PHILIP GREENSPUN: Welcome back. I hope you've got your coffee. I see somebody has a muffin. They'll be in a carb coma, Francis, I'm relying on you to answer all the hard questions. That's not authorized.

All right, so multi-engine jets-- the piston twin, the good news is, when both engines are spinning, it's easier to fly than a single. Because you don't need as much right rudder or really any right rudder. It doesn't have all those left turning tendencies, necessarily.

The training and rating, especially the Seminole, which has counter-rotating props-- all your training for a multi-engine airplane is flying around on one engine. Because flying around on two engines is pretty much the same. So basically, almost all the flight time that you accumulate during your multi-engine training will be with one engine pulled back to idle or, in some cases, stopped altogether.

You have six power levers in a twin-engine piston airplane, two for throttle, two for mixture, and two for prop. You may also have cowl flaps to bring more or less cooling air into these piston engines. By FAA certification requirements, as I think I mentioned earlier, there is no required climb rate. It may be a truly crummy airplane on one engine.

So that's why people say that second engine either takes you to the scene of the accident. One engine expert, Mike Bush, he said-- he came to appreciate the Cirrus parachute. It's not like having that extra engine out there on the wing trying to kill you all the time. It just waits there quietly until you need it.

Piston twins have an illustrious history. Here is a Aero Commander piston-driven twin that was actually Eisenhower's Air Force One. This also tells you something of the growth of government. When Eisenhower was president and wanted to go to a smaller airport, this is how he would go, in an airplane designed for about six people.

OK, this is probably what you'll be flying, which is the Piper Seminole. It is unusual in that the props counter rotate. And that has some advantages that are beyond the scope of this talk. It's a design from the '70s based on designs from the '50s.

Where the problems happen-- so have a look here. Can anybody immediately see what one problem might be? I'd say, the left engine quits, and you have to manipulate these. What happens?

AUDIENCE: [INAUDIBLE]

PHILIP GREENSPUN: You're manipulating the controls for the good engine instead of for the failed engine inadvertently. So it's just an interface that's overly complex given human frailties. So, what do you have to do if an engine quits? You don't want the drag of that propeller out there that's not being driven by the engine.

So you push all of the levers forward and try to get maximum power out of your good engine. Push everything forward. You'll have to put in some rudder to correct the yaw, because the airplane is going to be pulled to one side or the other depending on which engine is still running.

And then there's the old adage, dead foot, dead engine. So if your left foot is flat on the floor and it's your right rudder that's in, then you know that it's the left engine that has failed. Then you try to verify the dead engine by pulling back that throttle.

So you'll say, OK, I think the left engine's failed. I'm going to try monkeying with the left throttle. And if that has no effect on the flight characteristics, you verify that it's the left engine.

Then you feather the dead engine by pulling the prop control all the way back. If you're in a two-pilot crew, you'll get your co-pilot to verify. I have my hand on the left prop control. And you pull that back, close the cowl flaps. And only now do you have any chance of getting an actual climb.

So imagine if this engine failed shortly after takeoff. It's a lot of stuff to do very quickly. You have to do it all right. And if you miss even one of these things, you may not be able to clear obstacles at the end of the runway.

Now, of course, your typical piston twin, takeoff is a stressful time for an engine 100% power. But there's definitely more engine failures that occur en route. So the generally negative impression of piston twins might have to be revised if your primary mission is flying around the Caribbean islands. You might, in that case, actually say, well, I'd rather have that second engine.

Is this within human capability, that sequence that you just saw? Yes, in World War II when engines weren't being made with as much precision as they are now, it would be ordinary to have one out of four engines or one out of two engines fail on any given mission. But they also

got it wrong.

There is one very famous guy, Louis Zamperini. Some of you may have seen a movie about him. He floated in a raft for 47 days. I think that was a record at the time for survival at sea.

He was on a four-engined aircraft. And one engineer quit. And I think there were about four pilots in the cockpit. Remember we talked about a flight engineer also being an airman. So if we count the flight engineer as a pilot, there were at least three or four experts up front.

And as a team, they feathered the wrong engine. So they killed a second engine that was actually good. And now they had two engines working on only one side of the airplane. And it was uncontrollable.

So they went in the water through human error. And Cape Air has a great track record. They've had a handful of engine failures over the years. They fly piston twins all day, every day in the Caribbean and around New England.

And when they have a problem, usually it's not a complete failure. But maybe there's an ugly indication on one engine. So they'll shut it down. But they do a lot of recurrent training. That's what they fly all day, every day.

The typical family airplane doesn't get flown as often. And the pilot isn't as proficient. So the capable twins are very inexpensive now, except for the Beechcraft Baron, which is the most sought after. They're a little more expensive to insure than the comparable single.

Just the other day, I got a quote from my local insurance agency called Plane Insurance. And we found out that if you look at a $200,000 aircraft being flown by a pilot that has 250 hours of experience in type in that exact aircraft and with a million dollars of smooth liability, that means no sublimit. So if there's just one passenger, they would pay, oh, a million dollars for injuries to that one passenger.

Some policies have, like, $100,000 per person sublimit. Anyway, it was about 50% more for the Baron, $3,700 a year versus $2,500. So there you have it.

Again, it's not insanely risky. You can quantify the risk. The insurance company has. But it is riskier.

OK. We have a lot of engineering geniuses in this class and one physics genius-- science.

Which one was it?

AUDIENCE: Brain in cog.

PHILIP GREENSPUN: That's close enough to physics, brain in cog. It takes a lot of physics to make your neurons fire. Obviously, my neurons aren't firing very well.

So, what's the limit to a piston engine's power? Why is it that we can't get 6,000 horsepower out of our piston engine? What do you guys think?

AUDIENCE: Cooling.

PHILIP GREENSPUN: Cooling is one. Sure. What else? What's fundamentally limiting our ability to produce power? Remember, all the power that we produce is by burning fuel and oxygen. Aziz?

AUDIENCE: [INAUDIBLE]

PHILIP GREENSPUN: Size, yeah. I think that's a good insight. It's the size of the cylinder. You only have so much fuel and air that you can combust. And once you've blown all of that up, what do you got? Nothing.

So if you want to know why you should never be like the Silicon Valley heroes and never hire anybody over the age of 30, the inventor of the modern jet engine was only 23 years old, I believe, at the time that the patent was filed over in England. He was a cadet when he conceived of the idea at the Royal Air College. And he said, well, look, these pistons-- no matter how high up you go, no matter what you do, all you can ever do is burn the volume of air and fuel that's inside the cylinder. So, what if we just adapt this gas turbine, which has already been invented?

It was kind of invented in 1791 but not really practical to fabricate at the time. But look, we're just sucking in all of this air. We can probably get 20 times as much air in if we just vacuum it in, and suck it into a turbine, and then light it on fire. So that was the idea, the fundamental insight for why a gas turbine is going to be a better machine for propelling aircraft.

He struggled with funding. So you can see, the patent was filed in 1930. And it was only in 1941 that it finally got flown. And that's a good lesson for you entrepreneurs.

A lot of MIT startups have the characteristic, but they're a bit too early. I remember, in 1994, I built the world's first electronic medical record system that had a web interface. So that had zero value at the time. And about 10 years later, that was a multi-billion dollar idea. So yeah,

Whittle died in relative obscurity in 1996.

So nobody else liked this idea at the time. I'll let you read that quote-- not totally wrong, of course. Because it did take quite a bit of engineering to make it truly practical. But that didn't take as long as people thought.

All right, you saw this figure before. This is the modern turbo jet or turbo fan engine, where you have this bypass error. So the outer ring is devoted to air that really never goes through and gets burned in the power section. And that provides a lot of additional propulsion for not a whole lot of extra energy. So these are much more efficient than the early pure turbo jet.

So just to remind you, you have the compressor section, where you have air being squeezed. Now you introduce some fuel. It catches on fire from the extreme heat or the igniters if you're just starting up. That drives these power turbines. And some of the spinning from the power turbines goes back to spin the compressor wheels, as well as the fan in front, which is kind of like the propeller.

All right, what about having to turbo jet engines? A lot of people like to see two engines on their aircraft, especially airline passengers. If you have an engine failure, what do you do? The answer is, pretty much nothing.

If it hasn't been done automatically for you already, you can advance the thrust levers. If the airplane is the yawing, that sometimes is automatically corrected for you to a substantial extent by the yaw damper. You will step on the rudder to do the natural thing and bring the nose back pointed to where you want it pointed.

And you'll keep climbing nicely. You've arranged everything both in terms of the design of the aircraft and the weight at which you took off so that, no matter the environmental conditions, you will be able to climb. And you will be able to clear the obstacles.

This can be a challenge. If you're taking off out of a mountainous, high altitude, hot airport, you're not going to have a full load of fuel and a full load of people and bags. But by regulation, you're going to be able to clear the terrain safely even on one engine.

Why is it so much easier? You don't have a propeller that'll drag back a wing. And therefore, there's no urgency about feathering.

You also have a little bit less of the crazy yaw. Because the engines are, in some aircraft,

pretty close to the fuselage. So basically, you can still apply that cardinal rule of flying jets. If the switch has dust on it, don't touch it. So you don't have to take immediate action.

All right, if it's turbo jet powered, though, you do need specific training. And you have to pass a check ride specific to that aircraft. So most of you guys, except for Francis, believe that Captain Sully was all by himself in the A320. but actually, anything that's more than about a 10 seater almost always requires two pilots. And according to the type certificate, it's not even legal to operate even the larger business jets with one pilot.

There is an old FAR 91.5, I believe, that says there has to be a proficiency check annually for the pilot in command of a two-pilot aircraft. And more recently, the regulations were updated for single-pilot turbo jets so that a check ride has to be done annually, which is not really that different from the insurance requirements of annual training. They just made it a little more formalized with FAA bureaucracy.

All right, turbo jets that you might own-- the single pilot business jet with a straight wing-- they said initially, the Cessna Citation was so slow that birds were hitting it from behind. But sometimes safety and having it be easy to operate by people of ordinary skill and people of lower skill levels is better than getting that last 50 knots of speed. And that's what Cessna figured out.

So they're still kind of a leader in this area. They produced the Cessna Mustang, which you see there at the right. Some of the Microsoft folks, they spun off a design called the Eclipse.

It was supposed to have these new cruise-missile-inspired engines from Williams. The engines didn't work. So the 1500 nautical mile airplane became a 900 nautical mile airplane with a Pratt & Whitney more conventional designed engine that's used on some of these other designs.

The Embraer Phenom 100 has the same engines essentially as the Mustang, same family. HondaJet has an innovative engine designed by GE and Honda. These have all pretty much been business failures. And the answer to that is the fixed costs of jet ownership are so high you can't just get a T hangar for $800 a month. You may have to pay at one of the busier airports $40,000 a year to have an FBO hangar it for you.

The insurance company will require simulator training annually. And you'll probably have to have two pilots as a practical matter go through training. Insurance will be expensive, because

the whole value is high. If you wreck a $5 million airplane or a $10 million airplane, that's a bad day for the insurance company.

You get charged a lot more for landing fees and parking at airports. When you're a little Cessna, they give you a break, because they don't want you saying anything bad about them on airnav.com. But if you show up in a Gulfstream, they figure you probably have a credit card somewhere.

So yeah, the Mustang, they actually stopped production of that plane. The Phenom 100 is still going from Embraer. But basically, I think the Phenom 300 is-- it holds about nine or 10 people. And I think it weighs somewhere in the 15,000 to 20,000 pound range.

At gross, those are the airplanes that seem to be popular. The Phenom 300 is about $9 million new. And $3 to $5 million used applies, including the things like the Cessna CJ3. A $3 million plane could be a CJ3.

All right, what about single-engine jets? The problem is they're more vulnerable to engine failure. Jet engines are a little bit more vulnerable to failure from, say, a bird strike or something than a piston engine. And therefore, you need some way of dealing with the consequence of having that engine fail.

The Cirrus jet is pretty slow. So it could actually be landed off the airport, perhaps, without too much damage. But it has a parachute in case. And F-16 and other fighter jets that are single engine, they obviously have ejection seats.

Twin turboprops-- let's talk about those. So if you want to land on a short runway-- we talked about turboprop engines, I think, on day one. They can produce a tremendous amount of power. So you can have a much bigger, heavier airplane.

But because they're driving a propeller, you get to take off and land short. They developed thrust very effectively at low speeds. And the prop is a huge drag, so when you land, it kind of slows down and stops immediately or almost immediately.

So the King Air from 1964 to the present with these Pratt & Whitney engines that were developed in the very end of the '50s, the PT6. Those have been hugely popular. When you hit a bird, it's a problem for the bird but not usually for the propeller. The King Airs and this ATR, have an auto-feather system. If one engine loses power, the propeller will automatically go to this knife-edge configuration.

I should have said what feathering is. You twist the propeller blades so that they're edge to the wind instead of flat to the wind. So you dramatically reduce the drag of the propeller.

So that airplane actually took care of itself or should have taken care of itself pretty well. You can read about that crash. I think it was in Taiwan. But the pilots decided to take heroic, immediate action-- or at least, one of the pilots did-- and shut down the good engine instead of just leaving well enough alone.

OK, single-engine turboprops-- as these engines got more refined and more reliable, if you look at the PT6 design, it has all kinds of tubes, and hoses, and vacuum going from one place to another and bleed air. You'd be surprised that it's as reliable as it is. But they supposedly don't really have to be shut down for a problem or fail more than about once every 300,000, 400,000, or 500,000 hours.

So after that insight, people said, let's just put one of them in. And we don't need that second engine. It'll save a ton of money.

So the Cessna Caravan is a great example of that. That's that sort of boxy cargo plane that you saw on floats in the other video. For personal planes that are pressurized and more comfortable, the Piper Meridian, which is down here-- this is my friend Arnold, who is at Hanscom. He says he funded his airplanes, because he was practicing during the golden age of gynecology. And that's what enabled him to afford his fancy, pressurized Pipers.

The TBM is a French design that's considerably preferred to the Piper, but it's a lot more expensive. And the Swiss Pilatus PC-12 is kind of a good airplane for a mixture of family use and charter use. The Piper and the TBM are too small to justify all the machinery around charter.

All right, so actually, old King Airs are cheaper than these single-engine airplanes, but they cost a little more to run. All right, when you're maintaining a jet-- I think I mentioned this earlier-- the manufacturer's guidance will supersede those catch-all rules of a 100-hour inspection for an airplane operated commercially or the annual inspection for an airplane operated privately. It can get expensive.

On one of those Cessna Citation jets that I mentioned, coming out with $100,000 bill from the annual would not be unexpected. You usually have a time limit on the whole airframe. And if

it's pressurized, it's getting expanded and contracted, expanded and contracted and a little bit of metal fatigue on every flight. So you may have a limit on the number of cycles, the number of times that's happened, and also on the number of hours.

So a 12,000-hour or 20,000-hour airframe life limit might be common. For the Pilatuses, it's 20,000 hours. And then they have life extension programs where they tear the whole thing apart and replace some structures or, at least, look at every structure. People have extended them out to about 32,000 hours, I think, now.

There's cycle limits, also, on the jet engines. So the turbine blades and stuff and disks, every time they're started and shut down, there's a huge amount of thermal cycling. So they say, look, after you've done that 15,000 times, you got to throw that wheel out. And that wheel inside the turboprop could be $100,000.

If you guys ever-- it may seem hard to believe now that MIT has stripped you of all of your savings, but if you do have a little bit of money at some future date and you want to get a type rating for your airplane, by far the cheapest type rating you get will be for a big airplane. So it turns out, if you want to pay flight safety for the Gulfstream rating, or a Cessna Mustang rating, or whatever, those are pretty expensive. They're relatively rare. Boeing 737s and Airbus A320s, so many were made that there's just a wide variety of simulators all over the world. And for about $10,000, you can jump in and get your instrument proficiency back up to snuff, as well as have a lot of fun.

All right, so as a summary, it's a good challenge to get that multi-engine rating. I wouldn't recommend practicing it unless you have an unusual application, like you live in the Caribbean, and you want to get from island to island. If you're nervous and somebody says, I don't feel comfortable depending on this five-year-old, 1,000-hour piston engine that's in front of us, the answer I think these days is it's better to get an airplane that has a ballistic parachute as your backup than to have the second engine as a backup.

And while you're formulating your questions, I'll show you. On the top left is a French design. That's called a Cri-Cri. It seats one person. And it's, I believe, fully aerobatic. So you can do all kinds of crazy maneuvers in the Cri-Cri if you want.

Each of those engines might be only 30 horsepower or 15. You can look it up. It's a truly crazy design.

Here is an AirCam that's an open cockpit. Although, this one has a canopy. That's from the Oshkosh seaplane base, a great airplane for flying low and slow over remote, somewhat wet locations.

Here's an L-39 Czech military trainer. And there's a company called-- I think it was called Code 1 Aviation. They had that at Oshkosh, where they took a regular American business jet engine out of a Hawker, and they stuffed it into the L-39 because it's cheaper to operate and maintain it as a lower fuel burn than the military engines. So you end up getting a lot longer range out of your L-39 if you want to-- those L-39s are only a couple hundred thousand dollars for a nice one. So you can actually own a jet that's fully aerobatic, and cool, and look like-- people will think it's an F-16 for less money than buying a Cirrus.

On the left is the ramp at Teterboro. I said I was talking about it. If you're working for Bernie Sanders and you want to start a revolution in the US, I would recommend starting it right at the Teterboro airport and just film the people getting in and out of their Gulfstreams. And this is Meridian. This is the lowest-cost FBO at Teterboro. And that's what the ramp looks like.

If you want to combine two piston engines in a jet, I believe each of these of is a Yak-55. And some airshow performer at Oshkosh glued them together and put a jet engine in the middle and calls it a Yak-110. So there you have it. That combines everything from this talk.

Any questions? Or should we jump right into night? Who wants to fly a jet? Excellent.

AUDIENCE: So you said Cessna Caravans are single engine. I know they fly those commercially in Hawaii island to island. How do you think they justify that?

PHILIP GREENSPUN: Yeah. The question is, is it OK to fly a single engine over water in Hawaii in a Cessna Caravan with only one engine? Well, first of all, the last crash of a Caravan in Hawaii from an engine failure, they operated it just a few hours beyond the manufacturer's TBO under a special program they had approved by the FAA. They were not doing anything illegal. Everybody survived the crash. One person was killed. Does anybody remember who was killed in that crash, and what was special about that person?

AUDIENCE: It was a flight attendant.

PHILIP GREENSPUN: Not a flight attendant. It was a woman who was a state of Hawaii employee. What was special about her? She was the person who certified Barack Obama's birth certificate as genuine. Think about that.

So anyway, if you really open up the PT6 and the manually would say, no, I'm not going to allow this. And I think in Europe-- Europe wouldn't even allow a single-engine charter IFR until just a year or two ago. They said, no, this is too much.

So I don't know. It's a balancing of risk. I don't think it's an unacceptable risk. People with Pilatuses, they will go back and forth to Europe regularly as individuals. But yeah, maybe there should be a warning to passengers. We only got one engine. Thanks for buying a ticket.