Let's see.

The original schedule today had Colonel Gordon Fullerton going to come and talk to us about both cockpit design, but primarily about test flying the Shuttle.

Unfortunately, he is in charge of Flight Operations.

Well, not unfortunately.

He is in charge of Flight Operations at Dryden Flight Research Center for NASA.

Unfortunately for us, since the time that we had agreed on this date, they scheduled, at the beginning of next week, a major base inspection.

And if any of you are connected with the military you know what that involves.

And, since he is head of flight operations, he really has to be there to make sure that they are ready for it.

He has rescheduled.

He will be here in November.

And I will make adjustments to the syllabus.

On Thursday, Bob Ried is going to talk about aerothermodynamics.

And what I thought I would do today is kind of a potpourri maybe doing a little bit of recap on where we've gotten to so far.

And also I brought a few videos just to give you a visual reminder of some of the things that we've been talking about with the Shuttle.

Any sort of general questions about what I handed back to you?

I am happy to meet with teams individually to discuss any specific questions.

OK.

Let's see.

One thing that I -- Hi.

I was just telling the class Gordon Fullerton was supposed to be here, but he has had to postpone to November because they're having a base inspection of flight operations.

So, he is not here.

I had an email from Professor Cohen who will be here.

And let's see if this is -- He had an idea that now that we've kind of started going into details on various subsystems that it might be interesting to work our way through a Shuttle flight and just remind ourselves of the different subsystems that are brought into play at various times during a Shuttle mission.

This is kind of part of the systems integration process.

And remember that we talked at the beginning how in the systems engineering process we always want to keep in mind the eventual operational use of the systems that are being designed.

So, the idea, for instance, would be start at the very beginning.

You're sitting on the pad.

You could even go further than that because remember we talked about how systems had to be developed, for instance, for loading the payload into the cargo bay.

They have that big payload changeout room.

They had to design the hypergolic reaction control and OMS motors in such a way that the pods were actually removable from the Shuttle because they were using hazardous hypergolic fuel and they cannot be serviced in the main hanger.

They have to be taken over to a remote section of the Kennedy Space Center.

And then, of course, the servicing of the tiles.

There is a lot of servicing and maintenance work that has to be done on all the subsystems.

And, ideally, it should be designed in from the beginning.

Of course, in many cases, we got a lot smarter after we started to use the Shuttle.

And, if we were doing it again, which is something that you will be thinking about, we would, in fact, have built certain things into the subsystems which would have made it easier for them to be maintained and repaired.

What I am going to do, just as an experiment here, let's think briefly about these subsystems.

And I've got a little video taking us through the launch and the entry stages.

And then I have one or two other things to show you, which will just illustrate certain other aspects of the Shuttle Mission.

Right at the moment of liftoff, just kind of to set the stage, the final countdown starts at T minus nine minutes.

They typically will have holds built into the count so that particularly when you're going for a very tight launch window, like if you're on a rendezvous mission to the Space Station, you have to launch when the Space Station basically is pretty much going overhead.

And, since the Space Station is in a 51-degree orbit, it takes more energy to get into a 51-degree orbit.

Because normally if you launch from Cape Canaveral, hopefully you understand the orbital dynamics, if you launch due east you get the full speed of the earth's rotation.

And since the latitude of Cape Canaveral is 28 degrees that puts you into an orbit which is inclined 28 degrees to the equator.

That is what we did when we did a rendezvous with the Hubble Telescope which is in 28 degrees.

In fact, I remember my brother was telling me that we launched about 4:00 AM so it was night.

And just about 20 minutes before we launched they saw Hubble fly over and everybody thought that is a good sign, they seem to know what they are doing.

[LAUGHTER] The thing is that when you have an object that is in orbit, and the orbit you can think of as being roughly fixed in inertial space, obviously it precesses a few degrees every day.

But if you think of it as fixed in inertial space on the time scale of a day or so then the earth is turning underneath it.

And you have to launch basically when you are in that orbital plane.

Now, if you have a little bit of extra energy to burn you can launch a little bit earlier or a little bit later and use that extra delta V to change your velocity to get into that plane.

If you're launching to rendezvous with Hubble, say, which is in a 28-degree orbit, you have a bigger launch window than you do if you launch into the Space Station at a 51-degree orbit.

Because, going into a 51-degree orbit, you are using a lot of extra delta V just to change from a 28 to a 51-degree inclination.

So the launch window to rendezvous with the Space Station is very short.

It is only about five minutes.

So in order to make sure that they have the maximum chance of making the launch window, they actually build in some extra large holes, even more so than for a normal launch.

But you pick up the final count at nine minutes.

The Shuttle, at that point, is on external power.

At about seven minutes, the pilot, that is the person sitting on the right-hand side who should be called the copilot, and I've talked about this with a few of you.

None of the astronaut test pilots, you know, these are kind of big ego people.

Nobody wants to be called a copilot.

The person sitting in the right seat is the pilot.

The person sitting in the left seat, who is really the pilot, is called the commander.

The pilot does not fly the Shuttle, except for usually if you have a nice commander he will let the pilot -- when you're pulling away from the Space Station it is kind of a tradition that you give the pilot the stick and let the pilot do a fly around.

And, in the old days, some of the commanders actually gave the pilots a little bit of stick time before landing.

But that generally doesn't happen now.

Anyway, the pilot is in charge of a lot of the subsystems, the main engines, the electrical power system, the auxiliary power units.

It is the pilot who has to throw a switch to put the Shuttle on internal power.

At about eight minutes before a launch you go onto fuel cell power.

Then at about 5.5 minutes before a launch you turn on the auxiliary power unit.

Remember we talked about that subsystem.

That generates the hydraulic pressure to move the flight control surfaces and the main engine bells.

And you will see, if you watch a launch sequence, starting at about three minutes after the auxiliary power unit comes on -- at that point you can sort of feel a little bit of humming in the vehicle when you're sitting in it -- they then move the engine bells back and forth through their entire range just to make sure that the hydraulics are working.

And actually the whole Shuttle shakes when that happens so you can sort of feel that when you're sitting there.

And then, of course, one of the challenges with a cryogenic engine -- and this going to be an interesting development project for the future when they want to have a restartable engine.

Remember these are cryogenic engines and so you have to do a cool down.

And so you start to flow the liquid oxygen and liquid hydrogen through the piping.

Again, inside a minute you can feel kind of a rumbling down below as valves are opening and things are starting to flow.

At 31 seconds the launch control center gives control over to the Shuttle computers.

And the last 31 seconds are controlled entirely by the Shuttle computers.

They look at thousands of data points to make sure that everything is working properly.

At T minus six seconds the engines go through an ignite sequence.

The engine starts are staggered.

And you will see that when you look at the slow motion of the video that I am going to show you.

That reduces the shock on the system.

It only takes a couple of seconds for the engines to come up to full power.

You certainly don't want to commit yourself to lighting the solid boosters unless you are 100% sure that your main engines are firing.

Because if even one main engine is not operating at 100% efficiency you cannot make it to orbit.

In fact, if you have one engine out on the pad, you have to do a return to launch site abort.

We will talk about the details of that whole process at some point.

AUDIENCE QUESTION You can abort launch right up to when the solid -- Once the boosters are lit you are going.

Just hope you're pointed in the right direction because there is no thrust termination on the solids.

And it has happened four times that we have had pad shutdowns.

The engines are monitored.

On two of those occasions it turned out that the problems were instrumentation.

On two occasions it turned out that there were, in fact, real engine problems.

And I would say, for a 50% success rate, you're doing well.

I mean it was the right thing to shut down the engines all those times.

Although, the very first time when they had an engine shutdown on the pad, well first of all, just an acronym is MECO, main engine cutoff, which normally happens about 8.5 minutes after launch.

The comment by Steve Hawley, who was the flight engineer in the center seat when they had -- this was on the fourteenth Shuttle flight -- when they had a pad abort, his comment was, "Somehow I thought we would be a little bit higher at MECO." And it turned out, they didn't realize it at the time, but they actually had a hydrogen fire on the pad.

Remember we talked about how there was a lot of hydrogen.

And, of course, before the engine ignition, we have those sparklers to get rid of the excess hydrogen.

But, in the process of shutting down the engines, there was also a lot of excess hydrogen which got into the engine [UNINTELLIGIBLE].

And the problem is that a hydrogen fire, as you know, is pretty much invisible.

And they didn't have any infrared cameras at the time.

And so basically everybody went around, the crew took their time and everybody went out.

Once they realized it, they put on a water douse.

Now we have infrared cameras.

And, whenever you have an engine shutdown, you have to be very careful that you don't, in fact, have a hydrogen fire.

Coming back to the subsystem, the last stage of the launch, the main engines have gone on.

You have turned on the hydraulic system both for the main engine and the boosters have their own hydraulic systems and the boosters have their own auxiliary power unit.

Guidance navigation and control, of course, is absolutely critical.

Now, first stage is what they call basically open loop guidance.

There is a specific projectory that you are supposed to follow.

Once the solid boosters are off you are following a closed loop guidance which is taking you to a specific point and velocity in time and space and the trajectory is actively adjusted to get there.

Because the solid boosters have so much thrust you don't want to do a lot of sporty maneuvering.

In fact, the biggest challenge from a maneuvering point of view is when you're going through max Q and maximum dynamic pressure and you have to relieve wind shear loads on the aero surfaces.

Basically, when the boosters are firing, from the crew's point of view, it is hands-off.

There is now way that you could take manual control over the boosters.

There is just too much power.

And just a little bit of deviation from your course and you will break up aerodynamically.

It is hands-off.

The fuel cells are generating all of the power.

The guidance, navigation and control is being done inside the Shuttle and the results are sent to the solid boosters.

The gimbals can move.

So the roll maneuver, for instance, is done by the solid engines.

How do the solids gimbal?

The solids can gimbal, yeah.

How do they gimbal?

The same way as the main engines.

I mean they are on a mounting with hydraulic actuators.

And so the actuators expand and contract.

And you can imagine the forces that are involved there because these are 2.5 million pound thrust engines.

It is pretty amazing.

Going through maximum dynamic pressure, SRB separation, main engine cutoff, basically the same systems are working.

The critical things are, of course, the main engine has to be throttleable.

This was a big challenge, as we heard, in making the main engine.

It is throttleable for two reasons.

Going through a maximum dynamic pressure.

And at that point, the solids are also, you know, the way the solid propellant is loaded, the actual cross-sectional profile is such that you don't have a constant thrust profile.

The thrust profile is very high right at liftoff where you need a lot of thrust.

It falls off as you're going through maximum dynamic pressure.

And then it builds up as you burn through the last two minutes of SRB firing.

The Shuttle is pulling about 2.5 Gs at SRB cutoff.

The aerodynamic separation of the solids got a lot of attention.

To have a re-contact would be a disaster, so you have four separation motors, two at the top and two at the bottom which basically push the solid boosters away from the Shuttle.

And, of course, those motors are pointed right at the Shuttle in order to move the boosters

away. It is pretty spectacular when you're inside, especially at night.

They are little solid rocket motors and they are firing right at you so visually it's spectacular.

But it also, unfortunately, leaves kind of a nasty coating on the front windshield most of which luckily gets burned off during reentry.

But the pilots were a little bit concerned that that might hurt their visibility in landing, particularly if you had a bad sun angle.

They always try to consider the sun angle for landing, as well as winds.

After SRBs come off, now you're back to about one G.

You have second-stage guidance, which is closed loop.

You're sensing acceleration and orientation.

Nowadays they often fire the OMS engines for part of liftoff as well just to get a little extra oomph when they're going up to the Space Station, so that's another system which is brought into play during ascent.

Then you get into, after MECO, 8.5, 8.75 minutes.

Now you have to get rid of the external tank and you've got a lot to do basically to power down the main engines.

Remember, you have been burning liquid oxygen, liquid hydrogen.

You've got a tremendous amount of ice which forms in the engine.

I have some pictures to show you of what that looks like when you get into orbit.

Also, you've got thousands of pounds of hydrogen and oxygen left inside the pipes.

And if you just close your valves, eventually that will all vaporize, build up pressure and actually could cause an explosion.

One of the first things that you have to do, when you get into orbit, is to vent the main propulsion system.

Let's see.

Actually, Professor Cohen did not put on RCS here, which is absolutely critical, because you have explosive bolts to separate you from the external tank.

But basically the external tank has no propulsion on its own so you, on the Shuttle, have to fly away from it.

So you use your plus Z.

That is the downward thrusters.

Remember we talked about how the Shuttle has two RCS systems.

It has the primary systems which have about 850 pounds of thrust for each thruster.

And then once you're in orbit and you don't have to do a lot of propulsive maneuvering, then we shut down the primaries and we use the verniers which only have 25 pounds.

That takes a lot less fuel.

But those primary thrusters we use not only the ones in the aft but in the forward so that you have balanced thrust.

If you're trying to move away from the external tank you want to fire the thrusters both in the nose and in the tail so that you move straight up.

Well, we're sitting up in the nose.

And when those thrusters go off, I mean I've never been in a war or a battle, but it strikes me that the sound is what you would get if mortar shells were exploding around you.

I mean it is just a boom.

And right after riding through launch, the first thing that happens is you go weightless.

But then the next thing is you're hearing these explosions all around you.

And it can be quite exciting.

Actually, I will just share a story with you.

On my first flight, they decided to do a special kind of a test.

There are fill and drain valves for the main engine on the side of the Shuttle.

Usually we vent the propulsion out through the engines themselves, but they wanted to look for a quicker way to do it.

Let's see.

This was the sixteenth Shuttle flight, which was my first flight, and they gave us what they call a detailed test objective where right after external tank separation we opened the side fill and drain valve.

And I remember the commander asked some of the guidance and control people is the Shuttle RCS going to be able to compensate for the extra thrust that you get?

They said, yeah, no problem, we've done the calculations and it looks fine.

And this is the reason why you do tests because, in fact, what happened was we came off the tank, opened the fill and drain valve and the Shuttle rolled over 90 degrees and the RCS jets started going like crazy to try to correct us.

They were in a force fight.

After about 15 seconds the pilot said to the commander, do you think I should shut the valve, because the noise was incredible.

Like I say, it was like you were in the middle of a battlefield.

And at that point the commander said, well, it's too late now because we had gotten through most of the disturbance.

And we did recover and got to normal attitude, but it was pretty exciting.

The point is that at that point you are in a transitional state.

Your computers are still in the launch configuration.

You have your primary RCS.

And what you have to do is transform the Shuttle now into an on-orbit configuration.

The Shuttle computers are so ancient.

Has anyone here ever, never mind used an overlay technique, but, even heard of computer overlays?

No, I didn't think so.

Back in the old days when computers had rather small memory and you had to run large programs, what you would do is you would have your entire program, well, originally it was on punch cards and then eventually on magnetic tape.

But you would segment your program and then you would load the first part of your program as much as you could fit into memory.

Run that, save the results, load the second part, transfer the results, run on that and so on.

Well, believe it or not, that's the way the Shuttle computers still operate.

It is an overlay system.

They cannot hold all the software for the entire flight so we have a launch overlay, an ascent, an on-orbit and an entry.

Now, the backup flight system is stripped down.

And so the backup computers hold the software for the entire mission, but there are a lot of things that they don't do that the main computers do.

What you actually have to do is perform what they call a major mode transition, which basically means you punch a few buttons, tell the computers to go into orbit mode and then all the screens go blank.

I mean it is a very kind of a strange feeling.

And you just have to sort of hold your hands and not touch anything for about a minute or so while the tape recorders are spinning down in the guts of the Shuttle and they're loading the stuff onto the Shuttle computers.

Now, I think they upgraded the tape recorders to solid state, I believe.

That's correct, isn't it?

Do you know that?

I don't think they use tape recorders in the Shuttle anymore, but they did, in any case, at the beginning.

I mean just maintaining this computer system has been a big challenge.

And then you get into the orbit configuration.

In the ascent configuration your vernier RCS isn't even enabled.

And inside the ascent configuration, of course, you have not just your nominal ascent but you have all of the launch abort modes or return to launch site, transatlantic abort and abort to orbit or abort once around.

All that gets flushed, and now you are on-orbit.

Your on-orbit software does not give you the ability to do entry and landing.

You are going to have to re-do another overlay or what we call major mode transition before you do that.

Yeah?

[AUDIENCE QUESTION] There are several different landings spots, right?

Right.

[AUDIENCE QUESTION] There is always one picked as a prime, but you have the ability to re-designate depending on where in the ascent you run into a problem.

[AUDIENCE QUESTION] All options are available, but there always is a prime transatlantic abort site which is chosen.

And usually what happens is, I mean there are several transatlantic launch sites, sometimes one or more of them is down because of weather.

And, in fact, if all of them are down, even if the weather is perfect in Florida, you scrub because you need to have an abort site.

OK. I am going to show you a video now.

OK.

I will try to walk you through some of these.

Remember that is the water deluge to stop the shockwave coming back.

Now you have the stage combustion.

These are the OMS engines, the RCS and the main engines.

Remember we talked about the off-angle thrust.

Those are the bolts which hold the solid boosters down.

All eight of them have to fire at exactly the moment of SRB ignition.

If you watch closely, when you see it go up, you can actually see it sort of moving that way, again, because of the off-angle thrust of the main engine.

This is the roll maneuver which puts you -- You go over on your back, headed towards the proper orbit.

And then, as you go through max dynamic pressure and break mach one, you often get those condensation trails.

This is a pilot's eye view now of a Shuttle launch.

This is speeded up by a factor of two.

That was the roll maneuver and the Florida coastline.

And I always thought one of the amazing things was actually how fast the blue sky turns black as you are going up.

SRB separation, you're up at an altitude of about 20 miles.

And you can see up there that very quickly the blue sky of earth is turning into the black of space.

This launch was a high inclination launch so they were actually going into a 58 degree orbit, so they flew literally right up the Eastern seaboard.

AUDIENCE QUESTION It was a SpaceLab mission, I believe, and one of the things they were going to do was observe the earth so they wanted to get into as high an inclination as possible.

Remember when Bass Redd was talking about the aerodynamics of the Shuttle he said that one of the things that they never were able to get quite right was the plume.

And he talked a lot about the angle of the skirt and how that affects the aerodynamics of the plume.

And you can watch how the plume is continually changing as you are getting higher in the atmosphere and you have less and less pressure.

You also notice some of the flames are getting sucked back.

In between the Shuttle and the external tank, of course that is where we had the problems with the foam shutoff, you've got supersonic shockwaves bouncing around.

It is a very, very nasty environment in there.

And you see, when the external tank comes off, often there is a lot of area here which is charred and burned out just because of the shocks.

You can see now that the plumes are tremendously expanded.

The other thing that you can -- Well, I will wait until SRB separation.

As I say, you are up to about 2.5 Gs at this point, and now you can see that the solids are starting to tail off.

You can see a qualitative difference in the flame pattern.

And now you can definitely feel this inside.

You see the separation motors.

The boosters fall off.

And, as you know, they were recovered.

Making sure that the thrust tail-off matches, as we heard, was critical.

Now here is a picture from a belly camera of the boosters falling off.

Now the main engines are firing.

When this happens -- I don't know if you have seen pictures of Saturn launches.

They actually have some of the most beautiful patterns of the reentering plumes.

But the plumes, as you get up into a vacuum, the exhaust plume expands.

And it actually folds back around the vehicle which is not a danger to the vehicle, but visually can be quite spectacular.

On the first night launch of the Shuttle -- During the day the plume is so faint that you really cannot see it from outside the windows.

From the ground you can see the bright points when you're looking right at the tail of the Shuttle but you don't actually see the plumes.

But the second flight engineer who has a good view out the overhead window, about five minutes into launch he asked the pilot, who is in charge of looking after the main propulsion system, is everything OK with the engines?

Yeah, everything is OK.

In about six minutes, everything OK with the engines?

Yeah.

And after they were on-orbit the pilot asked him why did you keep asking me about the engines?

Everything was fine.

Well, apparently the guy had been looking out the overhead window and had seen flames starting to come out which is essentially the expanding plume.

Of course it was the first night launch so nobody had ever seen that on the Shuttle before.

And so you're always looking for something off nominal.

But, as it turned out, it is just normal plume behavior.

Now we've got a few minutes riding on the main engine to build up to orbital velocity.

Essentially, we are flying up the Eastern seaboard.

And it will give you some sense of the acceleration.

Hopefully, you will recognize some of the geography.

When they talk about taking the Shuttle from Washington to Boston or back, this is the real thing.

It takes about 8 minutes, 8.5 minutes, to get from Cape Canaveral to Cape Cod.

There is Long Island coming up.

I heard Plattsburgh, New York was an alternate landing site?

Yeah.

We are really moving at this point.

You're going about five miles a second orbital velocity.

There is Cape Cod.

And now you will see a little bit of a pitch as we separate from the tank.

And here, again, is the belly camera as the tank comes off.

And you can see these little charred patterns in here.

That is where the big piece of foam came off which destroyed the Columbia.

We've talked about, for its orbital operation, it was all the different things that the Shuttle was supposed to do that really drove the design.

Speaking of which, how did things go last Thursday?

Colonel Young gave the lecture on the military.

I haven't had a chance to talk with him yet but hopefully maybe he had some new insights.

I know we talked a lot already about military requirements.

But, in addition to launching large satellites, of course we have repaired satellites, we have done science experiments, we have done a lot of educational activities.

And I am not going to deal with those subsystems so much now.

Remember that the computers now really don't deal with the main propulsion system anymore.

The only thing that you have to be concerned about generally in orbit you still have to maintain thermal control over all of the parts of the Shuttle, so the thermal subsystem is very critical.

We talked about the problems with hydrazine.

If hydrazine freezes and then it expands when it thaws it can break the lines.

Hydrazine leaks are very nasty.

We had one instance on a Shuttle flight where one of the thrusters did develop a leak, and you could just see the exhaust coming out of it until they shut off the isolation valve.

There are several sets of RCS thrusters, each of which is connected to the tanks by a set of isolation valves.

You have essentially triple redundancy in your reaction control system.

And if any one of the systems develops a leak you can isolate individual thrusters to tell them not to fire if it's a leak which only occurs when you fire it, or you can shut down an isolation valve for an entire set of jets.

I won't go into great details but we talked about the importance of redundancy.

And that is one of the ways that it is built in.

Let's see.

What else do we want to say about subsystems during orbit?

What are some of the other subsystems which get called into play for orbital operations?

Environmental subsystems.

Environmental.

Is that controlled by the computer or is that kind of done separate and automated?

A little bit of both.

For instance, pressure valves are mechanical so they will open at a specific pressure mechanically.

If you have an overpressure or you set your, we have different settings.

The normal setting is for sea 0:43:20.526 level atmosphere.

And, of course, you have to balance the oxygen and the nitrogen.

And so there is a fairly complex algorithm.

Well, it is fairly simple, I suppose.

But there is an algorithm which senses both the overall pressure and the oxygen partial pressure so that if your pressure goes down a little bit, the system has to know whether to open up the oxygen valve or the nitrogen valve.

Also, if we are going to be doing extended space walks, and I will be giving a talk on the airlock and the spacesuit and the other systems that get involved in space walks, so I won't go into that in detail here, but we actually have to bring the cabin down to two-thirds of an atmosphere, 10.2 pounds per square inch.

We keep the partial pressure of oxygen at sea level so that raises the oxygen concentration to about 30%.

And the reason we do that is to purge the nitrogen out of our bodies so that you don't get the bends when you go down to the 4 psi, at pure oxygen, which is what we run our suits at.

At that point, we actually have to trick the system because they didn't build in a 10.2

controller. They have a 14.7 psi controller.

But, in any case, that we control manually.

And we basically bring the cabin down to 10.2 psi.

Humidity control, we have the water system.

Of course, we make a lot of water with our fuel cells for the electrical power system.

There are five different water tanks.

One of the tanks is sterilized for drinking.

In the early days they put too much iodine in the water.

In fact, when I came back from my first flight my teeth were totally brown.

The dentist had a fit, and they actually have cut back on that.

And the water is actually reasonably palatable at this point.

You couldn't drink it early on unless you mixed it with Kool-Aid or Tang or something, which is even worse, but that's another story.

The rest of the water tanks, there is just a lot more water than anybody can drink, and so those are called supply water tanks.

And we use that water for cooling.

Remember that is another part of the environmental control system.

We have talked about all of these a little bit.

This is just kind of a review.

Remember that during ascent, once you get above 100,000 feet and during the early time on-orbit, we get rid of excess heat by water boiler.

Now, it is an interesting system, a multi-component system.

Out in the cargo bay we use Freon to bring the heat through the radiators.

First it goes through the radiators, and so once the payload bay doors are open, particularly if you're pointed away from the sun, you can radiate a lot of heat.

After the Freon runs through the radiators, if it is still hot, you can activate the water boilers.

And so if the payload bay doors are closed or if there is some problem with the radiators and you need excess cooling capacity you activate the water spray boilers.

Now the water boilers, if that is your only cooling system, they use water at a rate faster than the fuel cells produce it.

If you cannot get your payload bay doors open -- and that is part of the whole mechanisms, remember, which Henry Pohl talked about -- if you cannot get your payload doors open within a few hours, you have to turn around and come home because you will run out of water.

Now, on the other hand, how do you get the heat out of the crew cabin?

You don't want Freon running around the crew cabin because it is nasty stuff if you develop a leak.

There are actually two ways.

First of all, you circulate the cabin air which gets heated up both by the people and the electronics.

And you run the cabin air through a heat exchanger where it dumps its heat into a cold water loop. And the cold water loop takes cabin heat, and then the cold water loop is also circulated by some of the electronics.

Some of the electronics are air-cooled.

And, of course, there is no density driven thermal convection in weightlessness.

You have to have forced-air convection, so there are fans all over the place blowing air at the electronics and at the crew as well.

And these are all small fans running at very high RPM and so they tend to be very noisy.

In fact, the typical environment in a space cabin is dominated by high-pitched fan noise.

In fact, it gets so bad that in the Russian Mir, we found this once US astronauts starting to fly up there, it was actually causing permanent hearing damage in a lot of crew members.

And people were having to wear earplugs or headphones while they were working near some of the equipment.

From a human factors point of view, to have earplugs in and then somebody tries to call to you from the next module because there is an emergency, that is not a good deal.

Yeah.

[AUDIENCE QUESTION] No.

There are a lot of electrical signals up there because the crew uses wireless headsets, but everything is checked for electromagnetic compatibility.

And, in fact, if you try to fly a payload on the Shuttle or the Station, you have to pass a lot of EMC compatibility testing.

Anyway, the water from the cabin, which is taking the heat both from the air and the electronics, is then taken out of the cabin and passed through a water Freon heat exchanger.

And then the Freon takes the heat further aft where it is dumped into the radiator or the water spray boiler.

Cabin air revitalization.

We re-breathe the air.

It's not like in scuba diving where you take a breath of air and then you just blow it all away.

We cannot afford that so the air is re-breathed, which means you have to scrub out the carbon dioxide.

The Shuttle is not designed for long duration, and so we use lithium hydroxide scrubbers, lithium hydroxide plus carbon dioxide makes lithium carbonate plus water plus heat.

And so those are canisters which have to be replaced twice a day.

And, in fact, the preparation for replacing the lithium hydroxide scrubbers is you have to turn the cabin fans off so you don't get a lot of air going through the cylinders where you put the scrubbers.

For that one minute, you can actually appreciate the peace and quiet of being in orbit.

And then you turn the fans on again and you realize how noisy it is.

Because, after a while, you get used to it and you don't hear the noise until you turn it off.

So, that's air revitalization system.

Humidity separation.

You're pumping out a lot of humidity in your sweat, and that is put through a cooler and essentially a centrifugal, they call it a slinger which gets rid of the water.

And that goes into the wastewater tank, along with urine from the waste collection system.

And that is also dumped overboard.

There are separate dumps for the supply water and the waste water.

And, when the water is dumped overboard, of course up in orbit the pressure is below the triple point of water so liquid water cannot exist.

You either have gaseous water vapor or ice.

And so, as soon as the water comes out the wastewater dump valve, it solidifies.

And you get essentially a snowstorm blowing away from you.

And, if the sun is lighting it up in just the right way, it can be quite spectacular.

If I have time, I will show you a picture of that.

Let's see.

Other on-orbit systems?

Of course, we have the payload systems.

We talked about the remote manipulator, the robotic arm.

Anything else?

[AUDIENCE QUESTION] The crew uses lots of checklists and cue cards.

Typically, the center of the front cockpit has mostly the airplane-type controls which you use for flying the Shuttle.

The systems controls tend to be around the sides.

And then the controls for doing rendezvous and operating payloads are in the aft part of the cockpit.

The forward center cockpit is not used very much when you're on-orbit.

Overhead panels is mostly OMS and RCS.

And then electrical stuff is over the right.

And environmental control is over on the left.

[AUDIENCE QUESTION] Yes.

During the early phases of the rendezvous, when you cannot see anything, typically the commander and the pilot will sit in the front seats.

But once you get close enough to have visual contact, you typically don't approach straight on, you typically approach with your payload bay pointing towards the object you're rendezvousing

with. That way the rendezvous radar can pick it up.

There is a rendezvous radar system, KU band radar, which is on the starboard side.

And there are also star trackers which can pick it up when it is farther away.

And then visually you just look out the overhead windows.

And so you control the final phases of the rendezvous, which we call proximity operations, from the aft flight deck.

And there is a controller stick there.

And, actually, it is interesting.

This is part of the human factors.

Both for controlling the manipulator arm and the Shuttle, there is a switch.

For instance, there is a translational hand controller and a rotational hand controller.

The translational is to make the Orbiter go in plus or minus X, Z or Y.

Normally, you think of the Shuttle, when you push the stick back, you want the Shuttle to go in the direction of the stick.

And so that would be a plus or minus X, which is along the long axis of the Shuttle.

And that is the way the forward controller works.

And you can set the back controller up so that it is just the inverse of the forward controller so, when you push on the stick, the Shuttle goes backwards.

But, when you are actually looking out the window and you see the object -- the Space Station, or Hubble or whatever you're rendezvousing with -- is ahead of you and you want to go towards it, you would like to be able to push the stick.

And so what they've done is, here is the upper window, they have the stick actually at an angle.

Depending on how you set the switch, you can make it so that when you push on that stick it gives you a minus X or you can put it in the Z mode so when you push the stick it gives you a minus Z.

And that is a nice human factor.

They have a similar situation for the manipulator arm.

On the end of the end effector, when you're coming into a grapple fixture, there are actually three wires inside the end effector.

And those actually are moved around like so, so that they tighten up over the little knob.

But there is a camera up here.

And then above the grapple fixture there is kind of a bull's-eye with a little stick on it.

The stick is like this.

And if you're off to the side a little bit you can see by the angle on the stick both how you are in translation and in the attitude of the end effector.

The thing is when you're actually flying the (UNINTELLIGIBLE) and you're looking out the window, I might want to be able to push the translational hand controller and the end effector will move away from me in the cargo bay.

That is called a Shuttle Coordinate Mode.

And they have a nice setup.

Again, this was from a lot of human factor studies.

You can then go into a different mode when you're actually bringing the end effector right up to the docking fixture where you switch over into what they call end-effector mode.

Now, I am actually looking in the television picture and I see this image.

And I want to correct it and I want to move to the side a little bit and go in, but I want to do that in the frame of reference of the end effector.

And so by going into end-effector mode, when I'm working the translational and rotational hand controller, it actually works around that coordinate system.

And there are actually two other coordinate systems for different types of payload operations.

They have done a lot of work in these systems essentially to use computer-assisted modes to make it easier to operate both the robotic and also the Shuttle rendezvous and docking system.

What else do we want to say about on-orbit?

That will probably do it.

Let's take a two-minute break and then we will move ahead to entry.

Enough of a stretch.

Yeah?

Before we leave the on-orbit part, how much of the crews' time was taken up with changing the carbon dioxide scrubbers, dumping wastewater, just the general like you've got to do it to survive stuff versus [UNINTELLIGIBLE]?

Typically one person can take care of most of the on-orbit just maintenance activities.

You have to do things like periodically check your filters.

Every one or two days you have to go through with a vacuum cleaner and clear your filters.

You have to change the lithium hydroxide.

There you want somebody to help to turn off the cabin fans while the person downstairs is changing them out.

Periodically clean the toilet.

Prepare food.

I would say more or less one person around the clock can take care of most of the things that have to get done, if nothing goes wrong.

You kind of alternate between crew members?

Yeah.

Typically, you can have either a one shift or a two shift flight, depending on whether your payload requires 24-hour operations.

And typically the pilot and the commander are considered to be the Orbiter crew, and so they will take care of Orbiter-related things.

And other people concentrate more on the payload or doing space walks or whatever the mission is about.

Everybody is more or less trained to perform maintenance activities so you can share the load, but typically with a crew of six or seven you have the luxury of specialization.

Let's see.

I spoke at length about what goes on during entry so I am not going to go through all that again.

I will just run the video here to remind you.

But do remember, again, before you are ready to do your de-orbit burn once again you have to reconfigure your computer system.

Again, everybody gets in their seats, hands-off because you don't want to throw any switches, and you definitely don't want to touch the computer while it is going through this major mode reconfiguration.

It is sort of like when your computer is booting up, you don't want to mess with anything around.

You just keep your hands off.

Once you are in the de-orbit and entry major mode, that is actually then subdivided into sub-modes where one of the software loads controls your de-orbit burn and then another one is in effect while you are essentially in free fall before you hit the atmosphere.

And then, once you hit the atmosphere, you go through a series of sub-modes depending on your altitude.

And remember we spoke about how the flight control system continually has to upgrade its flight control laws depending on the atmospheric condition, so you need to know your nav.

state.

And then finally it switches into the final approach and landing mode when you go around the heading alignment circle.

That is the final step, which I don't think we talked about.

Remember I pointed out to you that since the Shuttle is a glider that energy management is absolutely critical.

And so you always come in with a little bit more energy than you are going to need because it is easier to bleed the energy off through a series of S turns.

And then they make the transition when you're essentially mach 2 or mach 3 and you are over the landing field, either in Florida or in California.

If this is your landing runway, a regular airplane will typically do a downwind, a base and then come in for a landing.

With the Shuttle, we actually want a much larger pattern to give you more opportunity for energy control.

At about 50,000 feet the Shuttle should be essentially overhead.

And then it makes a big spiral.

And, since you're in this big spiral, you have the option of either making the spiral slightly bigger or slightly smaller in order to control your energy.

If you're a little bit too hot, have too much energy, then you make your spiral a little bit bigger.

If you are a little low on energy you make your spiral smaller.

But by having every landing end in this spiral which you can adjust the radius, but the basic procedure and navigation is not going to change from flight to flight, so that makes the whole training process much easier.

You go into the so-called heading alignment circle and the pilot does have energy displays available so you get predictors.

It tells you where you will be 30 seconds, one minute and 90 seconds in the future.

You get a vertical display showing your energy, a horizontal display.

Unfortunately, and this is something for the people who are looking at displays, the horizontal and the vertical displays are not well integrated.

In the talk that some of you heard on the cockpit electronics upgrade, they had some plans to upgrade that and have a unified landing display.

But at the moment we don't have that.

There is active guidance so that there are guidance needles which you can fly to.

And, of course, the pilots are well enough trained that they are using their out-the-window cues as well to make sure that they get the right visual picture just in case something should be wrong with guidance.

Yeah.

This is a ways back.

How noticeable are the big changes in acceleration during like SRB separation or de-tail?

SRB separation, as I said, right before SRB tail-off, F equals MA and the force is pretty much constant at that point, but the mass is decelerating because you're burning a ton of fuel, over a ton per second.

So the acceleration is increasing.

And you've built up to about 2.5 Gs when the SRBs finally tail-off.

Then you drop down to about one G.

You're sitting in your seat.

This is one G into your chest.

Remember at this point the Shuttle is kind of upside down.

And, since you haven't achieved orbital velocity yet, you still have some weight pulling you out of the seat.

But you are strapped into the seat.

And mostly you feel yourself pulled back into the seat.

And, of course, as your velocity increases and you get closer and closer to orbital velocity then the downward acceleration to the earth essentially matches more and more the acceleration of the Shuttle itself until, by the time you're in orbit, you are in freefall.

MECO is different.

The same thing happens.

The main engines are working at maximum, well, 104% thrust.

We don't take them up to the 109% which is emergency only.

They are working at 104% thrust and your acceleration now starts to pick up.

After about seven minutes you've gotten up to 3 Gs.

And the Shuttle was designed for a 3 G maximum.

They wanted to have smooth, easy right for the payloads.

And they also wanted to make it possible for nonprofessional astronauts to fly on the Shuttle as well, the payload specialist scientists.

The engines start to throttle down in order to hold your acceleration to 3 Gs.

And they throttle down eventually to about 65% right at MECO.

So you are sitting in your seat pulling 3 Gs, eyeballs-in, for the last minute and a half or so.

3 Gs is not particularly comfortable but, on the other hand, any healthy person can tolerate 3 Gs for a minute or two.

It is not a real big deal.

There have been concerns.

If the pilots have to reach some of the overhead switches to reconfigure the OMS or the RCS at 3 Gs, could they actually reach it?

And some of the shorter pilots decided, with the Gs, they probably couldn't.

And so they actually made a special tool, we called it a swizzle stick.

It is an aluminum rod about, I don't know, 80 centimeters long, that has an interface so you can actually use that.

And you have a little mirror if you need it as well so that you can flick the overhead switches when you're pulling Gs.

You cannot ignore human factors in these things when you're designing it.

If you've really got to flip those switches.

And it is not just the problem of being able to reach it.

It's also you have a helmet on.

And, when you're pulling 3 Gs, your helmet which may have weighed 15 pounds now weighs 45 pounds.

And so you really cannot move your head around very much.

And so just being able to pull yourself away from the seat and look up, you cannot do at 3 Gs.

So you do need some assistance there.

In principle, for future designs, I would think taking advantage of the ability to send commands through computers would make a lot of that easier, if your computer is within easy reach.

This was the early days of fly-by-wire and people felt that they really wanted to have a hard switch that they could throw.

But, in fact, in most cases, not all, but in most cases the switches go through the computer system.

And it is possible, in fact, to go into the guts of the computer.

And all the switches tend to be multiple pole.

I am getting into some of the details now, maybe more than ever wanted to know, but just to give you an idea of the levels of redundancy that they have.

Every switch has multiple poles, and it is possible that you can get a little solder ball or a little piece of wire or just one of the pole units that stops working.

You can actually call up that switch on the computer and disable one or more of the poles or you can disable the entire switch and take over computer control of the switch.

Like I say, most of the switches work like that.

Not all of them.

But it is very much a computer-controlled system.

Yeah?

How does the acceleration compare to a de-orbit burn?

De-orbit burn is interesting.

When two OMS engines fire they only produce about a tenth of G acceleration.

However, you have been weightless for a week, a month, six months depending what your mission has been.

And I will tell you, the Shuttle is accelerating forward, although you're actually going backwards.

But internally, the Shuttle is accelerating forward, so everything wants to go aft.

And, in fact, it is kind of fun.

We have done just experiments and taking pictures of it where you can actually pour water at a tenth of a G and watch the water slowly go through an arc into a cup.

And then, of course, you've got to get it closed up before the burn stops.

And you can take a little pencil and push it in the y-axis and watch it gradually curve as you're accelerating.

It is only a tenth of a G but, I will tell you, it feels like you're pressed against the wall if you're not sitting in your seat, just because you haven't been experiencing any acceleration for all that time.

And then it gets a lot worse, as you hit the atmosphere.

By that time hopefully you are sitting in your seat.

It is kind of interesting.

What I tended to like to do is keep a pencil sort of floating in front of me.

And, after a while, you see very slowly the pencil is starting to come down.

And then you would pick it up and then it is coming a little faster.

One of the early things that you realize, you know, if you've seen pictures of people in orbit, you're hands are always floating up here.

The same thing as if you go into a swimming pool, just hold your breath and float under water.

Your natural total relaxed body position is sort of bent over a little bit and your hands are out front.

Try it some time.

It is quite relaxed, quite comfortable.

And it was a strange feeling.

Again, I got used to it after my first entry.

But the first time, when I realized that I was sitting in my seat and my hands were actually in my lap, and that hadn't happened.

I had realized all the time before that your hands were sort of floating out there.

And then I reached for the camera to take a picture out the window of the shockwaves behind the Shuttle, and all of a sudden it has got weight.

It is amazing how the human mind can get used to a very bizarre situation, you know, like weightlessness, such that when you get back it feels strange.

It doesn't stay strange for long.

I mean you grew up in one G and your body has a pretty good memory, so it doesn't take long to get back.

But there are potential vestibular problems.

We have people in the Manned Vehicle Lab who have spent their lifetimes studying some of these phenomena.

A lot of your orientations for up or down come from your inner ear, which have gravity receptors.

Well, those basically don't work very well.

They don't work at all, because the little bone particles inside there are basically floating around.

You don't get the proper feedback, but you still get visual feedback and you get rotational feedback from your inner ear.

And so your body has to essentially reprogram the feedback loops so that you can maintain your sense of orientation.

And that leads to space sickness.

And about roughly two-thirds of people who go up experience some form of space sickness.

It is sort of like seasickness.

Anywhere from mild -- [LOST VIDEO AND AUDIO] [LOST VIDEO AND AUDIO] -- the feeling ofweightlessness.

But launch is really an overwhelming experience with all the vibration and the power and the acceleration and everything.

And I remember thinking to myself at MECO when I started floating, I thought now I'm in an environment that I understand.

Because I had had so many 135 parabolas that the feeling of being weightless was not as overwhelmingly new as it otherwise might have been.

Although, what I realized after about a minute, I was sort of holding onto the seat waiting for the pullout.

That is when I realized, no, wait a minute, no pullout, you're really in orbit.

And that is when I got really excited and sort of floated over to the window.

And I basically couldn't wipe the smile off my face for about seven days.

Yeah?

What about the internal clock?

Do you still have 24-hour days?

Yeah, basically.

The sun rises and sets every 90 minutes.

What we try to do, this wasn't done in the early Shuttle flights, but often you have to launch at odd hours, if you're doing a rendezvous particularly.

For instance, when we launched to repair Hubble, the launch was 4:00 AM because that's when Hubble happened to be flying over.

Now 4:00 AM, typically your body is at about its lowest point in the 24-hour cycle.

You know, your basal metabolism, your temperature.

Not the condition you want to be in when you go through a launch in case there is any problem.

What you want to do is adjust your sleep cycle.

It is very hard to adjust your sleep cycle when you have the sun rising and setting every 90 minutes because you don't get any light feedback, but what we do is, starting a week before a launch, the crew goes into a medical quarantine so that you don't get exposed to any cold germs because you don't want to get sick on-orbit.

And so at that time what they have done is use some medical research over the last 20 years or so which indicates that bright lights, at the right time of day, can actually help your body change to a new time zone.

That's why they say when you fly over to Europe, you fly overnight and you don't usually sleep too much in the airplane.

You land early in the morning.

And a lot of people then want to go to their hotel and go to sleep for a while, but the doctors tell you that is the worst thing to do as far as getting used to the new time zone.

What you really want to do is go stay out in the bright sunlight at a time when your body thinks it should be dark, get the sunlight into your brain.

And that is what we do.

In the quarantine quarters everything is white.

The tables have white butcher paper.

And the walls and the ceiling are white.

And there is essentially wall-to-wall fluorescent lights on the ceiling.

And so it is really bright.

I mean you have to wear sunglasses when you first go in the room.

And it is too bright to watch television or even to use your computer, but it works.

And after about two days you are pretty much accommodated to the new time.

And then, if you want to go out during the day when the sun is out but it is a time when the sun shouldn't be out for the time you are trying to switch to, you have to wear really, really dark sunglasses so you don't get deprogrammed.

The problem is sometimes when you're on-orbit, because of the procession of orbits, you tend to have to re-enter, on a short shuttle flight -- this is different for the Space Station -- but on a short Shuttle flight you typically reenter a few hours earlier than your equivalent launch time.

And that means that you have to often do a sleep shift in orbit.

And that is much more difficult, particularly if you try to shift earlier.

It is relatively easy to stay awake for an extra hour.

I mean everybody likes to lie in bed for an extra hour.

That is easy.

But to go to bed an hour or two hours early it is hard to get to sleep.

And then you have to wake up two hours early, that is difficult.

But that typically is what you have to do.

The medical people have actually imposed maximum shifts both per day, per week and per month for how much the crew can be asked to shift their sleep schedule.

The Russians have another problem when they do space walks because they don't have a full equivalent of a TDRS system, tracking data relay system, like we do.

They like to be doing their space walks when they're making passes over Russia so that they can get ground tracking.

And so often when a Russian crew is preparing for a space walk, they have to shift sometimes by eight hours at a time.

And it can be really tough on a crew to have to do that.

If any of you have worked third shift.

It's not like pulling an all-nighter where the next day you go back onto your normal shift.

To actually stay on a different shift for three or four days at a time can be tough when you don't have any light cues to accommodate you.

Yeah?

Just an observation that all those measures to shift the sleep cycle are obsolete now with the no night launches, right?

As long as there are no night launches that is probably true.

And what that means, of course, is that they can only launch to the Space Station at certain times of the year.

That is the price you pay.

Yeah?

On the launch pad, what is supporting the entire weight of the Orbiter?

And, secondly, if you are on the mid-deck, are there any windows?

And, if not, can you see? I should bring in the launch bolts.

I have a couple in my office.

The entire weight of the Shuttle stack is supported on the two solid rocket boosters, so the bottom skirts of the boosters are actually sitting on the launch pad.

And so on each of the boosters there are four big nuts and bolts, four on each booster.

They are explosive nuts.

And at the moment that the solid rocket boosters ignite, all eight of those nuts are split in half so that the boosters can lift off.

Now, I asked the question what would happen if one of them didn't go.

And the answer was, well, we think that the booster is strong enough that it would just rip it out, but nobody wants to find out.

Obviously, these are redundant explosive bolts or nuts.

They did have, on one flight, they found that one or two of the redundant firing units did not fire.

And that got people's attention.

And I don't know what the final resolution was.

But basically those bolts, you know, if there is wind blowing and the Shuttle is rocking back and forth, all of that load is taken through those bolts.

The structure of the solid boosters has to be able to accommodate that.

You asked me another question as well.

Oh, the mid-deck.

The hatch, where the crew gets in, has a window in it.

Before Challenger, one seat in the mid-deck was right next to the hatch.

My first flight, I actually sat next to the hatch during ascent downstairs but had a great view out the window.

Now, after Challenger, we have an ejection pole, a telescoping pole which is suspended from the ceiling.

I think we talked about this before.

If the Shuttle is in a situation where it is in stable flight but you cannot make it to a runway, at about 40,000 feet you blow the hatch.

The telescoping pole, you release the pin, the pole will extend, and then one by one you clip onto the pole and you jump out.

And the pole takes you below the wing so that you won't hit the Shuttle structure.

And then eventually your parachute will open.

That now takes up the area over by the window and the three seats no longer have a view.

If you're sitting on the mid-deck how during a launch, how do you know what is going on...?

[UNINTELLIGIBLE] You hear the comm.

loop.

And if you have a nice commander he will tell you.

For instance, if you have a rookie astronaut onboard, they want to know when they go through 100 kilometers because that means you have officially been in space and you can get your astronaut wings.

So, if the commander is nice, he will call 100 clicks on the way up and congratulate the new rookies.

But basically that is about it.

And the same for entry, you don't have a view.

There are still plenty of physiological things to keep your attention, so it is not like it is a boring ride, but you don't have the view.

OK.

Let me run the entry picture here.

OK.

OMS engine ignition is when you see that big flame pattern.

During the burn you don't see anything.

Now, looking out the front, you see the plasma sheath.

It goes from a dull red gradually to orange and then eventually white hot.

You can only see this at night.

It is fairly faint, but typically a lot of flights you land during the early part of the day on the ground.

And, of course, you do your burn halfway around the world so the early part of your entry is very often at night and then you fly into the day.

And then I think there is another shot looking out the aft window where you actually see the plasma wake in the back of the Shuttle.

And you can see this is the old-fashioned computer screen.

That is the wake looking out the overhead window.

And, where these converge, that little point there they say is about 10,000 degrees Fahrenheit, which is the surface temperature of the sun.

It is remarkably stable, although every once in a while you get those instabilities.

And every once in a while you get big bright things go flying past, which I assume are gap fillers coming out.

And I remember I would always think to myself I hope that is nothing important.

You're basically riding on a meteorite because it is supposed to make it all the way down to the earth.

But that is essentially what you are seeing, that trail behind you.

And I am sure you have all seen these landings.

Remember all the talk about the landing gear and the brakes.

I looked for a video from my first flight to show you the blowout.

I couldn't find one, but if I find one I will bring it in and show you another time.

This is a landing out at Edwards.

Have you ever landed at night?

I have landed at night.

I was going to show you one other.

It doesn't have a landing light, does it?

No.

Do they light up the runway?

Yeah.

They have two banks of xenon lights which light up the runway for you.

Actually, this next video is from my last flight where we deployed the tethered satellite.

I am not going to show you all that stuff, but I wanted to show you the launch sequence because we have a few pictures showing the opening of the payload bay doors.

And then you can actually see back to the aft end of the Shuttle where you have the main engine.

And remember I talked about how the hydrogen and oxygen have now combined into water and that forms ice.

And so for the first day or so on-orbit there are just constant ice particles coming out of the engines, and you are surrounded by this cloud of ice.

Unfortunately the pictures are black and white because it is low-light level TV, but visually it is spectacular because these little ice particles glint in the sunlight.

And they are rotating so they go through all the different colors of the spectrum and you are surrounded by this.

You will also see one of the RCS jets firing.

Water deluge.

Main engine sequence.

Again, you see the whole tilt.

When it gets back to vertical we take off.

This is a much shorter sequence here for the launch than the last one.

How does it roll?

The SRB boosters go like that.

Is it the entire stack or just the lower...?

No, it is just the nozzle at the bottom.

This was Columbia.

You can always tell Columbia because, if you look at the vertical stabilizer up here, that is an infrared pod.

I will talk about that in a minute.

The payload bay doors open right away.

And so now you can see, when we've done the engine vent, you can see all the ice particles coming out.

And you will see a primary RCS thruster go in there.

It can be pretty spectacular.

And that just keeps going for about a day and then you've gotten rid of most of the ice particles.

OK.

That is enough of that.

Yeah?

[AUDIENCE QUESTION] That was a primary RCS thruster.

[AUDIENCE QUESTION] Yeah, absolutely.

In fact, all of the vernier thrusters are downward thrusting only.

Remember we talked about with the primary thrusters, they were designed and sized for rendezvous where you actually have to have controlled propulsion.

And if you want a Z propulsion of the Shuttle, you want to be able to get a pure Z so you fire thrusters on each end.

And the same for roll and yaw.

And you don't want a lot of cross-coupling because you're targeting your burn to fractions of a foot per second in order to get your rendezvous to come out right.

And so that is when you're using the primary thrusters.

Other than that, the primaries use a lot of propellant.

And so we disable the primaries and use the verniers.

With the verniers there are two verniers in the nose which are sort of canted down at about 45 degrees.

And, in the rear, there are two pointing straight down and two pointing straight out.

Typically, for a given maneuver, you will fire only one or two.

If you want to do a roll, for instance, you will fire the 45-degree down forward thruster and the downward pointing aft thruster.

But they are not completely balanced so you will get a little bit of pitch and a little bit of yaw.

And you don't use the verniers for propulsion at all.

Although, because all of the verniers are essentially downward firing, if you are, for instance, station keeping, if here is the Space Station and you're in the same orbit but, say, half a mile in front of it, now you're station keeping using your vernier thrusters, typically that does give you, after a while, a little bit of propulsive maneuver which pushes you in.

So, you have to compensate for that.

The verniers are single string.

There is no redundancy.

They do have access-to-access cross-coupling.

They are designed for attitude control only; 25 pound thrusters are reasonably efficient.

I thought at the end we could explore a little bit together some of the ideas of improvements to the Shuttle which you are going to be thinking about.

And one of the things that I thought would be interesting to think about, you know we talked about the fact that if you're designing the Shuttle to the same set of requirements that were originally put on it, your ability to change some of the major physical characteristics of the Shuttle are very limited.

We can do a lot with electronics and some of the other systems.

The new vehicle, the crew exploration vehicle, is being designed not just to go to earth orbit but they want a vehicle that can actually return to the earth from the moon or from mars.

That means instead of an orbital velocity of five miles per second you have a reentry velocity, a hyperbolic velocity, of about eight miles per second.

Does anybody remember the relationship between low orbital velocity and escape velocity?

If your lower velocity is V, what is your escape velocity?

Square root of 2V.

That is a nice thing to remember.

It is an easy way to keep those things straight.

First of all, you don't need wings to go to the moon.

They don't do you much good when you get there.

To have a winged vehicle that you can thermally protect against a hyperbolic reentry velocity just doesn't make sense.

It would be too heavy.

We don't think we can do that.

And, in fact, the Russians are now talking about building this new clipper vehicle which possibly will have wings on it or be a lifting body.

And that actually probably means that they will only use it for low earth orbit.

But it does bring up the interesting question, if you are designing a vehicle that is only designed to go to earth orbit as a passenger carrying vehicle, one of the first things that we ought to ask ourselves, if we're doing a new design, is should we have wings?

Think a little bit about the advantages and disadvantages of wings.

If you're sitting down now with a blank drawing board going through a design process, first of all, what are the advantages of wings?

You've heard quite a bit about Shuttle aerodynamics.

What advantages do you get from using wings during a reentry?

And, obviously, it's only during entry that the wings are going to help you because they are a real nuisance during ascent.

Greater cross-range?

Cross-range helps with the wings.

The glide?

Yeah, it allows you to land on a runway.

In terms of having to design against the shock, you know, the Crew Exploration Vehicle is going to land with parachutes.

And they still don't know are they going to use airbags or retrorockets or crushable structure or whatever.

They don't know.

But it is going to take a much harder hit.

That may potentially affect reusability, maintainability.

Yeah?

I was going to say just purely control while coming back in ...

[UNINTELLIGIBLE PHRASE].

Well, we had the cross-range.

But targeting I guess, too?

Targeting.

If you were to land, say, in a certain part of the desert in New Mexico, you would want to have a lot more accuracy?

Right.

For the CEV, they are just basically saying they are going to land out in the Western desert somewhere.

Now, the Apollo shots were getting pretty accurate.

The last couple of Apollos landed within visual range of the aircraft carrier that went to pick them up, so they were getting pretty good.

But that's within a couple of miles, which is fine when you're landing in the ocean.

And maybe it's OK if you're landing in the Western desert.

It is certainly not OK if you're going to land on a runway.

Hardly an engineering consideration, but how much thought in the design was put into making it a winged vehicle for it to be a comfortable and familiar look to people, especially if the idea was to have nonprofessional astronauts fly?

It seems more comfortable to get in something that looks like an airplane?

I don't know about comfort from that point of view, but there is no question that the whole aviation metaphor dominated discussion in the early days.

And I think you have gotten a sense of this.

The idea was we want a reusable vehicle.

That means we have to have airline-type operations.

Well, if you're going to have airline-type operations then you want a vehicle that lands on the runway.

You take it into the hangar.

You turn it around.

You launch it again.

I mean it's a very powerful metaphor.

What are some of the disadvantages of wings?

What are some of the things that argue against wings?

Again, we're going right back to the conceptual design exercise here.

And this is not what you're doing for your papers because we're totally changing the concept of the Shuttle.

But, for the purpose of the class, let's think it through.

What are the disadvantages of wings?

I think a lot of what we talked about is initial design cost versus, you know, and no wings obviously has a lot less initial design cost because you don't have to design the structure to support the wings and it is a lot simpler design, I think.

So, that probably saves you money in your initial development.

[AUDIENCE COMMENT] Now, on the other hand, I don't know how much any of you have studied the theory of reentry bodies, but the reentry of a ballistic capsule typically gives you much higher Gs than you can get if you have a lifting body.

And, of course, with wings you get much more lift.

You can actually decrease the G loading so that with the Shuttle we can have a reentry pulling no more than about 1.5 Gs.

Whereas, you come back in a capsule even from low earth orbit and you're going to be pulling 4, 5, 6 Gs.

And that does relate back to the idea that we wanted the Shuttle to be able to take much more delicate payloads and hopefully take people who were not necessarily trained astronauts.

So, again, it's an advantage but a disadvantage of wings.

The area under the wings is huge, so that puts huge demands on your thermal protection system.

I don't know what they're going to end up using on the CEV, but it is going to be a much smaller area that has to be protected.

Another interesting thing, when you think about a winged vehicle like the Shuttle, now I know that Buran, the Russian Shuttle, made its one flight unmanned.

They had some tense moments at the end, but they did manage to land it successfully.

But the way we fly our Shuttle, we have to have two trained pilots who spend a tremendous amount of time doing nothing but learning how to land the Shuttle.

Sometimes we don't think about the crew requirements on the design, but training is not an insignificant part of the cost of operating the Shuttle.

There is a huge enterprise involved in training astronauts.

And training pilots particularly is very expensive.

You have to keep them qualified as pilots so NASA maintains a fleet of T38 supersonic jets, which are great fun.

I mean I love to fly backseat in them.

But the only justification for having them is if somebody is going to be a pilot they have got to stay current as a pilot which means you have got to fly.

And we have the Shuttle Training Aircraft which I have spoken to you about.

And we have all the simulator time.

And then we have the problem that people said -- there was a time when they were talking about having the Shuttle spend extended periods of time up at the Space Station, you know, a month, maybe two months, make some adjustments to the Shuttle System so you can do that.

Then the problem is, well, who is going to land the Shuttle, because I talked to you about the spatial disorientation and everything that you feel during reentry.

Well, you don't want a pilot to do that.

And, if a pilot has been up in the Space Station for one or two months, has not had any stick time, is going to have potentially serious neurovestibular problems during entry.

And so the real question was what's the maximum time that it is OK for a pilot to spend in

space? We will never actually have to answer that because 17 or 18 days was the maximum Shuttle Mission.

That turned out to be OK.

And we are never going to do long duration missions with the Shuttle and the Space Station.

Yeah?

[AUDIENCE QUESTION] No.

They learn a lot of the malfunction procedures, but you don't actually fly the ballistic capsule.

I mean I am not in any sense denigrating the training that the Apollo astronauts needed to land their capsule, but it did not compare in the least to the amount of training, for instance, to land on the moon where you were actually piloting the vehicle.

OK.

Well, I hope just that very brief exploration will make you think about designing new vehicles from a slightly different point of view.

In other words, when we designed the Shuttle, it was just assumed as gospel essentially that if you want a reusable vehicle put wings on it.

I don't know what the right answer is.

It probably depends on some of the details of the mission, but you really have to go back and question your most basic assumptions.

When you're doing your concepts and you're setting out your requirements, you don't want to write your requirements in such a way that they presuppose the technical solution.

If you write your requirements for a winged vehicle you have already shut down a whole part of designed space.

And, as designers, you don't want to do that.

Yeah?

Last question.

[AUDIENCE QUESTION] No.

The Russians have actually taken, my understanding is, they have taken some of the electronics out of capsules and reused internal parts.

But the exterior shell of the capsules I don't believe have ever been reused.

OK.

We will see you Thursday.

Bob Ried is going to give a talk on aerothermodynamics.

And I will look forward to seeing your journals.

Any questions on the reports, the outlines that I returned, email me, come to see me.

I am happy to talk with you about it.