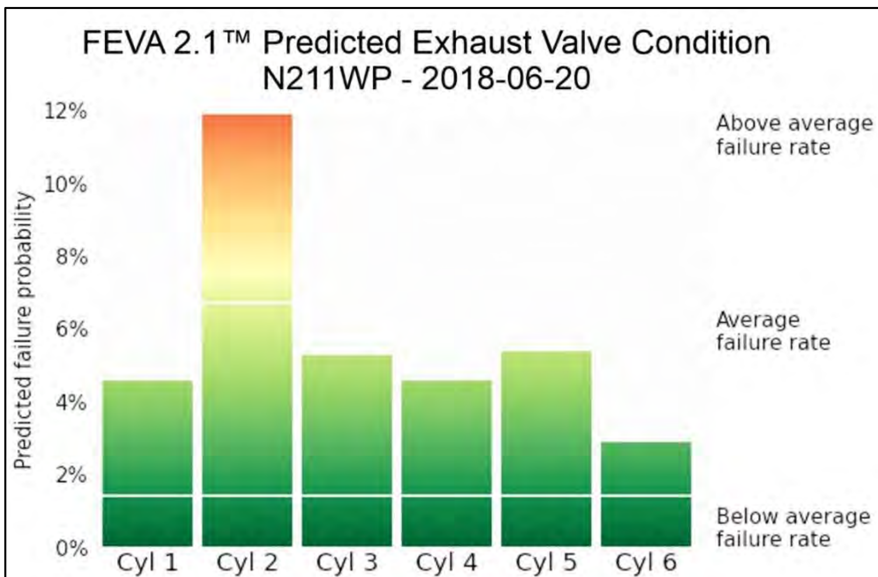
Predictive Maintenance



Your presenter…

Mike Busch A&P/IA

Columnist — AOPA PILOT magazine

Instructor — EAA Webinars

Podcaster — Ask the A&Ps (AOPA)

National Aviation Maintenance Technician of the Year (2008)

President — Savvy Aviation, Inc.

Mo 1000	#7	The EGT Myth
Mo 1300	#7	How Healthy Is Your Engine?
Tu 0830	#7	To TBO and Beyond…
Tu 1000	#7	Leaning The Right Way
Tu 1300	#7	Destroy Your Engine in 1 Minute
We 0830	#7	Cylinder Break-In: Do It Right
We 1130	#7	What Is Preventive Maintenance?
We 1430	#7	Cylinder Work: Risky Business
Fr 0830	#7	It's Baffling
Fr 1000	#7	Where Fuel Meets Air
Fr 1300	#7	Benefits of Running Oversquare
Sa 1000	#7	How Mags Work…and Fail
Sa 1300	**#7**	**Predictive Maintenance**

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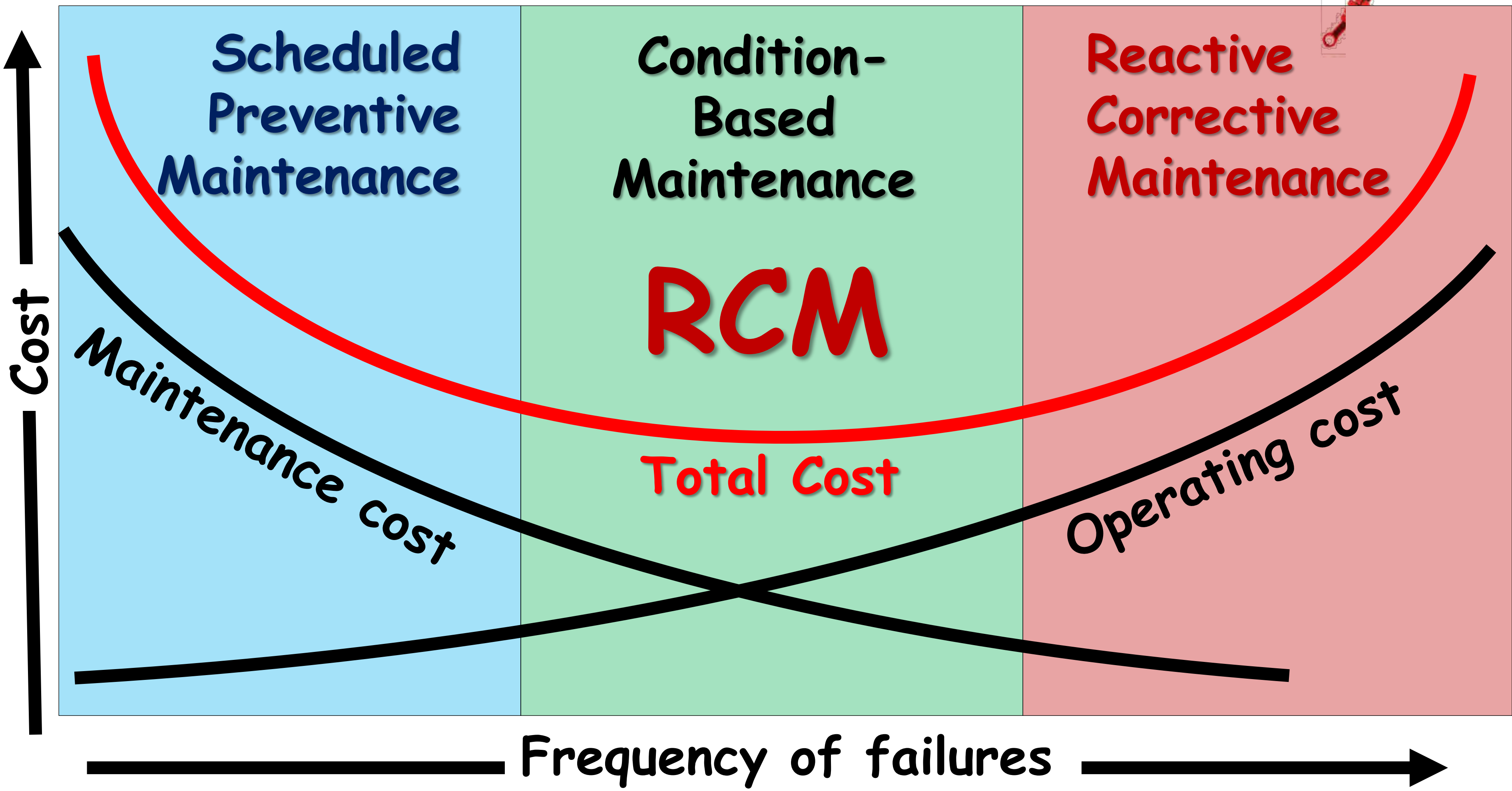
Reliability
Centered
Maintenance
THE RCM Solution
A Practical Guide to Starting and Maintaining a Successful RCM Program
Nancy Regan
Manifesto
Mike Busch


Scheduled Preventive Maintenance
Condition-Based Maintenance
Reactive Corrective Maintenance
RCM
Total Cost
Maintenance cost
Operating cost
Cost
Frequency of failures

Two tenets of RCM that reduce preventive maintenance drastically:

- Don't do PM to prevent failures that have acceptable consequences
- Do PM strictly on-condition wherever practicable

Condition-based maintenance requires determining condition

How can we do that?

- Disassembly inspection
- Direct visual inspection (incl. borescopy)
- Indirect evidence (compression, oil analysis)
- Sensor data (predictive analytics)

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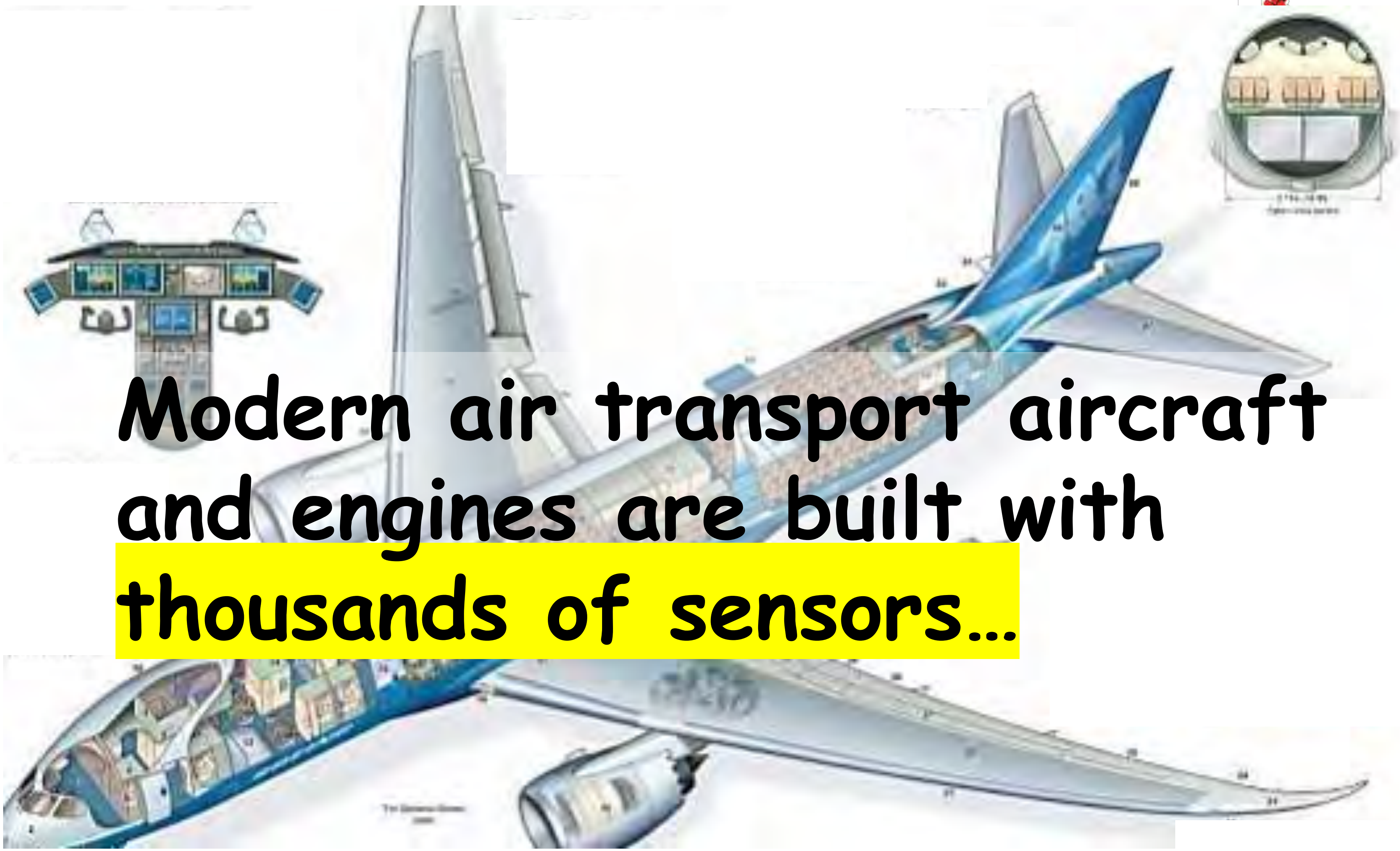
- Disassembly inspection
- Direct visual inspection (incl. borescopy)
- Indirect evidence (compression, oil analysis)
- Sensor data (predictive analytics)

During the past two decades, there has been a serious revolution going on in predictive analytics

- mostly with airlines

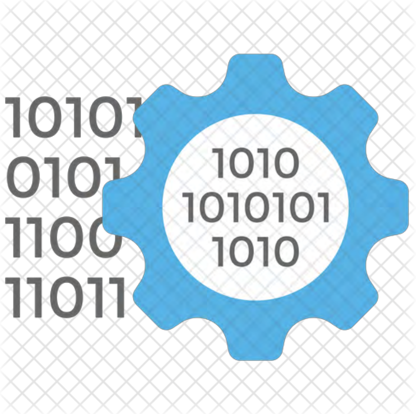
- quietly trickling down the aviation food chain



Modern air transport aircraft and engines are built with thousands of sensors…

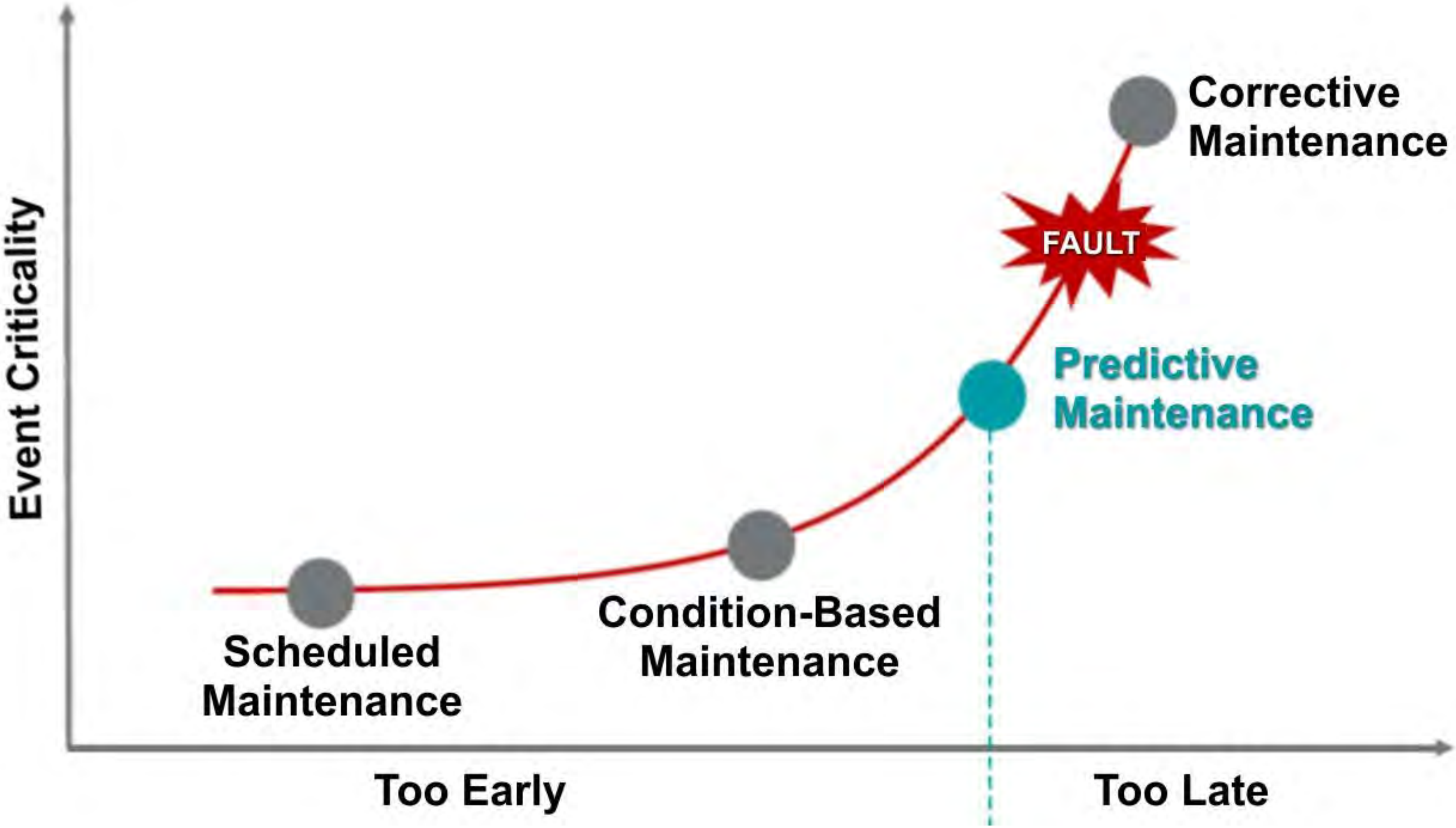
- Engine parameters
- Electrical parameters
- Hydraulic parameters
- Air data
- Vibration
- Flight control position
- Landing gear position
- Fluid levels
- Cabin pressurization
- Etc.

Sensor data is digitized by a DAU and downlinked in real-time or captured by a QAR



Predictive analytics employs computer algorithms to process this sensor data and detect patterns indicating

- preventive maintenance is necessary
- incipient component failure is likely


Event Criticality
Corrective Maintenance
FAULT
Predictive Maintenance
Scheduled Maintenance
Condition-Based Maintenance
Too Early
Too Late

Detection of parameter degradation, exceedance, or adverse trending

- low tire pressure
- high electrical bus voltage
- decreasing oil pressure

is generally pretty easy

Prediction of "rare events"

- contaminated fuel nozzle
- damaged compressor blade
- failing engine bearing

tends to be difficult and may require complex algorithms

Boeing pioneered predictive analytics in 2004 when it introduced a service it calls Airplane Health Management (AHM)

Boeing's AHM monitors the health of an airplane in flight and relays that information in real time to airline personnel on the ground

When the airplane lands and arrives at the gate, maintenance crews are ready to make any needed repairs quickly

AHM algorithms also try to predict when aircraft components are at risk of failing so they can be replaced or repaired at the next maintenance check

Nowadays, virtually every airline that flies Boeing's 777s or 787s uses AHM

BOEING

GE Aviation

AIRBUS

Pratt & Whitney
A United Technologies Company

DELTA

ROLLS ROYCE
Rolls-Royce

Airbus entered into a partnership with Delta Air Lines as the pilot customer for Skywise Predictive Maintenance on Delta's A320 and A330 aircraft

Delta claims a success rate of over 95 percent for pending failure predictions

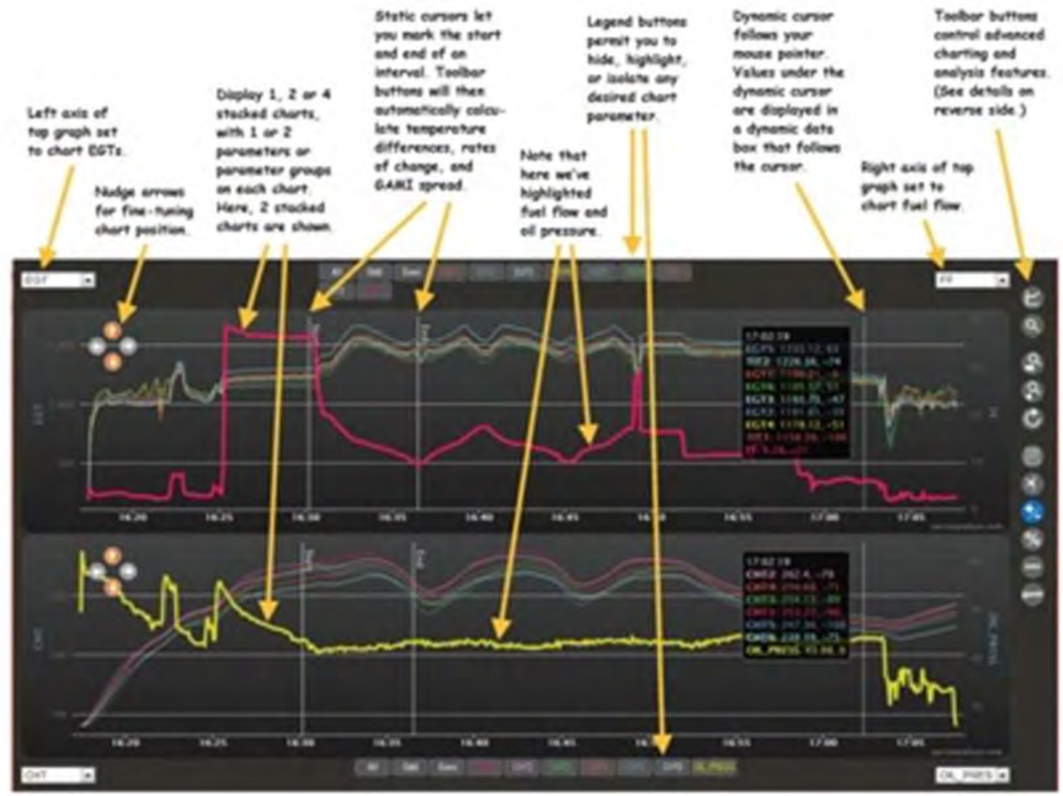
- 55 maintenance-related flight cancellations in 2018
- 5,600+ maintenance-related flight cancellations in 2010

What about piston GA?

Savvy Analysis

Launched in 2013

- Free
- Pro
- Pro Packs



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Savvy Analysis web-based platform

Universal, omnilingual: supports virtually all piston digital engine monitor makes and models (certified and experimental)

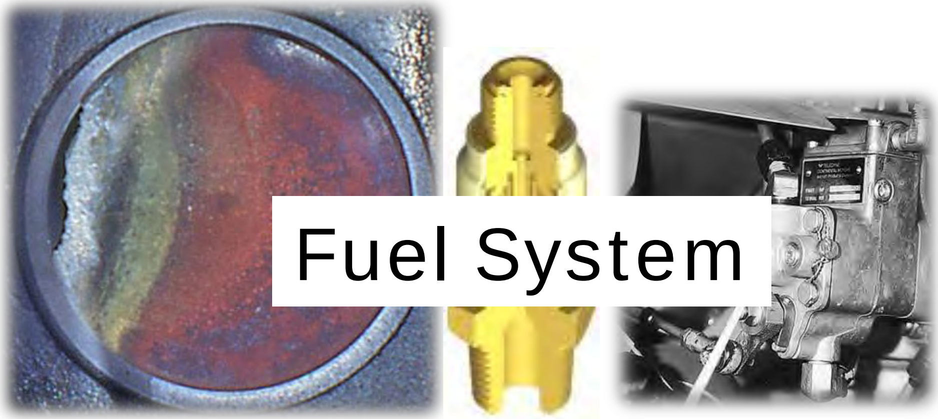
Accessible from any device

Incredibly powerful tool for **diagnosing** a broad range of piston aircraft problems

- Mechanical (problem with the aircraft)
- Operational (problem with the pilot)
- Instrumentation (problem with the equipment)
- Forensic (cause of an accident or incident)

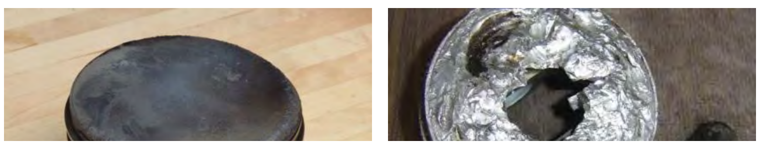
Totally **non-invasive**

Ignition System



Fuel System

Electrical System



Abnormal Combustion

Operational Issues

Sensors/ Instrumentation

Our platform has now aggregated data from 3,000,000+ flights

- An average of ~35,000 data samples per flight
- That comes to roughly 10 billion data samples
- Enough to do some interesting things

SavvyAnalysis Report Card

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SavvyAnalysis Report Card

Nxxxxx · SR22 Normally Aspirated · IO-550 · Perspective

Includes 27 flights between Nov 20, 2015 and Nov 19, 2016, compared with 46886 flights by a cohort of 741 SR22 Normally Aspirated aircraft.

Percent Power in Cruise

Description: Measures your engine's power output during cruise flight. High power output for extended periods can contribute to reduced fuel efficiency, elevated CHT and reduced cylinder life.

0% 25% 50% 75% 100%
57.2 65.2 75.8
45%Pwr 56.8%Pwr 61.2%Pwr 65.3%Pwr 90%Pwr

Savvy says: The median of your engine's power output during cruise flights is greater than 74% of the cohort, which will make you go fast, but at the cost of reduced cylinder longevity.

Altitude in Cruise (MSL)

Description: Measures the altitude during the cruise phase of flight. For turbocharged aircraft, higher altitudes generally provide better performance and efficiency.

0% 25% 50% 75% 100%
2940 7170 9500
2000 ft 5240 ft 7210 ft 9140 ft 18000 ft

Savvy says: Your cruising altitudes tend to be at mid levels, resulting in average fuel efficiency and performance.

Speed in Cruise (K.)

Description: We use TAS if available, otherwise ground speed. Higher speed might be due to high power output, resulting in high CHT and reduced cylinder life. Or possibly operation at higher, more efficient altitudes.

0% 25% 50% 75% 100%
134 164 175
110 KTAS 155 KTAS 164 KTAS 172 KTAS 225 KTAS

Savvy says: Your cruise speed is average when compared with your cohort.

Fuel Efficiency (nm per gal.)

Description: Measures your aircraft's fuel efficiency during cruise flight.

0% 25% 50% 75% 100%
8.71 11.2 12.1
6nmpg 10.6nmpg 11.7nmpg 12.6nmpg 19.8nmpg

Savvy says: Your aircraft's fuel efficiency is average when compared to your cohort.

Maximum CHT during Flight (deg. F.)

Description: Measures the maximum CHT attained during each flight, most likely during climb phase. Prolonged periods of high CHT can contribute to reduced cylinder life.

0% 25% 50% 75% 100%
331 375 407
300°F 346°F 361°F 376°F 475°F

Savvy says: Your maximum CHTs have been higher than 74% of the cohort which is higher than we like to see. We suggest you confirm that your full power fuel flow is adequate, ignition timing advance is correct, baffling is in good shape, and climb airspeed is high enough.

Maximum CHT in Cruise (deg. F.)

Description: Measures the maximum cylinder head temperature (CHT) during the cruise phase of flight, an indication of the stress placed on your engine's reciprocating components. High CHT correlates with reduced longevity of cylinder assemblies.

0% 25% 50% 75% 100%
276 351 377
250°F 316°F 337°F 355°F 450°F

Savvy says: Not bad. Your cruise CHTs have been moderate, with a median value higher than 70% of the cohort. We think you can expect average longevity of your cylinders if you continue operating with your current leaning procedures and/or power settings.

Maximimum CHT Spread in Cruise (deg. F.)

Description: Measures the median temperature spread between your hottest and coolest cylinders at maximum CHT during cruise. The spread is an indication of mixture distribution and the adequacy of cooling airflow to all cylinders.

0% 25% 50% 75% 100%
9 16 33
0.001°F 24°F 31°F 39°F 150°F

Savvy says: The median value of the maximum CHT spread during cruise flights is lower than 94% of the cohort.

Oil Pressure in Cruise (psi)

Description: Measures the average oil pressures during cruise for your flights.

0% 25% 50% 75% 100%
40.3 44.6 46
14.3psi 45.8psi 48.4psi 51psi 150psi

Savvy says: Your average oil pressures during cruise have a median value lower than 84% of the cohort. Your oil pressures are in the normal range.

Oil Temperature in Cruise

Description: Measures average oil temperature during cruise.

0% 25% 50% 75% 100%
162 171 184
100°F 171°F 177°F 184°F 250°F

Savvy says: Your average oil temperatures during cruise are lower than 76% of the cohort. Your oil temperatures are in the normal range.

Maximum Fuel Flow during Flight

Description: Measures maximum fuel flow during flight, most likely during takeoff. Sufficient fuel flow is important for proper cylinder cooling during high power operations

0% 25% 50% 75% 100%
26.9 28.6 29.3
10 gph 26.9 gph 27.7 gph 28.5 gph 50 gph

Savvy says: Your maximum fuel flow is higher than average when compared with your cohort.

Maximum RPM during Flight

Description: Measures maximum rpm during flight, most likely during takeoff. Maximum permitted RPM is necessary for the engine to develop full rated power during takeoff and in initial climb.

0% 25% 50% 75% 100%
2580 2680 2690
1500 rpm 2650 rpm 2670 rpm 2680 rpm 3500 rpm

Savvy says: Your maximum RPM is average when compared with your cohort.

Inactivity Periods (days)

Description: Measures the number of days your aircraft was inactive between flights. Inactivity can contribute to engine corrosion and reduced life of engine components.

0% 25% 50% 75% 100%
1.08 5.5 31.8
1 days 2.08 days 4.71 days 9.81 days 398 days

Savvy says: Your engine's inactivity is about average when compared to your cohort. Savvy recommends continuing to fly as frequently as possible

Interpreting these Report Card "thermometers"

How do the maximum CHT's for your aircraft's flights compare with the "cohort" of other aircraft of the same make and model?

Lowest, median and highest max CHT for your aircraft's flights

0% 25% 50% 75% 100%
388 392 409
333°F 373°F 383°F 395°F 436°F

25% quartile value of max CHT for your cohort's aircraft (25% had lower max CHT's)

Median value of max CHT for your cohort's aircraft (50% were lower)

Savvy's redline CHT!

For more information about the contents of this SavvyAnalysis Report Card and how to interpret it, see our FAQ page. If you have questions or comments, please let us know.

Predictive Maintenance

SavvyAnalysis Trend Report

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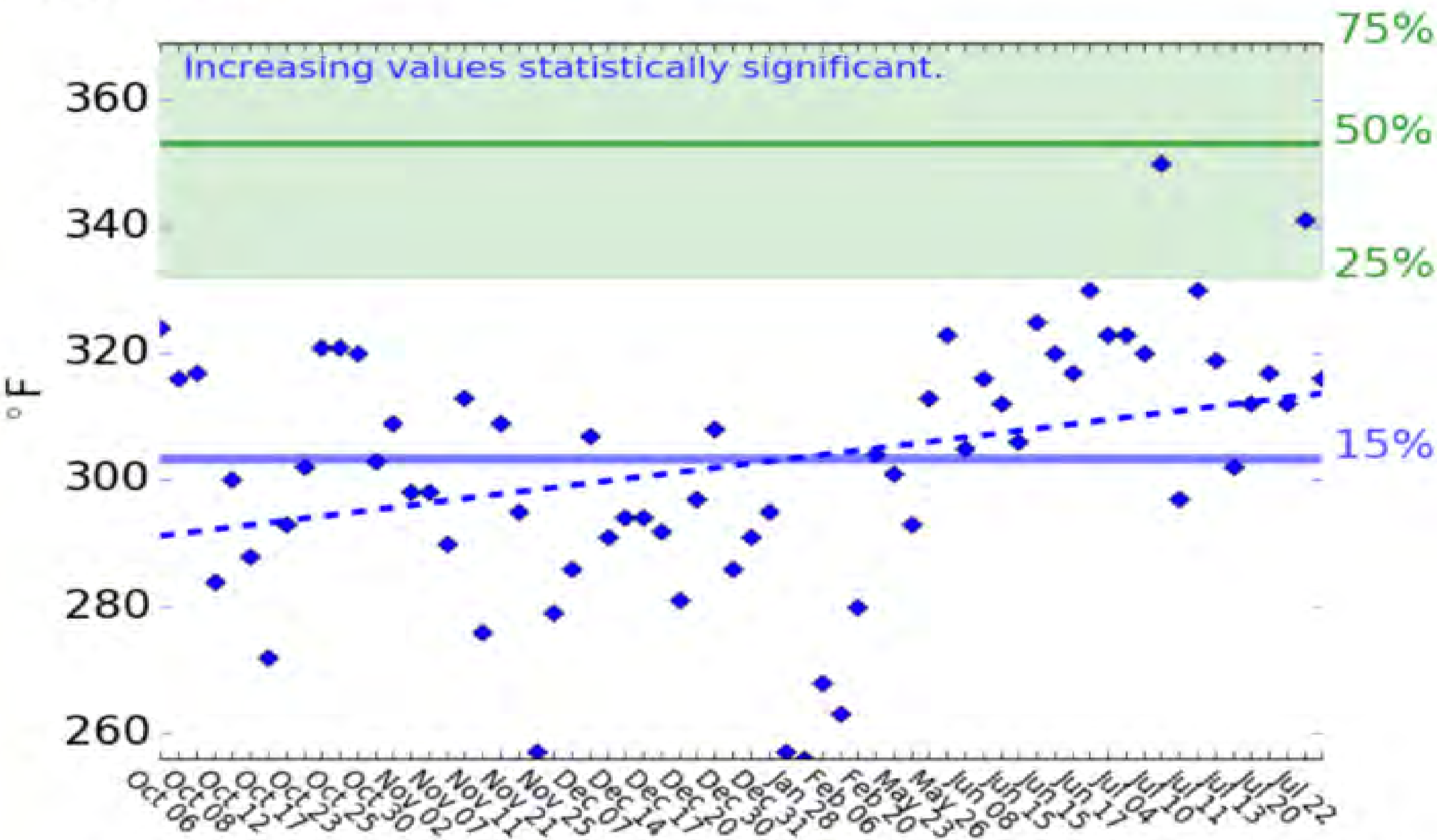
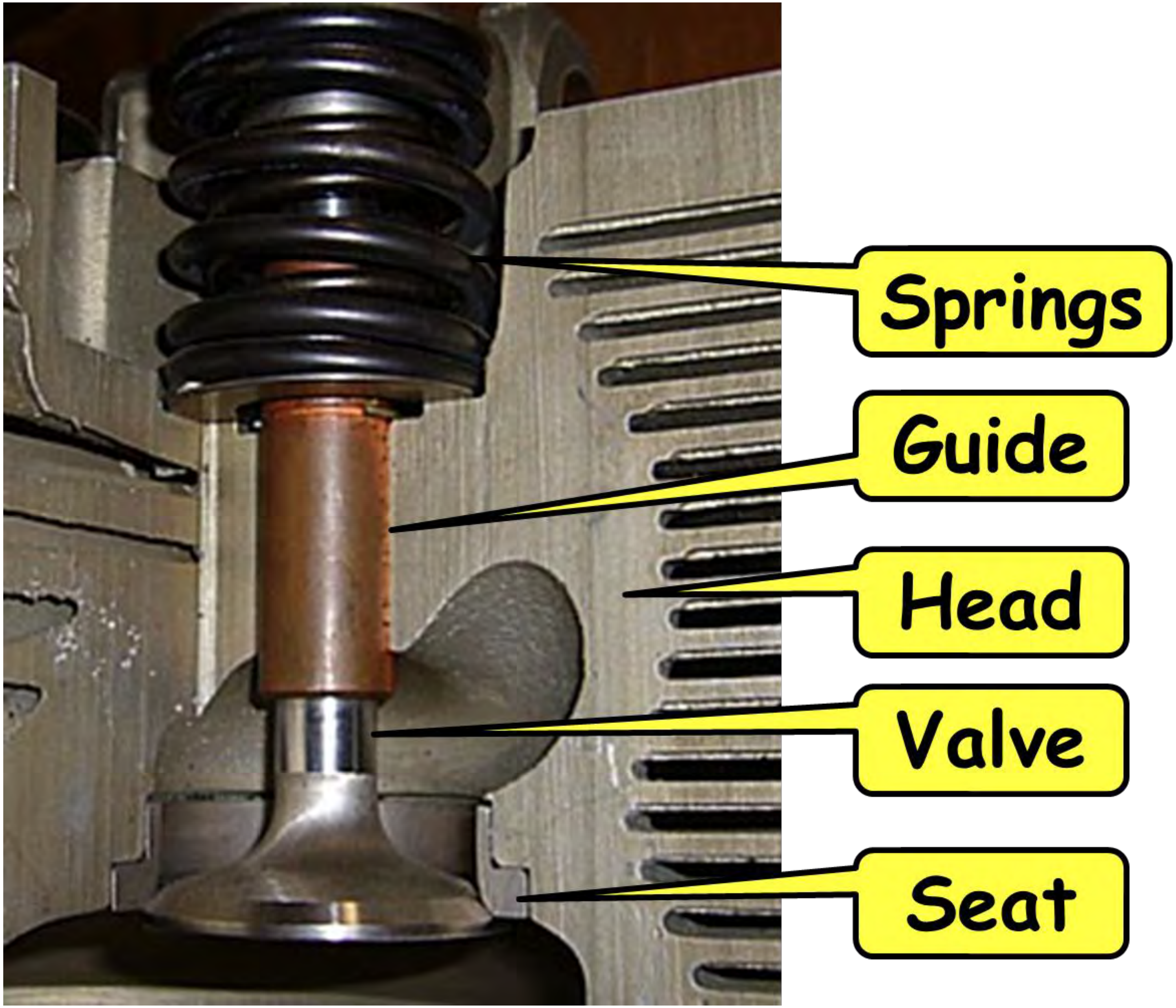
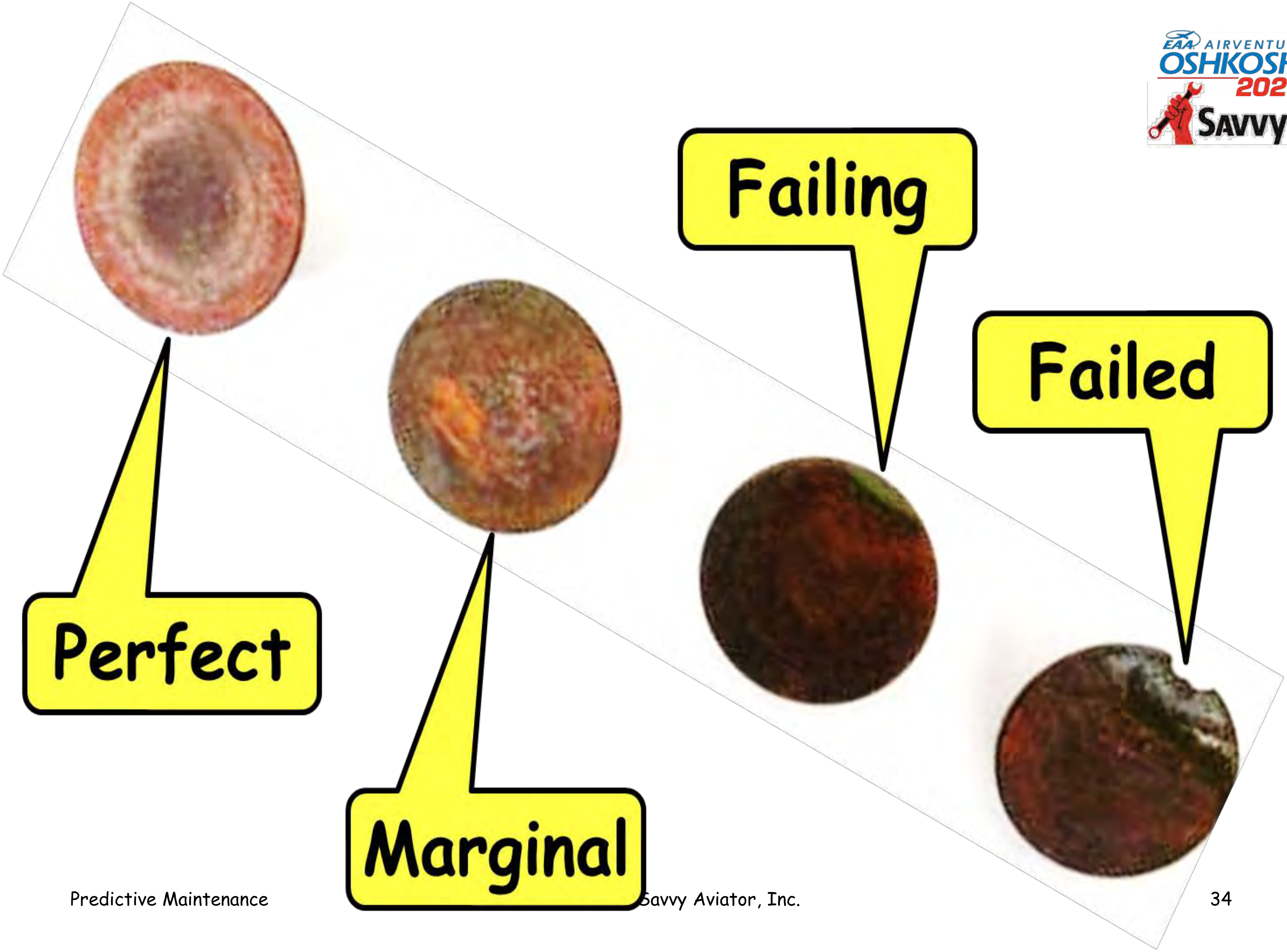
Maximum CHT in Cruise (deg. F.)

Description: Measures the maximum cylinder head temperature (CHT) during the cruise phase of flight, an indication of the stress placed on your engine's reciprocating components. High CHT correlates with reduced longevity of cylinder assemblies.



Our first attempt at predictive maintenance came in 2014 with FEVA: Failing Exhaust Valve Analytics


Springs
Guide
Head
Valve
Seat


Failing
Failed
Perfect
Marginal

When an exhaust valve fails in flight, the consequence is usually a partial loss of engine power

- At minimum, one cylinder shuts down
- Turbocharger damage sometimes results, causing additional power loss
- Catastrophic engine failure and total loss of power is rare, but happens on occasion

Worst-case scenario…

But there's some good news…

Valve failure usually occurs gradually

- On the order of 50-100 hours from the threshold of detectability to outright failure
- Borescope is the best way to detect

Valve failure is relatively rare

- Our data suggests that about 2% of exhaust valves are in the process of failing at any time

Borescope is the gold standard for detecting incipient valve failure

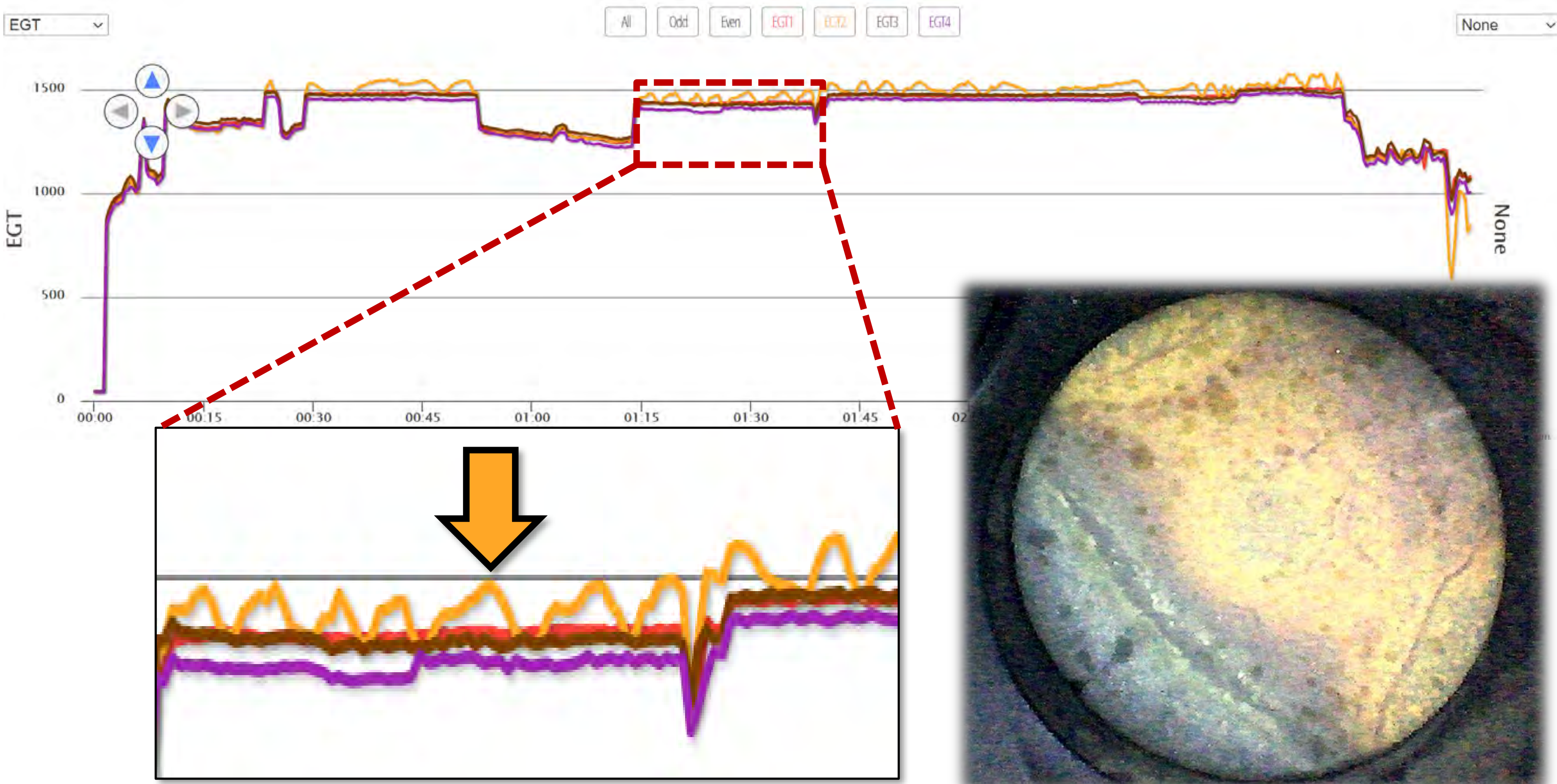
We recommend valves be borescoped at least each 100 hours, but this is seldom done

- Many aircraft mechanics still don't own a borescope, and many who do fail to use it regularly
- Can be legally performed by the aircraft owner, but few owners are comfortable doing it on their own

Perhaps we can use engine monitor data analysis to alert us when borescoping should be done soon (and not wait for the next annual inspection?)

FEVA 1.0 (2014)

- Our first attempt at predicting valve failure using engine monitor data analysis
- We had noticed that sometimes exhaust valves that are starting to fail produce a slow, rhythmic, cyclical EGT oscillation


EGT
All
Odd
Even
EGT1
EGT2
EGT3
EGT4
None
1500
1000
500
0
EGT
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
None

We created an algorithm to detect this pattern, and used it to screen all uploaded flights

- This was an "expert system": it tried to mimic a human analyst
- It looked at only one thing (EGT)
- It turned out to be not as accurate or sensitive as we'd hoped

We created an algorithm to detec… …d used it to sc… …flights

- Th… …stem": it … …an analyst
- It … …ning (EGT)
- It … …s accurate or … …ped

Maybe we can do better?

The fundamental limitation of an expert system is that it can only be as good as the human experts that it mimics

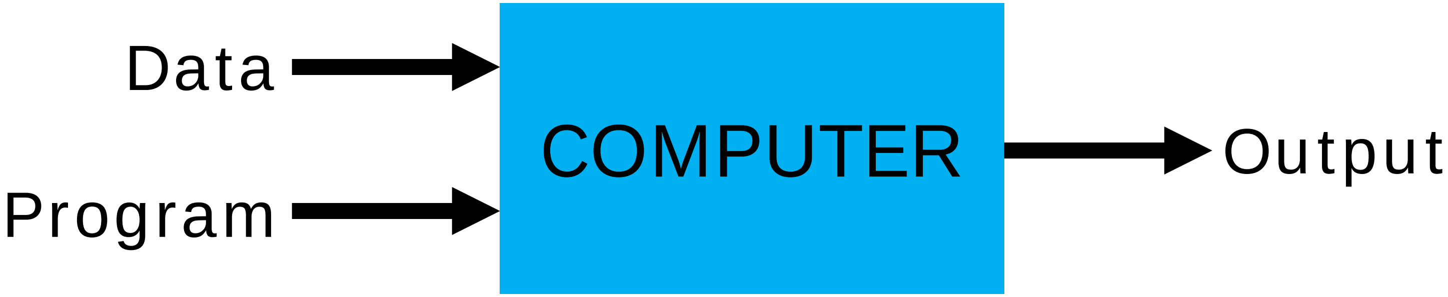
- Engine monitors generate huge amounts of data from numerous sensors
- Humans aren't good at recognizing complex interrelationships in big data

Can we do a better job of predicting exhaust valve failure if we look at more parameters than just EGT?

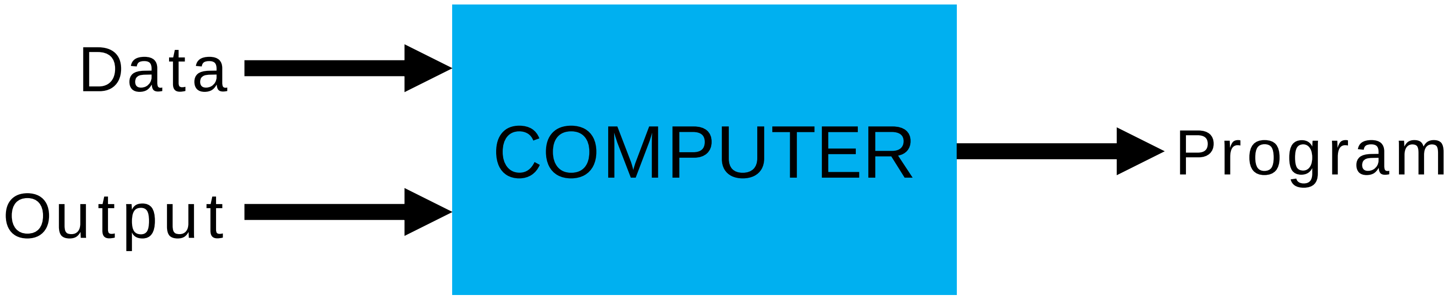
A computer should be able to recognize patterns and correlations in a large data set far better than any human could

Seems like a job for Machine Learning!

EXPERT SYSTEM



MACHINE LEARNING



SavvyAI
Smart maintenance

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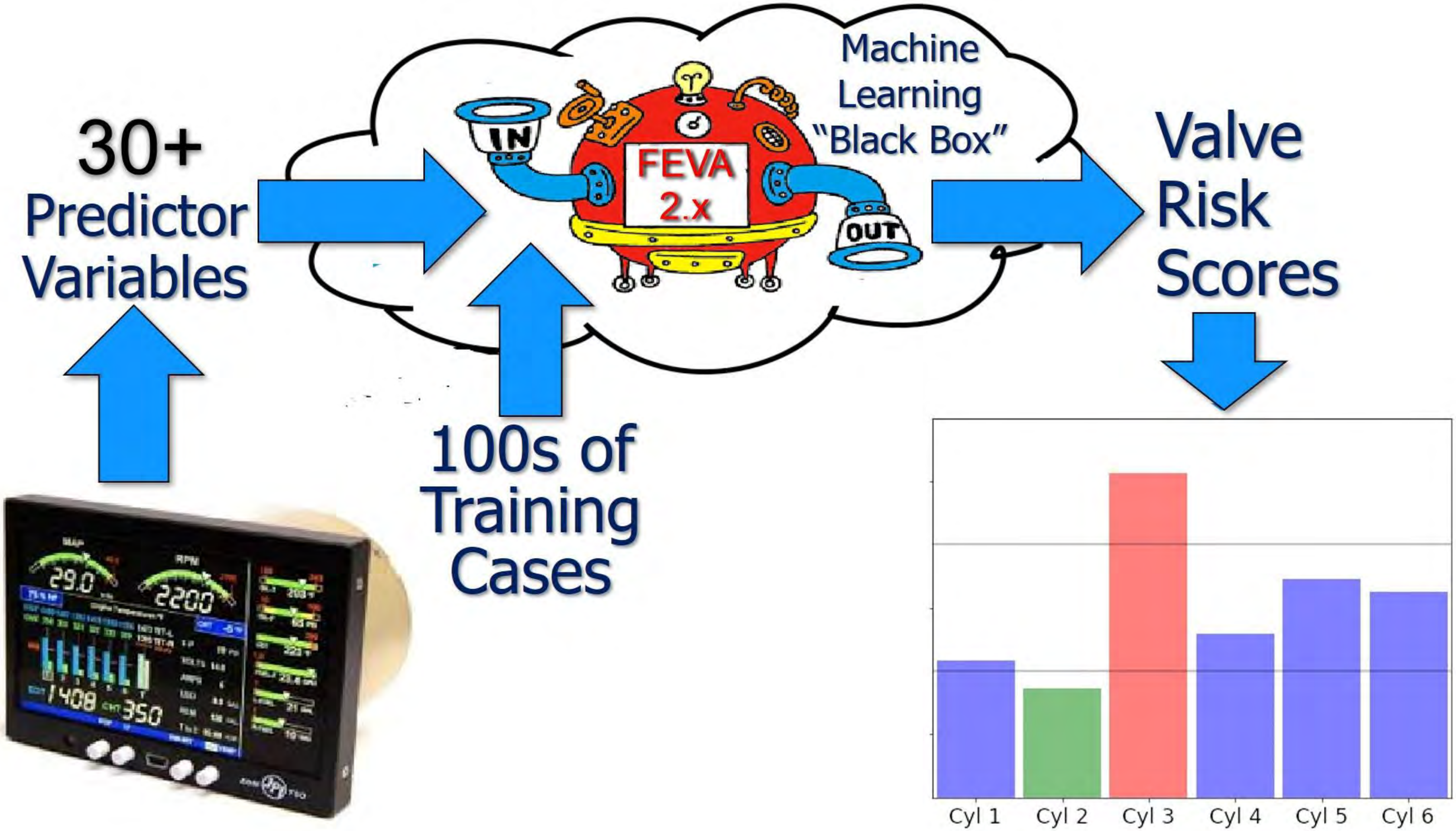
FEVA 2.0

A machine learning (ML) model to predict exhaust valve failure


30+
Predictor
Variables
IN
FEVA
2.x
OUT
Machine
Learning
"Black Box"
Valve
Risk
Scores
100s of
Training
Cases
Cyl 1
Cyl 2
Cyl 3
Cyl 4
Cyl 5
Cyl 6

Building the ML Model

- Data set not large enough for Neural Network model
- Trained on a variety of ML models:
  - Decision Tree
  - Random Forests
  - Support Vector Machine
  - ADA Boost
- Random Forests performed best

Building the ML Model

- We came up with 35 different parameters calculated from raw engine monitor data
  - We calculated mean and std. deviation
  - We analyzed phase of flight
  - We performed Fourier analysis on various parameters including EGT

Training the ML Model

We searched our maintenance ticket system and found 3,400 cases where exhaust valve condition was known, determined by borescope inspection

We identified each of these 3,400 cases as "Failing" or "Normal"

We split these cases into two parts: a training set and a test set

Training the ML Model

For each known case, we captured engine monitor data from up to 10 recent flights prior to the borescope inspection that determined valve condition

Measuring Model Performance

- **Sensitivity:** What percentage of failing valves are correctly identified by the model? (How good is it at identifying real failures?)
- **Positive Predictive Value:** What percentage of valves the model predicts to be failing are actually failing? (How good is it at avoiding false positives?)

So, how did FEVA2 perform on the test set?

What was the actual failure rate (per borescope) vs the FEVA2 predictive score?

- **Sensitivity:**
  The model correctly catches 50% of the actual valve failures

- **Positive Predictive Value:**
  3 out of 4 failure predictions are false positives

Stated differently:

- About 1 in 30 valves were actually in failure as determined by borescope
- A valve predicted by the model to have "Above average probability of failure" has a 1 in 4 chance of actually being in failure
- A valve predicted by the model to have "Below average probability of failure" has a 1 in 100 chance of being in failure

Is this good enough to be useful?

Let's think about this…

- **As a diagnostic test:**
  The model would be an abysmal failure due to the high (3-in-4) rate of false positives

- **As a screening test:**
  The model is extremely useful, since it's calling for a borescope inspection that has a 1-in-4 chance of finding a failing valve

Communicating FEVA 2 to our clients:

Missteps and lessons learned

Aircraft Owner Psychology 101

Since we started sending out FEVA 2 reports to our clients:

- We've gotten numerous complaints about false positives ("You scored me at risk for no reason")
- We've gotten ZERO complaints about false negatives ("Why didn't you catch this?")

Apparently, our clients prefer getting good news that isn't true to getting bad news that isn't true!

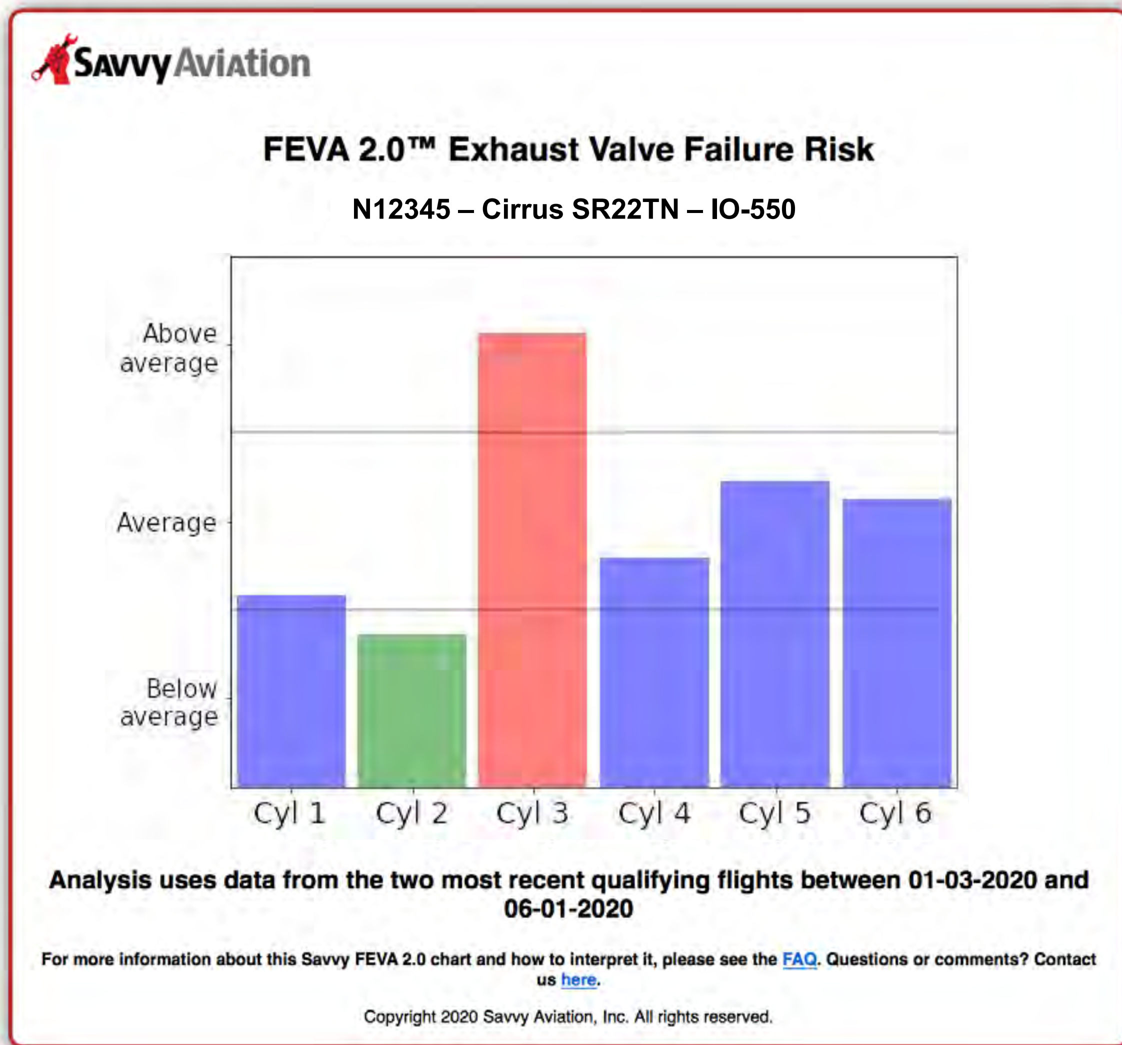
Lesson learned:

Must make clear the distinction between "Screening" and "Diagnosing"

- FEVA isn't condemning your valve!
- FEVA is giving you guidance whether or not early borescoping is worth doing

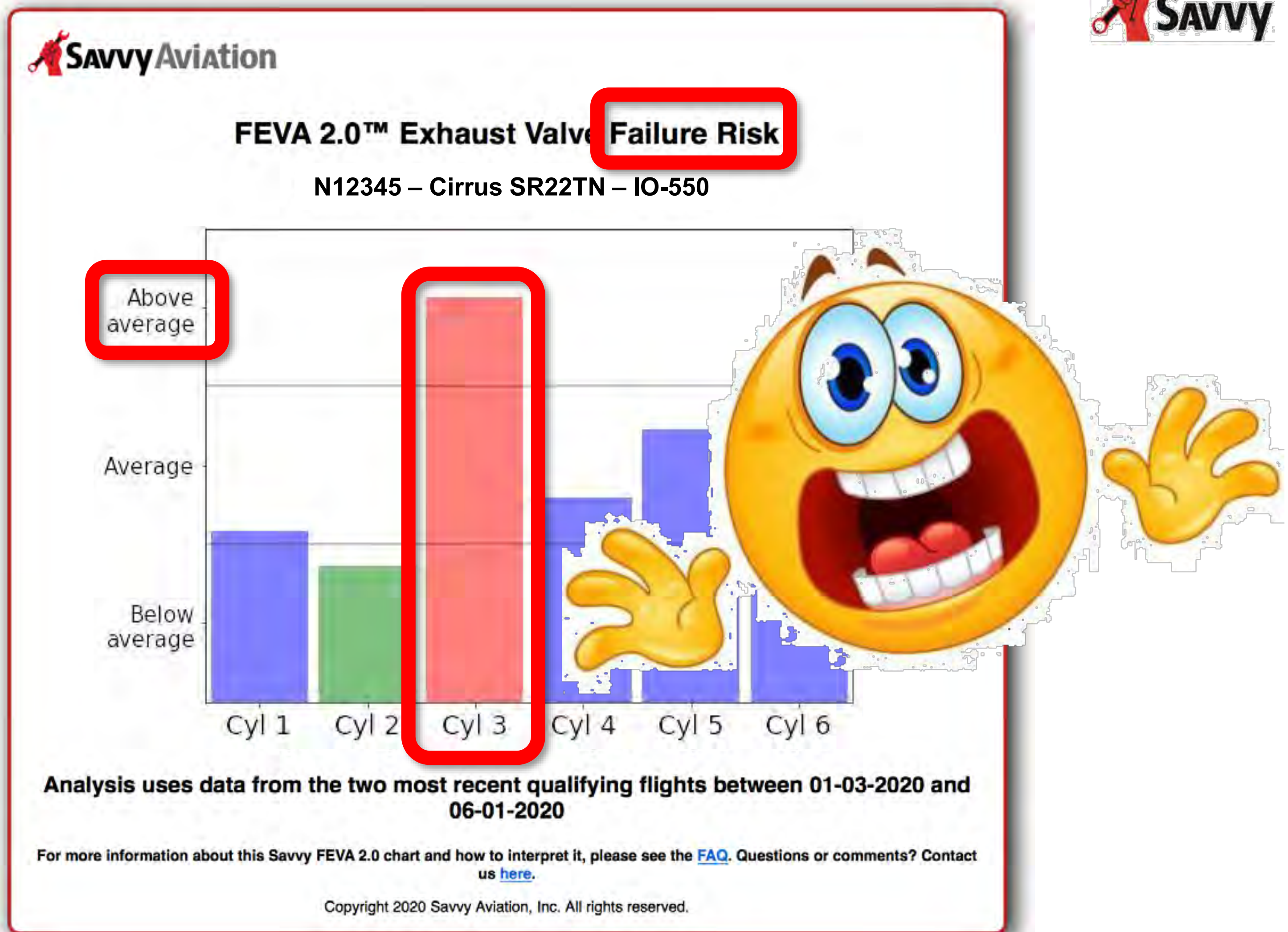
About 4x as likely to fail as average

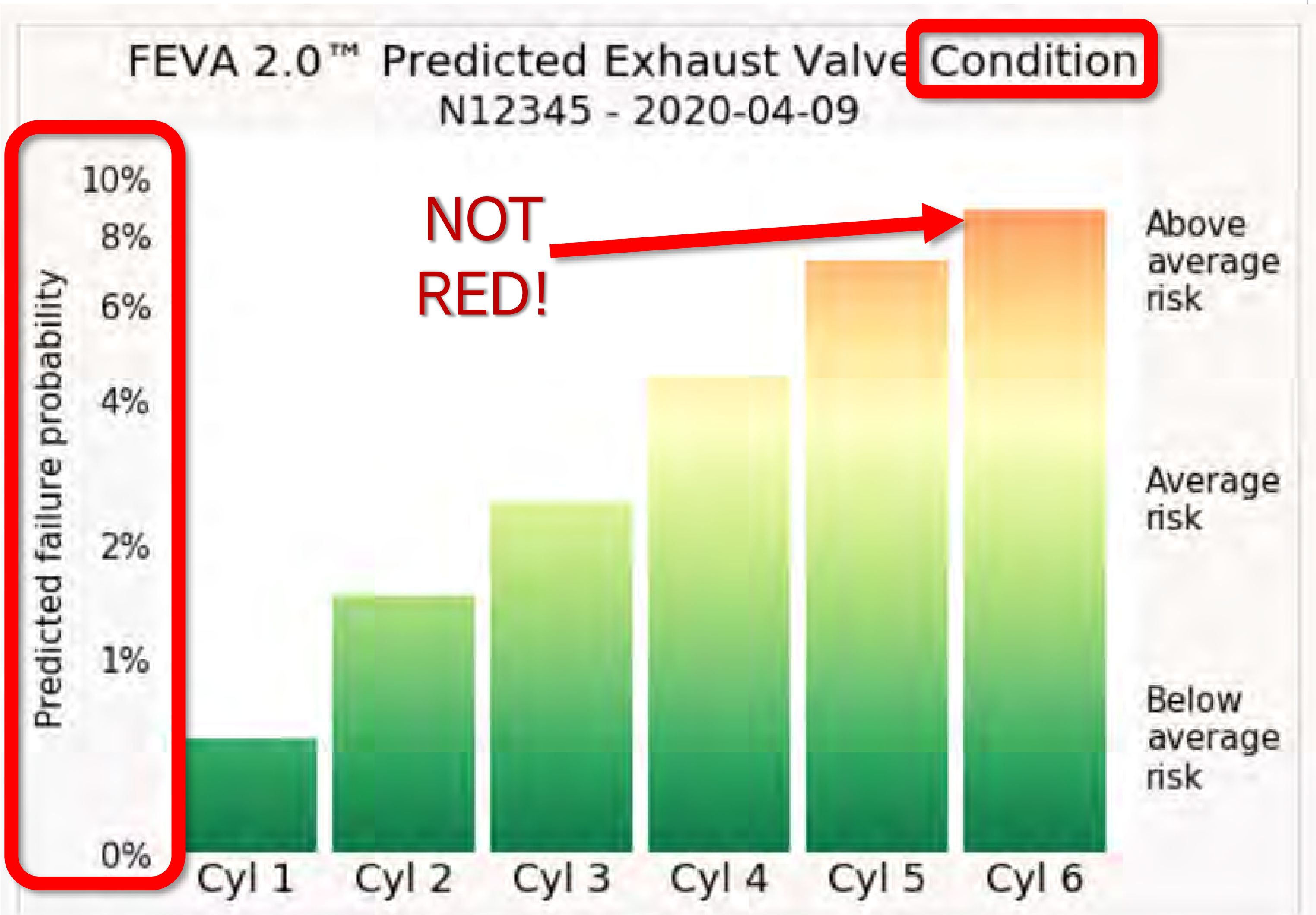
About ½ as likely to fail as average

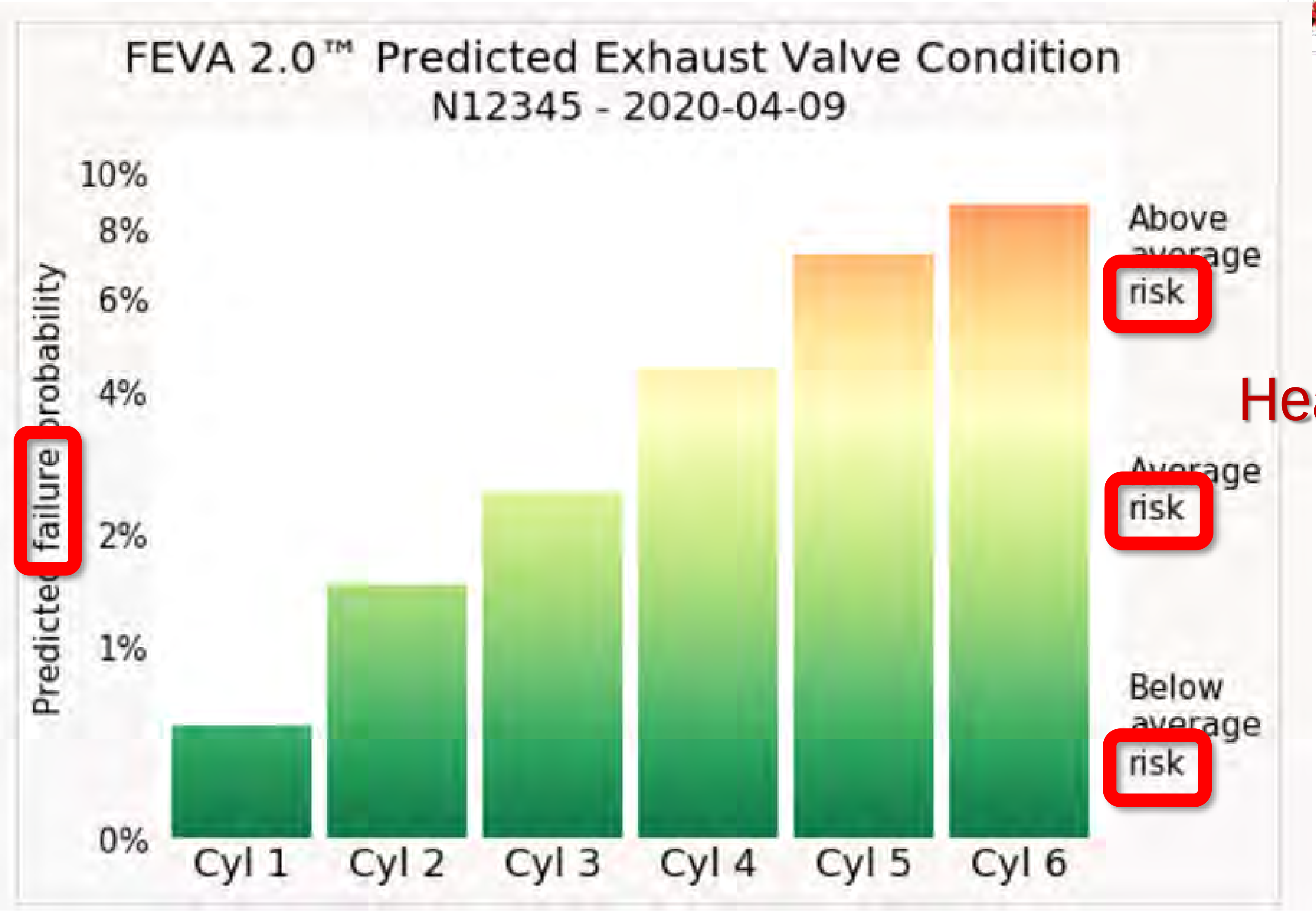


About 4x as likely to fail as average

About ½ as likely to fail as average




FEVA 2.0™ Predicted Exhaust Valve Condition
N12345 - 2020-04-09
Predicted failure probability
10%
8%
6%
4%
2%
1%
0%
NOT
RED!
Cyl 1
Cyl 2
Cyl 3
Cyl 4
Cyl 5
Cyl 6
Above average risk
Average risk
Below average risk


FEVA 2.0™ Predicted Exhaust Valve Condition
N12345 - 2020-04-09
10%
8%
6%
4%
2%
1%
0%
Predicted failure probability
Cyl 1
Cyl 2
Cyl 3
Cyl 4
Cyl 5
Cyl 6
Above average risk
Average risk
Below average risk

Health?

Framing model predicted failure rate helps understanding:

- **Lower than average**:
  1:100 probability of failing valve
- **Average**:
  1:30 probability of failing valve
- **Higher than average**:
  1:4 probability of failing valve

Cost of False Positive?

- Monetary cost of doing a borescope inspection that reveals a healthy valve is low (especially if done at next oil change)
- However, the emotional cost to the client can be high—unless the client understands what the FEVA 2 score means (and doesn't mean)

Sometimes You Can't Win…

☆ Jim L[redacted]

Re: N[redacted] Exhaust Valve Status Report

To: Savvy Aviation FEVA 2.0

This is mean. Not cool.

Sent from my iPhone

Sometimes You Can't Win…

We reviewed Jim's FEVA 2 report—it was actually quite a good report—no valves at above-average risk

We asked Jim to clarify what he meant by the report being "mean" and "not cool"

Jim said, "You sent me a report, so something must be wrong!"

For Jim, <u>ANY</u> report is bad news!

Clients don't read fine print!

In fact, if there is a chart, they don't read any print!

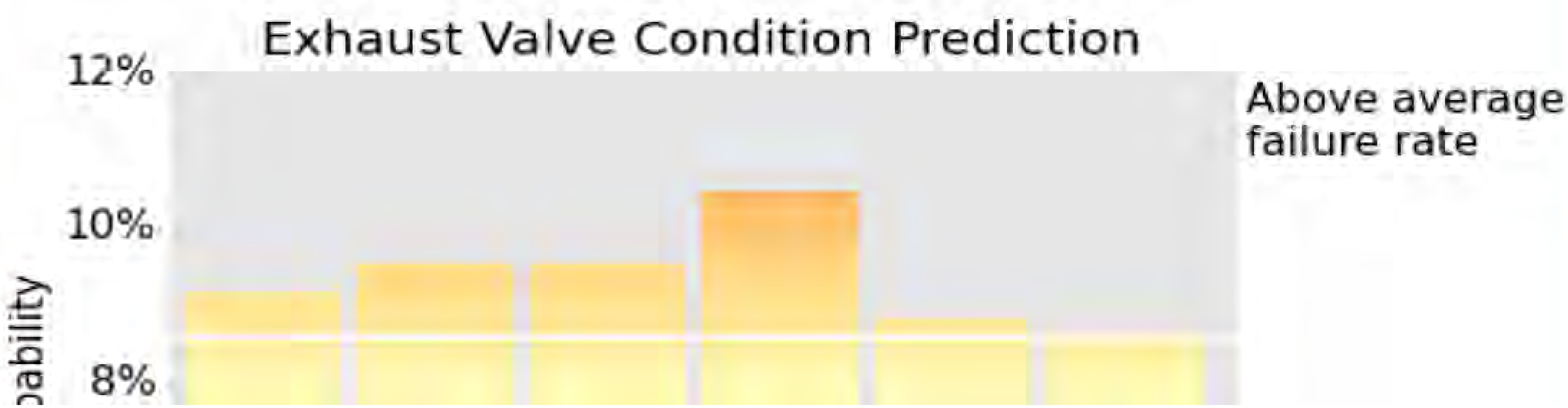
They fixate strictly on the chart

Lesson learned:

Make sure the chart is self-explanatory—don't rely on a textual explanation variables, mostly from engine monitor data, and combines them in a complex function that cannot be expressed in a simple formula.

We do know that variables related to oscillations in EGT with a period of approximately one minute (which is the time it takes an exhaust valve to make one complete revolution at cruise RPM) have a relatively high "importance" in the prediction. However, not all exhaust valve failure modes exhibit such EGT cyclicity, which is why the FEVA 2.0 predictive model considers many other factors as well.

When an exhaust valve failure does occur, Savvy's clients often ask us "What did I do wrong? How could I have prevented the failure?" The answer is: "Probably nothing." We have found that exhaust valve failure is caused primarily by factors outside the control of pilots and owners, such as variations in assembly tolerances and materials of cylinder assemblies. However, if you would like us to review your powerplant management technique using data from a specific flight, simply request analysis of the flight in the normal way and note that you would like us to focus on your operating technique.



Watch Your Language!

Avoid using "trigger words" that can elicit an emotional response

- "Risk" means something different to statisticians than to normal people
- Consider saying "Valve Health Report" instead of "Failure Risk Analysis"

The Flat Top Problem

Some clients upset if model's scoring bars are not completely even

- The highest bar is perceived as the "bad valve", even if clearly in "Average failure rate" category
- This was one of Jim's impressions

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What's Next?

SEVA—Sticky Exhaust Valve Analytics

- Valve doesn't slide freely in guide due to deposits
- Eventually can result in bent pushrod, valve strike, power loss, catastrophic engine failure

SEVA—Sticky Exhaust Valve Analytics

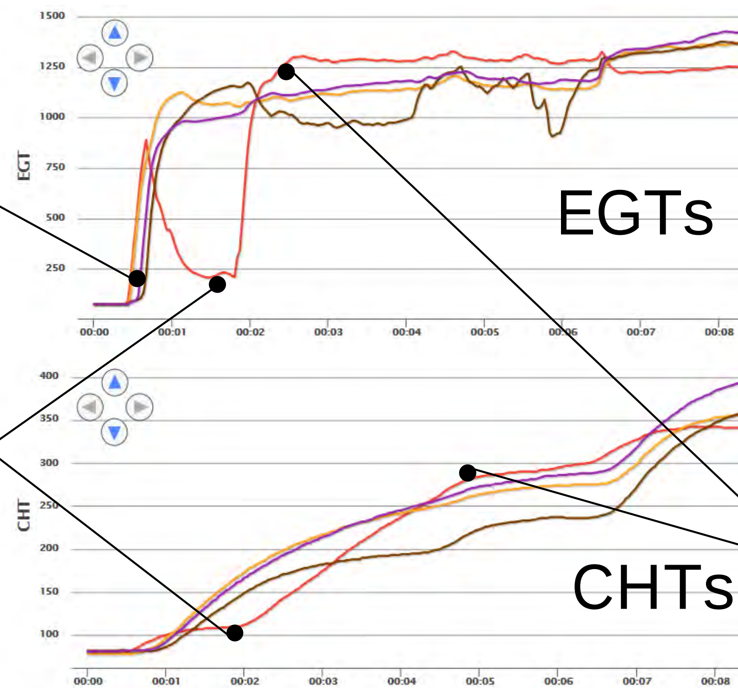
- Initial symptoms: "morning sickness"
- SEVA's goal is to identify this problem early before any damage can occur

Identifying a Sticky Valve at Engine Start

Flight 1540635
- Grumman Tiger
- Lycoming O-360

Engine start-up
Quickly rising EGTs

Exhaust valve 1 stuck open
Dramatic drop in EGT
Confirming change in CHT

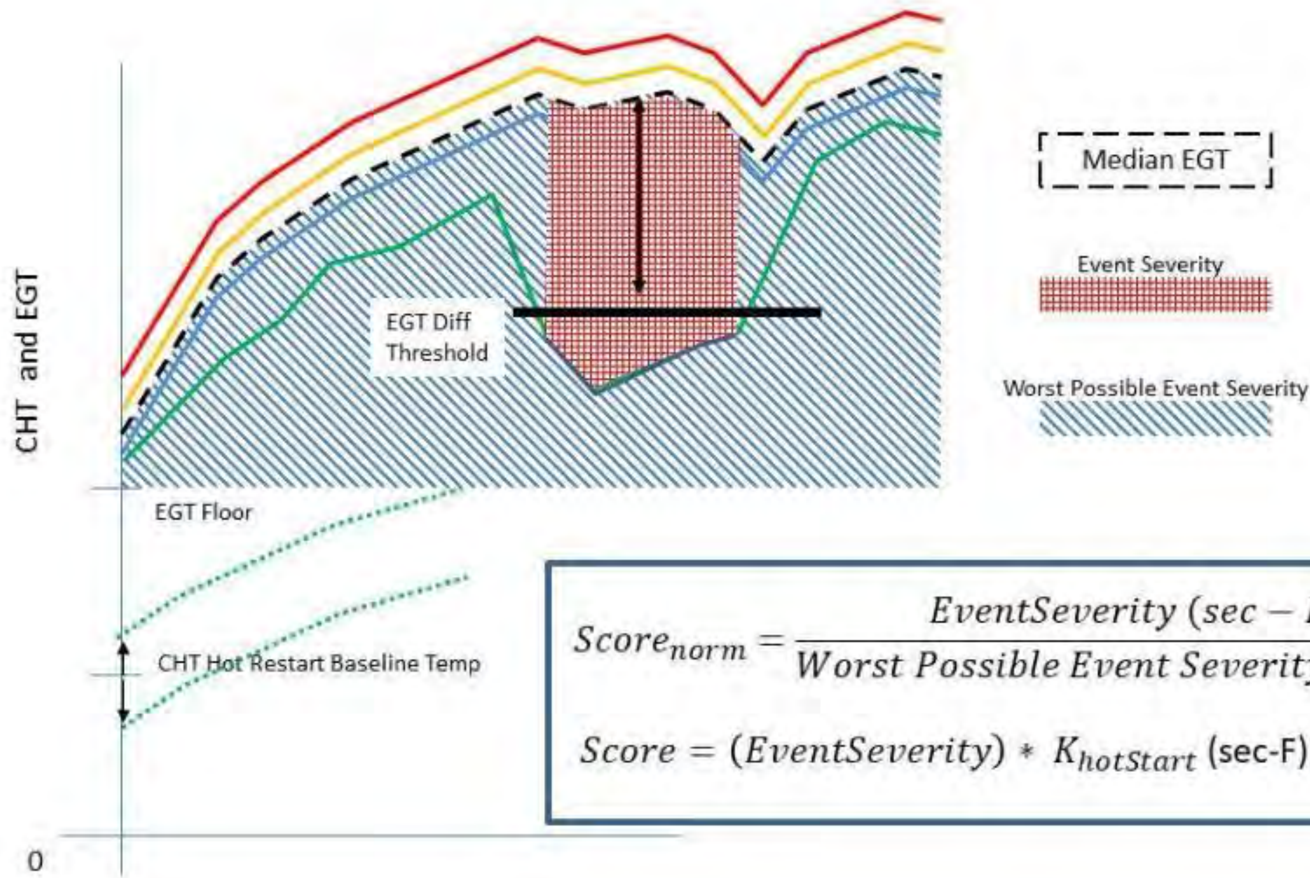


Start-up

8 min

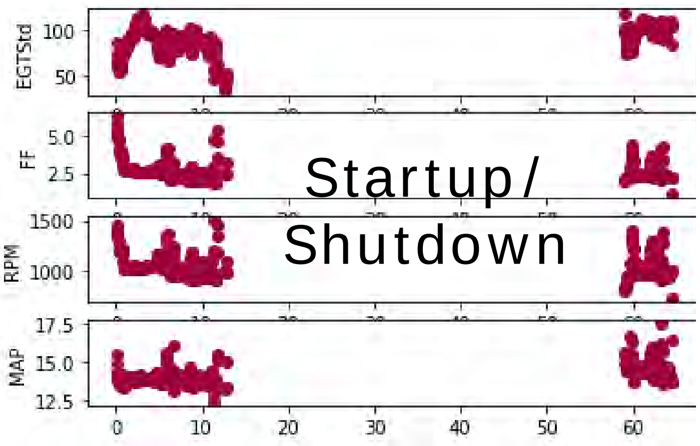
Valve becomes un-stuck
EGT re-joins the pack
Confirming change in CHT

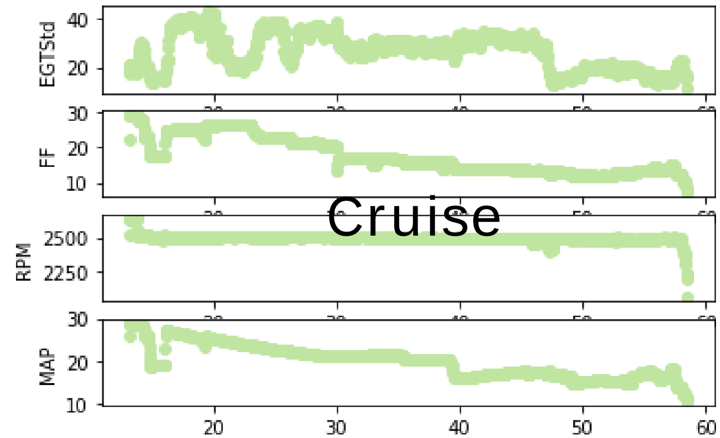
Sticky Valve Heuristic

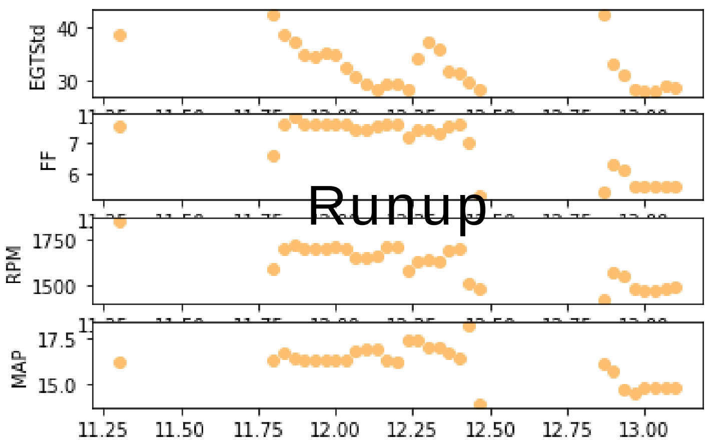


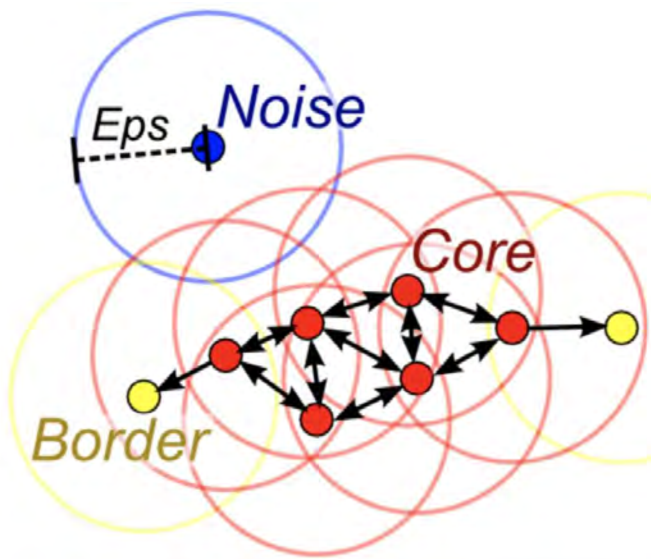
$$Score_{norm} = \frac{EventSeverity\ (sec - F)}{Worst\ Possible\ Event\ Severity\ (sec - F}$$

$$Score = (EventSeverity) * K_{hotStart}\ \text{(sec-F)}$$









DBSCAN

Density-Based Spatial Clustering of Applications with Noise

Ideas for Future Projects

- Detection of detonation and preignition events
- Detection of worn cam lobes and/or collapsed lifters?

With more sensors, the sky's the limit!

Predictive maintenance is clearly the wave of the future

The more sensors we have in our planes, the more comprehensive and powerful it will become

Over time, it will increasingly be our aircraft—not our mechanics—that tell us what maintenance needs to be done

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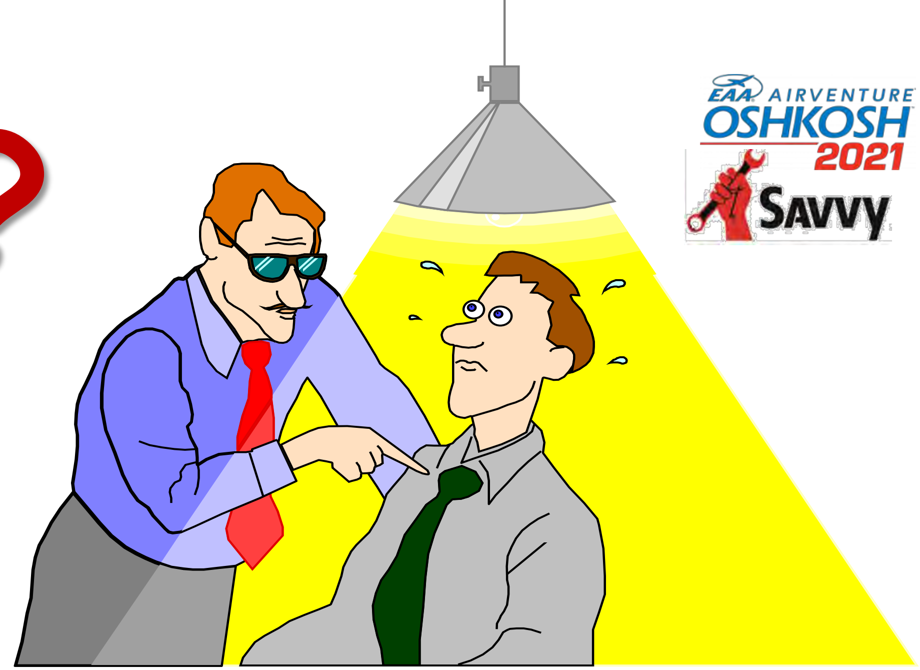

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