Exhaust Valve Sticking – What's the @!*)&% deal?

Part 1

Have you ever had a stuck valve? Ever had a terribly shaky startup that suddenly smooths out? Exhaust valve sticking can be an inconvenience or a serious problem, such as a bent pushrod and broken pushrod tube that allows all the oil to drain from the engine. The important thing is to determine early on that you have a sticky valve and do something about it before the worst happens.

Valve sticking may show up in multiple ways. It most often presents as morning sickness, the uncontrolled engine shake when the engine is first started.
As engine heat is transferred to the non-operational cylinder, the valve often releases and the cylinder springs back to life and smoothness returns. Many pilots treats this as a fouled spark plug, it is not.
A bad plug will show up during a mag check.
Any sign of morning sickness should be addressed with your mechanic immediately.

It can also show up while making a power change while either descending or leveling off after a climb.
It can be a subtle shudder due to intermittent sticking or it may stick solid and bring the cylinder off-line with the attention grabbing roughness. Engine analyzers will show wildly fluctuating EGTS and CHTs before the cylinder goes cold.

Over the years, much has been said and many articles have been written about valve sticking in piston aircraft engines. Many "solutions" have been tried - ranging from major hardware changes to miracles-in-a-can, but the problem persists.

What is valve sticking?

The exhaust valves rides in special tubes called valve guides (figure 1). They are shown installed in a cylinder in a cut away picture (figure 2). One end of the valve and guide is exposed to very hot combustion/exhaust gasses (Hot Side), while the other end is bathed in relatively cool motor oil (Cool Side). The valve stem fits snugly into the valve guide.
If enough deposit form on the valve stem or in the guide, the valve stem sticks in the guide.

There is good news and bad when it comes to sticky/stuck valves: The bad news is that there are two separate reasons for exhaust valve sticking Hot Side & Cool Side deposits. They are very different. The good news is we understand them both and minimizing them just involves subtle changes in engine operation and routine maintenance.

www.alamy.com - AJDFAF

Figure 2: Cylinder assembly showing valves guides and piston
Courtesy Alamy

Most everyone, including pilots, engine manufacturers and oil companies, widely (and wildly) misunderstand the causes of this problem. As a fuels and lubes chemist and longtime gearhead, let me try to shed some light on this issue.

The exhaust valve environment

To say that exhaust valves operate under severe conditions is a colossal understatement. The valves seal against controlled cylinder explosions with temperatures up to 4000˚F & pressures up to 1200PSI. And then, they have to survive jets of 2000˚+F exhaust gas blazing past the open valve, at up to 25 times per second!

The difference in temperature between the Hot Side and Cool Side of the exhaust valve can be as much as 1500˚F. The tulip end of the valve and guide are hot while the other side is much cooler as it's bathed in engine oil.

It is the heat along with the distinctive chemical activities at each end of the valve guide, which can lead to deposit formation and valve sticking.
These are distinct unique phenomena.

Hot Side Deposits

Lycoming states the maximum allowable CHT is 500˚F while Continental says 460˚F, but both prefer to see a max cruise temperature of 400˚F. And I agree. As to a lower limit, they really don't specify.

But, what is "too cool" and why?

Just because you can do something, doesn't mean you should. It seems that human nature has taken over once again when it comes to Cylinder Head Temperatures (CHTs) on our airplane engines.
If 380˚ is better than 400˚ then 350˚ must be better than 380˚ and then 300˚ must be better than 350˚.
Unlike our water-cooled car engines, we have some say when it comes to CHTs in our airplanes.
Throttle, mixture, cowl flaps and airspeed put some control in our hands and what we do with it has consequences in terms of engine reliability and cylinder life.

The race to the bottom, low CHTs, has evolved because of the confluence of several factors. One we have engine analyzers that inform us, literally to the degree, what the CHTs, EGTs and TITs are doing during every phase of flight. Two, we have the GAMI gurus that have opened our eyes to the wonder of LOP operations, like the airlines used to run their big radials. You can run cooler, cleaner and save fuel. And three, you have human nature, if less is better, then a lot less is a lot better (the flipped side of "if some is good then more is better") .

The convergence of these three effects has brought about a noticeable uptick in exhaust valve sticking reports. And while every engine is susceptible to this scourge, it is Lycoming engines that have most of the problems with this issue. Lately however, valve sticking has been reported in normally aspirated large bore Continental engines (470's, 520's and 550's).

This "Hot Side" example is the more common type of valve sticking, caused when lead compounds crystallize on the tulip end of valve stem, exposed to the hot exhaust stream. This deposit gets forced into the valve guide where it reduces the stem/guide clearance until the valve sticks.

The $64,000 question is what causes this kind of deposit to form in the first place and why is it seeming rearing its ugly head more often now.

I will delve further into the explanation of the Hot Side deposits, introduce the Cool Side deposits as well as how best to mitigate these problems in Part 2.

by
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Figure 1: Valve and valve guides. Courtesy CB Performance

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Part 2

In Part 1 of this article, I introduced exhaust valve sticking, the exhaust valve environment and the idea of “Hot Side” valve deposits.

To explain how and why these “Hot Side” deposits form, we have to turn to the research on the chemistry of leaded fuel combustion, much of which was done 50-60 years ago.

Lead Fuel and Lead Scavengers

100LL avgas contains approximately 2 grams or tetraethyl lead (TEL) per gallon. TEL increases the octane of the fuel. And it does this very well. During compression, TEL is rapidly converted to lead oxide, which is actually the active octane booster. However, it was quickly observed that lead oxide coated the spark plugs and they stopped functioning, something not welcomed in an airplane.

Thru trial and error, it was discovered that when ethylene dibromide is added to the leaded fuel, the spark plugs remain much cleaner. An exact amount of ethylene dibromide is added to the fuel to convert all the lead oxide to lead bromide. Not enough, and you get lead fouling of the plugs. Too much, and you form hydrobromic acid, which dissolves aluminum. Above 1100˚F, lead bromide is a gas, while lead oxide just coats everything as a solid. This difference is where the term “lead scavenger” comes from. The “scavenged” lead can exit the engine as part of the exhaust gas.

Solving the puzzle

The ideal process proceeds thusly. The tetraethyl lead forms lead oxide, the active octane booster, during the compression stroke and previous combustion cycles. During combustion, the lead oxide reacts with ethylene dibromide to form lead bromide that exits out the tail pipe with the exhaust gas. Unfortunately, the process is not that simple.

In actuality, tetraethyl lead quickly forms lead oxide, which then more “slowly” reacts with ethylene dibromide to form lead oxy-bromide in a series of 8 steps. The lead oxy-bromide eventually reacts fully to form lead bromide, which, as a gas at these temperatures, goes out the exhaust pipe. Chemical reactions are much faster at higher temperatures. It is the time it takes for this “lead oxy-bromide” to form lead bromide that creates the problem. And this time is intensely dependent on the peak combustion temperature. And guess what? You as pilot in command, can strongly influence the peak combustion temperature.

Explained more fully, if we look at the condensation temperatures of the lead compounds involved, a picture starts to emerge. The condensation temperature is the temperature below which a compound precipitates from the hot exhaust gas and collects on a surface, which in this case is the valve stem. Condensation is the opposite of evaporation and can be considered the “dew point” of a chemical compound.

The approximate condensation/evaporation temperatures for these materials of interest are as follows:

Lead oxide – 1630°F (888°C)

Lead oxy-bromide – Initially 1470°F (800 °C) decreasing to 1300°F (705 °C) after 8 temperature dependent steps

Lead bromide – 1100-1175°F (593-635°C)

As you can see, there is a big difference in the condensation /evaporation temperatures of these compounds – and as it turns out, the substantial time element involved in the process is very important. The time necessary to complete these reactions is VERY dependent on combustion temperatures , of which mixture setting is a primary factor. Combustion temperature is reflected in both the Cylinder Head Temperature (CHT) and directionally, the exhaust valve temperature, which we do not measure directly. (Exhaust valve temperature follows cylinder head temperature because the valve guide is located in the cylinder head, to which it transfers heat from the valve.) Valve temperatures do not follow Exhaust Gas Temperature (EGT).

It is the mixture and, to a lesser extent, throttle, rpm, ambient temperature and cooling airflow that affords us some control of the actual combustion temperatures and thereby the CHTs and valve temperatures.

If combustion temperatures are low enough that lead bromide cannot form in the allotted time, we end up with lead oxy-bromide condensing on the exhaust valve stems. This combined with reduced exhaust valve temperatures is a perfect recipe for valve sticking.

Exhaust Valve Temperatures

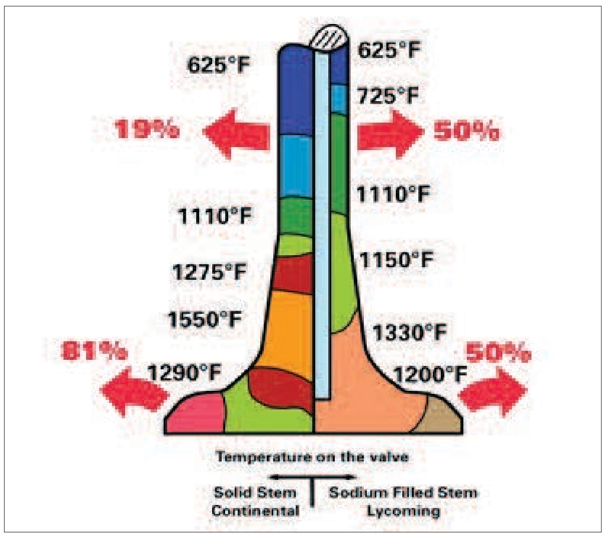

Figure 3: Relative valve temperatures for solid (left) and sodium-filled (right) valves
Courtesy TRW

Figure 3 shows the relative operating temperatures for sodium filled exhaust valves (Lycoming) versus the solid exhaust valves (Continental). Exhaust valves run very hot and have to dissipate a lot heat quickly or they will fail. The solid valve in Continentals dissipates most (81%) of its excess heat from the valve edge to the valve seat when the valve is closed. The remaining excess heat (19%) is transferred from the stem through the guide into the cylinder head.

In Lycoming valves, the sodium sealed in the stem, liquefies and transfers heat a lot better than a solid valve stem. This leads to 50% of the heat being transferred from the valve edge to the valve seat when the valve is closed. The other 50% of the heat energy is transferred up the valve stem to the guide. This means there is more heat throughout the valve stem and guide.

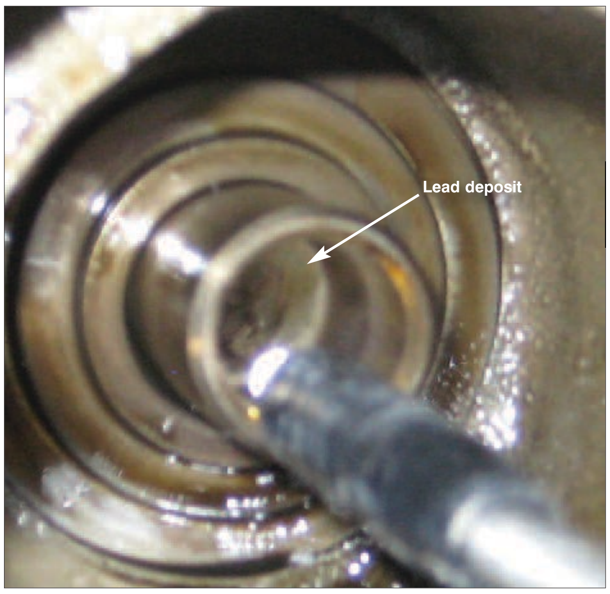

Figure 4 Lead deposit build-up in Lycoming exhaust valve guide. (Light part).
Courtesy Jerry Olson

Figure 4 shows lead oxy-bromide build-up in a Lycoming engine. The valve was stuck. This normally aspirated engine was run deeply LOP with CHTs well below 300´ F. The deposit crept up to within a quarter of an inch of the other (cool) side of the guide.

Figures 5 and 6 show a valve that stuck in a Continental IO-550. Notice the large build-up of deposits on the lower part of the stem before the tulip flare. Above this shoulder is the part of the valve stem that enters the guide. Note the staining on this part of the stem because the deposits are scraped off the stem by the tight fit of the guide. At some point, enough deposit is forced into the guide and the reduced clearance sticks the valve.

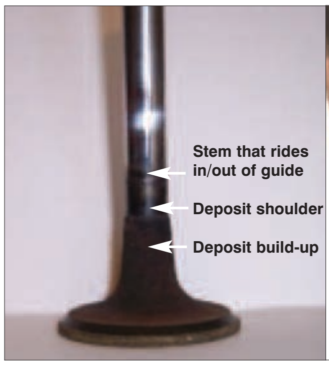

Figure 5. A solid Continental valve that stuck

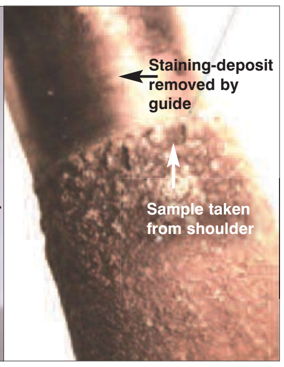

Figure 6. Close-up of the deposit shoulder of the Valve that Stuck

Chemical analysis shows this deposit primarily consists of lead, carbon, bromine, and oxygen. We exposed a sample to high temperature in a thermogravimetric analyzer (TGA). The sample was heated to 1470°F where, surprisingly, only 25% of the mass evaporated after 25 minutes. This means that one of the hottest parts of the valve had lead oxy-bromide deposits condensing/crystalizing on it. In summary, lower combustion temperatures don’t permit this conversion of lead oxy-bromide to lead bromide and the valves run cool enough to allow this lead oxy bromide to form on the stem and this leads to (Hot Side) valve sticking.

Running either too LOP or ROP lowers peak combustion temperatures enough to cause this deposit problem. The low combustion temperatures are reflected in lower cylinder head and valve temperatures. Low combustion temperatures reduces both the conversion of lead oxy-bromide to lead bromide and the exhaust valve temperature, which allows the lead oxybromide to crystalize on it.

I will complete this story in part 3.

by
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Exhaust Valve Sticking – What's the @!*)&% deal?

Part 3
Cool Side deposits

Compared with automotive engines, our piston aircraft engines are positively filthy. They have huge pistons and cylinders (to produce enough power while turning so slowly) and extremely sloppy clearances (because they're air-cooled and have horrible temperature regulation).

As a result, the amount of combustion chamber leakage "blow-by" into the crankcase oil is very large compared to small, tight, water-cooled car engines. Blow-by in aircraft engines is the root cause of deposit formation. And deposit formation can cause (cool side) stuck valves as well as stuck rings and sludge problems.

Figure 1 shows a cutaway of a Lycoming cylinder. Note the large clearance between the piston, on the left, and the cylinder, on the right, at room temperature. This clearance decreases as the engine heats up, however, it is always much greater than that found in a water-cooled engine. And greater clearance means greater amounts of blow-by contamination.

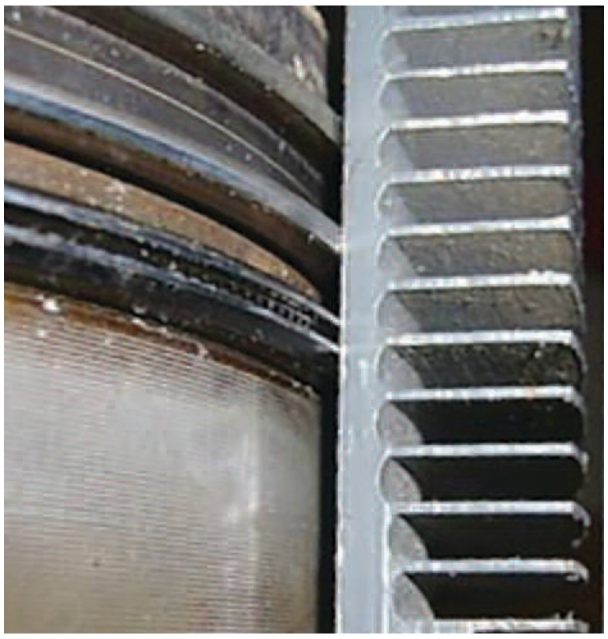


Figure 1. - Courtesy Lycoming

Blow-by consists of raw fuel, partially-combusted (reactive) Fuel, known as 'Varnish Precursors' (VPs), steam (water), lead bromide particles and a lot of heat. Most engines introduce one to several ounces of blow-by into the oil every hour of operation. The vast majority of blow-by goes out the crankcase vent (breather), however small amounts of VPs and water remain in the oil to cause us all kinds of grief.

Virtually all the deposits in the oil-wetted areas of the engine are caused by these blow-by VPs. Everyone is familiar with VPs. They are what you get when you buy a can of varnish. When applied from the can to a wood or metal surface, VPs react with each other in a process called polymerization, leaving the familiar 'varnish' film. VPs act the same way in an engine and looking inside most used engines, you can observe the formation of clear "varnish" films over most of the internal parts. These films darken with heat exposure becoming amber in color **(see Figure 2).**

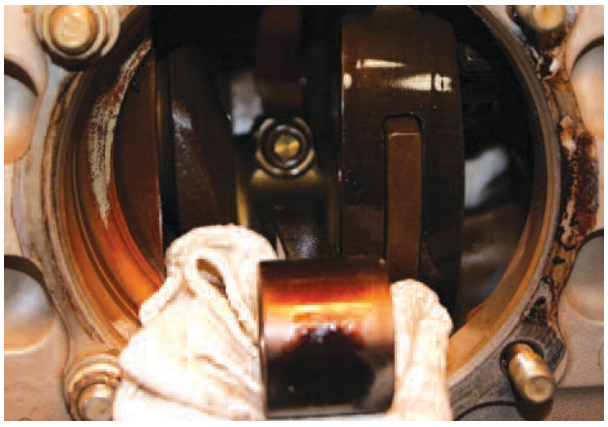


Figure 2.- Crankcase internals heavily painted with varnish

Figure 3. Underside of a piston with a carbon film deposit

Varnish films formed on the hottest parts such as the pistons or valve guides eventually degrade to hard black carbon deposits **(see Figure 3).**

Lines of Defense…

How well do aircraft oils deal with this filth?
Apparently, not well as we still find copious amounts of deposits in our engines when we service or rebuild them.

The first line of defense in the cleanliness war is the Ashless Dispersant (AD). It is considered a 'keep clean' additive as it does not clean up existing deposits. ADs work because they are attracted to the VPs and several AD molecules surround each VP molecule as it enters the oil. The AD molecules, encapsulate and suspend the VP molecules, preventing their polymerization into varnish films. The 'encapsulated' VPs exit the engine when the oil is dumped at oil change time.

It is a common belief that the dispersant holds the lead bromide particles in suspension, but this is incorrect. The only things the dispersants bind to are VPs.

Ashless Dispersant makes up 3% of the oil. So there is a limited number of dispersant molecules to keep the engine clean. The base stock, which makes up 90-95% of the oil, helps the dispersant by holding some VPs in solution. When both the dispersant is consumed and the basestock is saturated with VPs, deposit films quickly start forming.

During the 'break-in' period (the first 10-50 hours from overhaul), most manufacturers and engine builders recommend using a non-dispersant oil, commonly referred to as 'mineral oil'. Some think the dispersant interferes with the break-in process (it doesn't) and others want a thin film of varnish to form over the internal parts of the engine for rust protection.

Lycoming turbocharged engine owners must use AD oil for the life of the engine from break-in to TBO. This is because the manufacturer realized that any early deposits lead to future problems. Following break-in, everyone is instructed to use AD oil.

Another problem caused by varnish formation is sludge formation. Sticky varnish films capture lead bromide particles. (Recall that burning leaded fuel with ethylene dibromide lead scavenger forming lead bromide particles that end up in the oil). The lead bromide particles aren't a problem until they are captured in a varnish deposit, making it substantially thicker.

A little varnish, acting as glue, combines with countless lead bromide particles to form a dense heavy sludge. We see examples of this sludge problem throughout the engine as it settles in the low flow areas like the sump, constant-speed prop hub, and inside the crankshaft. Lead sludge has the consistency of room temperature butter.

When these carbon/sludge deposits build up in the exhaust valve guide, they cause (cool side) valve sticking, **(see Figure 4).**

How do you Prevent/Minimize Valve Sticking? There are some simple answers to this question…

Hot Side: Run your engine hard, at least occasionally, 65-75% ROP or LOP enough to just stay out of the GAMI 'Red Box' (www.advancedpilot.com/redbox.html) and Cylinder Head Temperatures (CHTs) below 400°F. These will maximize combustion temperatures and minimize lead deposit build-up on your exhaust valve stems. The ideal range for CHTs is from 325°F-380°F. A lower CHT is fine if you are at a higher power setting.

Cool Side: Change your oil frequently enough to prevent varnish build-up. For most aircraft, this is from 25 hours to 35 hours (or every 3-4 months). If you fly a lot, you can stretch it. If you have a big motor (L-540 or C-550) with a 6-8 quart sump, don't stretch it. The ideal oil temperature range is from 180°F-220°F.

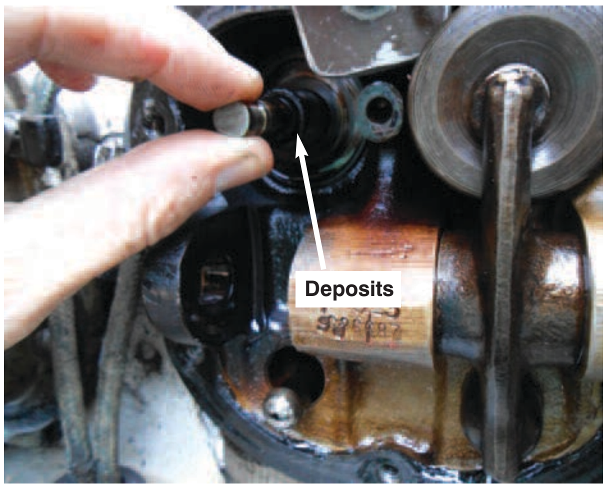
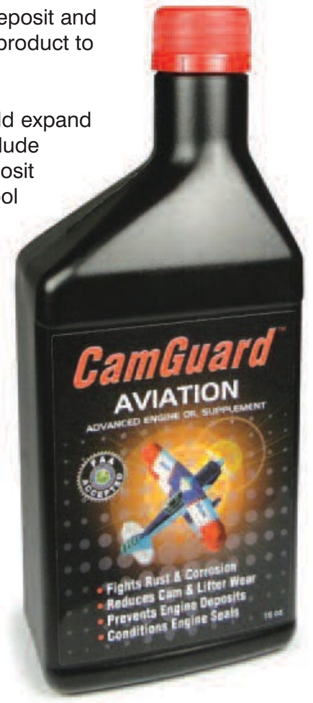


Figure 4. Deposits causing a stuck valve

You should also lean very aggressively when on the ground, as it reduces the amount of fuel entering the oil. Lean until the engine barely runs smoothly. This will keep your oil and engine cleaner and you will not be able to run to full power risking a take-off with a leaned mixture.

I will mention that the oil additive, Camguard, contains unique deposit control additives. These additives work in conjunction with the ashless dispersant to keep engines deposit and sludge free and it is the only product to offer this technology.

You and your mechanic should expand the use of a borescope to include looking for hot side valve deposit buildup as well as signs of cool side crankcase varnish deposits. Keeping an eye on these deposit buildups, and modifying operation accordingly is the best way of avoiding some costly problems.



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