Today Dr. Robert Ried, Bob Ried, is going to talk to us about aerothermodynamics.

He got a bachelor's in Mechanical Engineering here at MIT a few years ago, and then went on to get a doctorate at Rice University.

And he has done a lot of things.

You all have the biographies on the website so I hope you've looked at that.

And, like I say, it is better for you to read it rather than me to take five minutes at the beginning just going through it.

But he has played an important role in developing both the theory and the practice of atmospheric reentry both for Apollo and the Shuttle.

And, in fact, in many ways the experience gained through Apollo allowed us to design the systems for the Shuttle.

And so he is actually going to talk about both Apollo and the Shuttle, comparing and contrasting.

And I think it is going to be a very interesting opportunity for all of us.

And I am going to let Professor Cohen say one or two more words.

What I want to say is that Dr.

Ried has done a fantastic job in understanding aerothermodynamics.

If you look back on Apollo that was one of the technologies we really didn't understand.

Coming in at 36,000 feet per second from the moon in various atmospheres, what was going to happen?

And, in that era, we had to do a lot of research and development to understand the methodology of doing aerodynamic heating.

The systems engineering comes in as you heard Bass Redd talk about the aerodynamics, you heard Tom Moser talk about the tile system or the thermal protection system, and Dr.

Ried sort of tied that together.

Because he actually came up with based on the trajectory you were flying, based on the atmosphere, based on the materials that you had, what the surface temperatures were going to be and how you designed the thermal protection system to withstand those temperatures and still maintain the back-face temperature at a suitable level.

I have a couple of displays for you, and if you can start looking at them.

The first is a specimen that came out of Apollo 10.

That was a Lunar orbital mission, and it is a core sample out of an ablative heat shield.

It shows you the thickness of a thermal protection system was about two inches, and the depth of the char layer is about an inch.

And we always used to give Dr.

Ried a hard time, why couldn't we take some weight out of the heat shield?

But he always said he never flew the Design Reference Mission.

And he will talk about that a little bit.

So, that is one specimen.

The other specimen is a tile that flew on the 102 mission four times, I believe, that it got to 2800 degrees Fahrenheit.

The ablator got to 42,000 degrees Fahrenheit.

These will give you some examples of what the results of Dr.

Ried's work was in terms of designing the ablator for the Apollo vehicle and the tiles for the Shuttle vehicle.

That is really a systems engineering job.

I hope you can appreciate understanding the aerodynamics, understanding the guidance, navigation and control trajectory that you fly and understanding the materials that you're going to use.

That is really a systems engineering problem.

Let me now turn it over to Dr.

Ried to put all the details together for you.

Thank you.

Good morning.

We are going to try to cover an awful lot of ground here in short order.

First, I am going to try to go through aerothermodynamics in terms of the discipline and give you an understanding.

I am going to try to relate to what you've had in your basic heat transfer and fluid mechanics courses to actual application and where the technology is today.

I am also going to, as Aaron said, go back to Apollo which is really where the rubber hit the road in terms of being able to enter things at those types of velocities.

And then I will get into how that affected the Shuttle.

And the Shuttle is a revolutionary system in many ways, but particularly in terms of the technology associated with aerothermodynamics, computational fluid dynamics in particular.

And I am really going to talk about three levels of aerothermodynamics which I will explain as I get into it.

And then I will try to get into the systems engineering, as Aaron mentioned.

And, in fact, one of the major differences between Apollo and Shuttle, which we had to accomplish, is a significant accomplishment in systems engineering which I hope to get into.

First, I don't think people generally appreciate the perimeters of what we're working with.

Traveling at orbital velocity due east 25,000 feet per second, that is about five miles a second.

And the Orbiter is about a quarter of a million pounds.

And, I am sorry, I am going to use a lot of English units.

A quarter of a million pounds is a pretty good sized system.

Picture that at Logan Airport and one second later in this classroom.

That is five miles a second.

Another way of looking at it is that is about 125 tons.

If you take a supertanker, about a half a million ton, and just convert the energy, that supertanker would be traveling at 250 knots.

That is the energy that we have to dissipate.

Norm Augustine introduced the concept of rocket scientist.

Our job was to dissipate that energy.

If I was coming back from the moon that supertanker, which is about a billion pounds, a half million ton, would be traveling about 400 knots.

Almost twice the amount of energy.

Actually, the whole problem was relatively simple.

Basic parameters are first free stream density of the air that you're flowing into, the velocity that you're moving at and unit area that the mass flux is just density times velocity.

The momentum that that air has relative to you per unit mass is the velocity, so this is the momentum flux which basically is the pressure to a very high accuracy.

The energy that the gas has relative to you is one-half V squared.

And so we're looking at an energy flux coming to the vehicle one-half rho VQ.

Those are very important parameters.

Now, I am going to focus on accuracy and not on precision.

People have gotten lost in details in terms of getting parameters.

If you've got density and velocity, you basically have the gas parameters with some major exceptions which I will get into.

And that is relative to the equation of state, if you want, the constitutive relations.

The other thing is the geometry which is the major difference between the Apollo and the

Shuttle. All right.

Now, let's go back to the Apollo system, a nice, simple system flying at angle-of-attack.

One of the first problems that I was introduced to was a newspaper publication saying this system is going to burn up.

It is going to burn up from the thermal radiation from the gas cap.

Now, let's consider coming back initially at 36,000 feet per second.

Peak heating is around 33,000 feet per second, 10 kilometers per second if you want.

We've got a shock free stream density.

At some point, we get to ideally equilibrium air.

Out here you're basically at ambient temperature of ten to the minus four, ten to the minus three atmosphere density.

Here, once you get to equilibrium, you're operating at a temperature of about ten to the fourth degrees ranking.

The effective black-body radiation from the sun is 10,000 degrees ranking.

The distribution in terms of the spectrum.

That is the temperature of the gas at equilibrium.

At the wall of the vehicle perhaps 6,000 degrees ranking.

And we will get into that a little bit.

But what happened was there were experiments done in shock tubes indicating some very intense radiation.

This gas is hot enough to radiate.

And, in fact, at the peak heating about half of the heating is from the gas radiation.

The gas is ten centimeters thick, four inches, and yet it is hot enough and radiates enough that the heat transfer from that radiation is almost comparable to the convective heating.

The load is another matter.

But what happened is out here you've got molecular oxygen and nitrogen just sitting there at ambient temperature bouncing along.

All of a sudden it is swept up by this snowplow.

The degrees of freedom basically two rotation, three translation, five degrees of freedom, the gamma of 1.4.

Go through a shock, the density ratio is only a factor of six.

Here the density is 15 to 20 times free strain density.

And the temperature goes to 100,000 degrees ranking if it just stayed as a molecular gas.

Now, in fact, that temperature has no meaning other than if all the energy went into translation and rotation that would be the temperature.

Let me just plot temperature as a function of distance.

And these were monitored in shock tubes.

We worked predominantly at AFCO with an electric wired discharge in helium.

And we could get to ten kilometers per second or 33,000 feet per second.

Conceptually, what happens is if you plot temperate as a function of distance here, ambient temperature is negligible.

Initially, theoretically, you've got this ten to the fifth, so your translational temperature comes down to ten to the fourth.

And I will talk about the dimensions here after a while.

But the initial collisions, I mean basically the molecules are piling up into other molecules.

Quickly, you have collisions that give rise to vibration, ionize the electronic energy levels in the molecule.

Once it is vibrating it will also dissociate, so then you've got ionized atoms as well.

And we have characterized these as basically temperatures, a vibrational temperature.

Again, this is a very non-equilibrium situation so the concept of temperature really goes away, but it is sort of a measure of energy to equate, for example, vibrational and electronic.

Now, what happened was I mentioned how significant the radiation was from the equilibrium.

In the shock tube, the radiation in this region where the energy has not distributed itself into an equilibrium level was two orders of magnitude higher.

That led to the publication you cannot bring people back from the moon.

That radiation is just going to vaporize the capsule.

Now, things were with us.

The time to relax and the measurements of radiation, if you want, were extremely intense and then they relaxed to equilibrium levels.

It turned out that we used what was termed a binary scaling.

This relaxation distance depended on how many collisions you had.

Collisions depended on the pressure.

The pressure depended on the density.

The velocity is fixed coming in from lunar conditions.

It gives you the pressure.

In the shock tubes, we couldn't quite get to the low pressures that we had on Apollo.

And I will show that in my first chart, actually.

But what happened is at the pressures that we experienced, this distance came to be very small.

And that increased the rate so that even though we had two orders of magnitude higher radiation intensity, it was two orders of magnitude smaller in radiating volume.

And so the non-equilibrium radiation actually turned out to be a little less important than the equilibrium radiation.

Now, the point is that before we went to the moon we didn't have the foggiest idea of what was going on.

We knew that you couldn't use ideal gas, we knew that you had to go to equilibrium, and everybody was worried about trying to calculate equilibrium accurately.

All sorts of charts and tables.

We didn't have the computer capability that we have today.

Everybody was focused on equilibrium, but then initial results in one of the major facilities for aerothermodynamics which is basically a shock tube.

Does everybody understand a shock tube and how it functions?

Basically, it is a one-dimensional situation, just like I've described here, but the way it is generated is you have a driver section and a driven section.

In the driver, you try to get extremely high pressure with a high speed of sound.

Here you have a diaphragm.

Here you have, if you want, rho infinity.

This is the density that you're trying to test in.

What we had was an electric wire that exploded, got into the helium, went to tremendous pressures.

Basically, these were all battleship guns, if you want.

And we had to go to a two-inch diameter tube in order to get close enough to the Apollo.

Basically, you start with a pressure distribution that looks like this.

This is pressure as a function of distance.

Once you discharge there is a diaphragm here.

The diaphragm cannot take that pressure.

The diaphragm blasts and you get an expansion wave coming back here and a shockwave traveling in that direction.

The reason we had to go to two feet is you get a boundary layer building up.

And if you want some test gas -- I've kind of go this reversed here.

In here you've got the shock, you've got a boundary layer building up and, if you have two small tubes, the boundary layer will suck up the gas and you don't really have a test condition.

But AFCO worked everything out very nicely and we had a very nice test condition.

We basically had this condition going by, a little higher pressure than we experienced on Apollo, and we could measure the radiation.

The challenge at that time was the instrumentation and a quick response capability to measure all that.

We learned an awful lot.

We went from ideal gas like you get in Shapiro to real gas equilibrium.

In fact, James Fay, in course two, had done some real pioneering work looking at stagnation point heating and a gas dynamics.

I am getting kind of lost in that detail, but basically this was the phenomenological aspect that we had to understand in order to work with Apollo.

This was not why we had twice as much ablator as we needed, and I will get to that later.

Second area, what I'm talking about here basically is fluid convection and some chemistry or physical chemistry.

The next significant item is diffusion.

The simplest case, obviously, is thermal diffusion.

The first thing you learn in unsteady heat transfer, you have a one-dimensional situation, temperature initially, and you have a heat input.

You end up with a distribution of temperature which diffuses out.

The functional form of that, if you recall, T is proportional to an exponential, let's call this X squared over four thermal diffusivity times time, and there is the square root.

Think of it as a one-dimensional normal distribution.

Except instead of two variant squared here you've got four times the diffusivity time.

The significant thing is when we talk about ablators, when we talk about tiles or thermal protection systems, this is the significant parameter.

We have an extremely high temperature at the surface.

The job is to keep that from the structure.

Thermal diffusivity is prime parameter.

It is also, not thermal diffusivity, but if you now consider simplest fluid mechanics, flat plate, the first thing you learn about in terms of viscous flow.

You've got some velocity coming along here.

You've got a boundary layer that builds up.

The boundary layer compared to X varies as one over square root of Reynolds number.

Where does that come from?

The same diffusion.

It is a diffusion of the shear of this wall against the undisturbed flow, whether it be the thermal diffusion associated with heat transfer, the diffusion associated with the shear, the same phenomena.

When I first found this in fluid mechanics, I was told that was empirical.

And it basically is, but it really goes back to the fact that if you approximate the Navier-Stokes Equations in this one-dimensional situation you basically have a convection in this direction and a diffusion in the [UNINTELLIGIBLE] [Unthougtable]direction.

This is extremely important, not just in terms of boundary layer but also in terms of the Stanton number which is approximately heat transfer divided by one-half rho infinity V infinity cubed for the case of a sphere.

Now, this is a one-dimensional, obviously, flat plat.

A sphere is also one-dimensional.

If you look at a stagnation point on a sphere, this is a singularity.

If you go to spherical coordinates you've got basically the same phenomena.

The diffusion from the wall gives you characteristic dimensions.

It is very important because heat transfer is basically inversely proportional to the square root of the Reynolds number.

We have square roots showing up in the thermal diffusion.

We have square roots showing up in the heat transfer.

Now, when you put in the effects of real viscosity and everything else there is a little variation.

But first order is the behavior that we are looking for.

And that I will illustrate now.

If we go into a wind tunnel and we measure, well, let's just basically go to fly.

Let me do local heating over the energy flux.

I am going to do a logarithm of that as a function of log of what I'm going to call a normal shock Reynolds number.

All I do, as I go across the shock, the density of velocity -- The mass flux is conserved, obviously.

The viscosity is what changes.

I am going to use the normal shock equilibrium air viscosity because that is more characteristic of everything going on in what the Russians call a protective shock layer.

If I looked at either the wind tunnel data or flight data in the region of prime concern, I've got that minus one-half slope from that square root Reynolds number.

I will also have a bound up here that my heat transfer cannot exceed the energy flux.

And, obviously, if you go all the way to orbit you're basically one.

The molecules are coming in at orbital velocity, going into the material, releasing all their energy and then eventually coming off.

We actually do have that limit, although we never really worry about it too much.

The significant heating is in this laminar regime.

I feel like, because I understand Navier-Stokes Equations, because I understand the diffusion process and that limit of the Navier-Stokes, I sort of understand that flow.

However, we also have turbulent heating which incompressible flow has its slope on the order of [minus fifth?].

I don't really understand stand that, and do not claim to understand that.

It is a combination of the diffusion and the convection, all sorts of things going on.

And then we have transition from one to the other.

Theoretically, this would come out and come out lower.

Now, this is extremely important in the shuttle design, as I will get to when I get the charts.

But basically we go into a wind tunnel and can measure this on a particular configuration.

We got to flight.

And let me mention heat transfer and aerothermodynamics has been a field of study for many years.

People have built models, have done wind tunnel tests, shock tube tests, flown vehicles.

And there was a lot of money spent trying to fly vehicles to verify our understanding.

The difficulty, certainly with ablators, is measuring the environment.

Did you really have the right heat transfer or did the material just start to degrade?

What is really going on?

When we flew the Shuttle, we had a reusable thermal protection system which is the tile that is being passed around with a real thin coating and very low thermal diffusivity.

What better instrument could you have to measure heat transfer than that?

And the data from the Shuttle configuration is absolutely fantastic from a technological standpoint, from an aerothermodynamics standpoint.

Unbelievable.

So much better than anything that was done in the past with vehicles that were dedicated to try to get that information.

Let me say a couple words about, well, first let me address the facilities.

I mentioned the shock tube and went through that briefly.

And the value of the shock tube was to look at phenomena just like this.

You also can, which is where Professor Fay got his information, put a model in the shock tube.

Right here.

And all of a sudden you've got the flow at the right enthalpy and closer conditions to flight than anywhere else.

Getting to these energy levels is extremely difficult.

There are three facilities you can get to.

One is in a shock tube.

Second is a ballistic facility where you fire a projectile that looks like what you're going to fly.

And that does a good simulation job, except it is very small.

And getting any measurements is very difficult.

If you go into a wind tunnel you can get great measurements but you cannot get the energy.

The shock tube and ballistic facility, I will just put this down here, it has the difficulty of measuring things.

The other place you can get the energy is in an arc jet.

Now, an arc jet is a continuous electrical discharge, sort of like the shock tube, where you're discharging an arc along a tube about the length of these tables, a very high current continuous for a significant period of time into nitrogen.

And then you're expanding this and you're introducing a supersonic flow.

And you test materials like tiles or the ablator in as close to the environment as you can get on the ground.

That is for the times that are required.

Entry times are like 20 minutes.

You need something that has the energy and runs for 20 minutes.

Now, this is a continuous flow of electrons.

The thermodynamics here is not well-characterized.

People have studied it like mad.

This is very non-equilibrium.

You've got a very high density of electrons.

The temperature is immense in here.

It is not at all in equilibrium.

But, as you expand through a jet, collisions drop because the pressure goes down and it pretty much freezes.

But this is where we do research on ablators and research on service catalysis which I will talk about in a little bit which really can affect the heating, particularly on the Shuttle.

And I will show you some results there.

But, in any event, the arc jet is the other major facility from a TPS materials standpoint.

TPS being thermal protection system.

Wind tunnels are classic.

That's where NASA came from, NAC came from.

Aerothermodynamics is my field, spelling is another area.

Wind tunnels you're all familiar with.

And, on Apollo, we tested in every facility you could think of because we didn't know what we were doing.

And whatever the different facilities told us we tried to understand.

What we learned was energy is extremely important, the enthalpy.

And, frankly, going beyond mach 8, which is what everybody tried to do, get to the higher mach number, really doesn't work too well in a ground facility when you're talking about heating distribution.

It does give you mach number effects.

But the gas is not at all like what you have in flight.

And so on the shuttle we didn't really do much aerothermodynamic testing beyond mach eight.

That gave us the right normal shock Reynolds number region, it was closer to, on the Shuttle, the actual flight environment than if we had gone to a mach 12, a mach 16, a mach 18, a mach 20 facility.

Because the way they get the mach number there is to get the temperature very, very low.

It is very valuable information, but you really need to understand what you're doing with that.

You cannot just take mach number as the major parameter.

It is a significant parameter but you need to get the Reynolds number.

And, fundamentally, you need to get the enthalpy of the gas.

And there is not really a good dimensionalist number for the enthalpy of the gas.

Too much going on for that.

The other significant source of information is flight test.

In the early days with the capsules, and certainly with Apollo, we did a lot more testing, invested a lot more on testing than we do now.

For example, on the Apollo, I talked about this radiation, we had very good test results in a shock tube.

We thought we really knew what was going on.

NASA Langley went and built a small scale Apollo about so big to measure the radiation in flight because the shock tubes are operating at little higher pressures than we were going to fly the Apollo.

It basically had three brilliant heat shields with a quartz window in it.

It comes in zero angle-of-attack and gets to a given point where the window basically starts to melt.

You cannot see through it, you cannot make a measurement, it sheds that.

And ideally the second heat shield comes about right at peak heating simulating Apollo entry.

And then a third.

Well, we were really excited about that because the shock tube was great.

And we thought we understood everything.

Well, we flew Fire 1.

It was called Fire.

I don't remember what the acronym stood for, but it was basically a small Apollo coming in.

We got the data and it wasn't anything like what we expected.

What had happened?

Well, it turned out that in order to get the high speed, we launched the fire vehicle, and then we fired a rocket down back into the atmosphere to simulate lunar return.

Everything went well.

There was a spring between the capsule and the boost stage and they separated by design.

Fine.

But what happened was the booster lined up with the wake of the incoming test vehicle and just road the wake because there was a lot less resistance where the air has been sucked along, clobbered the back of the vehicle and it mutated.

And so we weren't looking at the stagnation point.

We were looking off at 30 degrees.

Not only that but the radiation was doing this.

Figured out the problem, sorted it out and had the second flight test which worked beautifully.

It turned out at altitude the radiation did not agree with the binary scaling that I mentioned, and basically the radiation profile here, as I said, was like two hours magnitude higher characteristically.

But at high altitudes it just wasn't there.

At peak heating it was.

But, prior to that, which was a significant heat load, it was not.

There were not adequate collisions to excite the radiators before the gas came to equilibrium.

Now, as I mentioned before, at peak heating conditions on Apollo the shock, I cannot draw it very accurately to scale, was on the order of about ten centimeters or four inches here at peak heating.

[Q]: Is that the thickness of the shock or the standoff distance?

The standoff distance, thank you.

Standoff distance.

The shock is relatively thin, a few mean free paths.

And some people might call this effective shock thickness, but I term the transition to higher temperature of the shock thickness and then a relaxation distance.

Any altitudes above that the flow could be completely out of equilibrium.

It hasn't gotten back to equilibrium because this characteristic time is directly proportional pressure.

And I erased it.

It is directly proportional to free strain density.

So at higher altitudes it out of equilibrium.

As you will see shortly, Shuttle is much higher altitudes than Apollo.

And I will explain why.

At lower altitudes this compresses and is predominantly at equilibrium radiation.

And that we were able to characterize.

OK.

Back to ways of getting information.

Numerical simulation.

This is a significant revolution that you're probably more familiar with than I am, but it really occurred right through the development of the Shuttle.

And frankly -- Well, I will show this in charts in terms of the design approach to getting the aerothermodynamic environment at flight, used the same technology that we used in Apollo.

And that was we take a scale model, go into a wind tunnel.

Now, this is a blunt vehicle, and so if you look at it as an inviscid flow, the close to normal shock entropy is basically the entropy of the entire body inviscidly.

And so the normal shock or strong shock gas dominates the flow around the vehicle.

As you go low angle-of-attack you get into an entirely different situation.

In any event, what happens in terms of the wind tunnel, the heating here compared to different distributions, is all pretty much proportionate.

And that is fundamentally what we used.

And that included even the wake region back here.

And I will talk more about that when we get into the charts.

On the Shuttle we get into far more complicated geometries.

And the major challenge on Shuttle was that three-dimensional geometry.

And we did a bunch of numerical simulation development.

We had focused on the subsonic region on Apollo which basically is most of the front side here, is basically subsonic.

About the middle of the vehicle down is supersonic.

And then, of course, you get into the wake here.

This was our flow field interest on Apollo primarily because of this radiation.

We had to understand the flow field in order to be able to compute the radiation.

About half of that radiation is optically thick from the ultraviolet deionization radiation and also line radiation from atoms.

Optically thick.

The other half, the radiation is basically optically thin, the molecular band radiation and other things.

We needed to understand the flow field.

We did some pretty crude engineering calculations in order to get that flow field, but we were focused on getting to a numerical simulation of the subsonic region in particular.

Now, in those days the computer was our real limitation.

And, of course, it was sort of embryonic.

We have collectively just become orders of magnitude beyond where we are today.

However, the design approach that I would recommend now is basically what we would like to have used on the Shuttle.

And, to an extent, we did.

Before we actually flew the Shuttle we had confidence as a result of numerical simulation.

It is a combination of these facilities and numerical simulation.

This problem of non-equilibrium is kind of beyond numerical simulation, in my opinion.

Now, you can correlate things, but I would like to point out the limitations.

You don't just go get a computer program and you calculate everything because there are some very fundamental things missing.

The way one gets reaction rates, for example, dissociation rates or recombination rates is to go into a shock tube.

As you approach equilibrium, the concept of temperature, the equilibrium constant makes sense.

So you can relate forward and backward rates.

And you do diagnostics spectroscopically on a concentration and you get rates.

And it gets to be kind of complicated.

There was a lot of stuff back in the early Apollo days said in terms of coupling between the different modes of vibration, the electronic excitation.

It is a pretty complex problem.

But, coming to equilibrium, is where we get our reaction rates for high temperature gases.

Coming back here, we're not close to equilibrium.

Temperature doesn't work.

Unless you start with an end body problem and Schroedinger's equation, you're not going to really be able to compute this.

Now, what is used in the field right now is the basic data and a jump condition in terms of what matches the relaxation condition.

I am not knocking it.

All I am saying is there are limitations to numerical simulation, whether it be in physical chemistry or just about anything you work with.

At the same time, it is invaluable in terms of relating what happens in a wind tunnel and what happens in flight or what happens in an arc jet and the phenomena.

I will say a little bit more about that as we get into the charts.

Before we flew, in regions of the vehicle, I made statements which I still would make, we could compute the heating on a wind tunnel model about as accurately as you could measure it in regions.

Not over the entire region.

Not over the separated region.

Not over conditions where the flow was turbulent.

But, in the laminar environment, we could compute it as well as you could measure it.

That is outstanding because now if I say I've got a program, I can tell you what the heating is, I can tell you all about the aerodynamics, I can tell you everything.

Good.

Run it on a wind tunnel test.

I will take the data, you run it on the wind tunnel test and we will see if we agree.

You've got a validation of numerical simulation in terms of the geometry in wind tunnel, in terms of the chemistry in shock tubes or ballistic facilities for that matter and certainly in terms of flight test.

And you've got Shuttle data and a lot of code validation for that Shuttle data.

Now, this is just from the heating standpoint.

I haven't talked very much yet about the thermal protection system or the structure and the rest of the things.

Let me say just a few things about configuration and then I will say a few things about the thermal protection system and then we will go to some charts that has some real information on it instead of just a hand-waving that I'm doing right now.

Configuration.

I mentioned dissipating this energy.

George Truhall [SP?] was in charge of the thermal protection system on Apollo.

And I used to come to him and say, wow, we take care of 98% of that energy by putting it into the air.

We compress the air, heat the air.

You only have 2% to deal with, a small percentage.

And he used to come right back to me and say I do the same thing.

I get rid of 98% of it and only 2% gets to the structure.

And, in fact, that it is true.

By design, if you look at a meteor coming in, the surface will vaporize.

And, depending on the angle of momentum, if it rotates it will vaporize all the way around on the outside.

And some of it will come in.

In fact, Professor Fay wrote a wonderful paper about meteors, what become meteorites and what are meteors.

An excellent paper.

Put it in a real perspective.

Broad range, much broader than what I'm talking about here.

The way George was able to get rid of this heat was by re-radiating.

And this has been kind of unique to manned vehicles.

Fundamentally, you've got a vehicle coming in, you've got a surface with the capsules far exceeding the material capability.

The heat flux coming in here gets you to temperatures that are far above any material capability.

And so what happens is the material degrades and is called an ablator.

And the initial concept and application for ablators is, as the material vaporizes, it basically pushes the air away to reduce the heat.

And this is sort of what happens in meteors if you want.

So, you lose some of the initial material.

And that sample that Aaron passed around, that black material, well, it was a little thicker when it started than the sample that he has.

But you see this what we call char layer where the material is decomposed?

That generates a gas which at high pressures and high heating rates basically tends to absorb the energy that is coming in through the chemical reactions primarily, and also due to the blowing.

But a fair more effective way of getting rid of that heat, for us in Manned Spaceflight, at the higher altitudes was to re-radiate it.

How do you draw re-radiation?

I guess sort of a wavy line.

Radiation is always a wave, right?

And so first order, 98% of this energy goes into heating the air which flows around the vehicle.

The other 2% that gets to the vehicle, George re-radiated 98% away with a high-emissivity, high-temperature surface.

Now, in the ablator, that char, think of it as a charcoal briquette.

You start with some material.

It degrades and all sorts of chemical reactions go.

If you've got a good ablator for our application what happens is you're left with a residual char which is black and very high-emissivity.

It is pure carbon, if you want.

That is the challenge, is to get a carbon surface or a high-emissivity, high-temperature surface that can re-radiate.

Just to remind the class, what is the most efficient radiator?

Black-body, there you go.

Thank you.

High-emissivity, black-body radiation, get rid of all that energy before it ever has to diffuse through the tile or through the ablator to get to the structure.

That is fundamentally what we use to protect the vehicle.

Now, while I'm on that, the ablators were developed for capsules.

And we kept getting lower and lower density because we wanted to minimize the diffusion of energy from the surface.

There needed to be a substant enough surface to hang together.

I mean if you just have charcoal and blow on it, it's not going to stay there.

With the early capsule, with the Apollo, we had a fiberglass structure in there that basically retarded the ablator from flowing away.

Now, everybody tells us we were twice too heavy on the ablator on a capsule.

And I will explain that in a bit.

It's a systems engineering problem, we got away from it on Shuttle, so pay attention when I get to that problem.

In any event, we were a factor too high over most of the vehicle but not in this region.

On that region, we were right on.

Not by knowing what we were doing, just by luck.

When you say right on, what you're saying is that the char layer went essentially all the way into -- We hit our temperature requirement on the structure.

If I blow that up a little bit, I've got a surface here of ablator which is [paralysizing?] [he actually said that! there's no reference in aerothermodynamics that refers to that term] and charing.

And I've got a flow over the vehicle.

I've got one heck of a pressure grid.

And I just described this char.

It's a nice porous carbon like a charcoal briquette.

Ever blow on a charcoal briquette?

You can blow your air right through it and it flames up.

That's exactly what happened here.

We had flow through.

The honeycomb wasn't as a high a temperature as the carbon.

That was just there to hold it as the system degraded.

So, the combination of the two-dimensional flow which we really hadn't simulated on the ground, all we could do, in the arc jet, was basically little pucks to test the ablator.

You're dealing with an awful lot of energy, and if you spread that energy over a large surface the enthalpy basically goes down.

The heating on the surface goes down.

We were testing six inch specimens characteristically.

We really didn't get the flow through.

In fact, we eliminated the flow through because we had one-dimensional models and we wanted to understand the process of one-dimensional.

But, in flight, fortunately we were a factor or two over just in that region.

Over this region, and I will show you a chart, we were way over.

And, again, I will try to address that.

And, again, the Shuttle has really helped us in understanding the leeside flow.

Configuration.

Everybody has got their own requirements for configurations.

From a heating standpoint, I want to put all that energy into the air so I want a maximum drag configuration.

I just want a flat plat normal to the flow.

Well, that's wonderful.

It's high drag but it's not stable at all.

Let's go to a sphere.

Now, the center pressure, no matter where the pressure is on the vehicle, no matter what the pressure is, it goes right to the center.

And that is probably also about the center of gravity if I flew a sphere.

Certainly if it was solid, but if I build a spherical spacecraft it would be neutrally stable.

Well, that would be great.

I could spin it and distribute the heating over the entire thing.

As they enter, that happens to some meteors.

Well, it's not too comfortable and I don't have control and I also generate a little left.

There are all kinds of problems with that.

One other problem, if I use just a section of a flat plate, if I look at the heating distribution, if I plot the heat transfer in this direction from ground test, not from flight, from ground test, you have some level of heating.

But then, when you get to the corner, it really goes up because of pressure gradient.

The same thing that we experienced on Apollo in terms of the ablator.

So, you want to give it some curvature, not only from the standpoint of stability but also from the standpoint of the heating distribution.

And, indeed, if you look at the Apollo at zero angle of attack it pretty much has almost a uniform heating distribution.

That is very efficient.

I can design my thermal protection system to be so thick and I manufacture it, produce it over the entire surface exactly the same.

That is wonderful, except I still have the corner problem.

And so I round the corners a bit.

This is only from an aerothermodynamic standpoint now.

And so I don't have this corner edge heating problem nearly as much.

Well, that's fine, except a zero L/D vehicle gets kind of high Gs coming in and you don't have much control.

And I will address a little bit of that, and you've probably already heard about the flight mechanics control.

In any event, I need some L/D so I got to angle-of-attack.

In order to go to angle-of-attack, I have to take the center pressure, which is basically the point about which the aerodynamic forces, if I put a string and pulled on that, that's how the aerodynamic forces are acting on that.

And I want the center of gravity ahead of that.

And now I've got a nice stable configuration.

Not too stable because the control people want to do things with it but stable from the standpoint of not having to fire RCS jets or have control surfaces and all that type of thing.

That is how we designed Apollo.

It worked very well.

And, in fact, if you look at the Shuttle at angle-of-attack with some liberties -- Son of a gun.

In two-dimensions.

In three-dimensions it is significantly different.

I think I'm about ready to go to the charts now.

OK.

Why don't we take a two-minute break.

We usually break about 10:00.

Great.

And I will get the charts set up.

Good.

Quick stretch.

Turn around.

I didn't ask if there were any questions.

I expected everybody to just raise their hands and start asking questions.

But, since there are no 8:00 classes, this is the first class of the day, maybe that's why we're not getting any questions.

That was my hand-waving.

I am going to get into specifics here after the break.

I have a series of charts.

Most of these came from a technical conference that Professor Cohen had after the Shuttle test flights.

We had five test flights, just for information.

We had 17 flights in Mercury before we put a man in the vehicle.

On Apollo, we never put a man on the vehicle or did anything before we had a test of the systems in the vehicle, before we'd put a man in it, with one exception, and that was the actual Lunar landing.

We couldn't really simulate that very well.

We couldn't test that.

On the Shuttle, we did as much testing as we could, but the design constraints forced us to go with men in the system initially.

And that was the least riskiest thing to do considering everything.

That's a whole different subject. All right.

This first chart is altitude in thousands of feet and velocity in feet per second.

What I've shown here is, first of all, this is one atmosphere total pressure.

This is a tenth of an atmosphere total pressure.

And first I would like to focus on the Apollo orbital return, and I am going to show data from actually one of these flights.

These bands are to show the flight regime.

And this is the Lunar return coming back 36,000 feet per second and then essentially going through an orbital entry.

You can see there is an order of magnitude difference here.

I'm sorry.

Here is the Shuttle.

This was the design coming from a polar orbit at 265,000 feet per second.

And these are the orbital flight tests, the five flight tests.

They are all laid together here, and you cannot really see much of a difference.

Now, this is the heating boundary.

If we went beyond that the tiles degrade.

Now, I mentioned three levels of aerothermodynamics.

The design level, well, I'll get into the design level a little bit later.

The first level was basically the Apollo technology.

That was we went to the wind tunnel, we correlated the distribution of heating on the Shuttle relative to a reference, and we used the one foot sphere as a reference.

And I gave that to the flight mechanics people and said do not violate these constraints.

So they developed the flight mechanics control and everything else to fly right along here.

Now, what isn't shown is we anticipated transition.

And I will show that in time histories.

There is another boundary for heating that actually comes along here.

These trajectories are very tight relative to having a re-usable thermal protection system and not having to completely refurbish the vehicle.

That was the target.

If we wanted a reusable system, we could turn around and fly again.

You've seen the ablator from Apollo and you've seen tile that really had some severe environment from the Shuttle.

But basically here we have a simple configuration.

Here we had a much more complex configuration.

We had capability to fly it and we had capability to avoid excessive heating.

It takes about 20 minutes to enter.

Ten minutes along this heating boundary where basically your heating rate comes up and you are on a plateau.

And you will see that in just a minute.

That contrasts the Apollo and the Shuttle.

And I mentioned on Apollo we did a lot of shock tube testing trying to get into this environment, about 33,000 feet per second for peak heating, when this thing comes down to also about max pressure on this chart anyway.

But Shuttle was significantly higher altitude, significantly more out of equilibrium, which is the bad news.

The good news is the radiation was not that significant.

In fact, when we calculated what the astronauts would see coming in -- On Apollo, when they were looking out the windows on the wake, it was extremely bright.

This is just in the wake which is orders of magnitude down from the radiation on the front side.

On the Shuttle, we suggested a 100 watt light bulb behind a table.

It worked beautifully in the simulator.

Significant change in environment from Apollo at 33,000 to 36,000 feet per second to orbital environment.

The heating basically increases.

In this direction, I don't show [UNINTELLIGIBLE PHRASE].[question about mars, that i miss to catch due to the cough some other person enters] Mars return is like 45,000 feet per second.

The convective heating goes up as velocity cubed.

The radiation probably goes up by two orders of magnitude.

The radiation is very, very sensitive.

Some of the people at Ames did correlations with velocity and with temperature.

And there were numbers like a temperature to the eighth power, a temperature to the twelfth power because it is not limited by black-body over a lot of the spectrum.

And, as the temperature goes up, there are more and more radiated degrees of freedom.

It gets much closer to a black-body.

Radiation becomes dominant on a Mars return.

On Lunar return it is a problem.

However, if you look at the radiative heating, it is first order proportional to two-dimension.

Whereas, a convective heating is just the opposite, it is inversely proportional square root.

As you go up in dimension, your convective heating is less important, as we did with the Shuttle.

And I will try to address that.

So we don't really have an ablator type of material that would work for Mars return?

I think we could develop an ablator.

But we would have to do it in an environment that gets as close as we can to simulating the radiation.

And these days there is a lot more capability there than there was in Apollo days.

But that is a real challenge.

Yes.

I have a couple questions.

Sure. [all/among the lines Why do they come backup] That was the basic flight mechanics that dissipate the energy.

And, actually, I will get into this a little bit more on the next chart and then go through an entry.

You wanted to not exceed the deceleration.

Actually, from an ablator standpoint, one of the most efficient ways to come in is hot and heavy.

Go to max heating rate but keep that time down.

You remember I mentioned the square root of time on the diffusion of the energy in.

You want to keep that time down.

And you're better off taking your lumps on heating rate.

Heat load is really what designs.

Did that answer your question?

[UNINTELLIGIBLE PHRASE] [i'm sorry enviroment noise plus air condition] This is the flight mechanics, and I'm not an expert on that, but basically this portion was designed to capture.

If you don't capture you're gone for another two weeks.

And so you didn't want to get beyond 20 Gs because nothing would take beyond 20 Gs obviously.

You didn't want to skip out.

This is a linear plot.

You're looking at an atmosphere and you're coming in at high speed.

I want to make sure you capture it.

Not too steep or you're blown apart, but if you miss you're gone for another two weeks.

First thing is capture.

Dissipate that energy.

Then we worry about getting down to a landing point.

In terms of corridor, they term that corridor, the Apollo vehicle had about a 27 mile corridor at 400,000 feet.

If you were too shallow then you would skip out.

If you were too steep in that corridor you would go in too deep and exceed the G level.

Coming back from the moon, 240,000 miles away, you basically had to a corridor about 27 miles in the earth's atmosphere.

And that was really what the guidance navigation system did for us.

And with the mid-course correction, of course you've got a lot of leverage, but it is a very tight corridor that you've got to hit.

Well, I can talk about it now.

No, I will wait until the next chart in terms of the systems engineering and everything.

When I was here, the computers were in the electrical engineering department and occupied an entire room.

Mechanical engineers like me, I mean we didn't understand all that stuff.

Generations.

Design and flight test environments, a lot of points I want to make here.

This is a log maximum heating rate and this is the maximum integrated heat load at design conditions.

Now, the numbers are not so important.

Apollo is triangles.

Shuttle is circles.

Filled is design.

Open is actual.

Let's start with the Apollo.

Our design is up here coming back from the moon.

Actually, there were two design points.

This was the maximum load which was the thickness of the ablator.

That is the weight.

We picked the material.

We got the best material we could.

Now the question is how thick do we make it?

And that's the weight.

Here is the design condition.

The heat load I mentioned before relative to the question.

We didn't have the trajectories of flight mechanics when we started the design.

We had to start to design the capsule, the ablator and everything else in parallel with the development of the computer capability and the flight mechanics and being able to actually fly this thing.

What happened?

We knew we couldn't exceed 20 Gs.

And so give me a trajectory that comes in and hits 20 Gs.

I've got to be able to handle that heating rate.

We also needed to capture.

If we skipped out and went another two weeks, that was kind of tough on the crew, so give me a trajectory that just stays in.

They are miles apart.

That point is up here on that chart.

For clarity and trying to illustrate other things, it is way up here in heating rate.

And there is sort of a range of entry of Apollo in terms of -- That's the maximum you could

get. All sorts of things in between.

This is an actual flight.

This is log paper.

A significant difference.

A factor of two.

Square root of that, 40% of that ablator that we didn't need is in the trajectory difference.

But now here is the systems engineering point.

When we started the Shuttle, we looked at Apollo and said how do we get this heat shield down?

Well, if you look at the aerospace industry or NASA you have specialists.

Everybody does their own little thing.

I am aerothermodynamicist.

George Truhall was the thermal protection system guy.

Tom Moser was a structures guy.

Then there was a materials guy.

All these different people, they all do their thing and work together as a team.

We're designing a system to go to the moon and come back.

Boy, I sure don't want to put too low a heating rate in.

I mean I don't want to be the cause of a failure, so I think the heating rate is going to be right here or whatever.

Well, I don't have that level of confidence, I've got some uncertainty, so I will put 10% or 20% at least in on my heating.

The ablator guy, he is testing on arc jets, and he does exactly the same thing.

The structures guy says, well, we want to do this and that.

Well, on the Shuttle, for example, our guideline was 100 missions, a structure that would take 100 cycles.

Well, if I don't exceed this temperature, you know, how well do I know that, what is the stress level, all the different variables, you know, this is what I expect but I better put a little pad in.

There is nothing wrong with that.

What was wrong is we didn't have communication with all these people.

Somebody gives me a trajectory and I calculate heat and I say, boy, this is what I think it's going to be.

And I'm going to show you some of that, in all honesty, which you won't see in journal articles.

But I better put a little bit of pad on that because I don't know this that well.

They compound.

We call it compound conservatism.

Everybody puts their 10% in and you get your factor of two.

Now, you just lost significant, if not half the payload on the Shuttle by doing that.

We did not do that on the Shuttle.

Now, let me very honest.

In the early days, when we recognized that, because we were getting beat on.

You don't need all that TPS.

When we realized where it really came from, we would go back to the management and say this is what you need to do.

You need a system where you have all this communication.

Well, that's going to be expensive.

We did it, but we did it informally.

We did it by communicating informally everybody understanding.

And we actually did a statistical assessment before we flew the Shuttle to give us confidence that things would work.

Extremely important.

I mean when you talk about systems engineering it is communication, different disciplines, different requirements, different everything.

Communication between people is very important.

All right.

Where was I?

Here is the orbital entry on Apollo, the two flight tests that we did, 201 and 202.

And, I'm sorry, I don't remember why we called them one, three, four.

This was a design, there's another design up here.

That was a conservative.

All right.

Here are the five OFT flights on Shuttle, heat rate and heat load, and there is the design.

We do not have a whole lot of margin.

But, as you saw from the previous chart, we can fly it.

We're obviously able to do it as long as the TPS and the structure are intact, obviously.

Any questions?

Yes.

How much does your ability to control the trajectory play into that?

I mean it seems like you'd be able to control the trajectory of the Shuttle a lot more precise than you would Apollo.

Yes.

Absolutely.

You've got a body flap on there, in particular, to trim angle-of-attack.

We also have RCS engines which we'd use if we would have to.

And, in some cases, we have to.

And you've got aileron settings which primarily are used later.

But, yes, crucial.

In terms of getting this level of precision you need control.

But isn't the most important factor the flight path angle, the angle between the velocity vector and the local horizontal at [400,000?] feet?

Initially yes.

On Shuttle you could modulate that.

Yes.

And, actually, you see some of these wiggles, you know, we have highs and lows.

We have hurricanes and high pressure areas, but the atmosphere is an exponential decay.

And any waves, any ripples, by the time you get to the tail end of the whip it can get very significant.

And so there are density variations that you really don't know about until you hit them.

And being able to control is sort of crucial there.

Coming back from the moon right on, that initial angle is crucial, and the de-orbit from orbit obviously the same thing.

Any other questions on this before we go to the next chart?

OK.

All right.

I mentioned three levels of aerothermodynamic methodology.

One is to correlate in the wind tunnel and relate everything to reference heating or stagnation point heating, which is what we did on the capsules which are good blunt vehicles.

The real technology challenge on the Shuttle was the geometry.

It was a lot more complicated than just the shock and a stagnation point and flow around a blunt vehicle.

You name it, you've got it, in terms of flow on this thing.

Now, the way this was modeled in terms of -- When we started, we didn't have computational fluid dynamics.

The design methodology that was used to actually design the system was to model the flow.

Obviously, up front here looks kind of like a sphere.

And so I calculate the heating on a sphere.

I go into a wind tunnel and look at the actual data and relate that and say, well, that's kind of like a sphere of two foot radius.

So that's my heating there.

I look at flow down the center line -- And, I'm sorry, this wedge isn't supposed to be wedge or a flat platted angle-of-attack.

This flat surface down here looks kind of like a wedge.

Well, I can calculate [a boundary?] on a wedge given the pressure which Newtonian would work fine.

Certainly, in the blunt regions and on a wedge, I can do that flow.

I can do a swept cylinder for the leading edge and I can do a comb for the boundary

layer. I can take diagnostics in a wind tunnel, look at the boundary layer path and say, boy, this thing is spreading kind of like a cone.

This is the design methodology.

These are all one-dimensional flows for the boundary layer.

These are geometric flow models where the boundary layer is basically one-dimensional.

And even though, for example, on a cone, the boundary layer is spreading, it's still a one-dimensional flow.

So I calculated in a wind tunnel what the heating would be at this particular condition.

I calculate, for example, flat plate.

This heating rate has a function of distance from the nose to the tail if you want.

This is what I calculate, here is what I measure, a little factor in there.

But I assume whatever I don't know in the wind tunnel, I don't know in flight, too.

But I take this analysis which can include the chemistry, all the nice things that go on in flight.

So I calibrate it to wind tunnel which is basically an empirical flow field now and I take that to flight.

It works pretty well.

It really does.

Better than my normal shock Reynolds number that I gave to the trajectory guys.

Actually, there are areas where there is significant disagreement.

But mostly they are pretty consistent because they're reflecting the basic diffusion of the boundary layer and the basic physics that I tried to talk about in the beginning here.

It is very important to normalize what you're doing to something fundamental.

If you cannot do it on the back of the envelope, have a question about it.

If you cannot back it up with the back of the envelope, have a question about it.

So this is the design methodology.

I mentioned the Apollo methodology which was used for quick numbers and for trajectories.

The third level is a computational fluid dynamics.

I'm only going to show results from the technology that we had at the time we flew the Shuttle.

Since then computers have done so much, we can do so much more, but I want to compare what we expected and what we actually got with the technology we had at the time.

Boundary layer transition.

I talked about the boundary between the turbulent and laminar heating.

Characteristically, and in the Shuttle level, your heating goes up by about a factor of three.

If you go to higher Reynolds numbers it can get significantly higher, so you want to avoid that factor of three.

Our initial estimate on the effect of roughness, I have to say, was not as good as it should have been, but the technology wasn't really there.

This is the logic.

And I won't go through in intimate detail.

Just to point out the complexity to recognize the level of effort that goes into getting a basic database to design vehicles.

This is all in that document in that conference report.

And there are two copies, I think.

I brought a copy, and I think there is a copy in the library that Dr.

Hoffman has on reserve, but this is all documented in there.

Yes.

And I won't spend much time other than to say we first looked at smooth body transition.

This is heating rate versus distance.

Smooth body.

And then we put roughness in.

We actually went to cryogenic models with simulated tiles to get that boundary layer to suck down to be a little better simulation of flight.

The alternative was to put bowling balls on the surface of the thing to try to trip the flow, and that didn't have anything to do with physical reality.

So a lot of work there.

We related and took the simulations for the transition and came up with an effective roughness relative to smooth body transition.

Again, I don't claim to understand turbulence, I certainly don't claim to understand transition and certainly on a complex configuration.

So then we correlated that and we had predictions.

And you will see some of that in a few minutes.

On the tile problem on the last mission when those little gap fillers came out, do you think that it tripped the boundary layer?

No, I don't.

On the other hand, some of the people that had been correlating the various missions felt that we would.

And the problem is it was the first time we had a picture.

Yeah, I understand.

We had tile gaps after we landed and we said oh, gee, this is the relationship.

There was a lot of correlation, but I'm not sure it was that valid.

I really don't think so.

Now, this is the surface catalysis.

I haven't really talked about that.

I talked about the gas going from molecular to dissociated, ionized to weekly ionized.

When you get back to the surface conditions, you're back to a molecule again.

Now, I am simplifying things here.

But I think the way I look at it is you start out with a molecule, you blast it apart, you have atoms, you get back to the surface of the vehicle.

And at equilibrium now you're back to a microstate.

Yes.

In the whole design process, was the shape of the wings and the underbelly designed first and then you calculated properties?

Or, did you have to go back and say no, this redesign is impossible?

Because of the heating do it this way.

Was there a [cyclic process?

(check)] or was it one way? It was primarily one way.

Here is the aerodynamic requirement in order to come in.

The biggest exception of that was on boundary layer transition.

That classic if the structures guys design an airplane or if the electronics guys design an airplane or the aerodynamic guys, they all come out to be different airplanes.

The prime thing was the aerodynamics, to be able to control it and bring it in.

We did alter it relative to where the thermal protection system was.

The other thing we did is don't fool with Mother Nature.

The structures guys like to make things nice and flat or cylindrical.

And the flow is a continuous radius curvature type phenomenon.

And that difference is very, very important, particularly for boundary layer transition.

So we did fair the geometry to keep the boundary layer transition essentially two orders of magnitude lower than it might have been.

But overall I would say predominantly it is aerodynamics.

And we tried to calculate the heating to the configuration that we had.

[UNINTELLIGIBLE PHRASE] [would you change?

< 3 or 4 of this type of question ] The only thing I would have preferred to have done is fly higher angle-of-attack which could have reconfigured the thermal protection system.

The tiles are a very efficient system.

They are fragile but are very efficient from [an entry?] standpoint.

The carbon nose and leading edge are heavy and they don't insulate worth a darn.

I mean that's a layer of carbon.

When it gets hot it radiates out, but it also radiates in.

And so you have to have an insulation behind that.

And, in fact, the way we're able to reconcile the environment with the temperature capability of the carbon is it's sort of like an oven.

And it's easier to illustrate on a leading edge.

Just picture a two-dimensional air foil at angle-of-attack.

And a carbon section, if you want, covers from here to here.

Now, if I look at the heating distribution, here the heating is quite high, still high over here, still high over here, still high over here.

Boy, it drops off very quickly over here.

Well, if I can radiate this energy over here, this basically becomes a uniform temperature oven first order.

And insulation is back here.

I don't know how you illustrate insulation.

Insulation is back here to keep the lower temperature structure from getting too hot.

I don't think a lot of people realize that, but behind the carbon-carbon, on the leading edge of the wing and the nose, there are actually tiles in there just like on the outside of the rest of the Shuttle.

So this is sort of a staged thermal protection system.

And if we didn't do that, if we put the tiles right up here then this temperature could exceed the carbon capability.

By flying at high angle of attack, I could reduce the amount of carbon.

What was the problem going to a higher angle of attack?

You said there was a conflict.

Yeah.

The problem was one of the requirements was long cross-range, and you don't get that at high angle of attack.

I mean high angle of attack just comes in ballistically, if you want.

You roll around the velocity vector so you get a little L/D.

But, if you want to go range, you need more lift so you need to drop your angle of attack.

A very significant design parameter for Shuttle.

And if you recall the trajectories, it was primarily needed from a polar orbit where you're trying to get to a particular runway.

You don't have as much capability coming from polar orbit as you do from equatorial or lower inclinational orbits.

You remember we were talking about energy management, and I talked about how if you end up low on energy you actually have to decrease your angle-of-attack even more and no S turns or anything, just straight in.

But there is a thermal boundary.

I don't remember whether it was 38 degrees or 37, but 40 degrees was nominal.

And you really didn't have a whole lot to play with.

If you drop your angle-of-attack in order to increase your lift so that you can stretch your trajectory to make the runway, at some point you're going to violate thermal constraints and start melting your thermal protection.

There were years of concepts and vehicles that were developed and flown, test vehicles with different emphasis.

And there were some aerothermodynamic vehicles nice and smooth.

I mean it just looked beautiful.

It looked like something an architect would come up with, if you want.

And, from a heating standpoint, they worked well.

But the structures guys, it was very heavy from a structures standpoint to get all these compound curvatures, this, that and the other thing.

There were also vehicles that were designed specifically from a structures standpoint.

And I'm not knocking the structure people.

I do a lot of structure work, too.

But there was one that had discontinuous two flat surfaces to be able to handle all kinds of good stuff.

And that was a terrible configuration from an aerothermodynamic standpoint.

So there actually was a heritage of all kinds of attempts.

The big challenge was how do you land some of these things?

A nice hypersonic aerothermodynamic configuration and aerodynamic configuration, OK, now you try to put it down the runway and it is hot.

A lot of test pilots had some problems with some of these vehicles.

There are all kinds of heritage of people pursuing this, that and the other thing.

And one of them was aerothermodynamic design.

And it didn't have these big wings that we have on Shuttle, but it was hot as can be coming in.

I think the Shuttle frankly, I mean I don't look at it just from an aerothermodynamic standpoint.

If I look at it overall, we needed all the lift we could get on landing.

And, as it was, we had to build a pretty special runway to do that or go to the dessert.

So, from an aerodynamic standpoint, we would like a lot higher lift.

In fact, that is a nice area for innovation.

Some of the earlier concepts for vehicles, you're probably with familiar with, capsules with rotogyros on them that power up as you come down.

Boosters, if you wanted a cylindrical configuration with a straight wing on it that swings out.

Now you've got to lift an airplane when it comes in to land, but there are problems with

all of them. In that case, the weight estimate for all the hardware and all that kind of good stuff was excessive.

Anyway, that is a real challenge for design.

I understand you folks are going to come up with a better design, some real innovative thoughts in terms of how to marry all these different requirements.

In my opinion, the mindset for hypersonic vehicles was [UNINTELLIGIBLE] [fibercups] have straight wings.

Supersonics like this and, boy, hypersonic ought to be like this.

I mean that's just kind of the mindset.

And it kind of works.

But an entry vehicle is a whole different vehicle.

Capsules work fine for their requirements.

Shuttle has been a fantastic marriage of different requirements.

The challenge today, and I think the reason for the class, is how about some new and better ideas.

It's not going to be easy but there's a big need.

OK.

Surface catalysis.

First order, start with molecules in a free strain.

Atoms.

Some ionized.

And then I get to a surface back here at equilibrium, I am back to molecules again.

They're pretty hot but they are still molecules.

Well, Professor Fay did a wonderful job in looking at a stagnation point on a sphere and saying, well, we've got limits.

If we're at equilibrium, that is the chemistry is fast enough that you're always at equilibrium, all the way through to the boundary layer, you get this amount of heating.

And that amount of heating included not just the conduction but the chemistry changes going from dissociated atoms, if you want, and putting that energy back into translation and rotation into molecules.

Or the other limit is completely out of equilibrium where all you get is the translational energy.

And what happens there, however, is if the surface is catalytic -- That is I have atoms coming into the surface and they are, if you want for discussion, absorbed on the surface.

And then another atom comes in, recombines and forms a molecule that releases that energy.

That is a catalytic surface.

So you have sort of two limits, a completely catalytic surface and a non-catalytic surface in a non-equilibrium environment.

And that is very significant on Shuttle, and you will see that in some data I am going to show here in a short while.

This is just the concept which, again, as Aaron mentioned is in the report.

We had to go to arc jets and spectroscopic diagnostics and flow models of what is going on in the arc jet to understand the surface catalysis of tiles and carbon.

We had to model the flow and model the chemistry to come up with an efficiency.

Then we go to flight with similar analysis and predict, and I will show some predictions of this.

This is a significant phenomenon at the high altitudes, low density for the Shuttle.

Any questions on surface catalysis?

I always found it amazing that you don't think of designing a space vehicle that you have to worry about chemistry.

There are lots of things you have to worry about, but chemistry I had never thought about.

But when I first heard about the surface catalysis problem, there are just so many things you have to take into account.

This is the flow field.

At the time of this conference and the OFT flights, again, the design was the methodology that I explained where you use simple configurations, model it and extrapolate the flight.

This is sort of the level of the technology, and this is at 20% of the vehicle length.

If the vehicle length is 1.0, it is 0.2, 0.4, 0.5 cross-sections.

And it's just the cross flow speed contours.

The only point I'm trying to make here is this is kind of the level of CFD that we had at the time.

Since then, boy, we've gone gangbusters.

But this kind of the level.

We did not have the finite rate chemistry in this.

That is a lot more computer than we could handle.

At this point, we were trying to develop algorithms and grids.

And, as I said, we could, in certain regions of the body, compute the heat transfer as accurately as we could measure it in the wind tunnel.

But that's not at flight.

That is just sort of a picture of where we were, and that is where I'm focusing in terms of comparing what we expected from what we actually got.

Now I'm going to show results in terms of temperature as a function of time.

This is the entry time from about 400 to 1,000 seconds.

You notice this plateau.

You're talking about 20 minutes entry and ten minutes of flying it so you don't exceed the thermal protection system.

I am going to show three locations.

Right up here at the nose, just behind the carbon, mid body and aft body.

Now, the flow field technology, we had a heck of a time getting from our starting solution, subsonic flow, which used one particular algorithm [to match?] supersonically down the vehicle.

We succeeded in doing that prior to flying.

And we were able to compute up to the point where the shocks from the wing intersect the shock from the fuselage.

And then we had another subsonic region and we weren't able to handle it.

Now we can do that.

But at the time we flew, we could only compute up to about here.

Now, this is not what you'd see in a journal.

I will show you one you'd see in a journal here in the middle.

This is right behind the carbon.

Now, what we did is we computed at different times through the trajectory and then there were correlations to get the history.

This is JSC prediction right here.

Now, we didn't worry about exceeding Stanton number one.

That is we didn't worry about the heat transfer being higher than the energy flux to the vehicle up here because it doesn't, I mean it is, if you look at these numbers, we should have accounted for that, but it's not that important so don't worry about that portion of the curve.

Up here is very important.

Now, this is temperature.

And I just mentioned epsilon sigma T to the fourth.

That means the heat transfer is four times a bad.

We did a terrible job up here, and I will get back to that.

Now over here what happens is I've tried to stay laminar.

I come down.

And this was really a stretch.

We never got turbulence heating up on the nose.

Way beyond wind tunnel, way beyond our experience base, but the model just went up there.

So we really didn't expect that.

That was a pretty conservative boundary layer transition.

And then, son of a gun, the actual temperature is higher than turbulent even though it would appear to be laminar.

What is really going on here?

This is right behind a carbon.

The carbon is an oven.

As the service temperature of the tile drops, which drops very quickly because it re-radiates.

Not because it diffuses.

We control that.

It re-radiates so, as soon as the heating drops, the temperature drops.

I mean this is almost identical to reflecting what the heating is.

It is dropping like mad.

And, indeed, we're agreeing quite well.

We're kind of out of the real bad chemistry and surface catalysis which is part of the problem here.

And here, all of a sudden, the laminar is higher than the turbulent.

The carbon is this oven.

It doesn't cool down.

Even sitting on a runway it is as hot as can be.

If you think about it, it's got this oven.

It can only radiate out of surface and inside it is still radiating.

Just like when you turn your oven off at home, it takes a while for it to cool down.

The flow is going across the nose and actually heating the air.

At least changing the boundary layer profile so that the heating is higher.

How do I know that?

[Here is your tank?

yup].

Over here there can be a little bit of that effect also, and it takes a while to preheat the oven, if you want, if you're doing any cooking.

There is a little bit of that.

But, predominantly, this is the chemistry.

See, we come much closer together here in time.

This is predominantly the chemistry.

At this time, this non-equilibrium relaxation distance is about six inches.

Now, we're not into radiating gas but we're certainly not into equilibrium.

That is also a factor and that is not well-included, even today in my opinion, other than through correlations of the shock in what's going on here.

You won't see that on paper because we did a terrible job there.

We did not exceed design material requirements.

And I don't think I put anything in there about -- Well, when I get to the thermal protection system, I will go through the philosophy of having confidence to fly.

And, obviously, with our predictions, we would not exceed the top capabilities so we could fly.

But we were off here badly.

But at least you were off in the conservative direction.

Well, that's the way we tried to be.

This I will get into.

This is really what we expected, to the best of our understanding.

Yes, I was surprised at this also.

We did consider service catalysis, which I will show here after a while, but we did not really include the nonequilibrium flow in the inviscid, what I've been talking here about Apollo.

That was beyond our capability to do finite rate chemistry in the inviscid flow field.

Why don't we go to mid body now?

All right.

Here is something you might see in a journal.

Right where we wanted it.

And that's where we had the most confidence, too.

We got away from the subsonic, supersonic condition.

We were into a marching solution.

That is as good as we could do it those days.

And we knew that transition was going to be later than what we predicted because wind tunnels, you've got walls.

You've got all kinds of reflected noise.

And wind tunnels are notoriously conservative relative to boundary layer transition.

But, amazingly, the turbulent heating correlated quite well.

And that even works with normal shock Reynolds numbers.

I mean when you go back and look at all of the Shuttle data with a crude back of the envelope normal shock local heating to reference heating, including turbulence, it is amazing.

It really is.

First order physics seems to hang in there, in spite of all the complications of chemistry and all the kinds of things that can happen.

You have to be careful, but overall things usually work for you.

Again, that is academic there.

If we put in a constraint it would look a lot better.

That is good stuff, but we can do even better now.

And, as you can see, when I said we could do a wind tunnel as accurately as we could measure, in flight basically we could do the same thing.

Mid body.

Everything is just right for the CFD folks.

Now we'll go to the rear where we go past CFD and more to the wind tunnel correlations, and we're not doing as well.

Certainly on transition we knew we'd be very conservative.

This is ideally how we design the vehicle.

Fly to temperature capability of the tile.

And on this STS-3 that's what we were trying to do.

Now, if we exceeded this that's all right, but we don't want to exceed the material capability.

And we obviously don't want to exceed the structural capability.

Let's see.

I want to talk about surface catalysis.

Then we will get into the thermal protection system.

I've got one chart I am going to spend a lot of time on.

This is distance down the vehicle from the nose.

I mean it is linear distance.

There is 50%.

This is surface heat flux at one particular time in the entry.

The circles are flight data.

These are catalysis experiments.

This is a fully catalytic or equilibrium heat transfer.

This is a zero catalysis non-equilibrium, boundary layer non-equilibrium.

The reactions are not occurring in the boundary layer.

This is the flight data that opens circles.

I don't remember what the measurement problem here was.

And here is this point way up front you can see again.

Now, this is a viscous flow field where we could do the chemistry but we couldn't do the fluid mechanics real accurately.

This is still a mix and match.

Look at the difference between the measurement and the prediction.

The same thing as before only I eased it by showing temperature instead of heat flux.

The surface catalysis is a predominant factor.

Now, there is some rambling in the data here, depending on particular location, et cetera.

But our friends at Ames developed a catalytic coding, and they coded tiles.

And they said we're going to demonstrate service catalysis, so they put these tiles at these particular locations.

If the whole vehicle was like that, the heating would have been up here.

But since there was just the tile, the boundary layer comes along here and all of a sudden, boom, it gets hit with a different boundary condition.

We've got all those atoms and they see this catalytic surface, the heating goes way up and then relaxes.

This is the computation and there is the measurement.

Indeed, here is a demonstration that chemistry can be important in this flight regime.

If you come down in altitude where everything starts going to equilibrium, it's not that important.

You're going to get this because the chemistry is going to, the gas is going to react.

But where we are, up in altitude trying to maintain conditions so we can be reusable, that chemistry is significant.

Now, I think the next one is probably the thermal protection system.

No, one more measurement.

This is the leeside.

This is normal shock versus film heat transfer coefficient.

Basically heat transfer.

Log.

Log.

This is the heating shown here as a function of normal shock Reynolds number.

Now, remember I said we designed the trajectories so we went up here and spent 10 minutes and then came down as normal a normal shock Reynolds number.

And here are three trajectories with a heating on one location of the leeside.

By the way, Max Faget told me to burn a hole some place on the leeside.

He didn't want too much tile there.

The only thing I was able to do was we exceeded heating here because we didn't simulate the flow very well in the wind tunnel.

We had to put tiles there after first flight.

So I told him that was as close as we came.

In any event, this is heating on three trajectories through normal shock history.

It's sort of like time.

Three different vehicles.

This is to reference heat.

This is our old Apollo level technology.

It works quite well all the way through to peak heating, and then it starts to change as the Reynolds number picks up and the weight characteristic changes.

In ballistic facilities, if you have a vehicle traveling at high speed, eventually your weight goes transitional and turbulent.

As you increase the Reynolds number that moves forward.

As that moves forward, you get more mixing.

As you get more mixing the gas in the wake gets hotter.

And I believe that is fundamentally what's going on.

It is very repeatable.

We cannot get this in the wind tunnel.

Now we'll go to TPS.

No, one more on the leeside heating.

On the Shuttle we had thermal couples located here, there, as many places as the aerothermodynamics could put them, the TPS guys, but we couldn't put them anywhere.

This is the 201 vehicle and it's on its side.

I apologize because of my chartmanship.

The vehicle is coming in angle-of-attack on here.

This is the windward side where there was charring.

This is white paint down here.

And, I'm sorry, it is a terrible photograph.

Because of some of the protrusions we had on the first vehicle, we also got some charring on this side.

This is not charring.

This is some charring.

And it is blown up here in the way the chart was made.

One point.

This is the first entry heating.

And the leeside was extremely important.

How well did we do?

How hot is it?

We got the data and it was all over the place.

It was down where we thought it probably should be.

And it was like an order of magnitude higher.

We thought that data is no good.

Well, then we went back and realized what happened is when the control system fired jets, a lot more dynamic pressure than the airflow.

A lot cooler.

So, when I fired a jet, all of a sudden it is like putting a big wing out there.

Tremendous disturbance.

And, indeed, we were able to correlate firing RCS jets with when the heating was way up here.

And flow times you're talking milliseconds for reaction time back then when we weren't firing a jet.

Unbelievable.

We went to learning something.

Again, interaction of systems.

Now, finally, this is my one and only chart on the thermal protection system which is the real hardware stuff.

This is temperature versus time at a mid body location.

Now, this is from STS-1.

We didn't have data until this time on that flight, which is why I haven't shown much aerothermodynamic today.

We only had late time data.

This is the design trajectory coming in from polar orbit.

Our design condition was we do not exceed 350 degrees Fahrenheit if we want to have a hundred flight life with this aluminum.

Aluminum is great stuff because it is a good conductor but it is low temperature and it expands.

[Bond line?] that means at the [hahahahahaha] bottom, just so that everybody understands.

Yes, thank you.

Those temperatures are much lower than you see on the surface of the tiles.

That's after the heat has diffused.

Right.

I think Tom probably talked about the SIP, the strain isolation pad.

I'm sure he did.

This is after you diffuse through the clouds and through the RTV bonds through the SIP.

This is the actual aluminum temperature.

Now I'm talking predictions.

This is what the vehicle was designed to experience.

Now, the design prediction was right here.

That was purposefully a little conservative.

The guy who is building it doesn't want to lose the vehicle.

He is not going to get paid, plus much bigger problems, but this is what we expected.

This is our best estimate.

And, again, if you recall, I showed you where we really knew where the heating was.

This is really a TPS test right now.

If you read the TPS section in that report, those guys with the heating, they were just way too hot.

Right here we were right on.

This is a purely TPS test, except it turns out it was my fault here.

In any event, here comes the data.

This is the prediction for this particular flight STS-1 right here.

This is what we predicted for STS-1.

This is what we would have predicted for design.

And this is the design technology prediction which has a little conservatism in it, obviously, and on purpose.

This is yes you can fly the vehicle with confidence.

We're flying this STS-1 no problem.

And we're pretty sure we can fly a design but things have to go right for us.

We did a pretty good job along here.

And this structure is intricate and everything.

The thermal modeling has to take into account all kinds of geometry, materials, et cetera.

And all of a sudden right here, boom, what happened?

I admit to overlooking this.

What happened is we opened the vents, we let some air in.

I mean you're up in a vacuum.

You do not want to let air in when it's hot.

The best way of burning a hole right through the vehicle is open a front and back door.

The absolutely worst thing that could happen to you.

You cannot radiate the energy.

You don't get rid of that 98%.

It was just like a blowtorch.

But, once you get down, if you don't do something, you've got this vacuum vehicle and you're getting atmospheric pressure coming up on you.

And all of a sudden you're going to be crushed.

At some point, OK, it's all right.

We open the door.

We open a vent.

This particular location, not all locations, could experience that.

And, not only that, but the air is expanding so it is chilled as it comes in from outside.

Still cold compared to what we've been working with.

I overlooked that.

Now, in fairness, there are a lot of areas where there is insulation, you don't get that cold air and so you cannot use it in many places.

But the point is, looking at the overall system and the kinds of things that could happen, you could take advantage of those in designs if you're cleaver, if you're innovative.

And so there was, not 100 degrees, a significant difference there.

You could take advantage of that if you design a vehicle that you pop it at the right time and get some cold air in there because that's what we're trying to control, this temperature, from a temperature standpoint.

The other thing in the Shuttle, which I'm sure Tom discussed, was the thermal stress.

I mean if the belly gets heated and the wings don't, the whole wings will pop up.

That is one big integrated problem which gave us a lot of difficulty.

Again, with the simulation and computational capability we have today, I think we can do a much better job of that.

And also just understanding the importance of it.

I think those are all my charts.

No, I'm sorry.

I have one more which is not a Shuttle chart.

We were looking at an experimental orbital transfer vehicle, a [low WOCDA?] vehicle running from geosynchronous to low earth orbit, and then we use the Shuttle to go from low earth orbit to the ground.

We were trying to make that reusable because you don't want to go up and put an ablator on a vehicle in orbit on a space station.

And we thought we could do that.

Now, this is not coming back from the moon.

This is coming back from geosynchronous.

It's not quite as bad.

We had a design.

And, to prove the concept, we had a little model we were going to build and fly.

This came from a paper I gave discussing that.

Basically, this is the analysis and testing from research to an actual real hardware system, from the fundamental equations down to numerical simulation.

Back of the envelope or perspective fundamentals, that's kind of the fun part that I enjoy.

Then modeling as we do, for example, in the design approach on Apollo.

Correlations of data, numerical computation and then numerical simulation where you're trying to do as good as we understand with the equations.

Fundamental research.

The technology development which is where NASA's major emphasis is.

Component development of systems.

And finally subsystem, model and system testing.

You need all that stuff.

You would like to go right down the matrix here, have a good, firm foundation so you really understand what you're doing.

Therefore, you have confidence in doing it.

And, therefore, you develop capability.

There are no shortcuts.

Shuttle has done a fantastic job in both these areas all the way down to computational fluid

dynamics. It is not limited just to NASA Shuttle people or aerospace people.

And certainly in this area, in Apollo, but all the human space flight.

We've got a lot of experience.

That needs to be taken advantage of for our future systems.

It is not just it looks like this or it looks like that, it's going to use this system, it's going to use that system.

It's an overall integrated take advantage of the experience in what we've learned.

Yes.

I just have a question about the chart.

I'm just wondering if the inner section points on those lines correspond to a particular path or something like that?

I used this from the standpoint of we were trying to do a flight test model.

We were going to predict what happened to an aero braking vehicle coming in, and so I was focused on this and also on the numerical aspect.

Marrying those two, at this point, which was the reason for this flight test.

But I just thought that is applicable today in terms of where we're going in general.

I didn't get very many questions.

It must be because it's the first class of the day.

Well, you were going at a mile a minute.

I think we got a few in there.

But, yeah, the content of what we've been exposed to today has been tremendous.

We really want to thank you.

If they want to do some simple calculations, what reference would you give them?

Are there any simple calculations they could do?

[Faye and Rodell?

yes] has the boundary layer activity.

That is a crucial reference.

In the paper that they have, the Shuttle Technology Conference, I have a list of references that were to date in the various areas, whether it be service catalysis, TPS, you name it.

And those were the best references at the time.

And the individuals named, many of them have gone on and done much better work.

Plus, there are lots of younger people, too.

I think that would be the best source.

OK, Bob.

Thank you very much.

Thank you.

[APPLAUSE]