Henry has been a longtime colleague of mine working in the early days of Apollo and Shuttle.

He is an old country boy but he has created more innovative designs on technical problems than anybody I know.

And we will try to bring some of those out because he has really created some very innovative solutions to technical problems.

And I am going to set Henry up a little bit so let me set the stage for you a little bit.

I was manager of the Space Shuttle Orbiter, and the engineers came to me and said, Aaron, the waste management system on the Shuttle is not working very well.

Now, the waste management system, in simple terms, is the toilet.

They said the toilet is not working very well, and we really need to go off and design a new toilet.

I thought for a moment, well, that's probably a pretty important thing to do, so we did.

Well, it turns out the original contract, and I am quoting a little bit from memory, was about $10 million.

Now, $10 million for a toilet when you can go down to any place and get a toilet for a couple hundred dollars is a pretty high number.

But that wasn't the worst of it.

The worst of it, about six months later they came to me and said, Aaron, guess what?

It's not $10 million.

It's $20 million.

Congress got wind of this and wanted me to come up and testify.

And you can see what kind of fun they are going to have.

Waste management, they're really going to have fun with this subject.

And you may know some people in congress, but the name was Mr.

Sensenbrenner from Wisconsin.

I remember very clearly.

He is still in congress now.

He was head of the Science Committee, and that is who we had to go testify for.

Well, there was a reporter for The Washington Post.

Her name was Kathy Sawyer.

Now, Kathy was the science reporter for The Washington Post.

Very, very good.

Kathy was very smart, very fair, but she really bore in on things.

Kathy got wind of this so she wanted to publish an article on it.

She called me and said would you please talk to me about the waste management system?

I said, boy, she is going to get me in trouble.

I said, I will tell you what, I've got somebody that could really tell you about the waste management system, and I will have Henry Pohl call you.

I talked to Henry about it.

Now, that is going to be Henry's introduction to this class of what he told Kathy Sawyer because it is a classic.

Henry, it is all yours.

Aaron almost forgot about Kathy Sawyer.

Kathy called me up and said can you explain to me how I might explain to my neighbor's 14 year old daughter why NASA has spent $10 million building a toilet?

And I said I will try.

And I thought for a little bit on how am I going to start out on this?

I said, you know, if you take the commode that you've got in your bathroom and you bolt it upside down on the ceiling, now try using it.

[LAUGHTER] I said that is really a little better situation than we have on the Orbiter because at least we know which way the gravity field is on that.

In orbit you don't know.

Most of the time you don't have any, but it might be to the right or left or up or down.

You know, that was the only reporter that I ever talked to it that put everything down verbatim of what I said, the questions she asked and what I said and printed that article in the newspaper.

But that kind of sets a stage for operating in the absence of gravity.

I explained to her that the Space Shuttle volume that the people had to live in is about the same volume as you have in a modern bathroom.

If you look at a bathroom with a shower and a room just outside with a sink and everything, we have just about that same volume in the Shuttle.

Now, you seal that all up, you've got a certain amount of air that you can use in there and you only have the air to replace gravity.

You've got to have a flow of air to direct whatever you want to direct in a certain direction.

You use that air.

You run it through.

You've got to deodorize it.

You've got to clean it.

You've got to run it back into the cabin almost instantly.

Otherwise, you pull the vacuum in the cabin.

And so whenever you start putting all of that equipment in there and all that stuff in there on something that has never been done before, $10 million or $20 million is kind of cheap when you get right down to it.

You look at the number of people that that will hire for a year working on it is cheap.

But to try to get that message across is not easy.

Go ahead and give me my first slide.

Let me just tell you another one since Aaron got me off on a tangent here.

The Chicago Tribune called me one day when we had a problem on Shuttle, and she was badmouthing the Shuttle.

And all she wanted to do was get a comment out of me that I agreed with something that she said since she could quote it.

And I said I don't agree with you.

I said you know that Orbiter is really a pretty good vehicle when you look at what it has to do.

I said you realize when it's in orbit it is going eight times faster than a bullet when it leaves the muzzle of a .30-06?

Silence on the other end.

What's a .30-06?

Well, I knew that wasn't a good example.

[LAUGHTER] But I told her that is a military rifle that was used in the Second World War.

And I used to fire that thing in the desert.

And I could pull the trigger and see that bullet hit the ground out of that 300 yards almost instantly.

Now, that shuttle is going eight times faster than that.

And I could see the headlines in the Chicago Tribune, the shuttle flies eight times faster than a bullet.

Long silence.

She said maybe I ought to find something else to write about.

I said why?

She said I don't think I have a story here.

Well, it wasn't a story because it wasn't negative.

Kathy Sawyer was the only time I ever got a good story from the press.

I want you all to feel free to ask questions.

I'm here more to talk about what you're interested in talking about than my thoughts, so feel free to ask questions any time.

I would like to talk about a half an hour.

Somebody is going to have to tell me when a half an hour is up.

And then I would like to have some time for some questions.

My first involvement in the Space Shuttle was Max Faget kind of came up with this idea of a winged vehicle going into space.

And we kicked it around for a while.

And he formed a little committee, very small, about 20 people as I recall.

Put the people in a room.

He wanted to keep it quiet.

He wanted to keep it secret until he got enough data so that he could know whether it was feasible or not.

Well, they wanted me to send the best engineer I had over there.

And he appointed a guy by the name of Jim Chamberlain to head up that group.

I sent a guy over there.

They closed the doors, had a guard in front of the doors so nobody could come in, no information could get out.

On the third day, Jim Chamberlain called me up and said I need to have a talk with my engineer.

I said why?

He said he balked.

I said what do you mean he balked?

He says, Henry, you know what an old mule does when they balk, don't you?

I said, yeah, they won't go.

He said, well, that's your Mr.

Kindrick, he won't go.

I called up my engineer and said what's going on over there, girl?

He said, oh, they don't know what they want.

He said they gave me some requirements.

I designed them an RCS system for it.

They gave me another set of requirements.

I designed another RCS system.

They gave me some different requirements.

I designed them a different RCS system.

And then they came out with another set of requirements.

I'm just going to wait until they decide what they want and then I'll design them an RCS system for it.

Well, what he didn't understand was that's the way you go about setting the requirements.

You get a small group of people together.

You set down a set of requirements.

You try to put a vehicle together and see where it punches out.

Usually weight, CG, something.

So you change the requirements up a little bit and you design another system.

You do that very quickly and you look at where that one punches out.

And then you change your requirements again and you look at those requirements and where it punched out.

The first requirements, where it punched out.

You change the requirements a little bit and see where it punches out.

Very, very quickly you run through many configurations.

That got the Shuttle started.

After it got started we kept changing the requirements as we went through the program.

I would suggest that you understand your requirements very, very clearly, and the impact of your requirements very clearly.

Things like fail op fail safe, or fail safe fail safe fail op are very, very good buzz words.

But unless you really understand the impact of those, they can actually make a system less safe.

I can make a very good case that a two engine airplane is safer than a four engine airplane simply by the way that you set your requirements.

FAA has a requirement that an airplane has to take off with one engine out.

If you've got a two engine airplane then most of the time you've got 100% more power than you need.

If you have a four engine airplane you only have 25% more power than you need.

Most airplane crashes are caused from lack of power at the right time.

If you've got the power when you need it then you can get out of most bad situations.

Our original requirements on the Shuttle, after we got that started, was to keep the operations cost low.

We wanted to keep the maintenance cost and the operations cost low.

We initially were looking at oxygen/hydrogen systems.

In fact, all of the early orbiters had the hydrogen/oxygen onboard.

In place of their payload, we had hydrogen tanks and oxygen tanks in there and carried the hydrogen/oxygen onboard.

And we actually looked at using the hydrogen out of those tanks.

You get it free to power the OMS and the RCS.

And we looked at all kinds of ways of getting the pressure up high enough to be able to use the residuals to power the vehicle.

One of the students asked the question the other day and we didn't give a very good answer that we did at one time look at putting the hydrogen in the payload bay of the Shuttle.

All of the very early configurations of the Shuttle had the hydrogen and the oxygen in the Shuttle in place of payload bay.

That was the very early configuration.

Later on, as DOD got involved and other people wanted big spaces and carrying greyhound buses up there and things like that we had to use that space and that's when we came up with the external tank.

And that's when we came up with a side-by-side configuration on it.

That's the way I recall it.

But we looked at oxygen/hydrogen.

Then we went to methane because we were looking at bulk densities so that we had smaller tanks, smaller volumes.

Then we looked at oxygen/alcohol.

And I really thought we had a good system with oxygen/alcohol.

I had a lot of confidence in that system.

We used it on Redstone.

My first job was working on Redstone.

I really liked alcohol.

I thought we had developed a good ignition system for the RCS so we didn't have to worry about the thousand starts.

But obviously that was going to cost us money and cost a lot of development money.

And, as time went on, we changed from having low operational cost to low development cost.

And when we went to low development cost then we went to bipropellant on the OMS and initially to monopropellant on the RCS.

When I say bipropellant, what I mean are storables, monomethyl hydrazine and nitrogen tetroxide.

Both are storable propellants.

They are self-igniting so you don't have to have an ignition system for it.

That simplifies the design a whole lot.

We had a lot of experience with those propellants on Titan II, on Agena and on Apollo, all of the Apollo stages used either aerozine 50 and nitrogen tetroxide or monomethyl hydrogen.

So, we went to that.

On the RCS, we initially went to hydrazine as a monopropellant because it was the simplest system, the cheapest system, but very quickly the weight got out of hand and we had to go to something that had a little bit more performance than a hydrazine because all of that weight was in the backend of the vehicle.

And the backend of the vehicle was getting too heavy.

If you only remember two things out of this exercise and what I have to say today, two things I want you to remember is that it is just not natural to think in terms of the absence of gravity and it is not natural to think in terms of the absence of pressure.

When you think about it, you live in it around here on the ground, it is so natural that it's hard to think in terms of designing systems and the impact that the absence of gravity has or the absence of pressure has on the design of the systems.

The other thing I would like for you to remember is that there is no substitute for a good well thought out test program.

Let me give you the OMS as an example.

We did not have a vibration test program on the propulsion systems, on the OMS or the RCS in the program because, by that time, we had good structural programs, we could analyze the effect of vibration and stress on the vehicle.

But we had a good propulsion test program and we built an OMS pod, just like the ones we had on the vehicle for qualification.

And when we got through with all the propulsion tests on it, and we went through that program in a breeze, we had no problems at all with it, so we finished it early.

We took that pod down to JSC, we put it in a vibro-acoustic facility, and while we were running the QVVT the low level vibration test on that pod just to get the response of how things responded to everything, the helium bottle fell out.

Five minutes after that helium bottle fell out every structural guy in the world could tell you it should have fell out, it would fall out, but nobody thought about it in advance.

What happened, we had taken a high pressure helium line coming out of the bottom of the tank and going five feet or eight feet over to the structure and bolting it to the structure over there.

Now, when you started shaking it, that was acting as a torquing element on that tank and torquing that tank this way.

And the struts they had coming down holding the tank, it was fatiguing where they were put onto the tank.

It fatigued them right in there and broke them off very quick, but we didn't pick it up.

The OMS was very, very straightforward from a development standpoint.

We came out with a platelet injector that gave us very good combustion.

You have to explain what a platelet injector is.

OK.

A platelet injector is one where we used photographic techniques to etch holes in the injector.

You could get a very, very fine pattern.

You made it in very thin sheets and you coated the sheet with a coating where you could put them in a press and heat them and glue them together.

You came up with an injector design that was made out of many, many thousands of very thin plates that set up the manifolding on it.

Normal injectors you have to do a lot of very integrated drilling.

Normal injectors, you drill out a manifold in the back, and then you take the face plate and you have to drill holes in it.

And the problem we get into when you start doing that is with these very small drills they tend to walk or bend.

And you don't get a straight hole.

You don't get a good spray pattern.

With a platelet injector we could get a very close match.

We could just kind of dribble a field in there and oxidizer in there where it always matched real well.

We got very high performance out of it.

We're talking about the injector up here where you have the fuel and oxygen, and then you have to have a whole bunch of holes in a pattern such that the fuel and the oxidizer are properly mixed when they ignite inside.

You need to get the oxidizer to impinge on a fuel very precisely so that with an aero-storable propellant, a hypergolic propellant as we call it, that is self-igniting.

And basically what you have is when the two fuels come together it is like having a very strong acid and a very strong base coming together.

The first reaction that you get is a heating reaction.

That chemical reaction that you get will take the propellant temperature up to 800, 1000, 1200 degrees.

Anyway, it gets it up to the combustion temperature and then you start the combustion process.

So you don't have to use any other ignition source.

All you do is bring those two propellants together and you get that chemical reaction that provides the energy, the heat to heat the propellant to the combustion temperature.

Like all high performance rocket engines, we had a stability problem with the OMS.

And we had to put big acoustic cavities.

38% of the injector on the OMS was cavities designed and sized to damp out the stability, so we had a very good stable engine.

The RCS, on the other hand, is a totally different design.

Now, we put the propellant tanks on the RCS up in front of the OMS tanks for aerodynamic purposes.

That gave us a 30 foot propellant line down to the RCS.

Then we would manifold three, four, five engines on the end of that pipe that is pulsing in and out of phase or steady state.

Some of them were running at 40 millisecond or 80 millisecond pulses.

Some of them might be running at four times that on a pulse width.

And some of them may be running at steady state.

Anyway, the dynamics, the pressure in that line that the engine sees varies somewhere between vapor pressure and about 1000 psi.

And, since one propellant is 1.6 times the density of the other propellant, when that valve opens down there, that pressure wave has got to go back up to the tank and come back down to the injector before you get basically any flow out of it.

Just the compressibility that you have in the pipe will come out.

The pressure essentially drops to vapor pressure.

And we use helium to pressurize those tanks.

When we use helium to pressurize those tanks, the helium is dissolved in the propellant.

When it gets down to the engine it comes out as solution.

The engine has to be able to stay together at any mixture ratio and almost any pressure.

And you are looking at hundreds of thousands of starts over the life of one of those programs on one of those engines.

And we talk about pulse width.

Pulse width is the minimum ohm time that you can have on a rocket engine.

Now, there is a volume between the face of the valve and the face of the injector that we call dribble volume.

The larger that volume is the larger the pulse width you need on it.

You would like to have the seat of the valve to be the face of the injector so you have zero dribble volume in there.

That way you would get closer to a square wave pulse.

And your friends in Guidance Control, they always want to square away pulse.

And they want it to have an infinite thrust level and zero width so that you put an instantaneous pulse.

It makes it easier for them to calculate where the vehicle is going to go than if you get one that builds up kind of slow and goes down kind of slow.

The dribble volume, the volume that you have between the valve seat and the injector phase when the engine shuts down, when the valve closes that flow stops and that amount of propellant stays in there.

Now, in a vacuum, when it gets down to the vapor pressure starts boiling out and goes out through the chamber.

And you have a refrigeration effect from that boiling of the propellant.

If the pulse width is too short then the refrigeration effect will overcome the heating effect from that short pulse and you keep reducing the temperature of the hardware.

The colder the propellant gets the more heat you have to put in the chemical reaction, when it first comes together, to get it to ignite.

You get an ignition delay in the thing and then you start getting into hard starts if it gets too cold.

So, we set our pulse width on the Shuttle at 40 milliseconds.

That was the neutral point at which the refrigeration effect equaled the heating effect from the pulse, and so you would maintain the temperature.

We later on went to 80 milliseconds on it because we added the Veniers.

That gave us a little bit of heat input.

It's a pretty tough design in itself.

The valve that we used for a 1000 pound rocket on the Orbiter weighed less than the valves that we used on the

Apollo program for 100 pound thruster.

And what we did is we went to a pilot operated valve.

That was kind of my concept that I borrowed from Sears Roebuck.

If you ever take a washing machine apart on a Sears Roebuck and you look at how the valve is designed, it is a pilot operated valve.

And they use the water pressure to open the valve.

Well, I thought that was good way to go.

You put a very small coil in there, a quick acting coil and replace that rubber bellows that used on a Sears Roebuck washing machine with a stainless steel diaphragm and you've got it made.

Well, unfortunately the water pressure in a house doesn't vary as much as the water hammer does on the Space Shuttle.

So, before we got through with the design of that valve, it got to be a very complex valve.

And it was a very expensive valve but it worked.

Probably the other thing we ought to say about designing any system that is going to work with these hypergolic fuels, I mean they just eat away at things like O ring seals.

I mean it's just nasty stuff.

And so, in addition to the mechanical problems that Henry is talking about, you've got all the materials problems which just makes your life harder.

We really wanted to stay away from hypergols, from the very strong acids and the very strong bases for the simple reason that there are very few materials that are compatible with

them. As a matter of fact, the main reason we went to a hydrazine RCS in the beginning was to avoid having an expulsion system in the oxidizer because we had no material available that you could put in there as a diaphragm to push the propellants out that was compatible with N2O4 that you could make cycles with.

We could have used metal bellows, but they weren't very reliable.

They were extremely heavy.

And so we had to come up with a better system than that.

And then we kind of got to looking into putting in screens in the system.

And that was really a hard sell.

I mean I spent lots of time with Aaron.

I was convinced that system would work because if you look at an automobile gas tank, every fuel tank on every automobile has got a sock in it.

That sock is about an inch and a half in diameter, and it will suck every drop of fuel out of that gas tank.

They putit in a little sump in there, and it will just draw that tank dry before it will break down and let air go through it.

I was convinced that we could build one of those systems and make it work.

But if you look at an automobile, you know it goes over rough roads, it bounces, you've got G fields, you've got all kinds of forces on that thing, and yet it works very good.

The problem we had in trying to sell that concept to the program, though, was how do you prove it?

The only technique we had to prove it was through analysis.

And you're trying to prove that something like that will work purely from analysis.

And qualified by analysis was a hard, hard sell.

We, later on in a program, came up with techniques where we could wrap tape around most of the screens in there so that we close up most of the area.

And so we would draw a propellant in, in very small areas with aerospaces on top and prove that you could get down to a certain delta P and cross it before it would break down to qualify our analysis.

We still were not satisfied with that so we made up a system with a glass tank, we put it on our vomit comet and flew it.

And that was the only time where I ever road that thing.

If we had made one more time it would have been all over for me.

[LAUGHTER] But you get up 38,000 feet and you make a dive on that thing.

And you can maintain zero G in it through that 30 second or 38 second period of time.

And by expelling the right amount at the right levels we could prove that it would work.

And it has worked very, very well on all the flights.

In the future design of the spacecraft, what is going to be the difference in the RCS system?

Because every system is going to have to have some kind of reaction control system.

What do you think they are going to go with in the future systems?

I really believe that we ought to go with either methane and LOX or alcohol and LOX.

I think it's a much cleaner system.

We developed that little piece of electric igniter for the Shuttle Program.

We never used it after we went away from those systems.

But you buy these little latch torches now that you push a button and pull a trigger on it.

And they light off most of the time, although the last one I got didn't light too well.

But we have good, reliable ignition systems now.

And I think that you can design a system now that has the reliability that you need for a space system.

Otherwise, we've done nothing in this country since the Shuttle Program on developing [OVERLAPPING VOICES].

The things you have got to remember is that the thermal characteristics are very, very different in a vacuum than it is on earth.

It is very different in the absence of gravity.

You wouldn't think gravity would make any difference in it but it does.

You've got some fluid in the tank.

You put some heat on the bottom of the tank.

Where does heat go?

It goes to the top of the tank.

The top of the tank is always the hottest part.

When you've got a liquid in one G, you put it in zero G, you put heat on the bottom of the tank, a bubble forms down there, it pushes the liquid away from it and nothing comes out of the tank.

Let me have some questions.

I'm slightly confused on the fuel that the system uses.

Both RCS and the OMS use hydrazine or hypergolic?

I'm confused.

Hydrazine is N_2H_4.

We use that as a monopropellant.

A bipropellant earth storable.

A monopropellant system you normally run it over a catalytic bed and it decomposes.

Yes.

There are two monopropellants out there that work very good.

One is hydrogen peroxide.

And if you can get it above 90% it gets a little more stable.

And the other one is hydrazine.

Both of those you run through a catalyst.

When it hits a catalyst you get the reaction out of it and it breaks down.

The hydrogen peroxide breaks down to steam and oxygen, and hydrazine breaks down to hydrogen and ammonia, NH_3.

But both of those give you hot gases then for propulsion.

You mix that with an acid and you get combustion.

And we used aerozine 50 which I mentioned.

Aerozine 50 was 50% hydrazine and 50% unsymmetrical dimethylhydrazine.

Monomethylhydrazine is just that, monomethylhydrazine.

It is a lot more stable than is hydrazine.

It has a wider freezing /boiling point than hydrazine.

Hydrazine has a lot of the characteristics of water as far as density, freezing and boiling.

It will freeze at about the same temperature as water, it will boil at about the same temperature as water and it has almost the same density as water.

Monomethylhydrazine has a little bit slightly less density, it gives you a slightly better performance but it freezes at like minus 63 degrees or something like that.

Monomethylhydrazine and nitrogen tetroxide.

The same thing for the OMS.

Now, one of the things we do is we put about four-tenths of a percent of nitric oxide in the nitrogen tetroxide to keep the tanks from breaking.

We have titanium tanks.

And on the Apollo Program we got into a very serious problem because a tank started exploding.

It turned out with aerozine 50 or monopropellant hydrazine, we had a little bit of water in there and that gave off a little bit of free hydrogen.

And that free hydrogen, titanium just does not like hydrogen.

How many people have taken fraction mechanics?

Well, fraction mechanics really started from that.

That's when we started working with a gentleman called Dr.

Tiffany at Boeing.

We worked with the whole world on that problem.

That's how fraction mechanics really got started.

You were going to ask something.

While we're talking about fractions, one of the other problems of dealing with these hypergolic fuels is the freezing problem.

Maybe we will talk a little bit about that.

Because, unlike water, when the hydrazine freezes it shrinks.

And so if you imagine that you've got hydrazine liquid in a line under pressure and now it gets too cold so it freezes.

And now that leaves a little bit of free volume so you get more liquid that comes in there and that will freeze.

Until finally the entire line is clogged up with solid hydrazine.

Now, when it warms up it expands and you crack the line.

And now you've got a hypergolic leak which is really bad news.

So, in fact, maintaining thermal control of the OMS and RCS propellant lines becomes a very critical issue.

And there are heating coils all over the place and thermostats.

And so, again, you don't just have a propulsion system in the systems engineering that we talked about.

It affects the thermal, the electrical system, because all these things are inner-related.

If you lose an electrical system so that you cannot run the heaters then you run the risk of losing your propellant system.

And so then you have to have redundant heaters and so on.

And it gets more and more complicated.

That was a major, major problem we had on Apollo 13.

We didn't have enough power.

We had to turn everything off quick.

And trying to get those people to let that temperature go down out of limits was not easy.

And I remember sitting down and spending an entire night running out the thermal calculations and calculating out when we could turn the heaters off or we could keep the service module off of that vehicle and not freeze the propellant and the RCS on the command module.

And then I got really, really worried.

I gave myself four degrees above freezing on that system, and I missed it two degrees.

It got two degrees colder than we had planned.

The design of the RCS system was very, very complicated.

How many RCS specialists do we have on the Shuttle, 40?

Thirty-eight primary and four Vernier.

And so it's a very complicated system in designing it.

It had a lot of requirements placed on it.

On the other hand, the OMS engine, as I recall, we have never had a failure on the OMS engine.

The OMS engine has been very, very successful.

It is a very straightforward program.

By getting the combustion close to the injector on the OMS then we could make the chamber small on the OMS.

And, by making the chamber very small on the OMS, then you could cool it.

You could put cooling channels down the chamber and run the fuel down there and keep the chamber cool so it wouldn't burn out.

Now, we also did the same thing on the RCS a little bit different.

The RCS is a buried installation.

We have to run that engine for 500 seconds or more if we want to use it for de-orbit in case the OMS plays out sometimes.

That engine has to stay together on these very, very short burns.

It also has to stay together on these very, very long burns with fluctuating inlet pressures and fluctuating mixture ratios.

We found that if we make a very, very short chamber -- And that's why when you look at the RCS it is a big chamber, it is very short.

We could put enough fuel down the walls of that chamber to effectively cool the chamber so it would only go up steady states to a certain safe temperature and still have good performance out of it.

So, we put a lot of fuel down the walls on it.

Looking in this direction, if this is the injector plate, the holes around the outer most layer, those are all fuel.

So, you basically get a fuel bath coming along that actually comes in contact.

And if you have a fuel-rich mixture, the same as in a car, the fuel mixture burns cooler.

The thing that you're really afraid of, in fact, you have to deal with a lot of contingencies on this system, what happens if you get a clog in one of your feed lines?

The worst situation you can get in is that you get a clog in your fuel inlet line, and that gives you an oxidizer-rich mixture which burns hot.

And you can then actually get a melt through.

And so you've got to shut your engine down in a hurry if that happens.

These are very, very small orifices, and a lot of them around the outside of it.

And if you get a couple of these orifices plugged then that becomes a hot spot on the side of the chamber.

And we used columbium, which has very poor heat transfer.

We used molybdenum on Apollo which has good heat transfer.

To return to your point about the possibility of using the RCS as a backup for reentry, what prevents one from using a series of relatively short burns [carried on the mass?] of the Orbiter to smooth out the velocity chain?

Why do you have to have a single file of second burn?

Before you start to burn, to come back in, how much time you can put in between those and how short, a 1,000 pound thruster for deorbit takes a fairly long burn.

And the engine goes to steady state fairly quick, you know, in a matter of 20 seconds.

[UNINTELLIGIBLE PHRASE] We ran RCS engines for the Shuttle up to an hour and a half on a single burn.

[UNINTELLIGIBLE PHRASE] Even though you put it in multiple burns you still have to have fairly long pulse widths on each one of them.

And that impacts the guidance very, very badly.

Let me help with a little orbital mechanics.

We talked about this before.

You're in orbit.

When you do a burn, you can do a retrograde burn which lowers the other side of your orbit so that now becomes the perigee.

The thing is, from orbital mechanics, the most efficient way to do a burn is to have, like Henry said, an infinite thrust with a zero pulse width.

You do what they call an impulsive burn.

But, in the real world, that never happens.

Now, it is 45 minutes from here to here, it's a 90 minute orbit.

Now, when you have two OMS engines, a typical deorbit burn lasts two to two and a half minutes.

You're burning over this segment.

It's pretty close to an impulsive burn.

You lose one OMS engine and now you have to double it.

Now you're up to a five minute burn.

But, if you lose your second OMS engine and now you have to do an RCS deorbit, now you're getting into a 10, 15 minute burn.

And so you're actually really far away from optimum.

And the burn gets much less efficient.

And so if you have plenty of propellant you're fine, but if you're low on propellant you need to worry about the efficiency of your burn.

If you were to do a little bit of a burn and then shut it down to let your engines cool off and then you try to complete the burn around here, now it has gotten really, really inefficient and you might run out of propellant.

We spent an enormous amount of time with our orbital mechanics people and our guidance people trying to get the OMS strut down as low as we could get it.

Because the lower you can get it the smaller the hardware, the lighter the weight of the hardware and the performance is essentially the same.

The ISP for a 3,000 pound engine is essentially the same as it is for a 20,000 or maybe even a little bit higher for 3,000.

We had 5,000 pound thrust in there.

We had 4,000 pound thrust in there.

I think we finally wound up with 3,500.

Been left up to me, I think we could have done it with a 1,500 pound thrust engine.

But we compromised.

Yes.

Professor Cohen once mentioned that some people suggested putting some RCS thrusters on the edge of the wing tips, but that would be very difficult after the design was finalized.

All of our early configurations that we had, we had the RCS pods out on the wing tips.

It made the RCS very efficient.

Our RCS was the OMS at one time, and we had it all out on the wing tips.

It didn't make our structures friends too happy at first because that puts a lot of mass out into the wings and they didn't like it too much, but after they got looking at it that turned out that really wasn't much of a driver.

It made the RCS very efficient.

The thing that kind of changed that is when we put the big payload bay on the inside of the vehicle and then we had to put a big OMS pod on there.

And then to put the RCS pods out on a wing tip of a delta system out there just didn't weigh out good.

It was more efficient from a weight standpoint to put the OMS and RCS together because we actually had those two interconnected.

If we have to do an OMS burn with the RCS, we can take the propellant out of the OMS tank to feed the RCS.

And so it just made a more efficient system to bring it all in.

We had another requirement.

When we went to the acid-based propellants, we had a requirement that we had to have removable pods.

You had to be able to take the propulsion system off of the orbiter and take it over to another facility to rework it because we knew we were going to have a lot of work and rework on those systems, at least early on.

You had a question right here.

To what extent can you change orbits due to a higher or lower orbit [UNINTELLIGIBLE]?

That is very limited, but we do have the capability to go up and down in orbit.

I don't know, maybe 50 miles.

I don't know.

I don't have a good answer.

I don't remember that.

That has been too long ago.

With a full load you have a few hundred feet per second, I would have to go and look up, you cannot make the plane change.

No, plane changes are out.

But we certainly have gone from, let's see, like 180 nautical mile orbits down to a 105 mile.

I remember one flight where we did that.

To go up, you know, what you really want to do is, of course, use your main propulsion system to get into the right orbit that you want to go to.

Then, if you're going to do a rendezvous, you have to change the height a little bit.

But you typically try to get orbit insertion within about 20 nautical miles, so about 40 kilometers radius of your ultimate intended orbit.

For some special missions, like I was on one mission where we were up at about 180 nautical miles doing various operations, but then the last couple of days they wanted to look at the interaction of the Orbiter with the atomic oxygen and nitrogen which causes this orbiter glow phenomena, which maybe some of you have heard about.

We had to go down to about 105 nautical miles, which is about as low as you can go and stay in orbit for more than a day or so.

And so, yeah, that was OK because that was just you're doing part of your deorbit burn but then you stop.

What you wouldn't want to do is go to a 105 mile orbit and then go up, and then you would have to come all the way down again.

I think we will take one more question and go to break.

It is awfully easy to decrease the orbit because you're using part of the energy that you have to use to come back home anyway.

When you start trying to go up is when you're adding.

But we have a lot of contingency propellant onboard.

We've got contingent propellant in case the main engines shut off early.

Then you have to use the RCS.

If you've got a docking mission we've got propellant in there for three or four attempts at docking and things like that.

There is extra propellant that you can use to give you a little bit of a boost.

You had a question here.

Going back to the comment that was made about the [UNINTELLIGIBLE PHRASE] and presenting a hazard that way, what kind of feedback did the crew have when something like that was happening?

Were there sensors in that system [UNINTELLIGIBLE PHRASE]?

I don't hear too well.

The question is what sort of sensors do we have for the operation of the engines?

There are pressure sensors.

There are temperature sensors.

Again, remember when we were talking earlier, though, sensors don't always tell the truth.

Sometimes you can get sensor failures.

And so we spent a lot of time practicing.

And you work out all the different scenarios.

This is what you will see if you have a real failure.

This is what you will see if you have a sensor failure.

And, before you shut down a good working engine, you would like to confirm the fact that it is really an engine problem, not a sensor problem.

On the other hand, you don't want to take a chance that you're going to get into an oxidizer-rich situation and blow up your engine.

You practice and after a while get pretty good at diagnosing the problems fairly quickly.

The computer doesn't normally shut down the OMS engine on its own.

The computer will not shut down any of the propulsion systems on its own.

It will shut down the main engine, but none of these will it shut down on its own.

Somebody has got to take some action to shut it down.

We get an awful lot of data on the ground, too, that you don't have in the cockpit that you can look at different instruments and backup things and try to understand where there is a sensor failure.

Any other questions on OMS/RCS?

During entry, when you're coming down using the RCS for like trajectory guidance before your aerosurfaces are usable, how much propellant would you typically use?

Is there like a certain percentage that would be average?

That's a pretty low percentage, and I don't recall.

That has been a long time now, and I don't recall the numbers.

But I would say it's less than 10% of the propellant.

What did you say?

About 10%.

Well, at least that ought to be a pretty good number.

[LAUGHTER] It's not a lot of propellant come back in on it.

The vehicle is a fairly stable vehicle.

Now, on Columbia, I guess they either ran out of propellant or just about ran out of propellant on it trying to hold it.

RCS was doing all it could to try to hold that vehicle on course after it started picking up drag on one side.

And we actually did have procedures in place for what we called a no RCS entry if you had run out of propellant entirely.

I don't know if it would have worked.

You tried to get it into a stable aerodynamic situation as possible and just hold it there.

I never had to actually do it.

Anymore OMS/RCS questions?

Otherwise, why don't we take a little break and then we will come back for APU/hydraulics.

Two minute break.

Thank you all.

Appreciate it.

You're not finished.

APU/hydraulics.

And I guess I need to point out some acronyms.

Calling the APU an APU was the biggest mistake we ever made.

That gave me more grief than any other system that I had to deal with, the acronym.

APU stands for auxiliary power unit.

And the Aerospace Safety Advisory Committee -- I will tell you, Henry, my kids growing up used to think it was a three letter bad word.

I mean they thought APU was a bad word.

[LAUGHTER] Because every time I got a call there was something wrong with it.

If we would have called it primary power unit then we would have had a lot less grief in trying to defend it to the outside world.

APU/hydraulics, like the OMS and RCS, all of our first activity was directed toward keeping the operational cost down low, keeping the maintenance cost down low.

And we looked at those kinds of systems that gave you clean propellants, easy propellants to deal with and you didn't have to worry about the strong bases and strong acids to work with.

Later on, as time went on, we got more into looking at what we could do cheap from a development standpoint and let the operational cost float, because it is obvious that the money was not going to be there to put into a big development program.

The control of the vehicle in the atmosphere was a major, major activity to try to find out what you could get by with versus what you would like to have.

You try to move these huge barn doors fast and a whole lot, there are huge forces on those things.

It takes lots and lots of power to move them and move them quick.

And our aero people and our guidance people would like to have, like we were talking a while ago, an instantaneous impulse into that vehicle.

When it starts to drift a little bit and they want to move it some other way they like to put an impulse in there and just kick it right back where it is supposed to be instantly.

But that becomes impractical when you look at these kinds of systems.

We started out with dual tandem actuators.

Now, dual tandem actuators is something that fail op fail safe criteria.

In other words, you had two pistons and one actuator driven by two different hydraulic systems and you would move them together.

When you start looking at all of the failure modes associated with dual tandem actuators, even though it meets the fail op fail safe criteria that makes the safety people happy and the people that are looking at the buzz words, it actually was making the system less safe.

Was that because you had a single passenger [using up?] all the hydraulic fluid?

No.

What happened in a dual tandem actuator, in order to get them to work well, if you busted an actuator then that became a big sponge?

You didn't have any way to take that space out.

Trying to have that actuator work when the other half went out made it very, very difficult, from a design standpoint, to come up with a system that you could lock it in place.

And we even had designs where if one hydraulic system failed that that shaft would actually lock itself.

With the absence of pressure it would lock itself.

Well, that becomes a failure in itself because if that mechanism fails then you've got a locked actuator.

One thing you cannot stand on an aeroplane is for an actuator not to move.

We were finally able to convince the people.

And Aaron was having lots and lots problems about that time because all of the weight was in the backend of the vehicle.

The dual tandem actuators were extremely heavy and the backend of the vehicle was getting too heavy, so we actually went to a single actuator.

And we put switching valves in there where we could switch any one of the four APU systems into that actuator.

And we had four APUs at that time.

Weight was still a problem so we were able to convince the community that we could live with three APUs and have one APU fail and come home normal mode with two.

And if you had two failures you could still land the vehicle with one actuator.

You lost a whole bunch of systems but you could still land it with one APU.

And we almost did that one time, because if someone would have told me that we would ever have two failures of the same type on the same flight of the nature that we had I would have never believed it.

But we came home on one flight with two APUs burning.

We had a fire in both of the APUs.

And the reason for that, after the fact again, is very, very simple.

We went through a very good quality program.

We did everything that we needed to on those things only to find out that we had not planned on landing the vehicle in California and piggy backing it back down to the Cape over and over again.

What happens when you do that is that you land the vehicle, there is a little bit of residual APU hydrazine in those tubes between the valves and the injector.

You go back up into a vacuum or low pressure.

All the air goes out of the system.

And then we come and land in Florida.

It is always humid in Florida.

There is a lot of moisture there.

And as that moist air started feeding back in the engine, it went up past the [cat?] bed and got in those tubes between the valve and the injector and set up a very, very corrosive environment of residual hydrazine and water.

And that gave off free hydrogen.

And you had hydrogen or intergranular corrosion in those tubes.

And we had two of them break on the same flight, but it worked.

We spent an awful lot of time looking at power sources to power the hydraulic systems.

And we even looked at going with all electrical systems.

DOD had some very good fuel cells out there that had a lot of promise.

It put an awful lot of power at that time.

Let me just digress a little bit and talk about shuttle fuel cells.

I don't think anybody can cover that.

On Gemini the fuel cells never did work.

We always came back with half voltage or partial voltage and most of the fuel cells out.

On Apollo, it only took 14 PhDs to start them and shut them down.

And then you couldn't start them again.

On the Space Shuttle, those fuel cells, it is just a very, very good battery with the chemicals stored external to the battery.

They would make an outstanding DC welder.

I mean you could put electrodes in that thing and put an electrical rod in there and strike and arc and weld with them and break the arc, strike and arc and weld and break the arc.

And they just do it repeatedly.

You can throw a switch, they are on, you throw a switch and they are off.

And so they are very, very simple.

I really, really wanted us to go with an all electrical system using electrical motors and power hinges and electrical mechanical actuators to drive the systems because I was absolutely convinced that one of these days we were going to have a leak in the hydraulic system.

And when we have a leak in the hydraulic system we are going to have a fire.

All airplanes have hydraulic leaks.

Now, you don't have to worry too much about hydraulic leaks on an airplane.

You have enough pressure where you seldom have to worry about a fire.

We went from 5606 hydraulic fluid to 83282 hydraulic fluid simply because it was advertised as being more flame-resistant.

It is really not more flame-resistant.

The 83282 hydraulic fluid has a much, much lower vapor pressure than does 5606.

And a way that they test it is they have got a Bunsen burner out here.

They take a pipe cleaner and dip it in the fluid, clamp it in this device that rotates past that Bunsen burner and they count the number of times it will go across it before the fire starts.

Well, with 5606, it will usually start on a third burn.

With 83282 it takes 10, 11, 12 passes before it will ignite and start burning simply because it has a lower vapor pressure and you cannot burn any liquid in a liquid stage.

You have to get it warm enough so that it will gasify.

And then you have to heat it enough in a gas phase to get it up to the combustion temperature or put a spark in it after it is in the gas phase.

But it won't ignite as a liquid.

Well, with 6506, if you have a leak in the hydraulic system going uphill you probably don't have to worry about it coming home because it's gone.

It all boils off and is gone.

With 83282 all it does is soak out into the structure and in the insulation and all over the place.

And then when you come back home, if it gets in a hot spot and you start heating it up, it forms a gas and you're going to get an explosion in the back of the vehicle.

So, that was a bad decision, Aaron.

We went in a bad direction, but it gave everybody a warm feeling.

We would have went with an electric mechanical system but, by that time, we had a lot of hydraulic people working on the program.

And we would lay those people all off and we had our whole bunch of electrical mechanical people, and a lot of people were concerned about the immaturity of those systems.

And again it boiled down to development cost.

Did we really have the energy source that could handle that?

Oh, I'm convinced that we could have put six or eight of those fuel cells that we've got on there right now and could have handled it.

Broke it down.

And the fuel cells that DOD had under development at that time were very, very good fuel cells.

If I was upgrading the shuttle today that is one of the things that I absolutely would go to.

I would go to something to get rid of the hydraulic fluid.

It creates a lot of other kinds of problems that you have to deal with.

Actually, before the decision was made that the shuttle was going to be retired in five years, NASA was working on upgrades if we were going to fly the shuttle for another 20 or 25 years.

And one of the upgrades, which actually got to a fairly advanced stage in the design, was just what you were saying.

Get rid of the APU/hydraulics, use the latest technology now available for electromechanical actuators.

But the problem, I don't know the details of it, but the costs just kept going up and up and up.

And by the time it went up above about $300 million they just said we cannot afford to do this.

The problem we always had in trying to upgrade the propulsion, we could have gone to an alcohol/LOX space RCS/OMS on it.

We could have upgraded to an electromechanical system, but it seemed to me like that the displays and those kinds of upgrades took a lot of computers.

Those systems took a lot of priority in where the monies went in trying to upgrade the Orbiter.

We did go from four to three systems.

We did go from 4 APUs to 3 APUs and still having the ability to land the vehicle with one APU.

We look at hydrogen/oxygen APUs.

We looked at bipropellant APUs.

We looked at monopropellant APUs.

We looked at pulse modulated versus pressure modulated.

If you don't know what I mean by that, pulse modulated is when you have a valve that goes open and closed and you get steady state pressure in your gas generator while it is on.

Pressure modulated you have a throttle valve where you throttle the flow down going to the gas generator to give you just the power that you need for the load that you are trying to pull at the time.

And that was the easiest system to come up with simply because we did not know at the time if we could build a valve that was capable of millions and millions of cycles and not a leak.

But the problem with a pressure modulated system was that most of the time you're operating at very, very low power levels.

The power just peaks up every once in a while to high power levels.

But when you're running very low pressures in a gas turbine, the turbine becomes less efficient.

And the less efficient the turbine becomes the more propellant you have to burn and, again, the weight goes up.

So we kind of bit the bullet on that and went to a pressure modulated system where we varied the ohm time.

In valve development we were very successful.

We had very little trouble getting a valve that would work, except for contamination.

We always had a little contamination.

We had a lot of problems down the Cape with early valves leaking.

We finally put good filters in the system and that eliminated that.

Yes.

Was the reason to go from four to three APUs just a weight issue?

It's again a weight issue.

All of that weight was in the back of the vehicle, and the back of the vehicle was always too heavy.

And every time we could take a pound out of the back of the vehicle, we could take a pound of ballast out of the front of the vehicle, so there were two pounds you didn't have to carry.

So, it was strictly weight.

I'm sorry, the APUs are turbines?

I mean you're combusting [UNINTELLIGIBLE]?

The APUs we settled on was going with a monopropellant hydrazine, feed that through a catalyst bed and then through a turbine.

We looked at dual stage, triple stage turbines.

We finally wound up with a single stage turbine running at about 38,000 to 45,000, I don't remember the exact number now, RPM.

About ten inches in diameter [UNINTELLIGIBLE].

The gas went in and then made a pass and went back through, so we got maybe 5%, 10% more power out of it the second time through, a little bit more power out of it the second time through.

When we contracted for the APU, the contractor did not have altitude facilities.

And so they proposed that we did not need to test the APU in a vacuum because that was all structure and all they had to do was pull a vacuum on the exhaust and could get the performance out of that.

So we did not have it in our quality program to test the APU in a vacuum.

Fortunately, Dr.

Cohen gave us enough money to buy an APU offline of the Shuttle Program.

We brought it down to JSC.

We put it in our vacuum facilities there.

And we programmed the vacuum facility to go down in pressure.

The Orbiter was going up in altitude.

And we ran the ascent profile and shut the APU off just like we would on a first flight.

And five minutes after we shut it off it exploded, it detonated.

I mean talk about things coming unglued.

Everything came unglued.

Aaron came unglued.

We got another APU.

We brought it down there.

We brought all of the contractor people down, everybody down there.

We repeated the test.

It exploded again.

[LAUGHTER] By that time we discovered what the problem was.

We have a requirement in the program that you can only have hot surfaces up to about 500 degrees.

I don't remember the exact temperature, but some temperature like 500 degrees.

If it is higher than that you have to shield it.

The gas generator is obviously running over 500 degrees, probably up around 800, 900 degrees, so we put a heat shield around it.

We covered that whole thing up and had about a half-inch standoff in the insulation on that thing.

When you run it in one atmosphere, if you shut it off it acts like a chimney.

The air heats up between the insulation and the hot surface and goes out the top.

It draws cold air in.

It goes out the top.

It draws more cold air in so it cools it off.

So the heat never did soak out into the valves and get the valves too hot.

When you put it in a vacuum there is no place for that heat to go.

And so all of that heat that was in the gas generator and all of the catalyst and all of that soaked back out through the structure and through the tubes back up to the valves and got the valves up to the temperature at which hydrazine will detonate.

And it did.

It is so simple.

It is so easy to understand after you know about it.

But to think about it, I remember sitting around there one night to 8:00, 9:00 with all of my troops discussing the pros and cons of an altitude facility.

Do we have to have it?

Do we have to direct the contractor to put one in?

And we could not come up with a good reason to put an altitude test in the program so we didn't put it in there.

Fortunately, just like on ohms with the helium bottle falling out, we had a backup because some of the people weren't confident in flying the vehicle without that test.

And we found something that we didn't expect.

The message that Henry is giving you on testing is the same message that J.R.

Thompson gave you on testing on the main engine.

And, in contrast, we didn't really do that type of testing on the solid rocket booster, the fair we had and on the foam.

And that is the difference, we really tested.

When we saw a problem we tested it.

And we came out very fortunate, but we did do it.

Another thing with the development of the APU, we flew those things on airplanes all the time in case they lost main engine, our fighter aircraft and then some of the other airplanes including that supersonic plane that we had.

It had APUs in there in case they lost engine power to provide hydraulics to be able to land the vehicle.

And that got a lot of the flack because the Aerospace Safety Committee told me that those systems never did work because they're called auxiliary power units.

They never worked when you needed them.

But they had those systems.

And they were good systems.

But when we tried to use that same kind of design on the Shuttle the oil wouldn't go back to the sump in the absence of gravity.

You sling it out and it just coats the walls on an automobile.

You put an oil pan down the bottom, you put a pump right at the bottom, you put a little filter in there and pump the oil out and pump it through the engine and use it over and over and over.

But when you have no bottom, you have no place for that oil to go.

So we had to come up with a technique where we could use the gears as oil pumps.

And we came up with very, very close tolerances between the gear and the case, and let the gear sling the oil out or pump the oil out into a cavity and pipe it off to where we had a sump to where we could pick oil up with an oil pump and pump it back through the system.

And we had some problems with some hydrazine getting in there and gelling it one time.

And Fram came out with this deal where you could pay me now or you can pay me later kind of thing because they still aren't changing the oil filter.

Hydraulics was mostly off the shelf at the time, the pump and that stuff.

We did go to titanium propellant lines or hydraulic lines.

We did develop a special fitting to put titanium lines together.

It turned out to be very, very good.

We did have to add a water boiler to cool the hydraulic fluid because on airplanes just put a little radiator in there and use the atmosphere to cool it, but that didn't work in space.

The first one they came up with was a bucket and it had a core of tubes in that bucket with a pipe that went out with some baffles in there to keep the liquid from going out.

But there, again, they did not understand the absence of gravity.

When in zero G and you put heat in that water, it just pushes the water out away from the tube.

And all the water would go out the exhaust pipe and you would have nothing but gas in the tank.

We had to change that design and go into what we call a water spray barge.

To pulse the water in there as a spray is more efficient.

But complicated that system very much.

It still does.

It is very, very difficult to handle water in a vacuum.

Getting back to the RCS one moment, the first rain we had down there at the Cape, the RCS jets filled up with water.

And they wanted to launch that system assuming that the water would boil out when they started going uphill.

But, no, what happens is when you put water in a vacuum, about 60% of it will go to a gas and 30% will freeze.

When it freezes then it is a solid, you cannot get it out, it just has to sublime which takes weeks and months.

Now, trying to get us a water boiler, we had valves in there that were supposed to open and close when the pressure built up.

Well, when you get past that valve, when that valve would open up that steam would instantly freeze on the outside and it keeps growing back.

Finally, the valve would be stopped up and you would build the pressure up way high and would blow the ice out.

The pressure would come back down and start working again.

So, we went to an orifice.

Trying to size that orifice to the right size where it maintains a little pressure in there, and you've got a variable load on the system and you're putting variable energy into it, that's difficult to design that, too.

The water boiler still freezes.

We still have a freezing problem on it.

It is not an easy solution to it.

Questions?

Do you lose that water?

Yeah, we just dump it overboard.

We have a whole bunch of tubes going through this water, and we spray the water in, in a spray.

And it makes one pass through those tubes and then it goes out the exhaust.

If you wanted to come up with some kind of regenerative system where you would use the water over and over and over then you've got to go through some kind of system to cool the water or you have to carry too much water aboard.

Well, if you want to cool the water, the only way you really have got to cool it is by using more water or supplementing some of that water.

In a vacuum, you cannot just put it out on a surface some place.

I guess the temperature varies maybe.

Henry, could you say a word about the flight control hydraulics lab, the tests we ran with the hydraulic systems.

The hydraulic system was probably one of the most thoroughly tested systems that we had as far as mechanical systems were concerned.

We built a whole hydraulic system integrated with the avionics, and we had it designed so you could put loads on it and react the loads.

And you could program in what you thought was typical emissions where you could vary everything.

The only difference is instead of driving the hydraulic pumps with APUs, we drove the hydraulic pumps with electric motors because we had ground-based electric motors to drive them.

And one of the things we ground ruled out was the use of flex hoses -belts- simply because they, at that time, were notorious for fatiguing and breaking and not working very good.

So we put trombone tubes in.

Take a long tube and bring it back this way and tie it in.

And now, as the actuator moved, it could move.

And you had enough spring or enough give in those tubes.

On the very first time they fired that thing up, standing up in there in the control room looking at it, those trombone tubes just vanished.

They would be there and then all at once you wouldn't see them.

And I mean you couldn't see them.

You're standing up there in the control room looking and there are no tubes in there.

They were shaking so bad that you couldn't see them.

So we went through a big effort to figure out ways to damp those things and isolate them so that they didn't vibrate.

We had a major failure.

It was a hard, hard sell to convince the people to go to a single actuary, from a dual tandem single actuator.

Well, no more than we got our first single actuator built, the initial design had too much slack in a tube that went from one side to the other side because you had to have an expansion joint in there.

And we had an O ring in there.

And they had too much slack in there and it blew one of the O rings out.

Well, of course, when you blew an O ring out you lost all the hydraulics not only from that system but all three systems because it was downstream of the switching valves.

And when one system ran out of fluid it would switch over to the other one and you would run out of fluid.

Had we not had a very, very strong guy in the Program Office at that time that never gave up on anything that would have probably finished us off as far as single actuators are concerned.

But we were able to convince the program that if we tightened the tolerance up on it, paid very close attention to the tolerance on it that it could not happen.

And it has not happened again.

Another question?

Yes.

You talked a little bit before about maybe substituting an electromechanical system for hydraulic.

Would there be any other changes you would make in the design if you had to go back and do it again?

Oh, if I had to do it again, I definitely would go with electromechanical systems.

Now, that takes on many varieties.

You could have small electric motors driving a hydraulic system right at the unit.

Like you put an electric motor on an actuator.

And that electric motor drives a small hydraulic pump that would move the actuator if you did not have confidence in worm gears and screw jacks and those kind of things to provide the mechanical force, power hinges and things like that.

But there is absolutely no question in my mind that one of the safest things you could do for the Orbiter right now would be to replace the APUs in the hydraulic system with an electrical system.

We have the motor technology, we have, I think, the gear and the ball screw technology to be able to do that.

I think we could do it cheap.

I think that would really change the operational cost.

It would reduce the operational of cost immensely.

It would move the CG further forward on the vehicle so you probably could take out a little bit more of the ballast that we usually fly on the front-end.

I guess we're still flying it.

We always did.

I have another question.

You talked earlier and you had it on the slide, but you didn't really talk about it, how you were shifting weight between budgets, when it came to like the controls people versus the hydraulics people and the APUs.

And I was wondering if you could kind of just expand on that of how, in an actual development program, it goes back and forth.

I mean does it usually come down from high you're going to do this and you're going to do that, or is it usually they let you kind of work it out between the groups or what?

The control people have no weight budget.

I mean their budget is the electrons that flow back and forth and the requirements.

What they do is they start out a requirement that they would like to have.

And it is usually two, three, four times what they absolutely have to have.

And then you have to sit down and start negotiating with them and explaining to them what it is costing.

And often it gets down to the fact that the vehicle won't fly.

I mean it just flat won't fly.

And when they are convinced then that it cannot fly then they are willing to concede that they can get by with a little more.

And it still won't fly and so they can get by with a little bit more.

And that's kind of the way you get it done.

That's what you do.

You have a work breakdown structure, and you parcel that work breakdown structure out to your subsystem managers.

Now, there was an issue in the Shuttle and the Apollo Program, since I was a project manager, you give the subsystem managers the requirements and the authority technically.

You tell them what their constraint is for dollars, you give them the weight bogies or the weight requirements, the function requirements, performance requirements, the schedule requirements, but you keep the dollars.

Now, that's been a very long argument.

Do you allow the subsystem managers to actually have control over the dollars?

We decided not to.

That was a very big argument of whether you should let the other people have the dollars.

I kept the dollars.

They had to come to me if they wanted to make a big change outside their work breakdown structure because I had the problem of trading off the dollars between the propulsion system and the structure system or the aerodynamic system.

And you can argue that was the right or wrong thing to do but that was how we did it.

And I am not sure if aircraft companies like Boeing now or Lockheed Martin how they do it, but they all start off with a work breakdown structure of some type.

Yes.

At that stage,do you also give them target weights?

You can target weights also, yeah.

Negotiated target weights and negotiated schedules.

And they develop the performance.

You basically use the target weights, from the preliminary designs that you've done, to look at the concept that you're looking at to make sure that it is feasible.

And when it looks like that is a feasible design, then you break up the weights and you give all of the subsystem people their target weights to stay within of which almost immediately the weights start growing.

That's right.

And, when you're a project manager like I was, it is career limiting.

The first thing is your weight starts to go up.

The next thing is you start to have schedule slips because you're finding technology problems.

And then the cost starts to go up.

You really come with a lot of career limiting problems in project managing, but you have to have good people working for you.

I think, Henry, another interesting thing you might talk about is, they've seen Bass Redd talk about the aerodynamics, they are going to have Phil Hattis talk about the guidance, navigation and control, you might give them your perspective with the hydraulic system of tying those systems together.

You mentioned it a little bit but it is probably a little bit harder than you think in putting the requirements on the hydraulic system.

I probably spent more personal time dealing with the avionics people, the guidance people and the aero people than I did working with the subsystem designs early on just trying to get some reasonableness in the requirements.

Trying to get the size of the OMS engines down, trying to get the size of the RCS down, trying to get the pulse width a little bit wider.

On the hydraulics, that was a major, major issue because those were really big weight items.

On the OMS and RCS it was not a big weight impact, it was a performance impact of how much propellants you had to carry onboard.

But on the hydraulics, on the design of that system, how fast you had to move one of those flaps on that thing was a big big issue.

And I spent lots of time going over and looking at their data, looking at what they were coming up with, looking at their what-ifs.

That is what drives a system, is what if this happens or what if that happens?

Another problem I remember we had was the gimbal rate of the main engines.

The requirement they put on the gimbal rate.

That was a compounded problem, too, because you were kind of dealing between centers.

But, yeah, the gimbal weight.

And the need for a gimbal system on the solid rocket motors, if I had my day in court, we would take the gimbal system off of the solid rocket boosters.

That would save six or seven or eight tons of weight back there.

If you would take that system out, it would make the solid rocket boosters much more reliable because they've got those great big old boots in there and those big springs.

They horse those things back and forth with huge actuators on them.

And the only reason we could not eliminate the gimbal system on the SRBs is that we had one SRB that burned out with the max burn time.

And the other one on the other side burned out with minimum burn time.

And we lost the top engine on the SSME on the same flight.

Now, you know the probability of that happening is once in a billion.

But, yet, that is what drives the requirement for having the gimbal system.

We would have to gimbal the main engines another two degrees to make that work.

But that is what drove the design, that requirement that we have on the solid rocket motors.

So, if I can leave you with one message, it is understand your requirements extremely well and understand the impact that that requirement is having on your system and on the flyability of the vehicle.

I told you that Henry had a lot of innovative design.

Talk a little bit more about the RCS.

I thought you were going to mention that before.

When they got water and how you solved that problem.

This is Henry Pohl's solution to a very complex problem on the RCS system, on the pad.

When we got the RCS engines filled up with water we needed to come up with a design to keep the water out of the engines in case of rain because it always rains at the Cape.

So that requirement fell on the contractor to design a system to keep water from getting into the RCS engines.

They came up with a plug with the throat and another big seal to go around those big scarf nozzles out there with an O ring on that.

And that was all tied together with cables.

And they stuck a big pole upside the vehicle.

And just before liftoff they were going to pop that pole over and jerk all of that stuff out.

And they were going to jerk it out fast enough so that those big tanks would not fall down and hit the tile and knock all the tile off.

Well, that looked kind of complex and complicated to me.

We had a grocery store across the street by the name of Wine Gardens, and I went down and got a roll of that wrapping paper that you use to wrap meats in that has wax on one side and then paper on the other side.

I call it butcher paper, but butcher paper is actually a little bit different.

If you go down and buy something it is freezer paper, but I bought a roll of that.

Then I got back up into the meeting by the time it was over and said this is the way to fix it.

And I started tearing off sheets off and passed it around to the managers to look at.

We are going to glue that on the surface with the wax side out and glue it on with RTV.

And then, when you lift it off, it would come off.

It was light.

It wouldn't hurt the tile.

If it impacted anything it wasn't going to hurt anything.

If it didn't come off when you fired the RCS you would blow it off or burn it off.

And that is what we did.

And we glued that on all of them.

[LAUGHTER] It sounds funny but it is true.

You look at the Orbiter sitting on the pad and all the RCS jets are covered up with paper.

But after I left they changed that.

They changed from butcher paper to a special paper developed special for that purpose that is made out of Teflon.

You have to tell them one more story about the SSME on the launch pad and the hydrogen.

This was JR's.

When we did the first firing on the pad -- Just a test firing on the launch pad to make sure that everything worked right, we blew the back end out of the shuttle.

When those main engines light off, each one of those engines dump out about 125 pounds of hydrogen before it ignites.

That hydrogen is cold.

It is fairly dense in liquid form.

It is 4.5 pounds per cubic foot or something.

By that time it is a little bit lighter.

It goes down in the flame pit.

It mixes with a lot of air in there.

And then the flame hits it and detonates.

And it blew the backend out of the vehicle.

We needed a quick fix because we're going to launch that thing in three or four days.

I looked at the problem and said we will just put Roman candles under it.

You put a bunch of Roman candles under there that fire those balls out across there and the hydrogen comes out.

That will ignite the hydrogen.

It will burn and won't accumulate behind the pit.

And that is what we did.

Those sparklers you see coming on before the main engines light off, those are my Roman candles.

And as long as we're talking about blowing the back end of the Orbiter out, maybe you can talk about the pressure wave as well.

The pressure wave that came back and the water suppression.

We had another problem, more of an acoustical problem from the pressure waves coming back up under the Orbiter, and we needed some kind of a solution to do that.

Back while I was in Huntsville as a test engineer in a test lab there in Huntsville, we blew the windows out seven miles away when we started firing the Saturn 5 vehicle.

We spent a lot of time on sound suppression techniques to reduce the pressure effect.

And one of the things we came up with is we found water is very good at damping that.

When we had that problem down the Cape what we did is put those sausages, the hammocks across down there and fill them with water to damp out the pressure wave that came back up to the back of the vehicle.

There is another one of them.

Essentially like big water balloons.

We called them sausage.

It was a fabric across the bottom, filled it up with water and it was strong enough to hold the water up.

And then that dampened the sound waves, the shockwaves that came back up through the vehicle.

Again, just remember that it is not natural for earth-bound humans to think in terms of the absence of gravity and the absence of pressure.

I cannot stress that too much.

You take a pot of water, you put it on the stove and it gets hot on top.

You put it on a stove at zero G, it does not get hot on top.

It pushes all the water out.

Heat transfer.

You don't realize how much heat is transferred out through the atmosphere.

If you have no atmosphere you don't get any of that heat transfer out.

The other thing to remember is that there is absolutely no substitute for a very well thought out test program.

It is not easy to test in the absence of gravity.

It is not easy to test in the absence of pressure when you are reducing large quantities of gas or chemicals.

But that is very, very important.

And that is the one thing that really separates a space program from anything that we do here on earth, is that you have no atmosphere and you have no gravity to help you in your design.

Yet, all of our thought process is based on having gravity and having an atmosphere.

And some of the designs of various experiments that I've worked with on Spacelab flights

and other flights, numerous failures. And over half of the equipment that failed, this is stuff generally that we use inside the shuttle, it was because of thermal problems that they would overheat just because people didn't get the calculations right.

You have no convection.

And getting the thermal design to work is just really difficult.

Convection is one of the major problems that is overlooked because when you put heat in one place on the ground it goes up.

If you take the gravity away it will not go up.

And that changes the whole complex, the thermal matrix.

Henry talked a little bit about the screen system that was developed for the OMS and RCS tanks, but just to make sure you appreciate the complexity of this, you've probably seen pictures of astronauts playing with food and liquid, you blow these big liquid bubbles and they just sort of float there.

Well, the liquid does the same thing inside a fuel tank.

And when you push the button because you want to turn your engine to turn on, how do you get the fuel to flow into the engine?

And, as Henry said, in the old-days you had kind of a diaphragm.

Everything was in like a little balloon and you would pressurize the outside of the balloon and that would force the fuel out, but that balloon would get eaten away.

I mean remember that was a system that is only used for one flight.

Now we have a system that has to be reusable.

And if you didn't want to replace those diaphragms or balloons every flight you needed something that was a different system.

And that is where they came up with the idea of the screens which would have surface tension so enough of the propellant would stick to the screen.

And then you would get the helium on the other side that would push it out of the screen.

With the OMS, of course, once you got the system started then you're producing an acceleration.

And it is always in the same direction so that the OMS tanks are designed so that they only have to feed enough propellant through the screening system to get the engine started.

And then everything, I won't call it gravity-fed, but is fed by the acceleration.

When both engines are burning, it is about a tenth of a G.

But the RCS, that can push you in any direction.

And so you have to have a system which will continuously feed, no matter which direction your acceleration vector is.

It is a really complex and cleaver system.

And the design is based strictly on surface tension.

Why are there so many RCS engines?

For example, in the nose, there are 16.

Is that for redundancy?

Part of it is for redundancy and part of it is to make sure that you've got one to cover every direction.

I guess we've got six going down in front.

Now, we need two of those for certain maneuvers.

So you can lose four of them.

And we have four going out.

You can lose one on either side.

And remember you need a couple pair.

You would like to be able to do a pure rotation.

If you just fire one engine in the aft you're going to get a rotation, but you will also get a translation.

So, you need a couple pairs.

And then for redundancy we have three sets.

If you add up the x-axis, the y-axis, the z-axis, you've got to be able to translate in three axies, you've got to be able to rotate about three axies, and then you need dual redundancy for each of that axis.

You add it up and you end up with 38 primary jets.

And then, on top of that, those are 850 pound jets.

They use a lot of propellant.

When you are in orbit generally and all you worry about is your attitude and you're not doing a propulsive burn for rendezvous or anything, we shut down the primary RCS system and we just use six little 25 pound Vernier thrusters, all of which are pointed down.

When you use those for attitude control they do give you a little bit of propulsive impulse as well.

But it is a small enough thrust that it doesn't change your orbit by very much.

Let me tell you another story about the expulsion devices on the Shuttle.

Back in my young days, I grew up in the country, and we had a Ford tractor.

The Ford tractor had a screen in the fuel tank and it stood up about that tall.

And it had a little stand pipe in there.

And the valve was such that when you got down you could set the valve one way and it would leave about a gallon of fuel in the tank.

You turn it the other way at the end and it would use that gallon of fuel out, kind of like a gas gauge on the early Volkswagen.

Well, what happened is that I had that out one day and it had a tenth of an inch diameter hole punched in that screen about halfway up on the screen.

I said that screen is not doing any good if it has a hole in it.

I got me a ball of solder and I stopped up that screen.

You know, after that, you could have it set where the fuel are supposed to remain in the tank.

And when it quit it was empty.

You'd switch it over and it still wouldn't run.

You couldn't get home.

You would have to walk home.

Well, it turned out that they had put that hole in there as a vacuum breaker to break the vacuum on it.

And that is the way that the Shuttle system works.

The screens that we have in there, it is fine enough so that the surface tension across those small pores is strong enough so that it will keep the air from punching through, unless you put a big hole in them.

We had to make sure.

And that was another one of the things that convinced me that we could design a screen system that would work in the absence of gravity.

It goes back to a Ford tractor.

It goes all the way back to 1947 and a Ford tractor.

Henry, we've come to the end.

Let's thank Henry.

[APPLAUSE]