A Detonation Scenario

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A Cessna 401 departs Huntsville, Alabama and begins climbing to its requested altitude of 11,000 ft. Aboard is a new mold for a plastic injection molding machine. This 330 lb chunk of high-precision electrically heated and water cooled steel is worth nearly $600,000. The Dothan, Alabama customer, anxious to get the mold installed and producing parts, has willingly paid the cost of having it flown in.

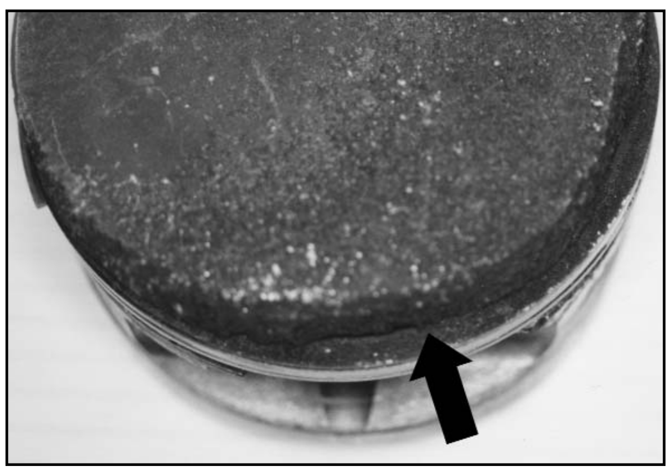
It is a hot August afternoon. Since the flight is taking place in Alabama, there is a better than even chance of having to dodge a thunderstorm or two. Otherwise, it will be a quick, easy and profitable flight down and back. The pilot does not have a wealth of experience – he is flying freight to build twin-engine time, working toward the qualifications that will help land him an airline job. Despite his lack of experience, the pilot takes his work seriously. He studies constantly, knows the flight characteristics of the equipment he flies, treats that equipment well and doesn't take chances. He hopes to live to a ripe old age, like those pilots he had learned so much from.

Unbeknownst to the pilot, a conspiracy is afoot. It is not a conspiracy hatched in some smoke-filled room by evil men – but its result will be just as insidious as if it had been planned. Deep inside the left engine, a Continental TSIO-520-E, the center cylinder on the right side (No. 3) has started to detonate. With the onset of detonation, piston and cylinder head temperatures have started to rise dramatically. Although the pilot is keeping a careful watch on the engine instruments, he detects none of this. There is no discernable noise, vibration or smoke – at least not yet. There is also no indication of temperatures rising – the one cylinder head temperature probe that came standard on the Cessna 401 left engine is on a different cylinder, one that is running happily and normally along.

Although detonation in general aviation aircraft engines is rare, it is far from being unheard of. GA aircraft engine detonation is nearly always the result of excessive cylinder head temperatures brought about either by incorrect handling of the engine by the pilot, or by maintenance problems. In the case of this Cessna 401, the pilot is flying by the book, but deterioration of some aging components has eradicated the detonation margin provided by the engine manufacturer's design.

In the case of the high-time left engine, this degradation has allowed several small things to conspire in a most cruel way. Baffle seals (little strips of silicon rubber that separate the engine cooling pressure chamber from the surrounding nacelle interior) have deteriorated, allowing air leaks to bleed away some of the pressure so essential to proper engine cooling. A small crack in an inter-cylinder baffle has propagated, allowing a large piece of the inter-cylinder baffle between cylinders 1 and 3 to break away, resulting in localized heating of the cylinder head between the lower spark plug and exhaust port. A small leak in the No. 3 exhaust gasket has grown larger and is directing a jet of hot gas at the lower spark plug, further increasing the heat inventory of the No. 3 cylinder head. Finally, a dirty injector nozzle is restricting fuel flow to the No. 3 cylinder just enough to raise the exhaust gas temperature to 50° F rich of peak, the point that produces the greatest heat loading on the cylinder head and piston.

Hot day, climb power, turbosupercharged engine, cooling problems – the perfect scenario for a detonation disaster. In cylinder 3, part of intake charge, hot from compression by the turbosupercharger and further heated by the hot cylinder head, the compression stroke and radiation from normally burning fuel, decomposes into unstable end gasses that explode rather than burning smoothly. General aviation engines must demonstrate worst-case detonation-free operation



An IO-520 Series Piston that has Suffered Severe Detonation Damage. Note that piston crown erosion has progressed to the point that a path has formed around the steel top-ring insert (arrow) that is cast into the piston. The most visible damage appears in the sector between the exhaust valve, which would be near the arrow, and the lower spark plug, which would be on the right. (Les Waters) during certification. But detonation margins can diminish, possibly to zero, with cooling deficiencies, exhaust leaks and improper tuning.

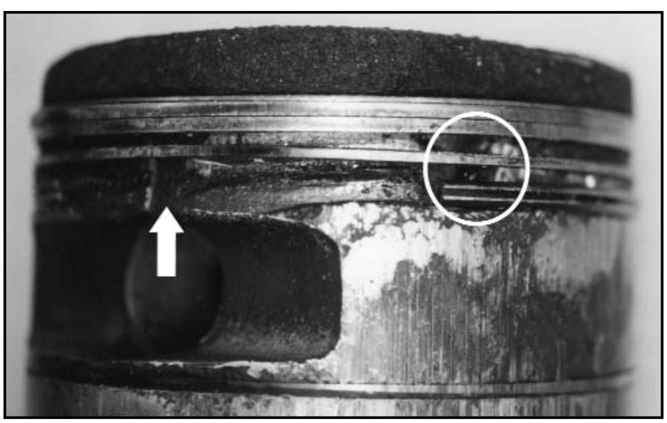
Detonation usually occurs near an exhaust valve, which is already operating at a red heat and contributes to end gas heating through radiation. The explosion of the end gas creates dramatic local heating. More importantly, each detonation event creates a shock wave that bounces around the cylinder, scrubbing away the boundary layer gasses from cylinder head, valves and piston crown, promoting further heating and delivering considerable mechanical distress The extra heating rapidly overwhelms the piston's ability to dissipate heat, and the piston crown starts to melt and erode in the vicinity of the exhaust valve. This erosion begins at a poorly-cooled region of the crown edge near the cylinder wall. The metal shed from the piston crown gets everywhere; into the exhaust port, on the cylinder head – it will probably foul a spark plug.

Once the piston top ring land becomes exposed, it gets the full effect of both the flame licking into the crevice and the repeated hammer blows of the detonation waves. The crown circumference is rapidly damaged. The destruction is further accelerated as metal from the piston erodes away from the top ring. In most engines, around 30% of the heat from the piston crown is dissipated to the cylinder wall through the top ring. When this heat-flow path is compromised, it leads to even higher piston temperatures and more severe detonation.

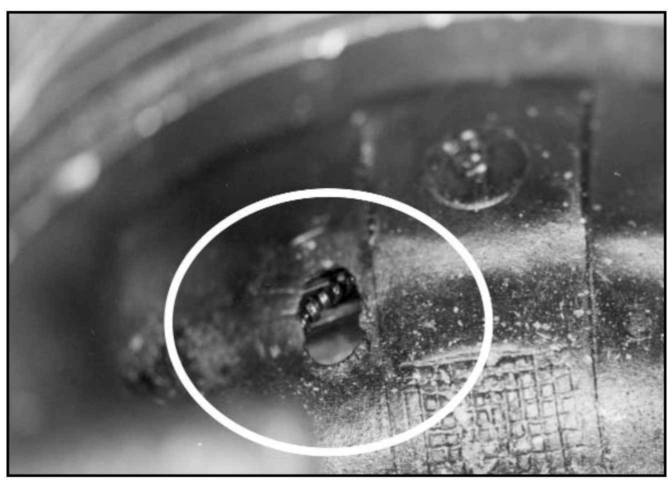
Now the erosion makes its way down the side of the piston and into an oil drain hole under the oil scraper ring. Though not as hot as at the piston crown, the flames are still hot enough to enlarge the hole and allow a terrific amount of blow-by. In addition, the unsupported rings break and their liberated particles create additional collateral damage. The hole in the piston may eventually grow to the point that it relieves enough of the compression pressure for the detonation to cease. The engine continues to run and the pilot still has no clue as to what is going on.

The failure scenario now takes a different path. Excessive blow-by pressurizes the crankcase and the oil spray normally retained in the crankcase spews overboard through the engine's breather. Unless someone is carefully watching the trailing edge of the wing, this too will go unnoticed. The oil supply of the left engine is quickly diminishing. The oil temperature has started to rise and the oil pressure is diminishing as the supply nears exhaustion. Starved of oil, one of the connecting rod bearings (not necessarily No. 3) has heated up. This heating melts the bearing material and the steel backing extrudes from the bearing, forming metal chips that look like corn flakes. The heat has also started to sap the strength from the connecting rod bolts, which begin to stretch. As preload disappears from the rod bolts, they are subjected to a repeated hammering from the inertial forces of the piston changing directions at top dead center. One of the weakened connecting rod bolts fails, releasing the rod cap and loose end of the connecting rod into the crankcase. The loose connecting rod finds its way between the rotating crankshaft and camshaft in just the right way to break the camshaft. The loose rod cap is driven through the crankcase top, leaving a hole the size of a man's palm. It takes less than five seconds for the engine to reduce itself to junk.

Meanwhile, the pilot has gotten busy. He has



Once the top ring land is compromised, flames make their way down the side of the piston, causing further erosion (arrow) and eventually finding their way into an oil ring drain hole (circle). Liberated metal particles find their way throughout the engine, leading to the scratching on the piston skirt evident in this view of the piston. (Les Waters)



A view of the underside of the same piston shows oil hole enlarged by flames (circle). This allows significant blow-by, which pressurizes the crankcase and rapidly depletes the oil supply, resulting in further engine damage. (Les Waters) switched radio frequencies as his flight path took him out of the coverage of one ATC sector and into another. Almost simultaneously, he has requested a slight westerly diversion, which will take him around a building thunderstorm. All this activity has diverted his attention away from the engine instruments. He has failed to see the rise in oil temperature and the loss in pressure. He is completely unaware that anything is wrong until he is startled by a loud noise, vibration and then a yawing to the left. From his training, he recognizes that the left engine has failed. He quickly feathers it, shuts off the fuel supply, assesses the situation, declares an emergency and heads to the nearest airport, glad all the while that none of this happened at a lower altitude.

Could this incident have been prevented? This specific scenario is one that could happen between even very thorough 100-hour inspections. Modern engine monitors that measure temperatures in each cylinder could detect and announce the rapidly rising cylinder head temperature that heralds the onset of detonation. A total engine failure could have been averted by throttling back and nursing the sick engine to a maintenance facility. More frequent inspections, ones made by the pilot with the aid of a small flashlight, may have detected baffle damage and the exhaust leak before either became problematical. Now that he knows what to look for, it is a sure bet that the pilot in this scenario will do his part to avoid future cooling problems.

A 10" dual-fuel piston from an engine used to power large electric generators. The piston has been subjected to pre-ignition. Note that, unlike the detonation example, the thermal damage is evenly spread over the piston crown. The piston is made of nodular cast iron, which melts at more than 2,000°F. It must have been subjected to an enormous heat load! The small depression at the center accommodates an eye-bolt used to remove the piston for service. (Les Waters)

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Les Waters has been involved in diesel and gasoline engine design and development for 50 years, including 5 years fuels and lubricants research at Shell. From 1975 to 1982 he was Vice President for Engineering at Teledyne Continental Motors.

Pre-ignition

Many aircraft engine problems are blamed on pre-ignition, which is really not all that common. Unlike detonation, pre-ignition, occurs because the ignition event occurs early. Several things can cause this, but the usual culprits are a cross-firing ignition system or incandescent hot spots in the form of a cracked or broken spark plug insulator, the end of Heli-coil wire from a spark plug thread that protrudes into a cylinder, or combustion deposits on the cylinder head or exhaust valve. With pre-ignition, the fuel/air mixture is ignited while the piston is still on its compression stroke, producing prodigious heat and mechanical distress.

Pre-ignition can also occur in large industrial engines. Some of these once powered pumps on natural gas pipelines, burned natural gas and were spark ignited. It was not uncommon to have over one million horsepower pushing gas along a pipeline. Other large dual-fuel industrial engines power electric generators. These compression-ignition engines mix air and natural gas during the induction and compression. Ignition is achieved by injecting about 3-5% of total fuel input as diesel fuel near T.D.C. Most dual-fuel engines are capable of automatically switching to all-diesel fuel opeartion if the natural gas supply becomes unavailable.

In both cases, the combustion process is very similar to that in gasoline engines – the fuel and air being well mixed before an ignition source is provided. This combustion system works quite nicely until an irregular situation results in early ignition, well ahead of T.D.C.

A leaking gas inlet valve can remain alight through the exhaust and intake strokes and provide a "torch" to the air/fuel mixture during the compression stroke, resulting in pre-ignition. When this happens on one cylinder, it is usual that high pressures on the compression stroke result in negative work, reducing engine speed. The governor detects speed reduction and compensates by increasing the fuel supply. This runaway condition results in rapid heating of the cylinder heads and pistons. A rate of temperature increase of 20°F per second has been observed at the cylinder head combustion face. It is seldom possible to shut the engine down before permanent damage is done.