Let's get started.

Again, just putting things in perspective, Professor Cohen talked about how in a big engineering design project you work through the various stages.

And the first stage is phase A where you come up with the basic concepts.

And I think the level of detail of the system and subsystem lectures that he is giving, last lecture and today, we could sort of look at as being on kind of the phase A level to show the basic feasibility and the overall structure.

Those of you from aero-astro have certainly been familiar with our approach to systems engineering which we call CDIO.

Someone from aero-astro can tell me the C is conceive, design, implement, which actually means manufacture and test, and operate.

So we're kind of dealing in these first few lectures.

And this could be looked at as phase A and then the detailed design, that's your phase B.

That ends with the critical design review after which, in principle, you're supposed to be ready to cut hardware.

And then you get into the phase CD where you actually build and test.

And then, of course, we operate.

My sort of background, the way I got into engineering, and I probably should have mentioned this at the beginning as sort of truth in advertising is I was never trained as an engineer, unlike Professor Cohen.

I was actually trained as an astrophysicist.

But, when I went to NASA, I spent so much time working with all the technical systems and interacting with the engineers and the people who use them that I learned certainly a lot about the way these systems are designed and particularly operated.

So my approach to a lot of these engineering situations is very much from an operator's point of view.

And I will try to emphasize that as we go along.

Very important, right from the beginning of the design, I think that you think about how you're going to operate the system.

We have had too many examples that I've come across and many people who have to actually operate systems where you build something without really thinking of how the system is going to be maintained and taken care of.

One of the things that we have been doing for the last few years is to take a group of undergraduates down to the Kennedy Space Center every January, an interim activities period, and have them spend a couple of weeks with the engineers and technicians who have to maintain and operate the shuttle system.

And they hear lots of stories from the engineers and particularly from the technicians who say, boy, I would like to have a chance to talk to the person who designed this little system.

And I have to get my hand all the way around.

And it takes five hours to turn the bolt or something more fundamental.

And we will probably discuss this when we talk about the main engines.

The fact that originally the main engines were supposed to be reusable without being taken out of the shuttle so that you could cycle them many times.

Well, it turns out that in order to get sufficient confidence that the engines are ready to fly, we really do have to take them out after every flight.

And they are extensively borescoped when you look inside.

But some of the engineers in the main engine shop pointed out that, for instance, if certain diagnostic test equipment had been built into the engine so that you could have taken data as the engines were shutting down over and above the data that we actually get, possibly we would have been able to reduce considerably the maintenance on those engines.

Again, the shuttle was the first time we had really tried to design reusability into a space vehicle and engines.

And we've learned an awful lot.

So I think it's very important when we discuss the systems in the course of the term that we don't just look at the detailed design but we also consider the operations.

That's very important.

In that spirit, Professor Cohen is going to continue his introduction to the shuttle systems.

And, Aaron, I will turn it over to you.

OK.

Thank you.

As Professor Hoffman said, I'm really giving you what I would call a technical management overview because, when we talk about structures, on the 22nd Mr.

Moser is going to come and talk about structures and he's really going to go into the details, how the loads were calculated, how the stressors were calculated, how NASTRAN was used, how we came up with the basic structure.

But I'm just going to really give you sort of an overview on it.

And I think it's interesting to note that the structures may be a very good system to look at for your project because it weighs a lot.

We certainly didn't have all the tools for calculations that you have today to make it a more efficient structure.

The materials are a lot different.

But basically this structure, if you start at the front of it, the crew cabin, which I showed you a little bit about being made, a welded configuration, and the forward fuselage are basically an aluminum skin-stringer structure, very basic aluminum.

If you go back down to the mid-fuselage, which is the large part there, it's, again, a skinned structure.

Interestingly enough, the forward fuselage and the crew cabin where made by Rockwell International in Downey.

The mid-fuselage was made by General Dynamics in San Diego.

So we had various people putting the structure parts together.

The wings were made by Grumman.

So we had this vehicle being built all over the country coming to Palmdale, California for assembly.

And the aft thrust structure was built by Rockwell.

The vertical tail, I believe, was built by Fairchild on Long Island.

Some of these places don't exist anymore.

But then you go back to the vertical tail.

Again, it is machined skins with honeycomb.

The aft fuselage, as you can see, is very complicated.

It has all the plumbing, all the wiring, all the auxiliary power unit, so it is a maze of plumbing and wiring.

You could get lost in there and they'd never find you again.

But it is a maze of wiring and plumbing.

And it's made basically of aluminum.

But a lot of the support structure are boron/aluminum thrust structure panels with graphite epoxy skin panels.

And then the payload bay doors, which was our innovative material going into large composites, we use graphite epoxy, that was the first time that really a large composite structure was used in a vehicle.

Now it's used quite commonly in the Air Force and a lot of places, but graphite epoxy were the panels we used.

And that saved a lot of weight.

One of the problems we had, though, was when we built these panels we found we got moisture trapped in it.

And, of course, the moisture, when you heat it up coming back it would pop the panels off.

So, on the pad, we had to go in and drill little holes in these panels to be sure we could get the moisture to escape.

So those are things you learn when you do new technologies.

But, as I said, Mr.

Moser is going to go through a very detailed explanation of this.

This may be something you want to consider because there could be a real innovative way of reducing the weight and making the vehicle more robust, so I suggest you think about that for the structure.

Now I'm going to talk a little bit about guidance, navigation and control.

And some people asked me yesterday where they could find some information on it.

Actually, in those orange or yellow books, I've forgotten what color they are, that we showed you that are on-hold in the library, have a very detailed analysis and discussion of how the guidance, navigation and control system was formulated.

And it is probably as good as you're going to find.

It was very early in the program.

It's a little bit different than it is today, but it's a very good description of the redundant computer set, the fail-operational, fail-safe system.

So I think you could really get a lot out of going through that book.

I should just say it turns out that we have two sets of those books in the library and they are on reserve so you can only use them for two hours at a time.

There really should not be any problem with everybody in the class having access to those books when you need to go and look at them.

That will probably be the best source, except when Phil Hattis from the Draper Labs comes and talks about the guidance system.

I will talk a little bit more about that.

This chart or this schematic or whatever you want to call it was originated by the Johnson Space Center and Rockwell International.

It took us many hours but it basically is the architecture, I am going to go through it in some detail, for the guidance, navigation and control system.

Now, this was the original one.

It is a little bit different today, and I will explain the differences that we have, but this was basically the guidance, navigation and control system main architecture.

And you can see on the left side, and the left side is what I would call sensors.

First of all, in a very simplistic term, some of your experts in guidance, navigation and control, but guidance, navigation and control, navigation is actually determining where you are, guidance is getting to where you want to go and control is controlling the vehicle and its stability and its characteristics around the center of gravity.

So that's basically control.

This is for the total guidance, navigation and control system.

Interestingly enough, the contractor for this was IBM Federal Systems Division.

We used their computer and they did the software.

Much of the hardware was designed and built by other contractors, and Rockwell International basically did the integration.

And they did the integration on a system called the Shuttle Avionics Integration Laboratory.

It was basically a vehicle that was in the laboratory that had all the electronics, the cockpit and everything in it.

It simulated the actuators.

The hydraulic system was simulated and the engines were simulated, but basically all the hardware and software was in the Shuttle Avionics Integration Laboratory.

I imagine you spent some time.

We actually had two.

We had one in Houston and there was one out at Rockwell.

And, when Professor Cohen says that it was a vehicle, you have to appreciate that it was actually laid out just like the shuttle so that they had the controllers, which were in the aft end, like in the engine compartment, were a hundred feet away from the crew cabin and the computers and all the lines, the data and power lines were laid out as closely as possible to physically duplicate the layout in the shuttle because there was concern about the timing of signals going back and forth.

And they wanted to run the simulation as accurately as possible.

And then, of course, you have to have a set of simulation computers to try to determine the environment that the shuttle would be flying in so that it could make the inputs to the rate gyros and the other parts of the measurement units to try to duplicate the flight regime.

And here is an explanation of the alphabet soup of all the systems, subsystems, components.

On this side you see really the sensors.

That's the information that you need to do your navigation part of it.

And then, of course, that information then is sent to the computer through a multiplexer demultiplexer, MDM, which basically is an analog to digital converter, digital to analog converter.

The computer does its computations and then sends it to the effectors which actually change, whether it's the RCS, reaction control system, whether it's the orbital maneuvering system, whether it's the aerosurfaces, the SRB actuators, the solid rocket booster actuators, the main propulsion system actuators.

So you've got sensors, computation and effectors.

Let me talk a little bit about one sensor which probably many of you can relate to, and that's the IMU or the inertial measurement unit.

And Draper Labs is famous for its inertial measurement units.

I worked with Draper Labs or MIT Instrumentation Lab on Apollo, and we had the original initial measurement developed by the MIT Instrumentation Lab in that vehicle.

The initial measurement unit has gyros on it to determine angles and it has accelerometers on it.

And it is aligned with the star tracker.

It's basically a stable platform.

It's aligned with the star tracker to get a reference system in inertial space.

And when you make a maneuver you get acceleration and you send it to the computer.

And you integrate it once, you get velocity and you integrate it twice and you get position.

And it's also used during powered flight and it's used during entry but that then goes to the computer.

So the inertial measurement unit is very critical.

Just to give you an example, here you have three of them and you have four computers.

I'm going to talk about the computers in a minute.

You have three of them.

You have to recognize when we went to the moon on Apollo we had one IMU and one computer in the Command and Service Module, and we had one IMU and one computer in the Lunar Module, except we did have a backup system called a strap-down system.

The primary system was built by Draper Labs, MIT, and the backup system was TRW.

So we had two different contractors.

Then you have rate gyros and accelerometer assemblies primarily for ascent, for the stability of the bending of the vehicle.

Here's the air data transducers that we talked about yesterday for entry.

Then you have the microwave landing system, the tactical navigation, radar altimeter, rendezvous radar.

These are all sensors you use during various phases of a mission, which again go through the MDMs or multiplexer demultiplexers to the computers and then to the effectors which change your position and velocity as need be.

Let me talk about the computers for a moment.

You see four computers.

That was the real test of this system.

We had four computers that were synchronized.

This vehicle, as we talked about yesterday, for aerodynamicists we decided to make it statically unstable.

We saved a lot of weight.

By that I mean a regular airplane, a normal airplane that's stable.

When you get a disturbance it will still come back.

Without any augmentation it will come back to its original position.

With this vehicle, if you get a disturbance it will diverge.

So you had to continually have augmentation.

So you had to have a fail-operational, fail-safe system.

And that's why you have four computers.

It's fail -operationa/ fail-safe You could lose one computer and your fail-operational will use another computer.

That means you have two left.

And you're fail-safe and you come home.

So that's what it is.

Now, the real concern about it is these computers are synchronized.

They essentially communicate with each other 440 times a second.

Now, I'm recalling a lot of this from memory, but 440 times a second.

And they actually vote on each other to simplistic form terminology.

And if one computer is out, it votes it out and another computer takes over.

Basically that's it.

But the concern we had was that in doing this we could have a generic failure and lose all computers or we could have what we call a two on two split.

And these would be sort of diabolical errors which would cause the vehicle to fail.

So we decided, after this was made, to put in a backup flight system, a backup computer, a fifth computer.

Now, it turns out there was an argument there.

Should we have the fifth computer a different computer and different people or should we have a same computer with different people?

And we argued long and hard on how to do it.

And we had a lot of experience with the Draper Labs.

The Draper Labs just did an outstanding job.

The MIT Instrumentation Lab just did an outstanding job on the Apollo vehicle, both on the Command and Service module and Lunar module.

We went to the MIT Instrumentation Lab, Draper Labs, and asked them to actually take the same computer but put it outside the loop.

It's not part of the redundant set.

It's outside the loop.

I didn't show the schematic right because it gets all the same information that the other computers get, but it then can take over if the primary system fails.

Now, Phil Hattis did this work for the Draper Labs, for NASA in this backup system.

He's going to give you a lecture.

He's very good to lecture on this total system.

He can tell you about the total system.

We thought we'd put the backup flight system in just for a short period of time to give us confidence in the primary system, but it turns out that we started putting things in it that now we needed so we could not take it out.

So, it's really part of the major system.

That is a very different part of the system today.

I don't think we ever really had a diabolical problem in flight.

I think we did have one in the Shuttle Avionics Integration Laboratory one time when we had a two on two split.

But when we did the approach and landing test where we had the Orbiter on top of the 747 and we separated the Orbiter and landed, I remember that first flight, I was sitting in the Control Station at Edwards Air Force Base, and at that time I smoked a pipe, and when we separated a big X came across the screen because we lost the first computer.

I guess the shock actually broke a solder joint in the computer.

The power shock from separating actually broke the first computer so we had to go to the second computer.

I bit my pipe in two.

But it did prove that the redundant set did work because it took over and landed.

We had a very successful in-flight test, not planned, but it turned out to be a very successful in-flight test.

Now, when you make the computations, you get the information on position that the computer computes, it sends it to the effectors.

The effectors, during the high part of entry, may be to the reaction control system, the forward RCS system or to the aft, or it could be to the OMS systems if you're trying to make a maneuver.

Or, when you get down lower in the atmosphere, it could be the aerosurface actuators.

And then, during ascent, it's to the solid rocket boosters or the main propulsion system.

So, those are the effectors.

The flight control system is a very interesting system for entry because, as you can envision early in the entry you don't have any aerodynamics so your aerosurfaces aren't of any value to you, you use the reaction control system.

But, as you get farther into the atmosphere, the loads become so high that the reaction control system becomes ineffective and then you have to use the aerosurfaces.

So it's a blended system.

And the system has to know when to handle the aerosurfaces versus the reaction control system.

And, of course, then you also have displays to the crew and actually information that the crew could use to make certain decisions.

So that basically is the guidance, navigation and control system.

There is one additional change, that I don't have on this chart, which they have incorporated the global positioning system in the shuttle.

The GPS is now part of the system.

It took a long time to do it because I remember it wasn't done when I left.

And were you still there when it was implemented?

Yeah, they did put it in.

And GPS you can essentially get position.

If you could get attitude then theoretically you could eliminate the inertial measurement.

And I don't think they do it that way.

But theoretically, the GPS, for you looking at the guidance system change, this again becomes a very interesting system to look at.

Would you do it different today?

For example, the computer that was used, I cannot remember all the characteristics of it, but it's basically the IBM 4 Pi computer, which is a very old computer.

It was probably made before many of you were using computers.

Or, weren't born.

[OVERLAPPING VOICES] which I think was a design from the early `70s.

Yeah, it is the early `70s.

This would be a very neat system to take a look at for your system.

Not only that, you could probably get a lot of support from Draper Labs and that type of thing.

So it would really be a good system to take a look at.

And I'm sure you could make a lot of improvements.

Those improvements could theoretically be used on the new CEV, the crew exploration vehicle.

I think it would land a lot of merit of you very smart people to take a look at the guidance, navigation and control system.

Yes, sir.

In the air data transducers, were there more than just torpedo tubes and static cords?

That's all there was, I believe.

I think that was.

We had a lot of problems with those.

I think it's just very old technology.

Yes.

I was going to ask, how you got position information before GPS.

Position?

Well, I don't know exactly.

But it's got 13 satellites going around.

Well, there were two ways.

I mean the desire for GPS, of course, was to give the shuttle autonomous navigation capability.

The shuttle with the star trackers and the IMUs, it has the autonomous ability to determine its attitude, but it doesn't know where it is because the inertial measurement units drift over time.

And so you need to be able to update the state vectors.

Originally, the only way you could do it was radar tracking from the ground.

You would track it.

You would get a state vector.

You would uplink the state vector and then the shuttle would know where it was.

And then periodically you would have to update it because of IMU drift.

Once we got the tracking and data relay satellite system installed, you do get navigational information by the Doppler navigation and from the signals coming back and forth through TDRSS, but it was generally calculated on the ground.

So it was not really until the advent of GPS that we got autonomous capability.

You need it for things like if you're going to deploy a satellite, for instance, you need to know your position pretty accurately.

Because the satellite is going to take that position and has to do its burn accordingly.

And, obviously, for your reentry burn or for rendezvous it's critical that you know your position.

When you're doing a rendezvous, the shuttle does have a rendezvous radar.

I don't know if we'll deal with that in detail.

Once you get close enough to the object that you're rendezvousing with such that you can get it either with your radar, or they actually use the star trackers to optically track the object, then you can start getting your relative position with respect to the object, Even though you may not know your absolute position.

And so, from that point of view, the shuttle gets a certain degree of autonomy.

Maybe I'll just say one other thing about the computers because people are amazed at how primitive the shuttle computers are.

But, like I say, the original idea and the concepts that we talked about, this was going to be an airplane-like vehicle.

And originally they wanted to use some off-the-shelf hardware.

And, of course, the AP-101s, as they finally used them, were not off the shelf.

But these original computers had 128k of memory.

And the memory they used, I don't know if any of you have read back in the history of computing where they actually had the little magnetic ring cores with the wires going through.

I mean this was really old stuff.

And they did finally replace that with a solid-state memory with a whopping 256k.

And, again, probably none of you have dealt with overlay technology but, back when I was a graduate student and we were using computers to do complex astrophysical calculations, sometimes you would have a program that was too big for the computer memory so you would have the whole program on a tape recorder and you'd segment it into what they would call overlays.

And then you would load it one part at a time and it would do its calculations.

And then you would stop and load the next batch of software.

Well, that's the way we have to run a mission.

The computers cannot hold enough software to do ascent, orbit and entry.

There are three segments of flight software.

You start the mission with the ascent software loaded.

Then, when you get up into orbit, you do what they call a major mode transition where you basically punch a button and everything goes blank.

And you sort of sit there saying I hope this is going to load properly.

And the tape recorder chugs away.

And then it loads the orbit part.

And the same thing when you're getting ready for entry.

Now, the backup system they decided that they didn't want to take that risk.

That if something went wrong in a major way they wanted the whole flight software on the backup system.

And that meant it had to be scrubbed.

The backup system is capable of flying the shuttle and getting it home safely, but there are a lot of capabilities which the main computer system can do which the backup system cannot do just because they're limited to the amount of software.

The one other thing I'll say is putting together this redundant set of four computers because, as Professor Cohen said, the shuttle will not fly without the computers.

I mean it's absolutely flight critical.

Hundreds of times a second, every computer is looking at the data from all the other computers.

And they are all voting.

And so you have this matrix, just to make sure you understand the way the system works.

If computer number one sees a problem with computer number three, it's likely that computer three is also going to see a problem with computer one because they're doing something different.

But if computer number two sees a problem with computer three and computer three sees a problem with computer two and computer four sees a problem with computer three, now you've got a three to one vote.

And so computer three will recognize that it is the problem and it will take itself out of the set.

And that's what happened, well, in that case, the computer actually shut down.

I remember that big X.

I bit my pipe in two.

And, at the same time, all of this information has to go back and forth to the backup computer.

Because, if you're ever going to engage the backup computer, it has to be ready to go at a split second's notice.

And there are situations where you can get a two on two split.

When we run through the simulations to learn how to work this, actually learning the ins and outs of how to work the computer system is probably one of the biggest trainings.

The astronauts become more knowledgeable than the designers.

Yes?

If there is this danger of a two to two vote, was it ever thought about to have five computers then?

Well, that's why we put the backup system in.

Oh, the backup system.

Yeah, the backup system.

That was why we put the backup system in.

It did a little bit more, too.

It was programmed by different people.

Even though it used the same computer, it was actually programmed and formulated by different people.

So, that was one way of saying take away any, you might say, systematic errors that were in the redundant set.

In other words, they kept the same software requirements document but the actual coding was done by Draper rather than by IBM.

That was the other problem.

Suppose all four computers are doing the same thing but there was an error in the code which never turned out so that something starts to diverge, what's your protection against that?

There was a big argument in doing that.

The real argument said should you really have this or a different computer?

Should you really just say just do everything differently?

Just have a different computer?

A different everything?

And, of course, there are advantages to that and there are disadvantages to that.

So, we settled on this.

I think there was another question.

Was there a question back there?

Yes?

You said this was the first fly-by-wire system.

I was wondering what competing ideas there were besides having [four computer systems?].

Well, fly-by-wire means when you put an input into the control system, whether you do it manually or whether the computer does it, nevertheless, ultimately your command just goes into the computer.

You put the stick to the left saying I want to do a left bank, all you're doing is telling the computer you want to do a left bank.

And now the computer has to figure out what's my navigation state, where am I if I'm coming down through the atmosphere, what's my altitude, what's the air pressure, what's my mach number?

And then it's programmed with aerodynamic control laws.

This is one of the big challenges.

Because, as I mentioned the other day, you hit the top of the atmosphere at mach 25, you do your initial control with the RCS.

As the dynamic pressure starts to increase, first the ailerons, the roll becomes active at about, I think, ten pounds per square inch, something like that.

You blend the roll control into your aerosurfaces.

At about 20, I think it's pounds per square inch, you can do the pitch control.

But because the shuttle is coming in at a 40 degree angle, the vertical stabilizer is pretty much shadowed.

So for yaw control you actually have to keep using the RCS all the way down to about mach one when the shuttle finally pitches down and the vertical stabilizer now has some effectivity.

The computer calculates all this information and it comes to the effectors, and you do the control laws on that.

And the problem is that the flight control laws, which the computer has to use in order to control the air surfaces in the RCS, are not constant on your way down.

I mean the flight control laws at mach 15 are very different from at mach 5.

And there is part of the flight regime, for instance, where if you want do a left bank, you actually have to start by commanding a right yaw.

And then the cross-coupling terms in the aerodynamics actually causes you to go in the other direction.

It gets very complex.

And the flight control system is continually changing as the entry progresses.

And so the idea that maybe you should have a direct backup link between the pilot's inputs and the aerocontrol surfaces, although it might give you a warm, fuzzy feeling, you could not fly the shuttle directly.

Because to be able to take into account these change in control laws on the way down, you just cannot do it.

In fact, the shuttle is uniquely, I mean, unless the shuttle knows where it is, if the navigation state goes bad the shuttle cannot fly.

You could have the runway in sight, but if the shuttle's inertial nav state is wrong you will lose control and you cannot land.

So it's a very complex system from that point of view.

This is a very, very, if you can envision the systems engineering that went into this system, it takes aeordynamics, it takes flight dynamics, it takes electrical signals, it takes guidance laws, navigation laws, hardware, software.

This is probably the biggest integration job, or systems engineering job.

It requires everything.

It also has to take into consideration aerodynamic heating.

I'm going to show you that in a minute, because you've got to be sure that you don't fly outside the regime that you were designed for aerodynamically.

I think you had a question.

Just real quick, how big are those IMUs?

Because nowadays you can get a solid-state one not quite that big.

Well, I don't recall.

It's a box, sort of like a shoebox.

The Apollo IMU was about this big.

That was built for the Polaris vehicle.

It was one IMU and it was a three gimble platform.

And I remember it was a big issue.

A three gimble platform has a singularity, so you had to maneuver the Apollo vehicle a certain way so you didn't get the singularity in it.

And one of our astronauts, Jim McDivitt, quite a famous astronaut who was a good friend of mine, said he wanted a fourth gimble.

And there was no way we could get an IMU in that day in time with a fourth gimble.

So, what I did was gave him a fourth gimble to carry with him on his flight.

A little gimble system so he had a fourth gimble.

We didn't have the gimble lock problem on the shuttle because it was a four gimble platform.

But I remember we went through that with MIT Instrumentation many times because all you could get at that time, because the IMUs were so big, a fourth gimble was almost impossible.

And McDivitt was a very good astronaut but he wanted the four gimbles.

In fact, he wound up being my boss.

Before we go on, let me just mention one more thing about the backup system.

Sure.

Go ahead.

The backup system actually takes a lot of care and maintenance and there's a lot of money that goes into that.

And this is not a dead issue because in the design of the CEV, NASA is going to have to make a decision.

There were some guidelines which were produced a couple of years ago out of the Johnson Space Center with a lot of astronaut office input about what are the requirements in the future for human space vehicles?

And they put in that you should have a backup computer system because basically that's the way we did the shuttle.

And, actually, that was an afterthought.

And yet now it's being listed as a requirement.

And this is now being questioned for the CEV because it's a huge financial impact.

And so we're going to have to deal with these problems all over again.

It's an interesting thing to think about if some of you want to delve a little bit more deeply.

I think this could lead to a very interesting activity for you.

Yes, sir.

Do backup computers have their own sensor or are they reading the same sensors?

The same sensors.

I just didn't show this very accurately because I looked at the chart, when I had it, I said my God this is the wrong chart.

But this was the original chart before the backup system so I quickly penciled in the backup system so I would remember to talk about it.

But, no, it has the same sensors.

It has all the same information.

But, again, most of those sensors are redundant.

Yeah, they're redundant sensors.

Not all of them but most of them.

Any one of the four computers can read any of these sensors.

It's not like sensor one is dedicated [to this computer?].

The sensor input is put on a data bus, and they have multiple data buses.

Like four data buses in each of the computers can read all four data buses.

I mean there's just a tremendous amount of redundancy built in.

Yes, go ahead.

Did they ever use the star tracker to update your gyros?

The platform?

Yeah, they do that.

There is also a procedure if you totally lose attitude.

Then you have to go right back and manually take a star site and orient.

And that we've only had to do in a simulator.

To look at the failure history of this would be very interesting.

In my tenure, I know we lost one inertial measurement unit.

We lost that one computer during the approach and landing test.

I don't know what other failures we actually had in this system.

The MDMs, this box was made by Sperry at the time in Phoenix, Arizona.

And I've visited that many times because that is probably the most complicated electronics box of this whole system other than the computer.

It's very, very complicated.

Yes, sir.

Computers have developed a lot faster so why do you still think that it will be a major expense now?

I don't think it will be a major expense now.

As I recall, and you're absolutely right, NASA does not put a lot of money into development of this technology because other people have done it.

It's so much more sophisticated than we have now.

We don't need it.

It turns out, though, at one point in time structures was the most expensive component of a space craft.

Then, of course, there was propulsion.

And then there became avionics and software.

And avionics and software for the shuttle is very, very expensive.

It's probably one of the most expensive things.

I think today, in today's environment, with the technology we have in both software and hardware, I think it won't be that expensive anymore.

So, I think you're right.

That's why I'm saying in redoing it, you could use new technology and really show how much less it's going to weigh because the IMUs are probably going to be smaller.

You could reduce the weight, you could reduce the electric power and you could reduce the cost.

But you're going to have another detailed briefing on this.

And Phil Hattis, I know him very well, I think he will do an outstanding job in explaining it to you.

Let me just show you very briefly, we talked a little bit about this yesterday, but here are some of the profiles that the guidance system has to be able to do.

It certainly has to take care of launch.

The abort modes, which are interesting, there is an abort mode that is a return to launch site.

And I guess you would use return to launch site primarily for a main engine failure, I guess.

If the main engine fails during ascent, you can go to a return to launch site.

Or, a total loss of cabin pressurization, something like that.

And I guess that's never been tried.

And I guess that's probably one of the most difficult maneuvers, most biggest fears the astronauts have if they ever have to come back to return to launch site.

But, of course, the guidance system has got to be capable to take care of that.

Then you have abort once around.

Again, when you have main engine cutoff, you have separation and you abort to once around.

Again, I guess that's primarily a main engine problem.

And then you have, of course, an abort to orbit.

And those are the three abort regimes you have.

Yes, sir. Transatlantic landing? Transatlantic. Yes, you have transatlantic abort.

That's right.

You do have transatlantic abort.

Yes, thank you.

That actually drives the launch window, because [if they don't have clear weather overseas they don't launch?] .

That's right.

So, the guidance system has to take care of all those abort modes.

Again, I'm sure Phil will go through this with you.

But first stage guidance really consists of attitude and throttle schedules as a function of relative velocity.

It's not completely open-loop, it's almost an open-looped system, but you do control the thrust vectors of the engine and the solid rocket booster actuators.

And the key thing, though, where systems engineering comes into play, it has to get maximum performance.

But the angle tack history has got to be shaped to control aerodynamic loads.

Because some of the highest loads you have, and you will find out when Moser talks about it, some of the highest loads you have on the structure is during ascent.

Control of maximum dynamic pressure.

And you have to provide the flight angle at SRB staging to allow recovery of the spent boosters.

These are some of the constraints that you have.

And, again, this comes out to be a real systems engineering problem.

And for entry, entry really becomes a task in itself because one of the basic problems you have to control is thermal control.

The thermal protection system, I should have pointed out on that structural slide that the back face temperature of the tiles have to be at 350 degrees Fahrenheit.

While the surface temperature may be 15 to 2000 degrees Fahrenheit the back face has to be at 350 degrees Fahrenheit because that's the limit of aluminum, so you've got to control the guidance.

The thermal control for guidance is to keep the vehicle within the temperature constraints in the peak heating region.

So, that's all got to be married together so that the tile system you design keeps the back face temperature to within 350 degrees on the aluminum structure.

Then you go into equilibrium glide.

Constant bank angle, we were talking about, is modulated for drag control.

And then the transition guides the vehicle from the high out braking to the lower angle of attack.

And then you basically land.

All this has to be tied together for your guidance, navigation and control system.

I have one more system that I'd like to talk about briefly.

Now, you're going to have another very detailed briefing on this.

This is the hydraulic system.

This ties in together with the other systems we talked about, the flight control system, the guidance system, the Department of Flight Control, because the hydraulic system is three systems.

It's a 3000 pound per square inch system.

And what does it do?

It basically is used during ascent and entry for it to control the thrust vector control of the engines, for the body flap, for the elevons, for the rudder speed brake, the actuators for the main engine, the doors for the external tank separation, main landing gear, nose wheel steering and braking.

So, that's what the hydraulic system does.

If you lose your hydraulic system you had a bad day.

And there are three systems.

I do believe there is one place where there's a single point failure in the hydraulic system.

It's pretty hard to eliminate all single point phase.

I believe that.

When Henry Pohl talks, he's going to be doing a very detailed discussion on the hydraulic system, you might ask him that.

I don't recall, but he'll tell you whether there is a single point failure in the hydraulic system.

And this is a schematic of the hydraulic system.

I am not going to go through the details of it because I'm not sure I could explain it.

But basically this is the hydraulic system that shows how system one, system two and system three is tied into the right outboard elevon, the right inboard elevon and so forth and so on.

The main engines.

The external tank.

And we've never had a loss in the hydraulic system.

We did test the hydraulic system in what we call the flight control hydraulics laboratory at Downey where we had actually all the hydraulic systems tied together with the computer system.

And actually flew the vehicle, what we called this iron bird, with a hydraulic system.

And we did have a failure there one time.

Early in the program, we had a single point failure and lost all the hydraulic fluid.

We had to go back and make a major change to the actuator system, to the hydraulic system.

Yes, sir.

I'm just wondering how the hydraulic system on the shuttle compares to the hydraulic system on an aircraft?

An airplane.

Yeah.

I'm really not sure I can explain it.

I think there's not much difference.

Let me tell you the only difference.

I think airplanes have three hydraulic systems.

The shuttle started out with four hydraulic systems.

We actually started out with four, but it was so heavy and so complicated we decided to go to three.

And I think the airplanes have three hydraulic systems, if I'm not mistaken.

Does anybody know?

I at least know quite a few that have three.

I don't know if all airplanes have three.

The big difference in it is that the hydraulic system in the shuttle is powered by what we call an auxiliary power unit.

And that's what pressurizes the system.

And I think on an airplane it's powered by the engine itself.

But this system is pressurized by what we call an auxiliary power unit.

An auxiliary power unit is a box about this big.

It generates 135 horsepower.

And it's got a ten inch turbine wheel that goes about 10,000 to 20,000 RPM.

And actually it's fueled by hydrazine.

And it essentially pressurizes the system to get you up to 3000 PSI.

Again, if this auxiliary power unit doesn't work, we have three of them, it's a bad day.

And I think we did have some problems with one of the auxiliary power units at one time during ascent.

But that's the major difference, I think, because I think we tried to copy pretty much aircraft designs using the same type of hydraulic fluid and everything else.

So I think we copied their standard in using this, as I recall, except we're pressurized by the auxiliary power unit.

Again, not to belabor the point, you're going to have a very detailed briefing or lecture on the hydraulic system, the auxiliary power unit and the reaction control system, the OMS system by Henry Pohl.

So, you will have more details on this.

Again, the hydraulic system might be another interesting thing to take a look at.

I hope what I'm trying to get across to you is how these systems all fit together.

You cannot do the guidance, navigation and control without the hydraulic system.

You have the aerodynamics and you have the aerothermodynamics.

You've got the structures and everything that has to fit together.

And you can imagine the systems engineering problem associated with trying to put all that together.

Just to remind you of a few other things that you have to deal with.

When you're working with a space system that also makes it a little bit different from designing for the ground.

For instance, you have a fuel tank with the hydrazine inert.

This is a generic problem with any liquid tank.

Once you're in weightlessness, how do you get the liquid to flow out?

This is actually a fairly traditional old-fashioned design where they have a diaphragm in the tank.

And, on one side of the diaphragm, you pressurize it with either helium or nitrogen.

And that pushes the material.

It's basically sort of like squeezing it out of a bag.

The problem is that hydrazine is nasty stuff.

And in the orbiter maneuvering and reaction control systems they decided that, for reusability, they didn't want to use diaphragms.

And so we'll probably learn more about some of the details.

But there's a very elaborate screen mechanism which uses surface tension to collect the material.

And just getting liquids out of a tank into where you want to go is something you have to worry about in space.

The second problem is a thermal problem.

You're not flying through the atmosphere so you don't have air cooling.

As you see, you've got the gear box.

You're generating a lot of heat.

And, actually, in order to cool, they use water spray boilers.

And you essentially, we actually do this to get rid of heat from the orbiter as well before we open the payload bay doors which have radiators.

While those are closed, it has to be done with a water spray boiler.

And so you get rid of all your heat by putting it into a heat exchanger.

And you basically shoot liquid water.

And, of course, in a vacuum the water flash evaporates and that takes the heat away.

And so, although in essence the control system is similar to airplanes, even there, there are a lot of special design features that have to be put in because this is a system that has to work in space as well.

That's a very good point.

The cooling is one of the biggest differences.

And because this system is so complex and heavy and needs a lot of maintenance and uses hydrazine, which is very nasty stuff, there have been, on various occasions, studies of could this system be replaced by an electromechanical system?

And as motors become more powerful and battery and fuel cell systems are more efficient, I think just about two years ago we gave up on the last effort, but it always turned out to be too heavy.

To get an electromechanical system which had enough muscle to move these air surfaces around, it is just beyond what we can do.

But that might be another good system to take a look at today.

It might be another good system.

The other thing.

You see where it has a speed control and safety for the APU controller?

The interesting thing about this turbine wheel, I forget the exact RPM, but it's pretty high.

I think it's at least 10,000 to 20,000 RPM.

If this shaft should break off, it's a very hard to control it in the box.

I mean it will go right through the box it's in and share the vehicle.

We've tried everything we know.

We've put protection around it.

We've put a lot of margin into the turbine wheel, into the shaft, but that's a very critical thing.

And, as Professor Hoffman mentioned, there have been many exercises to replace the auxiliary power unit.

And I think again this would be another good challenge to take a look at seeing what you could do to come up with a different design for the auxiliary power unit.

But there will be other systems that you might want to look at.

But I thought I'd just give you a little discussion of some that I personally think are very pertinent to look at.

That's the thermal protection system, the structures, the guidance, navigation and control, the hydraulic system, including the APU.

And these, I think, would be a very good system.

Now, you might pick others, but these might be very good ones to look at.

Let me wind up my discussion by talking to you about what I think you ought to look for in the system.

This is just a very simplistic chart, but this is my way of thinking about what you do when you go about designing something.

You need to look at the functions.

As we pointed out yesterday, the functions are very important because, when we talked about a thermal protection system , we looked at the functions of protecting the vehicle, maintaining that back surface temperature to 350 degrees Fahrenheit.

We worked that to finite detail.

We knew exactly how thick the tiles had to be, what the characteristics had to be, but what did we?

We forgot, oddly enough, that it had to be attached to the vehicle, which is sort of dumb.

And you would think, my gosh, they ought to be able to do that.

But you're infinitely smarter after you find out your problem.

One thing you ought to do is really understand what functions have to be performed.

And you might say that becomes your functional requirements.

The whole thing is understanding your requirements.

Then you ought to understand what performance is required.

In other words, performance requirements.

You ought to have a first order of magnitude calculation of what kind of performance requirements you need.

A lot of times this is going to have come from assumptions, talking to people, getting experts involved.

But what kind of performance requirements?

It is going to have to be iterated, but what kind of performance are you thinking about in this system?

Whatever the system may be, hydraulic system, thermal protection system, whatever.

Then we talk about the three-legged stool, as Professor Hoffman said.

We talk about schedule, cost and output weight under performance.

Because, as I told you before, the first thing you're going to wind up, in designing a system, is that the weight is going to get too high.

Then you're going to find out that performance goes down.

You have schedule slips.

But the first thing that usually happens is you wake up in the morning and you find out, my gosh, my system weighs a lot more, my subsystem weighs a lot more than they told me I could have.

So, you've got to understand your weight.

And then you need to think about what is the available technology?

What is the technology available?

As somebody pointed out, today the avionics technology is probably pretty high up on the ladder.

And you could probably pick something today right off the shelf.

Although, in my experience of the 30 years I had in the space program, I never was able to find something that was off the shelf.

Space programs just don't usually allow you to take something off the shelf.

People told me to go do it.

And, once I went and did it, we changed everything.

But today, in the technology we have in the avionics, you may be able to get a lot off the shelf.

So, what technology is available?

And then one of the key things, one of the biggest things you have to know is what are the interfaces?

If you could see the multitude of interfaces that are required for the guidance, navigation and control system, it takes into consideration all the interfaces you could think about.

And so you need to think about interfaces, whether they be mechanical, whether they be electrical, whether they be functional.

So, you need to think about what interfaces you're talking about.

And, to me, those are some guidelines you need to think about.

Of course then we talk about cost and schedule.

Usually your cost is going to grow, unfortunately, and usually your schedule is going to slip.

And those are, what I would call, career limiting problems.

That's the best way to get fired, to have your costs go up and you schedule increase.

So, these are some of my guidelines for things you ought to look for when you try to design your system.

I would be happy to answer any questions for you that you may have.

Yes, sir.

About taking technology off the shelf, I'm wondering, and I don't think, from what I know, it was really thought of much during the shuttle, but the idea of maybe putting something on the shelf, so to speak, the idea of designing something, a subsystem or something so it would have the flexibility to be used in future systems.

Do you see where I'm going?

No, I don't think I quite follow what you're saying.

Try again.

Well, you said there wasn't really off the shelf technology available then but maybe there is now.

The idea I'm thinking about is the idea of designing something not so much just for the shuttle in this phase, but so that it could be used for other things.

Well, that's a very possible thing to do and would be a very good thing to do.

In my experience, and we tried something like that, usually this tends to start growing into it.

You start saying, well, what is it really going to cost you to do that?

I know, when I was project manager, people would come to me with something like that.

And I used to be a pretty mean guy.

I'm not quite as mean as I used to be.

But that's the first thing I'd ask them, what about the cost, because that's what happens.

When you start trying to make multiple uses out of something, you usually drive the cost

up. And that's what you have to be careful of.

Yes, sir.

[UNINTELLIGIBLE PHRASE] Well, let me add to that.

I feel very strongly that had it not been for the MIT Instrumentation Lab or the Draper Lab or the people they had there, the technology they had there, we wouldn't have gone to the moon when we said we were going to doing it.

I mean I worked very closely with them, and I feel very strongly that Draper Labs, I keep getting them mixed up, at that time the MIT Instrumentation Lab was really one of the prime movers of the whole system.

It was really fantastic.

So the people working here, and you can take advantage of that, would be very useful for you to do that.

Any other questions?

Well, I will be back on the 22nd.

And I look forward to working with you some more.

One more question.

Sorry.

Yes.

It has not as much to do with the subsystems but to the overall concept of the shuttle.

I was wondering why, if you know at all, the military thought it was important to have the ability to capture a satellite and bring it back?

Was it because satellites were so expensive at the time and maybe they aren't as much?

Because I don't think we've really done that.

Well, it really wasn't the military.

Several satellites we did bring back.

I cannot recall which ones.

Westar and Palapa.

I have pictures of that a little later.

And we retrieved those.

And it turns out, interestingly enough, they were insured by Lloyds of London.

And that was the biggest salvage operation Lloyds of London ever achieved when they returned those satellites, bigger than anything in the ocean they ever picked up.

In fact, they rang the bell.

When they have a big recovery, a big thing in Lloyds of London they ring a bell.

And they came down to serve somebody, whoever he was, I don't recall who he was, but he was head of Lloyds of London.

And we had a big reception at the Johnson Space Center after we retrieved Westar and Palapa.

I don't think the Air Force really had that much demand at the time, or it went away, whatever it was, for retrieving payloads, but commercials did.

What the military was interested in was the possibility of refueling satellites in orbit.

That's right.

We did do that.

Because when you have recognizant satellites, very often you have to change their orbit to get them over to the right place at the right time.

And orbital maneuvering fuel is a limiting commodity on satellites.

And these are very expensive satellites to build.

So if you have the possibility of refueling then, in principle, you could extend the life of these very high value assets.

And we did do a demonstration.

Of course, the fuel, in most cases, is hydrazine which is very nasty stuff.

If you get it on your spacesuit you cannot come inside until you bake it off.

It's fairly dangerous.

And so we actually did do a demonstration just in the shuttle's cargo bay, but we've never actually done a real refueling of a satellite in orbit.

But they're still working on it.

Now I think the military is still working on possibly robotic refuelling technologies.

For whatever the next version of the shuttle or crew vehicle would be, is it necessary or even a good idea to have this huge cargo bay?

Well, I think that's what they're eliminating.

I haven't been that close to it.

But the CEV is going to be really a passenger carrier.

And then any cargo will be on an unmanned vehicle, I believe.

So, that's what they're separating.

Is that right?

I mean I haven't really been that close to it.

This is one of the guidelines now for future space vehicles, is to the maximum extent possible separate humans and cargo.

If the original concept of the shuttle had been realizable that the shuttle would be capable of flying frequently enough that it could basically satisfy all of our launch needs then you can make the argument, well, all right, we're doing this and people are in it to fly it and we'll just do it that way.

But given the fact that we cannot fulfill that goal then you have to ask why put humans at risk just to take a satellite up in the cargo bay and launch it when we can launch satellites using unmanned vehicles?

And, in fact, that was the decision after the Challenger accident, was any payloads that are carried into space on the shuttle in general, I mean there were some exceptions for various reasons, but you ought to be using the shuttle to do things where you need people to do them.

And some of those things, for instance, to service in the Hubble or the assembly of the space station, although even that could be argued that, had we planned it differently, we might have been able to do it without making such extensive use of the shuttle.

But there we do make full use of the big cargo bay.

But future human space vehicles, the CEV will be basically a people carrier with a small amount of cargo.

And any time you want to launch large amounts of cargo you will do it without people.

Let's take a one or two-minute break.

I'm going to get my computer set up.

Let me put this down here.

I want to give you a short presentation just to bring everybody up to a certain level of familiarity with what the shuttle does and what it looks like.

And, again, I tend to look at this from an operational point of view.

This will be informal, you know, ask questions as we go through.

As we've said, the two critical phases of shuttle operations and what makes this such a unique vehicle is it launches vertically like a spaceship with a tremendous amount of power.

And it lands.

You look at this, and you have to remind yourself that it looks like an airplane landing and, yet, a half an hour ago this was a spaceship going in orbit around the earth.

So it really has been a spectacular technological achievement.

Let's go through some of the maintenance operations, what is actually done to the shuttle.

We've talked about it a little bit, but I think if you actually see some of the images it will help to give some reality to some of this.

After the shuttle lands, here it's landing on the runway at the Kennedy Space Center.

And, as we mentioned, all of this is a bird sanctuary so sometimes you have to chase the birds away.

And there's a problem from time to time with crosswinds.

There is only one runway so, if you get wind blowing across the runway at more than 15 knots, you cannot land.

And so that's also a constraint sometimes to launch because when you take off you always have to be able to turn around and come back and land here, just like you have to be able to land over in Europe or Africa.

And so there are a lot of launch constraints.

What they do is, this was actually hooked up back on the runway, but they hook up air conditioning units.

They have to purge.

There's an ammonia boiler.

Remember we talked about getting rid of heat as you're coming in using water spray boilers.

But, once you get below 100,000 feet, the pressure is actually above the triple point of water and you cannot flash evaporate anymore.

And so they switch from a water boiler to an ammonia boiler.

And so, after the shuttle lands, there are ammonia fumes all over the place.

If you've looked at pictures of shuttle servicing on the runway, sometimes if there isn't actually wind blowing they bring around a big fan to blow the ammonia way.

And everybody has to stay upwind of the ammonia.

And there is also the possibility, of course, that there might be a hydrazine leak or who knows.

Anyway, the orbiter has to be safe.

And you have the people come out in what looks like space suits.

Escape suits they call them.

Self-contained, I don't remember the acronym.

But, in any case, we're bringing the orbiter back to the hanger area where it will undergo a lot more than 14 days of servicing.

I remember, again, just to give you a sense of the state of mind before we were actually operating the shuttle, as a new astronaut back in 1978.

Remember the shuttle didn't fly until '81.

We were getting a series of lectures on all the shuttle systems.

And I remember the lecture they gave us on turnaround, which was supposed to take 14 days.

And we got a briefing from the people who were planning the turnaround.

And I remember they told us we've studied this really carefully, and we just don't think it's going to be possible to turn the shuttle around in 14 days.

We've cut out every unnecessary step and we think it's impossible to do it in less than 16 days.

[LAUGHTER] And that's kind of the way people were thinking.

We were talking about it's supposed to make 60 flights a year, and people were skeptical.

There is no way they can make more than 40 flights a year.

People just didn't have a concept of how complex it was going to be to operate this vehicle because it is such a complex vehicle.

To operate it safety is difficult.

Now sometimes it lands in California.

And, in that case, you put it on the 747.

This is the same bipod fitting, just to essentially duplicate the way that the orbiter is put on the external tank, and the tail pod is, of course, for aerodynamics.

And that was also the configuration for the approach and landing tests.

And, actually, later, I think, in the middle of October, Gordon Fullerton who was one of NASA's premier test pilots, he still flies, I mean I'll have to find out from him how many different types of airplanes he's flow, he's just an amazing guy, but he was actually in the shuttle during that first approach and landing test.

So he can tell us about what it was actually like test flying the shuttle, as well as being on the third orbital flight test.

Yes?

Were they carrying anything on the airplane?

You mean inside here?

Yeah.

No, this is not your opportunity for a transcontinental vacation trip.

[LAUGHTER] I mean there are a few people who ride along with it because you need the maintenance people.

They also have an airplane flying about 50 miles in front of this checking for turbulence.

And, in the early days, they had a chase airplane as well.

I told people they were crazy trying to get them to do this because I thought it was the dumbest thing I heard of.

[LAUGHTER] OK.

Now a look at some of the details.

Remember we talked about how the engines are taken out?

You get a little bit of a view here inside the engine compartment.

I had the chance, on numerous occasions, to actually go inside the engine compartment.

I mean it's just amazing.

You get these huge big pipes.

And it really helps when you're going to be using a system like this.

We spent a lot of time in the simulators.

And you'll flip a switch, and that switch controls what they call the main fuel shutoff valve.

It's a big butterfly valve about 17 inches in diameter inside this huge pipe.

And you sit in the simulator and you flick the switch and the talk back shows that the thing is closed.

And then you actually go in the compartment and you look and there's this huge pipe and this area.

And you realize this huge thing that's moving around.

And it kind of gives a sense of realism.

And, in fact, that's one of the big safety concerns.

When the fuel is flowing, the butterfly valve is in a vertical position so the fuel flips by it.

Obviously, it's an unstable situation.

If it goes out just a little bit then the fuel flow can slam it closed and you've got an explosion on your hands.

So that was a major consideration.

This is the body flap.

So, you can see all of the plumbing.

And all these red things are removed before flight, stickers.

It's a very, very complex process.

And they pull the engines out after every flight now.

That's the thing, all of the platforms have to be designed so that they fold up and they fold down so that you can get access to all the places.

I mean it's a very complex system.

And a lot of the equipment, the launch platforms and everything, as we mentioned, were adapted from the Apollo program.

But the hangers, which we call the OPF, the orbiter processing facility was built specifically for the shuttle.

The tiles we talked about.

I mean that's just a huge amount of work replacing, maintaining and testing the tiles.

This is inside the cargo bay.

You've got the fuel cells.

You've got hydrogen and oxygen cryogenic tanks.

Helium pressurization tanks.

Nitrogen for your atmospheric system.

This is the bulkhead in front of which on one side you have the engine compartment.

On the other side you have the crew compartment.

And, like we mentioned, this has to be done essentially in clean-room conditions and yet it's on the scale of a battleship.

So, it's a real challenge.

This is the forward window.

On maybe one in every five flights we'll get a little ding on the windshield from a little piece of usually orbital debris.

In fact, more often than not, it turns out to be little paint chips.

Whenever they do that they remove the window, they replace it and do a chemical analysis to see whether it was a micrometeorite or a piece of space debris.

The windows, actually there are three panes.

There's a redundant pressure pane.

The two panes on the inside are capable of holding pressure and the outer is a thermal pane.

This is one of the orbital maneuvering system pods.

These are removable because, again, they contain nitrogen tetroxide and hydrazine.

And we mentioned the fact that these are called hypergolic fuels.

When you bring them together they ignite spontaneously, as opposed to hydrogen and oxygen you need a spark igniter.

So, in that one sense, it's a nice system because when you want to use them in your reaction control and you only want a very tiny tenth of a second pulse, you don't have to worry about an igniter which is a potential failure point.

You just squirt in the hydrazine and the nitrogen tetroxide.

But they're very nasty stuff.

They are extremely toxic and, of course, highly combustible and they are very corrosive.

So, these pods are serviced in a place far away from where the other activities take place for the orbiter so just in case there is a leak or an explosion it's not going to take down the rest of the critical facilities.

This is the orbiter maneuvering engine, and then they also have these smaller reaction control engines.

And there are two aft pods.

And all the fuel tanks with the hydrazine and nitrogen tetroxide are in here.

The aft system, the two pods, they actually have inner connects so that you can actually cross-feed from one system to the other.

And all of that stuff has to be hooked up.

The forward system is independent.

You cannot cross-feed to that.

The landing gears.

We talked a little bit the other day about the tires.

These things sit up in space for two weeks at a time.

You've got to worry about thermal control.

I mean can you imagine if you had a slow leak and you found out that your tire was flat before you started your reentry?

And then, of course, the problem of sealing this against the hot gas.

The tiles on the edge of the doors for the landing gear, that's a very critical section.

Anyway, after typically about a three month turnaround in the hanger they wheel the orbiter, actually, originally it was pulled over on its own wheels, but that required that they then stow the wheels in this big vertical assembly building.

This is the vertical assembly building.

Hopefully you've seen pictures of it.

It's huge.

It was actually built to assemble the Saturn rockets.

It's much taller than we need for the orbiter stack, but it has been adapted.

So, what goes on here is it's wheeled into the big vertical assembly building.

There it is actually on the inside.

You just don't get a sense of the size of this building from any picture that can be taken.

You have to be there and see it to really appreciate it.

In the meantime, you remember the solid rocket boosters are recovered after every flight.

And the Liberty Star and I think the Freedom Star, that's the NASA Navy.

These boats are positioned out offshore.

And they actually have divers who go down and put in plugs and floatation devices so that they actually float the boosters.

And they drag them back where they're disassembled and cleaned up.

The actual segments, which contain the fuel, are shipped back to Utah to Thiokol which is now ATK for cleaning, refilling.

And the other parts, the nozzle and the top, which contains the electronics and the parachutes, those are serviced in Florida.

And then they're brought in segments into the vehicle assembly building where they are stacked.

And remember those are the segment sizes.

Some of these are assembled in the factory.

Those are the so-called factory joints.

And then were these come together that's the so-called field joint, and that's the joint that failed in the Challenger accident.

This gives you a sense of the size of those solid rocket motors in the way the solid fuel is put in.

And they do all of these tests to look for the roundness of the motor and the flatness of the propellant.

Yeah?

Is that the fuel itself?

It is.

Although, what confuses me about this is I'm not sure which segment this is because most of the fuel is actually put in with a star pattern in it and they actually shape the way it's loaded so that you shape the thrust profile.

And I've not been able to get a good explanation of why that is not the case here.

In any case, this is now the process where they lift one segment, they put it down on top of another.

Of course, all of these are hazardous activities.

And nobody is allowed, except for the critical personnel, nobody's allowed in the VAB when they're doing this just in case there is a problem.

And then they actually put all of these bolts in to join up the field joint.

And now, of course, after Challenger we have a new and improved O ring configuration.

Now we have the two solid rocket boosters sitting on the mobile launch platform.

And, again, you can see you have to design all of these platforms so you have access.

Now, the external tank we talked about.

This is in [UNINTELLIGIBLE].

This has actually been damaged, not too heavily, but it did suffer damage from Katrina.

This is the oxygen tank upfront.

Notice how small this is compared to this is the big hydrogen tank.

And then this is actually the front side, but this is then turned around and the two are joined together inside the outer shell.

And, of course, the solids are joined to the external tank, the orbiter is joined to the external tank, so basically the external tank needs a strong back mechanism inside it because that's ultimately what's tying the whole stack together.

And the trust from the solids and the thrust from the main engines, ultimately they're linked together through the external tanks.

So the tanks themselves, the hydrogen and oxygen tanks don't have a lot of beefy structure.

But going through this is a very heavy structure.

Yeah?

The hydrogen tank there is about the diameter of the overall structure?

Yeah.

That gives another idea of the scale.

This is cleaning and polishing inside the big hydrogen tank.

I mean, again, the scale of all of this, it's important to get a sense of what's involved in taking care of these vehicles.

Do you know if they actually had to go in and scrub it by hand?

I guess.

I mean the scrubbing is only part of it.

The inspection is the really critical thing, to see if there is anything that's not quite right.

One thing that's interesting, the use of liquid oxygen, liquid hydrogen is wanted so much because of its higher performance.

But, on the other hand, if you would do something like liquid oxygen and kerosene you would get a much smaller tank or some other propellant.

And there is a tradeoff.

I think today people are realizing, especially from the Russians, the Russians don't really use liquid hydrogen.

You get a lower ISP but your tanks become so much smaller to deal with.

And hydrogen is very hard to deal with.

It's very hard to find the hydrogen level, and hydrogen is very hard to deal with.

My second flight, do you remember?

That was the one with the hydrogen leaks, remember that?

We were supposed to launch in May of 1990.

And we went down.

And before they fill the system they do a helium leak check.

And, of course, helium, for those of you who have worked with vacuum systems, helium will leak through anything.

And, if the system is tight against helium, they figure it is tight.

The problem is that that's done at ambient temperature.

And, when you fill it with the cryogenic hydrogen, everything contracts.

And so things which were vacuum-tight at ambient temperature are not always vacuum-tight.

But the problem is you don't know that until you fill it, which is only done a few hours before a launch.

So, we had gone down to the Cape.

We were in medical quarantine.

And we just got the message about six hours before launch there's a hydrogen leak, launch is scrubbed.

They did some checks.

They drained the tank.

They did another helium leak check.

It was fine.

We had gone back to Houston.

We came back.

The same thing happened.

How long did it take?

Well, in the end, we made six trips over the course of six months.

And we didn't launch until December.

And, actually, another one of the shuttles also had a hydrogen leak.

They actually alternated us.

They pulled us off the launch pad.

They put somebody else on.

I mean what had happened was they had somewhat changed the procedure of installing some O rings in these big hydrogen lines, and it required a process where the workers were actually working in an area where they couldn't see.

And the O rings were being installed slightly wrong.

But it was just terribly difficult to track that down.

So, yeah, there are a lot of problems using cryogenic fuel.

Now, the other thing is if you have a fully staged vehicle with a separate first and second stage, one of the things that you learn in rocket propulsion classes is that in the first stage the specific impulse is not nearly as important.

What's really important is to get a lot of thrust.

In your upper stages having a high ISP becomes much more important in terms of the payload that you can carry.

So, if you had a fully staged vehicle, and, in fact, that's the way Saturn worked.

The first stage of Saturn was kerosene and liquid oxygen and the upper stages were cryogenic with hydrogen and oxygen just for that reason.

OK, let's move on.

Now we have the external tank, again, suspended in the vertical assembly building.

That's lifted up and joined between the two SRBs.

This is the feed line where the oxygen comes down and this is where these two feeds lines, this is the hydrogen.

And then the orbiter has two corresponding feed ports where the hydrogen and oxygen comes into the engine.

And, actually, when you fill the tank on the pad, you actually put the hydrogen and oxygen into the orbiter.

And it flows from the orbiter back then into the external tank.

And it was on this oxygen fitting from the foam that they put around this, was what fell off in the recent Discovery flight where they did get a big piece of foam.

OK, so now we go back.

Remember we brought the orbiter over into the vertical assembly building?

Now, you put this strong back to hold the orbiter.

And this is really spectacular.

I mean you lift the whole orbiter up off the ground and tilt it up.

And you basically hang it and lower it.

And these are big pieces of equipment and yet you need millimeters of accuracy.

So, very skilled crane operators, to say the least.

Now we have the orbiter and the strong back laid down in position and all of the mating is done.

And we're on the pad.

Excuse me, we're on the mobile launch platform and they put the crawler transporter underneath it and then they roll it on these specially prepared pads which have very, I don't know how deep it goes into the ground, but this is heavy river gravel.

Most of the boulders are about the size of your fist, but after one or two trips of the orbiter it's crushed down to the size of pea gravel.

And then they have to replace it with new stuff.

And, of course, as you're going out to the pad, when you're rolling up to the launch pad, you're actually going up at an angle.

And so this whole system, you can see the crawlers down here, each one of these treads, each single piece of the tread weighs a ton.

Just to give you a sense, it goes about one or two miles per hour top speed.

It takes hours to get out there.

And it has to be capable of staying level to within a few degrees, even as you're climbing the ramp up to the launch platform.

What are those things supporting the [UNINTELLIGIBLE]?

The whole stack is basically sitting on the two SRBs.

The skirts of the SRBs is taking the weight.

These are the fuel inputs which are connected through the other side where the hydrogen and the oxygen run into the shuttle.

And, from there, the way I showed you before, it goes into the external tank.

Did they also keep it tilted back?

Did it have the tendency to [UNINTELLIGIBLE]?

Each of the SRBs has four bolts.

Actually, they give us, as a souvenir after a flight, they give us the big nuts that are explosive bolts.

There are eight, four on each of the SRBs.

And, essentially, that's what gives it its stability.

Again, this is a hill.

It's a little hard to see the perspective, but keeping the whole thing steady.

And we talked about how you can see this track here where the payload change-out room eventually could come around and cover the shuttle to give it protection.

This is actually going up the hill to get up.

And it's just a pretty picture that I like.

And here we are.

This is nice because you have both shuttles on the launch pad.

This is a big water tower.

In order to protect the launch pad against flame damage, and also to protect the shuttle against acoustic effects, they actually get a shockwave when you ignite the engines which can bounce back and do some damage.

Shortly, about 15 seconds before T zero, they open up the valves.

And all that water flows with little jets.

If you've seen pictures of a launch, sometimes they show that as part of the launch sequence.

In fact, in another class, I will show you some of the details of an actual launch picture.

That's the water deluge, and that goes for about 30 seconds.

And that cushions the acoustic load reflected back to the shuttle.

OK, that's enough pictures on the pad.

Oh, I know what I wanted to show.

This is called the white room.

And that's how the crew goes in.

You take an elevator up to here.

And then that actually joins up with the hatch.

So the hatch is sitting open.

And you put on your parachutes and the last few pieces of equipment to get in.

And this is a view inside the white room.

This is, I guess, from our last flight in 1996.

And, when you go out on launch day, the big thing that you notice that's different is there are very few people on the pad, only the essential personnel.

And the whole stack is creaking because it's now filled with the cryogens and everything is shrunk and it's sort of alive in a very strange way.

So, we talked about the mission profile.

I won't deal with this.

And I do want to talk about some of the shuttle aborts, but we will do that another time because I want to get finished with the slides.

I did want to show you, after Challenger they introduced a bailout.

We did mention that the basic survivability for the crew requires an intact orbiter.

It used to be that it needed an intact orbiter landing on the ground or ditching in the ocean, which was kind of an unlikely survivability because you're going to hit the ocean at 200 knots and probably break up.

So now there are circumstances where you can lose more than one engine during launch or you might have to do an emergency de-orbit where you basically can be flying along at 40,000 feet stably but with no place to land.

And so that's really the only situation which the bailout system protects you against, but there is a collapsible poll.

The reason for that is because the aerodynamic studies show that if you just jumped out of the open hatch with a parachute the airflow would carry you back on top of the wing and you'd hit the OMS pod, and that would not be a good deal.

So, you actually hook yourself to this escape poll.

And that takes you down below the wing, and then you can open the parachute.

And we actually practiced this where you go out into a swimming pool using the escape poll.

These are some actual tests conducted by Army parachutists in, I think, a 141 Transport.

The system has been tested in flight, although never with the shuttle.

And that's the test where they have a simulated hatch and you basically jump out into the swimming pool.

Once again, into the white room.

You can see the hatch out here.

And that's the last thing that they'll do, is they close the hatch.

Then they pressurize the shuttle by about 1.5 PSI just to make sure that it has pressure integrity before a launch.

And then we launch.

As you can see, you're burning hydrogen and oxygen in the main engines.

What's coming out there is just hot steam, not very visible.

Most of the smoke, the noise and everything come from the solid rocket boosters.

However, you do need these engines.

In fact, people have calculated that if you tried to take off without these main engines pushing up on the shuttle that the attachment between the shuttle and the external tank would probably fail.

Each of the main engines is about, well, it's a half a million pounds of thrust in vacuum.

It's slightly under 400,000 pounds at sea level.

You've got a little over a million pounds coming from the main engines, but these are putting out almost three million pounds a piece.

So, most of your early thrusts in the first two minutes are coming from the solid rocket boosters.

And it's a pretty rough ride.

I mean there's a lot of vibration.

When you go through mach 1, which is max Q, maximum dynamic pressure, the vibrations are even more pronounced.

The first time on my first flight, I really thought the wings were going to come off, there was so much vibration.

But, of course, they don't.

But I'd love to get a hold of it.

I actually saw a high-speed, well, a slow motion picture actually looking at the tail, as you go through max Q.

And you can actually see the tail fluttering back and forth like that.

I mean the aerodynamic loads on the vehicle during ascent are significant.

And you do actually have to move your elevons to what's called load relief in order to take the stress off that.

I really like this.

It gives a sense of the power that you're sitting on top of to get up there.

And that's just a nice picture of riding the fire.

OK, so you get up in orbit and you drop the external tank.

And, although now they're going out of their way to take even better close-ups of the tank to look at the foam shedding.

We've been doing that, in fact, throughout the history.

Now they especially time the launch so that you're guaranteed to drop the external tank with good lighting conditions.

That didn't used to be a constraint to launch but it is now.

You can also, by the way, see how the atmosphere quickly fades out into space.

And that's a telephoto so it actually makes the atmosphere look even thicker than it really looks.

OK, so there is the orbiter in space.

That was actually after it had delivered a payload.

This was taken from the space station.

And just a quick reminder of all the different things that we've used the orbiter for.

Launching satellites, you've seen that picture.

This is a payload assist module to take the satellite from the shuttle orbit up to geosynchronous transfer orbit.

We have used it extensively for satellite repair in orbit.

This is the Intelsat where it was put into orbit by an expendable rocket, but into a bad orbit because of underperformance.

And they managed to get it into a shuttle compatible orbit.

And I won't go through the whole history.

Why there happened to be three people out there is a whole story in itself.

This is one of the satellites.

Again, the satellites were put into orbit by the shuttle.

And the shuttle deployment was fine, but the payload assist module, which you saw before, did not perform properly.

And so the two satellites were stranded in a useless orbit.

We actually brought them back to the ground.

They were refurbished and re-launched again on expendable rockets.

The shuttle has also been used as a space station with the space lab on in the inside to carry out scientific experiments.

This is a large pressurized module which is put into the cargo bay.

And the original idea, as Professor Cohen mentioned, was you could just take your laboratory equipment off the shelf, plug it in here, 120 volts AC power, I guess, and it would be just like working on the ground.

Well, it never was.

But, having said that, I think the space lab program, as a whole, was extremely successful.

And then it's been used to service the Mir Space Station.

We certainly added several years of useful life to the Mir Station because we could carry up a lot more equipment than the Russians could themselves.

And that also gave us an opportunity to get some US astronauts on long duration space missions.

And then, as you all know, we're using the shuttle to construct the International Space Station.

And hopefully we'll get more of it built before too long.

The shuttle is also an excellent platform for performing EVAs, space walks.

And that's a picture of when we went up and repaired the Hubble Space Telescope.

I cannot overestimate the capability that the shuttle gives us as a work platform in orbit.

We can do this sort of complex EVA activity on the Space Station, but once we retire the shuttle we've essentially lost that capability.

To have the manipulator arm and to be able to use people and the robotic arm to move equipment around, it's just a very powerful work platform.

That's one of my favorite pictures floating up there.

This is a pretty picture of firing the orbiter maneuvering engines just to start your descent into the atmosphere.

Despite the fact that you're going at 18,000 miles an hour, you only have to slow down by a few hundred feet per second in order to lower your perigee down to essentially the surface of the earth so that half an orbit later you intersect with the atmosphere.

And, of course, that produces the aerodynamic heating which you can see on the outside.

This is looking out to the front.

That's kind of a dull glow.

It starts out as a deep red and then it gets orange and yellow and finally white on the outside.

The most spectacular thing, you know, you're a meteor.

This is a picture that was taken from Houston.

This is at about 250,000 feet at about mach 12 on the way to a landing at the Kennedy Space Center.

The shuttle is flying like this.

If you look up at the overhead windows, you can actually look back into the wake.

And this is really spectacular because you have these different colors, and it's sort of shimmering around.

And every once in a while, when I would be looking at this, you'd see a big bright light.

And I would think boy, I hope that was nothing important.

[LAUGHTER] What people said it probably was were little bits of gap filler.

You may have heard that on the last flight they discovered that some gap fillers were protruding.

And so Steve Robinson went around and actually pulled some of them out.

But they've probably been doing that the whole time and just have come off.

I mean this little point where you have the convergence of the shockwaves, this is about 10,000 degrees Fahrenheit, that's the surface temperature of the sun.

It's a spectacular visual view.

And then, again, at this point we're just going subsonic flying like a glider and ready for touchdown.

So, I hope that gives you some sense visually of what goes on in the course of a shuttle flight with an emphasis on the maintenance operations.

Without appreciating how complex it is to operate this system, I think it's hard to really make the link between the original concept and the difficulties we've had in getting the shuttle to perform in terms of the turnaround maintainability.

So, again, just wrapping up, that's kind of my farewell picture, the shuttle was an amazingly ambitious concept.

And, I think, what has been astounding is how well the shuttle has been able to perform and do all the things that it was designed to do in terms of the satellite launching and being used as a science platform, performing EVA, repairing satellites, building space stations.

It has given us experience and capability to learn how to do things in earth orbit which we never had before.

And, as I say, we may well miss them once we retire the shuttle.

But where we really did get it wrong, and this will be one of the things that we'll look at when we deal with the individual subsystems, is in the operations.

It turned out to be a lot more complex, expensive and delicate to operate than had been anticipated.

So hopefully there will come a time when we set out to design another reusable vehicle, possibly a reusable winged vehicle.

And I think a lot of what we've learned from the shuttle will be folded into that.

It still is a question of how re-usable the next crew exploration vehicle, the CEV will be.

Re-usability has been put in as a requirement, but that remains to be seen.

And certainly the experience that we've gotten from the shuttle is going to make people look really, really closely at what assumptions we're making about the reusability whenever we do this again.

OK.

Next Tuesday will be the last in kind of the conceptual part of what we're doing.

Professor John Logsdon from George Washington University is a very well known space policy analyst.

He did a seminal study on the Apollo program and has also written a lot and done a lot of research on the origins of the shuttle.

And so he'll talk to us then.

Let's see.

I had promised to post everybody's emails on the Web, and I got diverted and didn't get that done.

But I will do that before tomorrow, you know, in terms of forming your teams.

Put together an idea of what system you would like to work at.

If you're not able to form up as part of a team between now and Tuesday, just give me what your own personal preference is.

And then we can look and see if different people are interested in the same system.

We'll let you all know and help you form up teams.

I'll make sure your email is there in the student view.

[UNINTELLIGIBLE PHRASE] If you've already formed a group then just turn in something as a group.

That's fine.

If not, if you haven't hooked up with somebody, just let us know what system you're interested in working at and any ideas you might have of what you're going to look at.

Really, this is just a very, very short write-up essentially to get you started.

And that way, if you have any questions, we can talk about it next Tuesday.