Reliability-Centered Maintenance (RCM)

The science of achieving better safety & dispatch reliability by doing less maintenance!

Who uses RCM?

Airlines (1970s-)
- Air Transport Ass’n MSG-3

Military aviation (1980s-)

Non-aviation (industrial)
- Nuclear power plants
- Oil refineries
- Water treatment plants
- Marine vessels
- Heavy equipment manufacturing
Benefits of using RCM

Components subject to scheduled overhaul or replacement

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Traditional</th>
<th>RCM</th>
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<td>DC-8</td>
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<td>7</td>
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<td>DC-10</td>
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Man-hours of structural inspections (first 20,000 hours TIS)

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<th>Aircraft</th>
<th>DC-8: 4,000,000</th>
<th>B-747: 66,000</th>
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Benefits of using RCM

- **RCM has saved the airlines a fortune by**
  - Slashing the amount of scheduled PM
  - Eliminating most TBOs
- **Big surprise:** When PM was slashed and TBOs eliminated, aircraft safety and dispatch reliability improved dramatically!

- **Q:** How can doing LESS maintenance result in MORE safety and reliability?
- **A:** By reducing MIFs (Maintenance-induced failures)

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**Maintenance has a dark side!**

- **Maintenance is inherently invasive**—it often breaks things that were previously working fine
  - We call this a maintenance-induced failure (MIF)
  - The more invasive the task, the more likely a MIF
- **Performing unnecessary maintenance**
  - Wastes money and increases the risk of MIF
- **Eliminating unnecessary maintenance**
  - Saves money and improves safety and reliability
Traditional vs. RCM

**Traditional view:**
- Maintenance is a good thing
- The more we do, the better

**RCM view:**
- Maintenance is a necessary evil…like surgery
- The less we do, the better
- We should do it only when absolutely necessary, or when the benefits clearly outweigh the associated risks and costs

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Key RCM questions

- What are this component’s **failure modes**?
- For each failure mode:
  - **How likely** is this failure to occur?
  - Is the probability of this failure:
    - Higher when component is **old**? (“age-related”)
    - Higher when component is **young**? (“infant mortality”)
    - Unrelated to component age? (“random”)
  - How serious are the **consequences** of this failure?
  - Can we **detect** an incipient failure before it occurs?
TDM versus CDM

- **Time-directed maintenance (TDM)**
  - Attempts to avoid failures by retiring, replacing or overhauling components at a specific age (TBO)

- **Condition-directed maintenance (CDM)**
  - Attempts to avoid failures by monitoring component condition to detect potential failures before they become functional failures

- **CDM is always more efficient than TDM**
  - TDM should be used only when CDM is infeasible

Hierarchy of consequences

- **Safety consequences**
  - Failure might hurt or kill someone
  - **Example**: engine connecting rod failure

- **Hidden consequences**
  - Failure invisible to crew, and might reduce safety
  - **Example**: failure of standby vacuum system

- **Operational consequences**
  - Failure might make aircraft unflyable (AOG)
  - **Example**: failure of a magneto

- **Economic consequences**
  - Failure has no significant operational impact
  - **Example**: failure of #2 comm radio
**RCM decision tree**

- **Impacts safety?**
  - **Yes**
  - **No**

- **Impacts mission?**
  - **Yes**
  - **No**

- **Risks damage?**
  - **Yes**
  - **No**

- **Is CDM effective?**
  - **Yes**
  - **No**

- **Is TDM effective?**
  - **Yes**
  - **No**

**Perform CDM**

**Accept failure, redesign system, or add redundancy**

**Perform TDM**

**Run to failure**

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**Age-related failures**

**Traditional view…**

- **Useful Life**
  - **Safe Life**
  - **TBO**
  - **A few premature failures**
  - **Unacceptable rate of failure**
  - **Wear-Out Zone**

**Do our piston aircraft engines exhibit this failure pattern?**
Age-related failures

Engine-failure accidents (2001-2005 small piston airplanes)

Past TBO?

Infant-mortality!
Age-related failures

Second-generation view…

“Bathtub curve”

OVERHAUL AT TBO???

Age-related failures

Third-generation view (RCM)…

TBO makes sense for only 4% to 6% of the components on civil A/C

Non-age-related

UAL 1968: 7%

BROMBERG 1973: 11%

U.S. NAVY 1982: 6%

Time

68% 66% 29%

77% to 92%

Age-related

UAL 1968: 4%

BROMBERG 1973: 3%

U.S. NAVY 1982: 3%

Time

5% 4% 3%

8% to 23%
Simple vs. complex

- **Simple items**
  - One dominant failure mode (e.g., metal fatigue)
  - Failure probability often increases with age
  - An age limit, safe-life limit, or TBO may be useful

- **Complex items**
  - Many different failure modes
  - Failure probability usually doesn’t increase with age
  - Age limits, safe-life limits and TBOs are not effective

Condition monitoring

Scheduled inspection for potential failures (P) intended to prevent functional failures (F)

*Rule of thumb:*

For condition monitoring to detect potential failures reliably and prevent functional failures, we must inspect for potential failures at approximately one-half of the P-F interval.
Let’s talk about TBO…

Overhauling an apparently healthy engine at TBO makes very little sense

- Complex item, no single dominant failure mode
  - so overhauling at TBO is not an effective method of reducing failure risk

- Most likely catastrophic failure is infant mortality
  - so overhauling arbitrarily at TBO is more likely to increase risk than decrease it

- Why throw away years of useful life?
Let’s talk about TBO…

Operating an engine beyond TBO…

- …is absolutely legal
- …won’t void your aircraft insurance
- …won’t make the overhaul more costly
- …won’t make a catastrophic failure more likely
  - In fact, it will do exactly the opposite!

A tale of two engines

- My 1979 Cessna T310R has two TSIO-520-BBs
  - TCM’s published TBO is 1,400 hours
  - On first run, these engines ran trouble-free for 1,900 hours SNEW, then field overhauled
    - Why? Because I chickened out! (Pretty dumb, huh?)
  - At teardown, engines immaculate
    - All 12 cylinders re-valved and continued in service
  - At TBO (1,400 SMOH), running great
  - At 2,300+ SMOH (164% of TBO), still running fine
  - This time, I’m in no hurry to overhaul!
TBO do’s and don’ts

- **How we should use TBO**
  - Use it to plan reserve for overhaul
  - Use it to adjust fair market value

- **How we should not use TBO**
  - Don’t euthanize an engine just because it has attained some arbitrary age
    - Why throw away years of useful life?
  - Monitor engine health using all available tools, and overhaul strictly “on condition”

Compressing test
Compression test

- Mandated by FARs but problematic:
  - Very unrealistic test conditions
  - Poor precision and reproducibility
  - Sensitive to equipment, technique
  - Numerous “false positives”—tens of thousands of cylinders have been removed unnecessarily due to “weak compression”

- **Never** pull a jug solely because of a low compression reading!
Oil filter inspection

- Mandated by FARs
- Very important test, but has limitations:
  - Won’t detect microscopic wear metal particles <20 microns
  - May not detect large chunks >1/16”
Oil filter inspection

Will detect this…

But may not detect this…

Oil filter never saw this!
Oil filter inspection

How much metal is too much?

- TCM does not offer guidance

- Lycoming says ground the aircraft if filter is found to contain:
  - Any large pieces of metal (the size of broken pencil point)
  - Numerous small particles totaling \( \frac{1}{4} \) teaspoon or more

- Anything less, fly and re-evaluate

\( \approx \frac{1}{4} \) teaspoon of ferrous metal

On the tip of a mechanic's magnetic pickup tool
Dry particle analysis

When significant metal is found in filter:

- **Use magnet** to identify if ferrous or non-ferrous
- **Send filter contents to lab** for scanning electron microscopy (SEM)
  - Can often identify the exact source of the metal
  - TCM and Lycoming both do this
  - Also independent labs

Oil pressure

Transient in-flight oil pressure fluctuation may indicate chunks of metal (or other foreign material) passing thru pressure relief valve

- Land immediately!
- Check oil filter, pickup screen, governor gasket

In technically-advanced aircraft, might be an electrical gremlin—but you must assume it’s real unless proven otherwise
Spectrographic oil analysis

- Complements filter inspection
  - Detects microscopic wear metal particles that are too small to see
  - Establishes a baseline “wear signature” for engine, then looks for departures from that norm

- Oil analysis excels at:
  - Detecting very slow wear events
  - Early warning of accelerating wear

### Spectrographic oil analysis

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<th>Total Hours</th>
<th>----- Parts Per Million -----</th>
<th>Date</th>
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<tr>
<td></td>
<td></td>
<td><strong>Al</strong></td>
<td><strong>Cr</strong></td>
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<tr>
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<tr>
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Borescope inspection

- Internal cylinder inspection
  - Without cylinder removal
- Now “required” by TCM SB03-3 at each compression test and annual/100-hour inspection
  - FAA says it’s not compulsory for Part 91…but you’d be crazy not to!
  - Eliminates most “false positives” of compression tests
Borescope inspection

Best cylinder borescope I've found so far is a dental intraoral camera!

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This exhaust valve looks normal

Note symmetrical exhaust deposits
Borescope inspection

This exhaust valve looks fine

Note reasonably symmetrical deposit pattern

Borescope inspection

This exhaust valve is burned!!!

Note asymmetrical deposits, and area devoid of deposits ("hot spot")
Digital engine monitors

- JPI EDM-760
- Insight Gemini 1200
- JPI EDM-700
- E.I. UBG-16
- Insight GEM-610
Digital engine monitors

- JPI EDM-930
- E.I. MVP-50
- Xerion
- AuRACLE

Digital engine monitors
Digital engine monitors

Absolutely indispensable for real-time monitoring and diagnosis of:

- Burned exhaust valves
- Misfiring spark plugs
- Faulty ignition leads
- Improper magneto timing
- Clogged fuel injectors
- Induction leaks
- Cooling baffle problems

![Engine Monitor Image]

EGT

CHT

4 Hours
What's wrong with this engine?

~30°F

20 cycles in 30 minutes

#3 Exhaust Valve
Burned exhaust valve

- **Signature is “dancing EGT”**
  - EGT variation ~30-50°F, often ~1± cycle/minute
  - If your analyzer isn’t in “normalize” mode, you’ll never notice it!
- **Distinguishing from a failing probe or loose connection**
  - Usually rapid and random, not slow and rhythmic
  - Usually spikes DOWN (not UP)
Chapter 393

ROP → LOP

"Big Mixture Pull"

Rough Engine

#2 & #4 go cold

Enrich a bit

#2 & #4 come back

but EGT erratic

EGT

CHT

TCM IO-520

One Minute

EGT

CHT

#5 EGT and TIT drift up; others stable

Pilot goes full-rich, then leans a bit

#5 EGT and TIT are now stable

TCM TSIO-520

10 Minutes
Is it fuel or spark?

- **Fuel-related problems** usually cause CHT and EGT to move in **the same direction**

- **Ignition-related problems** usually cause CHT and EGT to move in **the opposite direction**
Troubleshooting high CHT

- **Two possibilities:**
  - Too lean
  - Poor cooling
- **If cylinder is running too lean:**
  - Hot when ROP
  - Cool when LOP
- **If cylinder has inadequate cooling air** (due to problems with baffles and/or baffle seals):
  - Hot when ROP
  - Hot when LOP
Using these tools together

Never remove a cylinder or tear down an engine based on any one test:

- If there’s a **real** problem, it will almost always reveal itself in several ways
- If the **preponderance of the evidence** all points in the same direction, you can be confident of the diagnosis

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**Example:**

- Feb. 2006, oil analysis shows elevated nickel.
- Apr. 2006, RE #3 compression is “funky” but exhaust valve looks fine under borescope.
- Mar. 2007 (11 months and 150 hours later), engine monitor shows RE #3 EGT jitters. Borescope clearly shows two hot spots on valve. Compression test shows RE #3 at 0/80.

- **Verdict:** Replace RE #3 exhaust valve & guide
A 21st century engine condition monitoring program includes:

- Oil filter inspection
- SEM analysis of filter contents
- Spectrographic oil analysis
- Oil temperature & pressure trend analysis
- Compression test
- Borescope inspection
- Spark plug inspection
- Digital engine monitor data analysis

Secrets of Cost-Effective Maintenance

Five simple rules that can dramatically reduce your maintenance expenditures, year after year
Maintenance is a team sport!

- **Certificated mechanic (A&P)**
  - Performs repairs and alterations
  - Analogy: “licensed electrician, plumber, roofer”

- **Authorized inspector (IA)**
  - Inspects and approves (annuals, 337s)
  - Analogy: “licensed building inspector”

- **Aircraft owner/operator**
  - Primary responsibility for maintenance
  - Analogy: “general contractor”

Why this teamwork breaks down

- **Asymmetric knowledge**
  - Owner is theoretically in charge
  - A&Ps and IAs are theoretically “hired help”
  - In GA, owner usually has no maintenance training and minimal maintenance knowledge

- **Conflicts of interest**
  - IA determines what work must be done
  - A&P income derives from work performed
  - In GA, IA and A&P are usually the same person!
Why this teamwork breaks down

Lack of “informed consent”
Aircraft owners routinely approve maintenance without knowing:
- What it is going to cost
- Why it is being performed
- Whether it is really necessary for safety
- Whether it is required by regulation
- How invasive it is
- What the risks are
- Whether the benefits outweigh the risks and cost

Defensive maintenance
- Explosion in litigation since 1994 (GARA)
  - 18-year limit on manufacturer’s product liability
- Prior to GARA, A&Ps worried about two things:
  - It it safe?
  - Is it legal? (i.e., does it comply with FAA regulations?)
- Since GARA, A&Ps have to worry about a third:
  - How will it look to a jury of citizens (who have no knowledge about aviation or maintenance) when spun in the most unfavorable possible light by a skilled plaintiff’s attorney?
The bottom line:

Most aircraft owners do a terrible job of managing their maintenance!

www.savvyaviator.com
Training may not be enough!

Managing maintenance properly requires a major investment in time, effort and study

- Some owners can’t do this because they’re too busy running a business or raising a family.

- Some owners feel they bought an airplane to save them time, not cost them time.

- Many owners are not comfortable telling their A&Ps what to do (instead of the other way around)
Rule #1:

Choose the right service facility and/or technician for the job.

An owner’s job #1

- As “general contractor” an owner’s job is to:
  - Hire skilled tradesman (IAs, A&Ps, other technicians)
  - Manage them to ensure they perform as desired and get the job done within schedule and budget
  - Fire them if they do not perform to expectations
- The most important of these is the first!
  - If you hire the right person for the job, the rest tends to work out well most of the time
  - If you hire the wrong person for the job, the best management skills in the world may not be enough to rescue the situation
Hiring the right shop

- Most owners do it the wrong way:
  - The shop is at or near the aircraft’s home base
  - The mechanic or DOM seems friendly
  - An aircraft-owner friend recommends it

- Much more “due diligence” is required
  - Interview the shop as you would an employee
  - Look for the three C’s:
    - Competent
    - Communicative
    - Cooperative

The three C’s

- **Competent** means the shop has extensive experience with your make and model

- **Communicative** means the shop is committed to keeping you continually “in the loop”

- **Cooperative** means the DOM is customer-oriented and willing to do things your way
Rule #2:

Insist on a written discrepancy list and cost estimate before approving any work or parts.

Avoiding “sticker shock”

Never approve maintenance until you know what it’s going to cost

- Get it in writing!
- Instruct the shop that they are not authorized to exceed their written estimate unless they give you an amended estimate and obtain your explicit approval
- If you first learn the cost at invoice time, it’s too late to affect the outcome!
What about inspections?

Require a three-phase protocol:

- **Shop inspects aircraft** (for a flat-rate charge) and presents owner with a written discrepancy list, with specific repair recommendations and detailed cost estimates for parts, labor, and outside work
- **Owner reviews discrepancy list and estimates**, asks questions, seeks second opinions, does homework to **ensure informed consent**
- **Owner gives shop specific written direction and authorization to proceed**

Rule #3:

If it ain’t broke, don’t let them fix it!
If it ain’t broke, don’t fix it!

- Every service manual contains hundreds of scheduled preventive maintenance tasks.
- Such one-size-fits-all recommendations make no sense!
  - Is aircraft based in Tampa or Tucson?
  - Does aircraft fly 30 hours/year, or 300 hours/year?
  - Is aircraft hangared, or tied down outdoors?
- Compliance is usually not required, and often is a huge waste of money.

Don’t do it “by the book”!

It never makes sense to maintain any component on a fixed timetable if it is feasible to monitor condition and determine when maintenance is actually required.

- CDM is always more cost-efficient than TDM.
- TCM should be used only if CDM is infeasible.
- Numerous studies show that CDM is feasible for about 95% of the components on civil aircraft.
Rule #4:

Don’t let them fix it until you’re sure what’s wrong with it!

(Complete the diagnosis before starting therapy.)

Troubleshooting failures

- Have you ever had this experience?
  - You put your aircraft in the shop to have a squawk fixed;
  - You received an invoice for parts and labor;
  - You discovered that the squawk wasn’t fixed?
- If so, you were victim of a troubleshooting failure!
- Incorrect/inadequate troubleshooting is the #1 cause of wasted maintenance dollars!
Troubleshooting failures

- A&Ps are often poor troubleshooters
  - They are trained as therapists, not diagnosticians
  - Many aircraft problems cannot be reproduced in the maintenance hangar
  - If a mechanic can’t reproduce a problem, he can’t troubleshoot it systematically (so he has to guess)

- What’s the solution?
  - Troubleshoot the problem yourself
  - Consult with an expert on the system in question

Rule #5:

Don’t let your shop overkill the problem!
Don’t overkill the problem!

- When your airplane has a problem and you’ve diagnosed it properly, get it fixed but don’t go overboard!
  - If you have a cylinder with a burned exhaust valve, repair the valve, don’t replace the jug
  - If you have one or two weak cylinders, don’t get talked into doing a top overhaul
  - No matter how many cylinders are bad, don’t even think about overhauling the engine

Review: The five rules

1. Choose the right shop and/or technician
2. Require a written discrepancy list & estimate
3. If it ain’t broke, don’t let them fix it
4. Don’t fix it until you’re sure what’s wrong
5. Don’t overkill the problem
Does this stuff really work?

You bet it does!

Lots of good info at www.savvymx.com