **To be capable of** [doing something] **in the event that** [something else happens].

Figure 4: How to Write a Hidden Function

Function of the Low Engine Oil Light



The Function of the Low Engine Oil Light following the model above is:

*To be capable of **visually alerting the driver** in the event that **the engine oil level decreases to the low level on the dipstick.***

What is the Multiple Failure?

The Multiple Failure in this example is:

1. *The oil in the reservoir falls to the low level on the dipstick.*
2. *The Low Engine Oil Light circuit is in a failed state.*

STEP 2: FUNCTIONAL FAILURES

Writing Functional Failures is the second step in the RCM process.

A Functional Failure is the ***inability to fulfill a Function***.

Total and Partial Failure
There are two types of Functional Failures - *Total* and *Partial*. A Total Failure is *complete loss of function*. A Partial Failure is the *inability to function at the level of performance specified as satisfactory*.

Total Failure of my 2014 Subaru Forester Primary Function

To transport up to 5 adult passengers and 3 medium-size suitcases along paved roads and highways, drive up to 360 miles without stopping, in climates that range from 0 to 115 degrees Fahrenheit, while protecting passengers from the elements, as required.

Total Failure: *Completely unable to transport*

Total Failure of my 2014 Subaru Forester Low Engine Oil Light Circuit

Function: *To be capable of visually alerting the driver in the event that the engine oil level decreases to the low level on the dipstick.*

Total Failure: *Incapable of visually alerting the driver in the event that the engine oil level decreases to the low level on the dipstick.*

But the Low Engine Oil Level Circuit can fail in another way, too. What is it? It can ***falsely illuminate the Low Oil Level Light***.

STEP 3: FAILURE MODES

A Failure Mode is what ***specifically causes a Functional Failure***. (Note, in this paper the terms "Failure Mode" and "Failure Cause" are used synonymously.) It is important to proactively identify all plausible Failure Modes that could cause each Functional Failure because then the remaining four steps of the RCM process can be used to figure out what (if anything at all) should be done to manage each one.

Writing Failure Modes

Failure Modes are written as depicted in Figure 5.

Noun + Verb + [as necessary: operating context]

Figure 5: How to Write Failure Modes

The following Failure Modes include a noun and a verb.

Compressor disc fatigues.

Power turbine blade fatigues.

However, at times, Failure Modes require more detail to ensure that an appropriate Failure Management Strategy can be formulated. Consider the three sets of Failure Modes depicted in Figure 6. The operating context is represented in *italicized text*.

Set 1	Hydraulic line chafes *due to normal equipment vibration.*
	Hydraulic line chafes *due improper routing.*
Set 2	Oil filter clogs *due to normal use.*
	Oil filter clogs due to *gearbox break-in.*
Set 3	Foreign object enters aircaft engine air inlet *during flight.*
	Foreign objects accumulate in engine inlet *while aircraft is on the ground with the engine off.*

Figure 6: Three sets of Failure Modes with operating context in italics.

In the first set of Failure Modes, without the operating context included, the Failure Mode would be the same: *hydraulic line chafes*. The same is true for *oil filter clogs* and the *foreign objects*.

However, Figure 7 shows how different the Failure Management Strategies can be for the same item. For example, if a *hydraulic line chafes* ***due to normal equipment vibration***, RCM analysis may determine to *visually inspect the hydraulic line every 25 hours of operation*. But, if a *hydraulic line chafes* ***due to improper routing***, then RCM analysis may determine to augment the training program so that hydraulic lines are routed properly. Similarly, different failure management strategies are documented for the oil filters and foreign objects in the engine air inlet.

This is why it is so important to write Failure Modes with the right amount of detail.

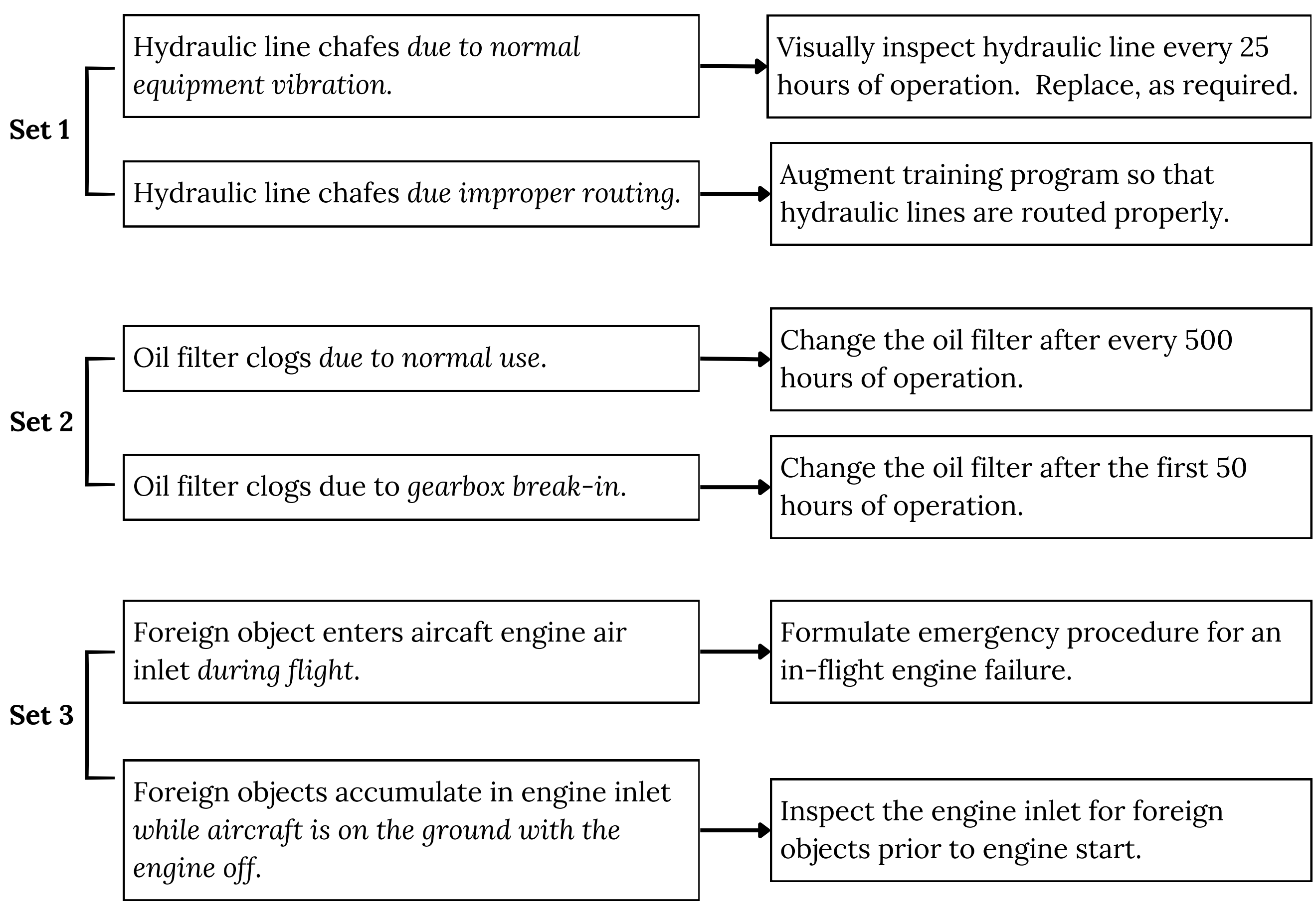
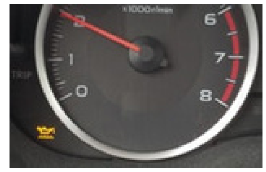


Figure 7: Three sets of Failure Modes that include operating context and the Failure Modes' associated Failure Management Strategies.

Failure Modes: Let's identify what specifically could cause (AKA *identify Failure Modes*) the engine oil to drop to the low level and thus illuminate the Low Engine Oil Light. While I was driving, when the light illuminated, I quickly ran through three possibilities.



1 Engine consumes oil due to normal consumption.

The Low Engine Oil Light could illuminate because the oil level is low due to "normal consumption." In that case, I had enough oil to make it home without damaging my engine because I only had another 150 miles to go.

2 Engine oil system leaks.

The light could illuminate because the oil level was low due to a leak in the oil system. That's the worst-case-scenario. Depending on the severity of the leak, low oil level leads to inadequate lubrication which could cause serious internal damage to engine components and possibly leave me stranded on the side of the road.

3 Low Engine Oil Light Circuit fails closed.

The light could falsely illuminate due to a faulty circuit (meaning the engine oil level is normal but the light illuminates anyway). If that is the case, there is nothing I can do about it until I bring my car in for service. But between now and then, my engine will be just fine (assuming I don't also have a low oil situation in the meantime!)

In all three cases, while driving, I couldn't know which Failure Mode I was dealing with. So, I was forced into Reactive Mode and had to pull over to check the oil level to troubleshoot.

Now let's move on to the fourth step in the RCM Process - *Failure Effects*.

STEP 4: FAILURE EFFECTS

A Failure Effect is *a story of what would happen if nothing were done to predict, prevent, or manage its associated Failure Mode.* Failure Effects should be written in enough detail so that Consequences can be assessed.

Failure Effects Include:

- A description of the failure process from the occurrence of the Failure Mode to the Functional Failure
- Physical evidence that the failure has occurred
- How it adversely affects safety and/or the environment
- How it affects operational capability/mission
- Specific operating restrictions as a result of the failure
- Secondary damage
- What must be done and how long it takes to repair the failure

The following example illustrates a properly written Failure Effect:

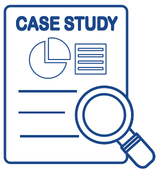
Failure Mode: *Feedwater pump bearing lubrication dissipates.*

> Lack of lubrication causes the bearing to wear abnormally. Vibration levels increase. Eventually, noise develops and just before failure, friction increases such that heat and smoke are generated. The bearing seizes, the pump stops, and feedwater is no longer supplied to the boiler. The water level in the boiler drops and is indicated on the water level sight gauge. If this goes unnoticed, eventually inadequate water is available to continue producing steam. The output steam pressure decreases such that less than 10 psi is delivered to the paper drying process. The drop in output pressure is indicated on the steam pressure gauge. When the steam supplied to the paper drying process falls below 140 psi, the low steam pressure alarm sounds. Up to 20,000 feet of paper are not thoroughly dried before the steam to the paper drying process can be stopped. The paper is scrapped for recycle and the feedwater pump motor is replaced at a cost of $100,000. Downtime to repair, 8 hours.

FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Steps one through four of the RCM process are make up the FMEA. In the context of RCM, the FMEA can also be referred to as the *Information Worksheet.*

Figure 8 details the FMEA for our Case Study for two Failure Modes.



Function	Functional Failure	Failure Mode	Failure Effect
1. To transport up to 5 adult passengers and 3 medium-size suitcases along paved roads and highways for up to 360 miles without stopping in climates that range from 0° to 115° F (-17° to 46° C) while protecting passengers from the elements.	A. Completely unable to transport. Operational Consequences	1. Engine consumes oil due to normal use.	During engine operation, the oil is gradually consumed by the engine. The decrease in oil is indicated on the dipstick. If this goes unnoticed, eventually the engine oil drops to the point that the LOW OIL LEVEL Light illuminates. The driver pulls over at the nearest service station and checks the oil. The dipstick indicates that the engine oil is low. The driver replenishes the oil and continues to the destination but with some delay. Downtime to repair, up to 30 minutes.
2. To be capable of visually alerting the driver in the event that the engine oil level decreases to the low limit as indicated on the dipstick. (LOW OIL LEVEL Light Circuit)	A. Incapable of visually alerting the driver in the event that the engine oil level decreases to the low limit. Operational Consequences	1. LOW OIL LEVEL Light circuit fails open.	This Failure Mode only matters in the event that the engine oil level decreases to the lower limit. The driver is unaware of the low oil situation and continues to operate the vehicle. The oil level continues to drop. Worst case, engine components are not properly lubricated and start to wear abnormally. Eventually, engine oil pressure decreases and engine oil temperature increases. The OIL PRESSURE warning light and/or the CHECK ENGINE light illuminates on the dashboard. Driver must pull over and cannot get to the desired destination on time. It is likely driver can find a safe place to pull over and call a tow truck. However, worst case, driver must pull over on a busy highway or on a dark country road at night. The oil system is repaired, as required. Any secondary engine damage is repaired, as required. Worst case, engine must be replaced. Downtime to repair, 3 days to 1 month at a cost ranging from $1,000 to $8,000.

Figure 8: FMEA for Two Case Study Failure Modes

STEP 5: FAILURE CONSEQUENCES

Assessing Failure Consequences is the fifth step in the RCM process. A Failure Consequence describes how the loss of function caused by the Failure Mode matters.

There are four categories of Failure Consequences:

- Safety
- Environmental
- Operational
- Non-Operational

STEP 6: PROACTIVE MAINTENANCE AND INTERVALS

After consequences are assessed, the next step in the RCM process is to consider **Proactive Maintenance** as a **Failure Management Strategy**. In the context of RCM, the proactive maintenance tasks that may be identified include:

- **Scheduled Restoration**: A scheduled restoration task is performed at a specified interval to restore an item's failure resistance to an acceptable level without considering the item's condition at the time of the task. An example of a scheduled restoration task is retreading a tire at 60,000 miles.

- **Scheduled Replacement**: A scheduled replacement task is performed at a specified interval to replace an item without considering the item's condition at the time of the task. An example is a scheduled replacement of a turbine engine compressor disk at 10,000 hours.

  Scheduled restorations and scheduled replacement tasks are performed at specified intervals *regardless of the item's condition.*

- **On-Condition task**: An On-Condition task (AKA Condition Based Maintenance task (CBM)) is performed at a defined interval to detect **evidence that a failure is impending**. In the context of RCM, the evidence is called a **Potential Failure Condition**. Once a Potential Failure Condition is identified, maintenance can be performed before the failure occurs.

  Potential Failure Conditions can be detected using relatively *simple techniques* such as monitoring gauges or measuring brake linings. Potential Failure Conditions can be detected employing *more technically involved techniques* such as thermography, oil analysis, or with continuous monitoring with devices installed directly on machinery.

In the context of RCM, all proactive maintenance tasks must be **technically feasible** and **worth doing**.

In order to determine if an On-Condition task is technically feasible, Potential Failure Conditions must be evaluated.

For the following discussion, refer to Figure 9, The P-F Curve.

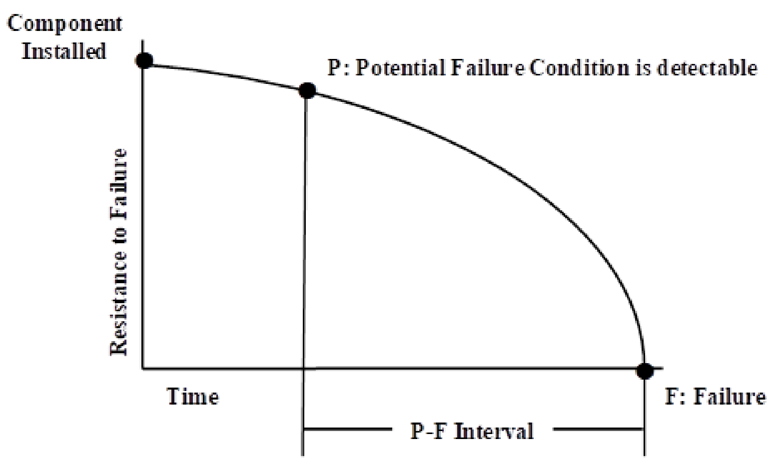


Figure 9: The P-F Curve

The P-F Curve

The X axis is "**time**" which can be measured in any units such as calendar time, operating hours, miles, cycles, etc. The Y axis is the "**resistance to failure**."

The time that a new component is installed is depicted at the top of the Y-axis indicating the maximum amount of resistance to failure. As most components remain in service, the resistance to failure declines and, eventually, the Failure Mode starts to exhibit signs of ***impending failure***. In other words ***Potential Failure Conditions*** develop. A Potential Failure Condition is represented by "**P**" on the **P-F Curve**. If the Potential Failure Condition goes undetected, eventually, Failure occurs.

Failure is represented on the P-F Curve as "**F**."

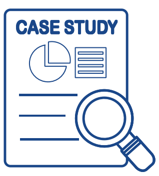
The P-F interval is the time from *when a Potential Failure Condition is detectable* to the point that *Failure occurs.*

On-Condition Task Intervals are Determined Based upon the P-F Interval.

The manner in which On-Condition task intervals are determined is a widely misunderstood concept.

- On-Condition task intervals are *not* based on *MTBF* (*Mean Time Between Failures*), or on average how often the failure occurs.
- On-Condition task intervals are *not* based on the *useful life* of a component.
- On-Condition task intervals are *not* based on the *criticality* of the failure.

On-Condition task intervals are based on the P-F interval. A general rule of thumb is to perform the On-Condition task at half the P-F interval. However, this is merely a guide. As long as On-Condition task intervals are performed at intervals less than the P-F interval, and the net P-F interval - *the minimum time remaining before failure occurs* - leaves enough time to *manage the consequences of failure*, then the On-Condition task interval is acceptable.



Using the P-F Interval, let's consider On-Condition maintenance for the Failure Mode, ***Engine consumes oil due to normal use.*** Refer to Figure 10 for a visual representation of the details.

When the *oil is replaced*, the **Resistance to Failure** is at its highest. After a certain amount of miles, the oil level drops and is indicated on the dipstick. Let's say that what we consider our *Potential Failure Condition* is that the **oil level is 75% to the "low level"** as indicated on the dipstick. And what we consider as "Failure" is **oil level drops to the "low level"** as indicated on the dipstick.

In order to determine *task technical feasibility*, we answer four questions.

1. If inspected, is it possible to detect evidence of impending failure (Potential Failure Condition)?
Yes

2. What is it? We defined it above as *when the oil level is 75% to the "low level" as indicated on the dipstick.*

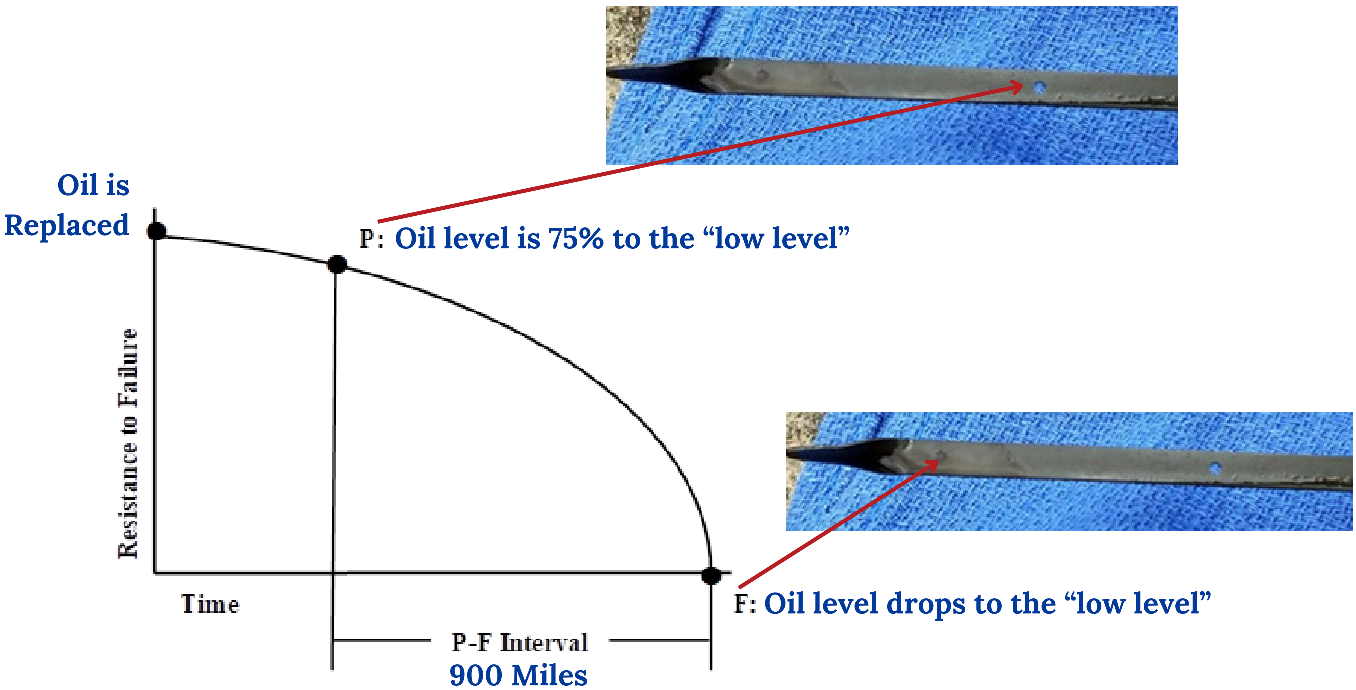


Figure 10: The P-F Curve for the Failure Mode *Engine consumes oil due to normal use*

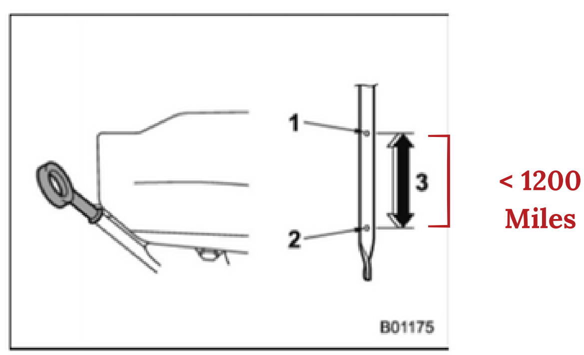
3. What is the P-F Interval? To answer this question, let's take a look at the Subaru Forester manual. Refer to Figure 11.

It it states that *consuming more than 1 quart per 1,200 miles" is abnormal*. So Subaru is saying that to go from *Full level* to *Low level*, worst case, is 1,200 miles. In other words, it's consistently at least as long as 1,200 miles.

Recall that we assigned our "P" as *Oil level is 75% to the low level*. And we assigned our "F" as *Oil level drops to the low level.*

Therefore, we can assume that, worst case, it takes 900 miles to go from 75% *to the low level* to the *low level* mark.

As a result, we **assign the P-F Interval of 900 miles**.



1) Full level
2) Low level
3) Approximately 1.1 US qt (1.0 liter, 0.9 Imp qt) from low level to full level

Figure 11: Engine Oil Full Level - Low Level per the Dipstick

Let's continue with our four questions.

4. Is it practical to monitor the item at intervals less than the P-F interval? Recall that the general rule of thumb is to half the P-F Interval to arrive at the inspection interval. In that case, we would do our On-Condition task (check oil level via the dipstick) every 450 miles. Let's check that out and see if it would make sense to check the oil level at every fuel stop by determining how far I can go on one tank of fuel.

My fuel tank holds 16 gallons. Let's assume I get 30 miles per gallon. That means I can travel 480 miles on one tank of gas.

[16 gallons of fuel] x [30 miles per gallon] = 480 miles

So, if I check the oil every time I stop for gas, that would be about every 480 miles. And that certainly IS practical.

5. Is it long enough to manage the consequences of failure? Yes. That still leaves me approximately 400 miles to take action if I find that the oil level is 75% or less to the low level mark. That is enough time to obtain the oil and replenish the reservoir.

We have just determined that it is technically feasible to check the oil level at every fuel stop!

Now let's **determine if it's worth doing.** We do so by answering the following question: ***Is the task cost effective?*** In other words, is the cost of checking the oil at every fuel stop less than the consequences of failure? Yes.

Therefore, in the context of RCM, we assign the task: ***At every fuel stop, check the engine oil level using the dipstick. Replenish the reservoir if the oil level is 75% or less to the low level mark per the dipstick***.

STEP 7: DEFAULT STRATEGIES

RCM isn't just about maintenance. There are a great many solutions other than Proactive Maintenance that can be derived using the RCM process. Examples include: Failure Finding tasks for Protective Devices, physical redesigns, modifications to operating procedures, updates to technical publications, equipment redesigns, and no scheduled maintenance. In the context of RCM, these recommendations are known as *Default Strategies*.

FACILITATED WORKING GROUP APPROACH TO RCM

The most effective way to carry out RCM is using a Facilitated Working Group approach. Organizations can capture an enormous amount of information by asking the right people the right questions. This is one of the most valuable tools in any RCM analysis.

When a Working Group is assembled, there are typically hundreds of years of cumulative experience at an organization's disposal. Because of the vast and varied experience and perspectives represented, it is a unique opportunity to formulate solutions that can make a remarkable difference to the organization.

By turning to people who know where the improvement opportunities are, a skilled RCM Facilitator can use RCM principles to consolidate their knowledge and lead experts in formulating solutions that can have a powerful impact on the organization.

CONCLUSION

That concludes our RCM analysis real-world Case Study. I hope this helps you to better understand the RCM process and some of the core fundamentals of Maintenance and Reliability.

If you have any questions, I invite you to contact me at: *NancyRegan@RCMTrainingOnline.com*

With my warmest wishes for all success,

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