We talked about and gone through the history of the Shuttle a little bit.

We're going to go into it some more today.

But, to refresh your memory, there really were three subsystems on the shuttle that were pressing the state of the art.

One was the thermal protection system which we talked about, Tom Moser talked about.

The other was the avionic system with the computers, the computer synchronized.

The four computers synchronized because, as we explained, the Orbiter really needs a computer to fly because it is a fly-by-wire system, which is statically unstable.

And the other system that was pressing the state of the art was the Space Shuttle main

engine. It had a high pressure, high temperature and high performance.

And so, you're going to hear about that today.

Now, the person that's going to talk to you -- Many of you, I'm sure, heard the term rocket scientist but you probably don't really know what that means.

Well, today you're going to meet one.

You're going to meet a true rocket scientist.

J.R. Thompson was responsible for the design, development, test and operation of the space shuttle main engine.

During Apollo J.R. had a very similar function in the design and working on the launch vehicle for the Apollo vehicle.

He became director of the Marshall Space Flight Center.

Then he was deputy administrator at NASA in Washington.

And now he's president of Orbital Sciences.

You're in for a real treat.

Thanks, Aaron.

Aaron asked me to consider this talk, I don't know, several months ago.

And I was a little hesitant at first, but then the more I thought about it, it's given me a good opportunity to go back and kind of recount some of the highlights and the low points in the program.

It was some 30 years ago for me.

So, there is some of this that's going to be still a little fuzzy.

But there is a lot of it that it's just like it was yesterday.

Actually, the Shuttle main engine has its roots back in the technology programs that were funded and came out of Apollo.

As early as the mid-1960s, people at the Marshall Space Flight Center in the same propulsion group that I was in, although my attention was focused on Apollo at that time, were heavily involved with Pratt & Whitney, Rocketdyne and Aerojet in developing the high-pressure turbomachinery that would one day be envisioned to use in the Shuttle, if there ever were a Shuttle.

So, that's back when it started.

And there was a good bit of effort put in at that time.

I think, as you probably know, Rocketdyne of North America won the contract in July.

Actually, July 13th of 1971.

So, shortly after Apollo.

Apollo was still winding down when the Shuttle Program got its legs.

And the Shuttle main engine was one of the very early awards because, as Aaron indicated, it was early on envisioned that that would be what we called back then the long tent pole in the program.

It came on the heels of a one-year Phase B competition between Pratt, Rocketdyne and

Aerojet. During this Phase B, NASA funded some technology demonstrations, requirements definition and that kind of thing.

Actually, Rocketdyne, at that time, did a very bold demonstration of what they call power head.

And I will show you what that encompassed in just a minute.

But it was a demonstration of the heart of the engine.

It only operated for a short period of time but very high pressure.

It was risky.

They pulled it off.

It was actually driven by a fellow called Paul Castenholz who was a guy coming out of Apollo that basically solved or lead the team that solved the combustion instability on the F1 engine.

Paul was a very ambitious fellow, very aggressive and very bold in trying to capture this award for Rocketdyne.

At that time, though, NASA envisioned what they called a fly back booster.

The Shuttle main engine was envisioned to be a common engine for the fly back booster, as well as the Orbiter.

In that early concept, there would be 12 SSMEs on the backend of the fly back booster operating at 550,000 pounds of vacuum thrust.

And on the Orbiter configuration it was three engines operating at 632,000 pounds of thrust in vacuum.

Because of the money that was forecasted at that time and that had been appropriated to date, NASA was always behind the power curve in the early phases of the program.

And they never got everything they wanted.

And I'm sure that Dale Myers and others that have preceded me have told you the ins and outs of why then NASA scaled back from the fly back booster to the solid rocket motors.

And so, at that point, the Shuttle main engine was refocused at 470,000 pounds of thrust.

And that was what's called the rated power level.

At that time, I think there was a full power level and an emergency power level of 109% of the rated thrust that was in the program, but I'll show you a view graph in a minute that has the specific parameters of the engine as it finally settled out.

After the award, Pratt & Whitney protested.

It was a hard fought competition.

NASA had specified that they wanted an engine bell configuration, a nozzle bell as opposed to Rocketdyne's aerodynamic spike that they had promoted in the late `60s.

I'm not sure if everybody here knows what an aerospike is.

You may say one or two things about it.

Well, it's a truncated nozzle.

Actually, it's packaged and derives the nozzle from the expansion of the gases here where the nozzle wall is formed by additional gases that come out in the cooling system.

And it's a very high performing engine.

Its packaging is certainly an advantage where you don't need a big boat tail, say like you would with the engine.

You're saving about 10 or 12 feet there and the weight that goes along with it.

Pratt & Whitney had been focusing on a bell nozzle all the time.

And frankly those of us that were kind of on the periphery of this program and still involved in the Apollo kind of figured that Pratt had the advantage in this because Rocketdyne was, of course, awarded the propulsion systems for the Apollo Saturn Program.

And it was kind of viewed as Pratt & Whitney's turn.

It didn't turn out that way.

I attribute a lot of that to the good proposal, the boldness and the demonstration program that Rocketdyne accomplished during the competitive period.

Anyway, Pratt & Whitney protested.

It took about nine months for the protest to be settled.

It was settled in favor of Rocketdyne.

In the meantime, Rocketdyne was allowed to continue to work with the contractors on the vehicle side because they hadn't made the selection at that time there.

So they could continue to support their work.

Anyway, in 1972, it was all settled.

The contract was awarded cost plus.

And, as I recall, it was $200 million for the development which was called Phase A, and $200 million for the production which was called Phase B.

And the Phase B program included, I believe, 26 production engines.

I won't comment as to what the costs eventually grew to, but very substantially beyond that.

Let me kind of highlight for you the characteristics of the engine.

I think I mentioned the thrust levels.

The rated power level was 470,000 pounds.

It had the capability, if an engine was out early and you wanted to abort the orbit to throttle the engine up to 109% of the rated thrust that was called full power level.

Early on in the program, I think it was termed emergency power level.

But, at the rated conditions, it accommodated or required a little over 3,000 pounds per square inch chamber pressure in the combustion chamber.

The area ratio of the nozzle was 77:1.

It had a very good specific impulse.

About 453, 454.

That compares to J2 in Apollo of about 442, as I recall, somewhere in that range.

Weight was about 7,000 pounds.

Life 7.5 hours and 55 missions.

That's quite misleading, though, let me tell you.

And I'll comment more on this as we go through.

But it was a very tough development program.

It took from '72, as I mentioned, through first flight in 1981.

I joined the program after Apollo and after Skylab in May of 1974.

And it was torture from there until the first flight in April of '81.

Early on it was envisioned that, as I mentioned, the SSME would be used for both the fly back booster and the Orbiter configuration.

It would use basically the same power head.

You would just change out the nozzles to give you the two engine thrust levels.

And so it was rather simple in that concept.

Of course, that's not the way it worked out.

It went to one configuration to service the Orbiter.

And so everything was optimized and focused on that.

Now let me say a few words about the schematic itself and what the engine looked like.

In conceptual terms, it had two low pressure pumps which were required to give the proper inlet pressures to both high pressure pumps to avoid cavitation.

It had the two high pressure pumps.

It was all fed through a common power head to a thrust chamber assembly and then into the nozzle.

Starting on the fuel side, the fuel pump increased the pressure to about 300 pounds per square inch.

And then that went into the high pressure pump on the fuel side where the pressure was boosted to a little over 6,000 pounds per square inch.

About 80% of the fuel all went to the two pre-burners, the fuel and the oxidizer pre-burner contrasted to about 12% of the oxidizer.

That was to provide a very fuel rich power system to drive the two turbines, the high pressure fuel pump turbine and the LOX pump turbine.

The turbine temperatures were in the range of 1750 degrees air ranking.

Almost all of the housing structure on probably 80% of the engine was Inconel, very tough steel.

Able to take very high pressures.

As I mentioned, the combustion pressure in the chamber was about 3,000 pounds per square

inch. At the entry to the pre-burners, the pressure could get up to 8,000 pounds per square inch.

It was a very high pressure system up and down.

It was all in series.

In other words, this was the way they achieved the high efficiency.

All of the propellant came through the low pressure system, the high pressure system into the pre-burners, in through the cooling circuits, all in the hot gas manifold, all in the main chamber, all of it exited the nozzle.

None was dumped overboard to simplify the flow pad.

A good bit of the fuel at the exit of the high pressure pump went directly to feed the two pre-burners.

A good bit of it, about 20% of it went to cool the nozzle, then up through and cool the -- Rather drove the turbine because, having cooled the nozzle, it was converted to a warm gas which then drove the low pressure turbine, came back in and was captured and served to cool the shell of the hot gas manifold.

The same similar thing on the oxidizer side.

By the way, I'll mention the speed of the low pressure fuel pump was about 15,000 rpm and high pressure fuel pump about 35,000 rpm.

The speed of the low pressure LOX pump was 5,000 rpm and of the high pressure oxidizer pump about 30,000 rpm.

The discharge of the low pressure LOX pump was about 250 pounds per square inch entered into the main LOX pump where the pressure was elevated to 4500 pounds per square inch.

Then it went some to the pre-burners and the rest directly into the main combustion chamber.

Some part of the lock flow then was further boosted to about a little over 8,000 pounds per square inch, which fed the oxidizer into the two pre-burners.

It was a very efficient cycle, very high pressured cycle.

A couple other features that you don't see on this chart, there was a heat exchanger wrapped around the high pressure oxidizer turbo pump turbine which served to preheat gas to pressurize the oxidizer tank.

I think those are the major points that I would make on the cycle itself.

Most of the problems, I'll just point out here, had very few problems with the two low pressure pumps.

A lot of technology in the high pressure pumps, both fuel and oxidizer.

The main problem with the high pressure fuel pump was sub-synchronous whirl, and I'll say a little bit more about this in a moment.

It was a very traumatic time in the early period of developing the Shuttle main engine.

It caused a lot of delays.

A tough problem to solve.

And I'll mention what caused it and how we solved it.

Then the high pressure oxidizer turbopump bearing overloads, LOX fires, explosions.

That was probably the single toughest component to developing the program as I recall it.

I think those are the major points that I'll make there.

Early on it was planned, because they had such a head start in planning for the development of this program, to be done in a very methodical way.

And they had, when I say they I'm talking about the people at Marshall with the people at Rocketdyne, a very elaborate system of design verification systems where you couldn't progress to the next stage until you had passed certain testing on a valve or on a low pressure pump.

And all this was envisioned to be done at Santa Suzanna which is right out a short distance from Canova Park up in the mountain on some test facilities that both NASA and Rocketdyne owned up at that time and that they were carried over and upgraded from the Apollo program to be done on the component facilities up there.

But because of the high pressures involved it became a very expensive undertaking, a lot of money, too much time, huge facilities, valves that were probably as big as that side wall over here, to be able to handle these high pressures to assist in the development of this high pressure turbomachinery.

I think it became pretty clear, pretty early in the program, that that very methodical way of developing the engine, and that is, before we go to an engine system test, let's develop it at the component level so we eliminate those problems.

Although, theoretically it sounded very good.

It just didn't work.

The facilities were not available in time to do that.

And the money was going to be exorbitant Kind of a side story.

There was a contractor Bovey Crail as I recall was the name of the contractor out in Los Angeles.

And early in the program when they were having contract discussions and Bovey Crail was late and Rocketdyne, at the instance of NASA, was withholding money until they made certain progress.

And so this fellow who was the president of Rocketdyne, Bill Brennan, I was spending a lot of time out there, and he invited me to sit in this meeting that he was going to have with the head of Bovey Crail.

I guess he thought maybe it would impress him that somebody from NASA was watching this thing.

Anyway, so I joined him.

I think it was a Saturday morning.

And both Bill and I had on suits, coats and ties.

And this contractor or head guy from Bovey Crail came in with some white bucks.

He had on some yellow pants and a pink shirt.

And he plopped down on Bill's sofa there.

And, before Bill could open his mouth, he said all I want is my blankety blank money.

And so it was a short discussion.

[LAUGHTER] He was there to collect his money and Brennan couldn't pay him because of some of the restrictions that NASA had.

So, it was a messy deal trying to get those facilities built.

And it became clear that we were going to have to develop the components in parallel with the engine test.

It was the biggest systems engineering challenge that I think we had in the shuttle program.

Certainly, there were a lot of challenges in major systems integrating the shuttle engine into the Orbiter, for example.

But down at the engine level, the systems engineering, to develop those components, the two low pressure pumps, the two high pressure pumps, the pre-burners, the hot gas manifold, the main injector, all the control valves.

And then we also had on the engine, which I didn't show on the schematic, a computer, redundant computers that were cross-strapped so that the input or the output could be cross-strapped and be very tolerant to failure.

We went to what we call an integrated subsystem test bed, ISTB.

That became the bobtail engine of the program.

Bobtail was a 35:1 area ratio nozzle which allows us to not only start the engine but to operate it at the throttle condition 50% of the rated thrust and the nozzle would still flow full.

It would not separate.

And so then we could proceed with the development of the testing or the development of the engine program.

It was an efficient way to go about the program so we didn't stall.

It was tough because we had to solve the engine problems in parallel with the component problems all at the same time.

And sometimes it was hard to tell which was the problem.

We started our first test in May of 1975.

That is me there on the left, and Norm Reuel who replaced Paul Castenholz they're in the center, and Dom

Sanchini who I view to this day as the strength of the Shuttle Program, or rather the main engine who eventually replaced Norm.

A few comments on the evolution of some of the people on the contractor side.

I mentioned Paul Castenholz who to me was the key to Rocketdyne winning the program.

At that time, and this is a personal view, I think Rocketdyne took a big sigh of relief after they won the contract, probably relaxed a little too long, got in trouble up at Santa Susanna in not developing that component facility.

The test control centers up there, Coke bottles were laying around, so it was not a well-disciplined

operation. They had gotten lax, I guess, was the best way to say it.

Norm Reuel came in to run the program at the request of NASA.

He had done the same job on a J2 and other programs within Rocketdyne for the Saturn Program and worked with me and the other fellows at Marshall.

And we appointed Dom to drive this ISTB to help us learn how to start the engine to how we could properly integrate a number of the components into the engine and proved in the long-run to be a very valuable tool.

This chart depicts the buildup of run time on the engine.

Test seconds are plotted on the right in thousands, and the number of tests plotted on the left and the year is shown down here.

We started, as I mentioned, in 1975.

We finally flew in April of 1981 on STS-1.

The title, someone asked me a little earlier, that's first manned orbital flight.

That's what we referred to our goal back at that time.

I've highlighted along the way, I believe, 14 major engine explosions all of which were very traumatic in themselves.

I'll show you some pictures shortly of what an engine looks like after it goes through that.

And then you can extrapolate that to envision what was in the boat tail of the Orbiter had it occurred in flight and what it would have done to the flight itself.

The test seconds curve is down here.

You can see the long plateau of about nine months where a combination of learning to properly ignite the engine without over-temping the turbine blades or other parts of the turbine combined with what I'll call this sub-synchronous whirl on the high pressure fuel pump.

Sub-synchronous whirl, there is a very exotic definition of it, but it's an orbiting of the shaft within the bearings themselves caused by a softening of that system.

And you can imagine the softening is attributed to overheating of the bearings.

You don't have the stiffness.

And so this allows the rotor to orbit there, vibrations get very high and we have to shut the engine down.

We couldn't get into the test, but about 2.35 seconds was the nominal time before we would encounter this very high vibration and then have to shut the engine down.

And then after that the engine and the turbomachinery were located down in Mississippi where we were doing the testing.

It wasn't like you could just try it again.

You had to bring it all back, replace the bearings, try to figure out what the problem was and put in some kind of a fix.

We went through a number of fixes trying to stiffen the system so we could be able to tolerate and drive through.

I thought at that time that if we could ever get through this period then we would be all right.

But, as it turned out [NOISE OBSCURES].

Well, it manifested itself in overheating of the bearings, spalling of the bearings in their raceways.

I think turbine speeds at that time, or the speed of the rotor was probably in the 15,000 rpm before you could catch the engine and shut it down operating for a second or a half a second with those high side loads, inadequate cooling, overheating of the bearings.

You'd get the bearings back and you'd put them in your hand and they were very much damaged.

I mean that was the manifestation of the problem.

We went into this for quite a period of time.

I think what I wanted to capture was the picture over here.

Ignore this.

This is more dramatic.

I will come back to that later.

But this is a high pressure fuel turbopump.

The sub-synchronous whirl and the overheating of the bearings occurred on the turbine side.

The coolant path is probably going to be hard for you to see, but you come through some labyrinth seals here.

You go down this passage, up through the center of the shaft and in through some provisions that were made to cool the bearings on a turbine end.

We brought in a lot of external consultants, had a lot of cooperation from people across the country, but after nine months it was one of the internal guys at Rocketdyne, Joe Stangeland, and some of the people in his turbomachinery group that came up with the idea that there was a vortex that was occurring in this cavity on a turbine end.

And what we had to do was to kill that vortex and then allow the coolant to go through.

And so he put a little what he called a paddle, which is this part you see right here, which is about the size of dime that was screwed into here to the rotor at that point.

And the first task, after we included the paddle right off the block where the engine had been stalled and couldn't get beyond about 2.35 seconds, went right up to the minimum power level, which is the power level we had set and planned all of the tests to accelerate to that level if we could make it.

And so it was a very dramatic solution, fix, and allowed the program to move on and see what was behind the next hurtle we were going to run into.

So this problem number one was just being able to understand and accommodate the start sequence.

You had to start the engine fuel rich.

Any excessive oxidizer would give you a cutoff because of all the sensors that we had.

The second problem and the one that causes the most time that I've mentioned is the high pressure fuel turbopump sub-synchronous whirl.

And then problem number three, which are duplicated here several times, are the LOX pump explosions.

They could be triggered by loss of a turbine blade on a turbine end which would unbalance the rotor, overload the bearings and then cause a LOX rich fire which very quickly consumed the whole engine.

There were numerous, well, I think three, rather four highlighted there.

We had some other problems.

I've noted a fuel pre-burner burn through, just a structural burn through of the [OVERLAPPING VOICES].

How did you eventually solve that, because the last failure you had was also the liquid oxygen explosion?

Well, I'm not sure I can differentiate between the LOX pump explosions.

But late in the program, probably at that time, we had been having for a long time problems with the turbine blades, very limited life.

Cracks would grow.

At that time, we didn't really understand how long we could run them before we had to replace them so we went to dampers on the turbine blades.

And this occurred fairly late in the program that eventually solved the vibration of the blades within the turbine wheel stack and allowed us to proceed.

Whether that was that one that caused the imbalance of the rotor or some earlier when they were primarily driven by bearing problems considered for some time.

We used ball bearings in the Rocketdyne turbomachinery.

Later in the program they had gone to roller bearings.

Pratt & Whitney has been contracted to develop that.

But the bearing problems and turbine blades were the major problem, as I recall, that caused the LOX pump problem.

As a matter of fact, yes.

Do you think you would have had similar problems if you had developed an aerospike instead?

The turbo machinery was going to have to be basically the same.

And so, no, I think you'd have the same problems.

The only problems that we had on the engine, we had a nozzle steer horn failure.

That was just a structural feed line that was in the shape of a steer horn at the aft end of the bell nozzle.

We had two of those structural failures that were very traumatic for the program.

No, they were both right here.

And, of course, as soon as you lose the coolant to the nozzle, you start shutting down a lot of the engine system LOX rich which causes a fire.

Certainly, you would have eliminated those.

You would have eliminated a number of I'll call them nuisance problems in terms of we had 1,080 tubes that made up the nozzle that we flowed the hydrogen through to keep the nozzle cool.

1,080 of them.

And we had a number of, again, I would call them nuisance cracks or splits in those tubes that we learned to live with.

We learned to go out and put a cap on them post-flight, braise over and just cap off the leak.

Certainly, you wouldn't have had those.

But all of the other problems I would have seen come in between the aerospike as well as the bell nozzle.

J.R., the shuttle main engine had the pressures that you mentioned, the 3,000 pounds per square inch up to 8,000.

Give us some feeling for just how much higher that was than the previous operational engine and whether the pressure itself was causing a lot of those problems.

Oh, yes, the J2, chamber pressure was about 700 pounds per square inch, as I recall it.

RL10, which was the first LOX/hydrogen engine in the country developed by Pratt & Whitney, chamber pressure was a couple hundred pounds per square inch.

This was a real push.

Was it worth it?

As you look back on the engine, you've now taken into orbit over 300 of these engines and 100 flights three at a time.

You have had one shut down because of a safety sensor that failed and shut one engine down in flight.

And we were far enough along in the flight so we aborted to orbit and the other two burned a little longer and went to orbit.

But it was a very costly program.

On some reflection, it was almost viewed in the late `60s as that's the challenge.

Not the shuttle engine but the technology.

I mean let's really drive the technology and make it very efficient, very high pressure.

Aaron and I were talking a little earlier.

The engine people, had the Orbiter flown a 100 times and had several major failures, people would have expected the Shuttle engine, I think, to have been the cause.

That's not the way it turned out.

And I'll comment on at least a contributor in just a minute.

But this is the aftermath.

When you're in the middle of a development program, you've got a lot of budget pressures, you've got the Shuttle's first flight date changed several times, you've got all that hanging over your head and then you're called down on Mississippi on a test and you look down on the engine and that's what it looks like, it's like a kick in the stomach.

You've got to start all over.

Well, that mental picture was in our minds 14 times in this program where you had to start over.

The recovery was typically it took about a month.

We formed a team, usually within Rocketdyne and one within NASA, to go solve the problem.

Probably half of the time it was fairly evident what the problem was quickly after the test.

Sometimes it took a couple of weeks to narrow it down it could have been this or that.

And then you fix both this or that not knowing exactly what it was.

And so it was a very tedious and time-consuming.

We were testing around the clock.

If it occurred during the holidays you just cancelled your holidays and jumped in, and we did what we had to do.

I will mention, as I look back, kind of one of the dumbest things that I did on this program was somewhat associated with the testing.

This happened to be, I think back early on in the sub-synchronous whirl days, we were changing out the turbo machinery after almost every test because we were doing the damage to the bearings that I described a little earlier.

And it took about three shifts to change out a turbopump down in Mississippi.

And then it took flight time to get the turbopump back to LA and then tear it down.

We had others in the meantime that we were bringing along, but it was very time-consuming.

And it was in the middle of the summer back in whenever it was, '75 or whenever, and a lot of rain showers.

And that was holding us up because when it was raining or it looked like it was going to rain, you couldn't open up the engine, drop the pump and take it back.

So, that slowed us down.

And so I had a brilliant idea of first of all, the engine, if any of you have ever been down to Mississippi on those test stands, it's on about the fifth level is the engine position, about the fifth level.

And so on about the seventh level I wanted to put here, what I want to call, a rain shield.

Put a tin roof a couple of levels higher than the engine so the workers wouldn't have to stop when it was raining.

Well, you can probably imagine what happened.

That was OK for a while.

And then we were back into a test and we had a hydrogen leak.

And we weren't using the igniters at that time at the end of the bell to burn off the leak.

So that leak just accumulated on those two stories up to that rain shield.

And then, when we went into the test and lit the engine off, the whole Mississippi sky, you know, there wasn't any fuel.

It burned all the wires.

It didn't damage the end canal on the engine structure.

I certainly got a lot of ribbing after that.

And, as I recall, the test was toward the evening.

I wasn't down there at the time to see it, but was listening to the test over the phone.

And the guys almost couldn't speak.

I mean the whole place went up.

These kinds of failures -- This was not evidence of a little fuel fire.

This was oxidizer and the fuel was the metal.

And so it was quite a problem for us.

I might mention at this time that just this last summer I attended a little event there in Huntsville where the Rocketdyne team came down.

And now the engine program had just passed its millionth test second mark.

And so you can see, for STS-1, the total test seconds were about 110,000.

A little over half of that, 65,000, almost 70,000 at the rated conditions, the conditions you flew it at.

And so it's gone up by about a factor of ten in the meantime.

Another key to the Shuttle engine program was the philosophy imparted by John Yardley.

I think he recognized early on that we had bitten off probably a little bit more than we could chew to have an engine that you could solve the problems of where you put the bearings in there.

The earlier view graph I had said 55 starts.

You ran them for five starts and they came out in pristine condition.

That wasn't going to happen.

And the turbine blades, one blade failure, I actually forget how many are in those two stages on that wheel, probably well over a hundred, but one would offset or offload the balance on that rotor.

Then you would overload the bearing going at the high speed of the 35,000 rpm's and would fail it.

The turbine blades, you just could not tolerate a failure.

But in evidence after testing, where you can tear the blades down and de-stack them and look at them under a microscope, you could see fatigue cracks.

And so all of us, I think, but John provided the leadership, recognized this fact.

And if the requirement were going to be that you wouldn't fly with turbine blade cracks, we weren't going to fly.

And so he encouraged us, in that instance, in bearings and probably other areas to test to failure, drive it to failure, know where the cliff was and then back off a sufficient amount.

And then conduct your certification with cracked blades, with spalled bearings so that it was clear to everybody, it was clear to the people that were running the program and others that had to fly that the problem was understood, we thought reasonably well understood, and it was tested to accommodate that condition.

And so that was the philosophy that was engrained in the Shuttle.

And probably not enough in some of the other areas.

The Shuttle Engine Program was a little bit blessed with this fear of failure.

It's the toughest technical problem so we got the most money.

I mean it's not all a downside.

So, we got the money to provide the test depth that provided the insight to the Shuttle managers that could make the call as to when we were ready to go.

The squeaky wheel gets oiled.

I contrast that with maybe the famous O rings on the booster.

That was a problem that was kind of observed, a few tests were run, but not enough, you know, not to failure.

It wasn't ever tested to failure on the ground.

It was tested so you could see that the O rings were split maybe but not to be staring at a picture like that as to what is going to happen when that O ring gives and very quickly can burn through.

And the other example I would make is a tank.

And this is the most frustrating to me because early on we all saw some of that foam come off, but not in the sized pieces that the Shuttle Program saw three flights before Columbia.

I mean that was a piece of foam about this size.

It came straight down the vehicle.

It made a small dent in the aft skirt of the solid rocket boosters that were subsequently recovered.

But that should have been an eye-opener that that piece of foam doesn't always have to go straight down the side of that vehicle.

It could get out in the slip stream and hit a wing or something.

That type of testing was never done.

Whereas, on the engine program, there were a number of flaws that were accommodated and we felt comfortable with.

Now, you go and read the Challenger report, you read the Columbia report, and they will almost tell you that NASA became comfortable with flaws.

And that lead to the problem.

But I take issue with that.

I viewed it different because that was almost the foundation of the Shuttle Engine Program.

It was built on flaws.

It was tested so wherever the soft spots were you knew it and you attacked it and tested it in the appropriate way.

John Yardley, I keep coming back to him, as a part of the certification program of which I think prior to the first Orbiter flight there were eight certifications completed.

One of those certifications was to be conducted.

And a certification, as I recall, was about 13 tests.

One was abort to orbit which was 623 seconds.

And a nominal shuttle test or mission is 520 seconds, I think.

And then an RTLS, return to launch site is 820 something seconds.

It had a mix of those in there.

The engine had some FPL, full power level.

It was tested at all of the limits, but in some of those certifications we had to go into the test with cracked turbine blades.

We started the test with a known crack.

And we knew, by analysis, what its growth rate was that we had judged from other tests.

And so we planted blades that did that.

We did the same thing with bearings.

One time both Dom Sanchini and I were trying to get the most on every test.

We put cracked blades and spalled balls and combined them all in a test.

Now, Yardley didn't mean that.

He didn't want to go that far.

But there was a lot of NASA leadership that bucked up the back of the program manager's, both myself and Sanchini.

I mean they knew the way to develop the confidence in this engine was to test it.

And that became the theme.

That isn't true today.

And that's what I worry about.

And I can come back and comment a little bit more on that in a minute.

I will say a few more words about Dom Sanchini.

He passed away about 15 years ago, probably in his early sixties, was the deputy program manager on the F1 engine to Paul Castenholz, a good engineer.

He was a lawyer by trade but had also accumulated a good background well steeped in engineering.

He was a hard driver.

He thrived on failures because he saw a failure as that's when you're on the steepest part of the learning curve.

You never learn more than in the aftermath of a failure where you're forced to go through and look at all of the data and postulate a lot of other different failure modes.

He thrived on it.

And he made sure that the whole Rocketdyne team viewed it in that light so he was a real strength to the program.

I want to allow a little bit of time for some discussion.

A few minutes ago I alluded to the fact, but that's not the case now.

The Shuttle engine, back in the hay-day or the time period when we were in the development program, we were building them around the clock out of Canova Park three shifts out on a manufacturing floor probably at a rate of about one a month, ten a year, that's about right.

So, a pretty high production right there.

I could probably ask for a show of hands, do you know how much a shuttle engine costs, you know, just to make one?

Do you have the foggiest idea?

My last count was about $40 million.

I imagine in today's money it's probably closer to $60 million a copy.

But today they build about three-quarters of an engine a year so the production rate is way down.

They test, aside from a lot of the terrible consequence of the two hurricanes down at Slidell, you know, they're not testing anything right now.

But, even prior to this time, the testing was very infrequent.

That's to save money.

You don't get that much out of it.

And that's the Achilles' heel, I view, of the Shuttle Program.

If you're not going to do it right, whether you cannot afford to do it right or you have other ambitions, you want to do something else in the Space Program or within NASA, you probably ought to stop it.

Because it's going to be the next failure if you don't treat it right.

Today you've got the Shuttle Program, back when the engine started.

It is a little over almost 3.5 decades old.

That's at a minimum two generational changes and a lot of small businesses that support the Shuttle Program.

And so you're going to lose a lot of the knowledge when you have the turnover of these generational changes.

And little things, I'll tell you, when you look back.

One of the major disappointments to me or traumatic times in the program was back in the late `70s when we were building the first three engines that would power Columbia on STS-1, when we were building those engines we had a mix-up of well wire in the Canoga plan.

And the mix-up was the well wire was, you know, one could take a heat treat and the other one couldn't take a heat treat.

I forget the application where you wanted the non-heat treatable well wire, but that was a mom and pop operation that came in, got the well wire, took it home and cleaned it and then delivered it back in baskets to Rocketdyne.

Well, they got it mixed up.

And so we built the first three flight engines with well wire that would not take a heat treat that we depended on.

You go out and look at those engines with inches and inches and rows and rows of wells that are not to the proper heat treat.

We had to go through and analyze every section and over test those engines at a little higher pressure than we normally would have to be able to show that having been built with the wrong well wire it was still good enough because the design was up to FPL and a little beyond.

That it could still take it and operate at the rated thrust condition.

It is mistakes like that, that without frequent manufacturing exposure, without frequent test use you're going to lose in a program and will become the next -- You know, the program has not been surprised by a problem yet.

I'm talking about all the shuttles.

The O ring failures, they winked early on, To Thiokol and then to Marshall before Challenger.

And the foam problem has been winking all the time.

And it got worse later.

I suppose it has something to do with the change they made in the insulation later on.

But, as you know and you read, the agency is at a very critical time today.

They've got to make some decisions in terms of where their priorities are and what they want to try to do.

And they don't want to spend money on the shuttle because they seem to be committed to replacing it.

And if that's what you're going to do, that's what you're going to do.

But between now and 2010, if that's the year they choose to retire the Shuttle, they are not going to be motivated to test.

The program is going to be at more risk over the next four years than it was in the first four years because of that reason.

You don't know where the ledges are, where the cliffs are.

And testing once a month or once every two months is just not going to do it.

You said something that I really never recognized.

You said there could have been a point of time in the program where you could have gone back and reduced the pressure levels and that type of thing to make the engine a little simpler to certify.

What effect would that have had?

Well, an easy way to do it, we looked at probably several years before the first flight.

We had seen enough, at that time, to know that even with the philosophy that we had adopted, we were on fairly shaky ground.

I would never have guessed that the Shuttle would have flown over a hundred times and never had a failure of the Shuttle main engine or some problem.

I would have never guessed that having looked at what I looked at.

We were starting to think.

And an easy way to do it is open up the throat on a main combustion chamber.

If you open up the throat you relax the pressures up and down the turbine system, the pre-burners, the pump requirements.

You wouldn't have to open it up much.

You'd lose a little specific impulse.

You'd gain a little in thrust.

And so you would get some offset there.

You may want to adjust the mixture ratio overall you operate at.

Instead of 6.0 maybe 6.2.

You could have done it with a modest performance here.

You're not going to get it for free, but you could have relaxed the pressures throughout that whole system by a change in one component.

And we were contemplating that and the monies never came.

It was a configuration change.

There is a lot of the -- What don't you know about that change is what would bother some people.

I don't want to oversell it as simple, but conceptually it was a simple change.

That would be one.

I think looking back and knowing the capability of the shuttle and, to be honest, being somewhat troubled, quite a bit troubled by what I hear and read about NASA wanting to retire it.

Although, I understand their reasoning.

Some view it as a flawed design.

I don't view it as a flawed design.

I think you need to relook at how you operate it.

I hadn't been particularly pleased with the operation of the Shuttle.

Watching all this foam fall off and not even raising your hand.

But then, after all that occurred, nobody stopped and stripped all that foam off and maybe replaced it with cork that's heavier, that's got some tensile strength that you can anchor it on there with glue or whatever you want to do.

And it's going to cost you some performance.

NASA has been biased too much.

And they certainly started this in the Shuttle main engine in the direction of performance where if you back off a little bit the system will be a lot more robust, serve you a lot better over the long haul, and maybe you don't push too much in some of these directions that have got us in trouble.

Do you think that we had a fictitious requirement with the performance we were trying to achieve with the Shuttle?

I don't think we needed it all.

Tell me the missions that we needed all that performance on.

It's not there.

You'd have to reset the manifest in some cases.

Well, speaking for the one element that I know the most about, the Shuttle engine.

If you folks were to undertake the job, OK, what would I do different?

They're talking about using a Shuttle engine on this heavy lift launch vehicle for a cryogenic upper stage engine.

I would open that throat up and look hard at that.

Rocketdyne knows how to do that.

They've done it.

We just haven't incorporated it.

Although, men aren't envisioned to be on that.

You're still going to be a lot better off.

I'll tell you a problem you're going to have with the vacuum start or at upper stage start is that start sequence.

This start sequence is very, very sensitive, and you're probably going to have to go to Tullahoma to get in some kind of a vacuum system to demonstrate that.

That's going to be expensive in itself.

But, yes, Aaron, I think probably across the board, we set the bar higher than we really needed to.

And it cost us in money.

And it has also cost us in margin that we don't have that we wish we had.

J.R., usually around this time we take about a two-minute break.

OK.

Give your voice a rest.

Everybody stand up, turn around and just stretch a bit.

Two hours is a long time to go without a stretch.

I'll just give one statistic that I remember really impressed me during our initial astronaut training when they were talking about the main engine.

And you talked a lot about the high pressure turbopump.

This is a device that is about the size of a typical automobile engine, right?

That's right.

It produces 50,000 horsepower just to pump the liquid oxygen at high pressure.

I mean that really gets your attention.

When you talk about pushing the state of the art and trying to get a lot of power out of a small volume that just really amazed me.

As was indicated, I think I would like to just make a couple more remarks and then maybe open it up for some discussion in terms of points that I haven't covered that are on your mind or other questions that you'd like to ask.

Just kind of in summary, if I look back on the program, I think there were two main keys that were paramount to the success that the Shuttle engine enjoyed, and is enjoying through its track record today.

One was a decision to use this ISTB, to get away from the serial component test and then the systems test to try to combine it and do a systems engineering job on a thing from day one.

In other words, that was key to me.

It might have been a little extra pain but saved a lot of time and a lot of money.

And I'm not sure we could have done it the other way anyway.

And the other one which may be a little bit more important, but just as important, was the philosophy in the program of test to failure.

Know where the failures are.

And certainly, if you look at that earlier chart, we had plenty of data points.

I mean we had encountered a number of them, some of them three or four times.

Maybe in some cases we were slow learners, but there wasn't just one problem with that high pressure LOX turbopump.

I think I'd be remiss if I didn't acknowledge some of the people as viewed from the engine that made major contributions to the Shuttle.

Not just the engine now but to Shuttle.

And in Rocketdyne, I mentioned Dom Sanchini a couple of time.

Bob Biggs, who has been there since day one and has done all of the test planning and is key.

He is the systems engineer on the SSME.

Byron Wood, who is now the president at Rocketdyne.

Joe Stangeland who was in charge of turbomachinery who designed this little paddle and solved this vortex problem that uncoupled us from this terrible time that we were at a standstill.

Matt Eck who was in charge of turbomachinery at Rocketdyne before he passed on several years ago.

And then, within NASA, I had mentioned John Yardley.

He has now passed on as well.

I don't think there would be a Shuttle without John's leadership.

Bob Thompson who you might get an opportunity to hear a little bit later, I think he was a driving force in the Shuttle.

Bob Lindstrom, who was my boss for some time.

Chris Kraft, who I understand you will hear or have heard.

Certainly Aaron, we had to interface with the Orbiter and he had an equal challenge.

Arnie Aldridge who I've always thought a lot of, as well as Dick Coors.

And then I'll mention Bill Lucas who was the director at Marshall and George Hardy, both of whom got caught up in a later controversy on Challenger.

Not necessarily fair, but that's life.

I mean they were both superb engineers and meant a lot.

And then also Gene Covert from MIT who, how shall I say this, came in periodically and chastised us appropriately and I think made a major contribution to the program.

At the time Gene was also head of the aero-astro department here at MIT.

I'm not sure who triggered bringing Gene in, but I know John Yardley was a key driver in that.

And so I'm not sure I've touched on the kind of things you'd be interested in, but I'll certainly be glad now to try to answer areas that perhaps I haven't hit or maybe make a few broader comments.

I understand the only element, other than the Orbiter and maybe the overall system, but this is the only propulsion element that is talked about, I think the tank, I've already mentioned there the insulation was their tough nut.

And I think having had some data there are certainly some things that we could have done differently.

The solid rocket boosters, there's quite a history there.

Thiokol has now been acquired by ATK in consolidation of the solid rocket motor industry, but they've also made major improvements in the way they manufacture that.

Those solid rocket motors are also made with glue.

That's put on by hand.

I remember, in visiting up there, after the Challenger accident back when I was a director at Marshall, a number of changes were made to automate a lot of that.

I think probably the solid rocket boosters, when properly used and appropriately tested and backed up by the right analysis, is an excellent propulsion system.

ISP is down some but they are more than adequate to do the job.

J.R., something that really strikes me as complicated and didn't really seem, or at least I don't think we seemed to have that much problem was integrating the engine to the aft end of the Orbiter.

That was a complicated system, but it did go pretty well.

Was it the main propulsion test article that did that?

Well, yes.

It was earlier when we went to school a lot on the integration of the J2 into the S4B stage and the S2 where the conditioning of the engine, prior to engine start, was important and was a big interface with the stage itself.

And certainly that was true with the boat tail of the Orbiter.

And the main propulsion test article, which Aaron mentioned, I guess we had a dozen tests done there, somewhere between a half dozen and a dozen.

As a matter of fact, we had a structural failure of a main fuel valve crack down in Mississippi in that test article.

And it caused some consternation along the way.

But the integration, as Aaron mentioned, went quite well.

I don't think in flight we have ever had any problems with over-pressurizing that boat tail or any problems with it.

There are a number of tests that we didn't conduct, or a few that we didn't conduct on the engine that I would have liked to, A, for curiosity and then, B, to fill a square so we knew exactly what would happen if we ever got in that condition.

And that was with a LOX depletion.

There is some thought that a LOX depletion is going to allow you to imbalance the rotor of the LOX pumps and they're going to rub, cause a fire and all that.

On the other hand, it is, by definition, going to be a fuel rich shutdown, I would tend to think.

But it was one test that we debated quite a bit about in the Shuttle Program and decided that the probability of getting in that situation probably didn't merit the test.

I will add that there was a lot of good tension within the Shuttle Program up and down at all levels.

I thought the whole management team was relatively cohesive, but there was good tension.

I mean we got the best out of everybody and arrived at the best answer by the balance that we had between the institutional managers.

I mentioned the contribution I think that Chris Kraft made and Bill Lucas.

I'd also add early on Rocco Petrone.

And then the program managers.

The John Yardleys and Bob Thompsons and Arnie Aldridges.

And then the so-called level three, which Aaron and I were.

I guess you were two.

I think it was a well-balanced management structure.

And I'm not sure you have that today.

Today, for whatever reason, the program has gotten into an operational mindset.

Center directors are more viewed to keep the grass cut at the centers and that kind of thing.

You don't have that tension.

Who is holding the program people in check?

I see that missing.

I always felt that there was another institutional side that had my hands cuffed at the right time.

And so I think, as NASA goes forward, and maybe some of you folks that are going to have careers in the industry, you ought to make sure that, A, you're surrounded by good people and that you're surrounded by a good system, I mean a good system that pulls you up at the right time or calls you in-check at the right time whatever you do.

Whether it's going back to the moon or mars or, maybe in retrospect, flying a shuttle a little bit more.

Here, let me slow down and stop a minute now and see if there are any other areas that you all would like to cover.

Yes.

We've talked in the past a lot about the slow kind of turnaround on the Shuttle, and part of that has been attributed to having to remove the engines and I'm not sure if it's overhauling them but basically taking them partly apart and looking at them and examining them.

And I was wondering if that was part of the original plan or what kind of changed the efficiency of that turnaround time, what caused it to change and slow down in the original plan.

Well, the original plan was for 55 missions on an engine.

But that just didn't materialize at all once we saw what we had.

I don't know what today's life on a set of bearings are, but it's a handful of missions.

You've got to tear down both of the high pressure pumps and replace a bearing.

The same on turbine blades.

You want to replace that stack after a few missions that are defined in a current certification program.

It's certainly less than a half a dozen.

And, yes, that has built in the time.

But you could overcome that by just dropping the whole engine and replacing it with another one and doing it all in parallel.

There were a lot of people on this program that I never envisioned you needed.

I think NASA did the right thing by turning it over to a contractor or a team of contractors, but they stayed too much involved so it was all done by a committee.

I mean I don't want to pick on anybody, but who was in charge?

Who felt they were really responsible for that accident?

I couldn't see it and I followed it and could offer my opinion, but I didn't sense that the program had somebody in charge.

There was another one.

Yes.

I was wondering if you could talk about any examples that you know where specific technologies that came out of the Shuttle main engines have either been used or avoided in newer launch vehicles today.

No, I think a lot of the materials will certainly be carried forward.

Coatings, seal technology, that's probably one of the areas in the turbomachinery that I didn't talk about enough.

There are a number of seals on those shafts that are very critical to the operation.

And there was a lot of technology advancement made in the development of the SSME on seals.

Those would be several examples.

Yes. I was wondering if there was much discussion before the project started on the risks in going from 700 psi operating [NOISE OBSCURES] whether there was some option to go to an intermediate pressure.

I am sure there probably was.

Again, I came in the program about a year after it started so I was on a periphery of some of the early stuff.

But I think the risk at that time more focused on NASA, particularly at Marshall.

I think they wanted a liquid booster.

Eberhard Greff, the German felt very comfortable with liquid boosters because you could shut them off, as opposed to the solids.

But cost and other things, I think they eventually became comfortable that the solids were fine.

I think the risk tradeoff was more on the booster.

You shut a liquid off.

When you light those solids you're going somewhere.

On the engine, I know they knew it was going to be harder.

I'm not sure they appreciated how hard it actually got to end up with those 8,000 psi pressures at the head of the pre-burners and what that did to the rest of the system.

And what it did to materials and what it did to crack growth rates and everything from then on.

You wouldn't fly today without it.

You understood the mechanism, you applied fraction mechanics, and then you applied several factors, and then you certified that and that's where you went.

Does the aircraft industry do the same thing because they have turbine blades, too, that crack, don't they?

I'm really not sure.

I don't want to fly on an airplane that has got a cracked blade.

J.R., you talked about the lack of testing nowadays compared to at the beginning of the program.

To what extent does the fact that, I mean after every flight they take the engines out and they borescope them and look at that.

I mean does that, to some extent, constitute continual testing?

No.

What's the difference between that and what you get out of the tests?

Well, I think probably -- Today's teams, they go to the log book and they read what was written down by the last generation and that's what they inspect.

That's fine and that's very thorough.

But the testing, the introduction of some kind of a small change by a mom and pop operation, that I alluded to earlier, that's what a test program will catch.

Some new problem that creeps in or will get caught that's not done there.

No.

Let me say it another way.

I believe it is very dangerous to execute this program in the way that I understand is planned to be executed between now and when they retire the Shuttle.

I think that's the most dangerous period in the life of the Shuttle because of that.

I mean the people that are in the program now have not been part of developing it.

I don't know how many pictures they've seen of a LOX pump that has burnt up.

You just think about things differently once you've been exposed to that first-hand, that's my view of it.

Now, how you transition out of a shuttle program onto something new, I don't have that answer.

I mean I think you've got to do both.

Like the wing-walker, I wouldn't let loose of a shuttle before I had something else in hand.

And today they're going to let loose this and hope this other thing comes along.

And I think there's some risk to that.

Along that line with the O ring issue and the foam issue, do you think that those were never solved, were never looked at because of lack of money or just confidence in the technology at the time?

I mean the O ring was kind of carried over a little bit.

The foam, I don't know how much of that was brand-new.

And nowadays are we just relying on the confidence that these things have worked for a hundred mission or so or is it just lack of money?

No, I cannot say there was a lack of money back at the time of the O ring.

Had the culture been and if they were inquisitive enough to pursue it, I think they could have gotten the money to do it.

On the Shuttle engine, out of necessity the culture was there.

I mean it was driven by people like Yardley.

I think another thing at NASA and aerospace, you know, you can do wonderful things with computers today, but too little of all this analysis is anchored by a good failure.

You've got the analysis, you've got a lot of programs, you can do a heck of a job on analysis today, but it's not necessarily anchored in the remnants of a good failure, one that has adequate data.

If I'm building a test bed now, how do I kind of intelligently justify it to my sponsors that I want to have a budget [NOISE OBSCURES]?

Well, I don't think you're going to sell it that way.

[LAUGHTER] Right. Well, I think your sponsor or whoever has got to have a good appreciation of how far you're going to be pushing the technology.

If you oversell it then you're not going to get the money to be able to stand those.

If you push too hard in that direction your sponsor is probably going to get disinterested.

That's going to be a fine line.

Pick a current example.

Pick at least, as I understand it, what NASA is trying to do with the Lunar project or the moon project.

I, for one, think that their yardstick is going to be tough.

Apollo didn't have any failures, why are you going to have any failure?

I think they are going to have to be very careful how they sell that program.

Just because they're using or will use shuttle-derived elements, an external tank, maybe a five or an additional segment to the solid motors, the SSME, that's not going to be a freebee.

I mean, I've already told you, I would do some things to the shuttle main engine in building a different program.

The tank, you know, they're not going to keep the foam from coming off on the configuration that they have.

And I also wouldn't assume that I don't have a problem now because I don't have an orbiter on the side of it.

The foam is not supposed to come off.

I would degrade the insulation and put on something that would stay, as an example.

Yes. How much of the original engine, the current engine right now, is it exactly the same as

the original one or what has changed. Materials? Is the computer the same?

Is everything exactly the same?

I think it is the same.

I'm sure there are, through engineering change proposals or fairly low-level change traffic, some things that have been upgraded.

But Inconel is still the basic material of the housing.

The turbine blades are still Mar-M 246 which is a high strength copper, I think.

That's the same thing.

They still use ball bearings when they fly.

And I don't know the change point on this, but Pratt & Whitney makes the high pressure turbo pumps now and they used roller bearings.

And that would be a big change, the two high pressure pumps that have now been incorporated in the Shuttle engine.

But other areas -- [OVERLAPPING VOICES] the high pressure turbo pumps?

Yeah.

At some point a couple of years ago, I think, they were incorporated and brought in.

Those would be big part number changes.

But a lot of other areas of the engine, I think it's the same.

And I think that's one of the reasons that they feel they don't need to test much.

They've got all that.

So, we will have to see how the next four or five years play out.

Anything else?

Well, since they're talking about using a lot of these with the next generation vehicle and they won't be reusable, what can be done?

I mean what's the way to go about kind of de-rating the Shuttle?

You talked about opening the throat, but all the other things that make the engine reusable and presumably make it more expensive.

Will it really be the same engine when they get finished?

I mean what has to be done?

I don't know.

I mean some may argue and suppose because the requirement for reusable engine isn't there will eliminate some of the things.

I don't know what they'd be.

But, having paid all that development, I would be more inclined to really minimize the change for change sake and do some things like open up the throat.

I mentioned that as an example that would reduce the operating pressures and, I think, give them more margin across the board.

On a tank, I would go to an installation system that is going to be a little less efficient.

You're going to have more boil off, weigh a lot more, but something that doesn't give you other problems.

J.R., let me ask a question that was asked of me and I couldn't answer earlier.

Did we ever look at putting the insulation internal to the external tank rather than the outside?

I'm not aware that it was looked at.

Somebody along the way, I suspect, could have.

No, I'm not aware of what it was or what it would have been.

Anything else?

Well, I've enjoyed it.

I hope you don't repeat the same mistakes that we made this time around.

And good luck in your projects.

Thanks, J.R. [APPLAUSE] I'm just going to take the last three minutes.

J.R. referred to the fact that we only had one engine shut down in the whole history of the program.

And that was due to a sensor.

Just to give you a sense of what goes into the operation of this system.

It was always recognized that you have sensors looking at the temperatures.

And the idea is that if anything starts to go wrong with the engine, you want to shut it down now before the thing blows up.

Because we can lose one engine and have an intact abort, but if the engine blows up and takes the whole boat tail with it you're not going to get back.

Generally, there's a little switch in the cockpit which enables the ability of the sensors to shut down the engines and you fly with that on.

But the problem is if you lose one engine and you get into an abort mode now, at least for the first part of that abort mode, if you lose a second engine now, with only one engine remaining, you cannot complete an intact abort.

What the crew does, if you lose an engine, you take that switch and you disable the automatic shutdown.

Well, what happened was a few minutes into the launch the sensor started to go off scale.

The engine was shutdown.

But they were far enough into the launch that they can actually do an abort to orbit.

They took the engine switch to disable, normal procedure.

When they got a little further along so that they were in what they would be able to, a little further on, I forget the exact details, but they took the switch back to enable.

But the main engine flight controller on the ground noticed that the sensor in one of the other engines was also starting to go off scale.

And, if that was allowed, it would basically take down a second engine.

That would have put them in a single engine, what we would have called an intact transatlantic abort.

But, by that time, they were too far to land in the normal abort site, and they would have ended up landing somewhere in Africa, I think, in the dark.

I mean it would have been a really bad situation.

And so the flight controller was sharp enough to tell the flight director we've got another bad sensor, tell the crew to take the switch to inhibit.

Luckily, the flight director's background was in propulsion systems.

He knew exactly what the flight controller was talking about.

They called it up to the crew, they took it, and so the second engine did not shut down.

And, in fact, they made it into orbit and they managed to complete the mission.

But these are decisions which have to be made in split seconds.

In fact, the flight controller who made that call was given a special award from NASA.

You really have to know these systems inside and out.

And that is, of course, why we have so many simulations where they run those sorts of failure cases so that people are able to make these decisions very quickly in real-time.

And that basically saved the Shuttle and the crew from potentially a really bad situation.

Is the orbit burn done by the main engines?

No, they're done by the OMS.

Once the main engines shut down, you've dropped the tank so you don't have any more propellant.

And there have been a few, I think four, engine shutdowns on the pad.

You start the engines about six seconds before T zero.

That gives them enough time to come up to full operating performance so that you can check out that they are OK.

Remember we talked about the twang because of the asymmetric thrust that gives you enough time for the Orbiter to tilt forward and then come back?

And then when you're vertical that is when you fire the engines.

I've got some pictures of this.

At one class I will show you some slow motion pictures of the launch.

You can see all that.

We've had four pad shutdowns.

Of those two were due to real problems with the engine and two were due to instrumentation problems.

It's always a problem of how much instrumentation do you put in and how much do you trust it?

And I know Aaron has made the point, on several occasions, of if you put an abort system in for the crew, is that going to be triggered automatically or does it have to be manual?

You certainly don't want to get shot off the end of a good working rocket just because your sensors have told you that something wrong is happening.

There are a lot of interesting engineering decisions to be made with that.

End of class.

We'll see you on Thursday.

And thanks again to J.R.