Space Launch System Update: Solid Rocket Booster
Bruce Tiller
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Coordinator: Welcome and thank you for standing by. At this time the conference is being recorded. If you have any objections you may disconnect at this time. I would like to turn your attention over to your host, Ms. Amelia Chapman. Madam you may begin.

Amelia Chapman: Great welcome everybody. This is Amelia Chapman and thanks for joining us today for a Museum Alliance professional development conversation, Space Launch System Update: Solid Rocket Booster.

First I have a few reminders for everybody. Please take a minute to make sure your phone is on mute not just on hold. And the slides for today's presentation can be found on the Museum Alliance and Solar System Ambassador site. If you have any problems contact me at amelia.j.chapman@jpl.nasa.gov.

It is my pleasure to introduce our speaker today, Bruce Tiller. Bruce is the Deputy Manager of the Space Launch System Booster Office at NASA's Marshall's Space Flight Center in Huntsville, Alabama. He leads the design, development, test, and evaluation of the solid rocket boosters for the Space Launch System or SLS, NASA's deep space flagship for a new era of science and exploration. Prior to this assignment, Mr. Tiller served as the Deputy Manager for the Ares I rocket first stage. Since beginning his civil service at NASA Mr. Tiller has held several key position within Marshall's engineering doctorate including supervisor of the thermal and combustion analysis branch, supervisor of the systems analysis branch and team leader in the thermal analysis branch.

Prior to joining NASA Mr. Tiller was a thermal analyst for two different NASA contractors. Bruce has indicated that he is happy to take questions as we go. So with that I am going to turn it on over to him.

Bruce Tiller: Thank you Amelia. This is Bruce Tiller good afternoon folks. This is a little awkward. I have got some charts here and I hope you are looking at them with me. But what I am going to do is go through this pack of charts and I am just going to go ahead and flip to the first page that talks about the agenda and what I want to talk about.

So this is an overview set of charts and it talks about SLS from the real high level on why are we building this big rocket? That is kind of the message I will be going through there. And then I want to focus on the booster because that is what I do and that is what my office does. And finally I will talk about a real exciting test we have got coming up here next week. So we are pretty fired up about this qualification test that we have got going on in Utah next week.

So with that let's just jump right in - and I will take questions. I will probably pause after every chart. I have no idea of your interests or how many folks are out there. So I am just going to pause when I get to the end of chart once I get into it and then people can ask questions and I am happy to go off on a tangent. This is sort of your time to help you if I can.

So let's go to the first one here that is called Journey to Mars. That is the title of this chart. You have probably seen this chart if you have seen the public affairs data that NASA puts out on the Journey to Mars. It is kind of a standard chart. But it is really good and so I want to spend a minute describing what is in it – why are we doing it in these phases like this?

And so if you look at the bottom of the – it has obviously got the Earth on the left and Mars on the right. And at the bottom they break this up into three different sections. The first one is called Earth Reliant. The second one is called Proving Ground and the third one is called Earth Independent. It may be obvious to folks but it is pretty important and that is when we are sending astronauts out you have got to spend a lot of time working on getting them home if something goes wrong.

We spend a lot of time designing systems to be highly reliable, very redundant but still things go wrong. So even with all that you have to think about rescue and how do you get people home in case something goes wrong? That's where this Earth Reliant comes in and that is where our International Space Station is such a big player. We can learn things there and try things there and people that live there as you know for over a year, a year and a half I think a Russian has lived out there. So then during that time if something goes wrong they can hop in that Soyuz recovery craft and they can be back on the ground pretty quickly. They train for that and we always have a rescue craft there on board so that they can get out if they need to.

That gives us a chance to learn some things about humans in space that you are going to need to know. The trip to Mars can be two to three years, as it says over there in the far right. So you have really got to prove some things out. It is not just how the body reacts over time but also all of the life environmental control - life support systems. The spacecraft itself has to be proven out.

So let's skip over to the Proving Ground then, and that is where this SLS fits in. That is where the Space Launch System fits in and that is sort of the middle of the road and that is really between us and the moon.

Between us and the moon we can try some things that are a little more sporty you might say where we can be out there for up to a year easy. But it takes us days to return. So there we can practice some of the systems that have to be more reliable, more redundant, all of that that I described before.

The shuttle if you recall, the space shuttle could not go past the space station. It was a vehicle designed to build the space station. I mean that was its primary function and so it went to what is called low Earth orbit which is close to the Earth's surface and that is where the space station orbits. It's a stable place where things can orbit. Not to get off into that. But with an SLS, with a much larger rocket, going back to an Apollo-size rocket - actually a little bigger than an Apollo - we can do some of those bigger longer missions out around the moon and further, actually, with the same rocket.

So that is what we are building is the one to do the Proving Ground. And our goal is once we have really tested some things out then we want to go further out to Mars and we have got some intermediate missions in there too. One of the bigger ones that has been on the table is called Europa. And that is one of the moons of Jupiter which will be a real exciting mission. It is not crewed at all but it is – and I will talk about this a little bit in a minute on why such a large rocket can help us even if you don't carry humans into space with it.

It provides an exploration capability that we haven't had - ever. So it is a really impressive rocket and this chart is just trying to talk more about all the different things we will do going to Mars. You have got orbiters. You have got landers. We have landers on there now right? The other day I was up at Cincinnati Electronics, one of our vendors and I was talking about the same thing and I said, you know, I can get this picture off my phone. I can get a picture from the Mars surface on my phone that was taken yesterday. And it is amazing because we have rovers on Mars today. Well it turns out one of the guys there told me afterwards. He said yes we built these. We are part of the imaging system that is on that rover that brings those pictures back from Mars.

Anyway, fantastic. We have a lot of things already going on Mars is the point of that. And this rocket is another step towards eventually getting boots on Mars, as they describe it. So I will pause there. Any questions on sort of the big picture of where we are going?

(Tish): Bruce I have got a question.

Bruce Tiller: Sure.

Tish: My name is Tish I am a solar system ambassador from Central New York State and so a lot of people up here who don't see the actual images of what is happening with the test. So this SRB test is really important that I show it to people. There are actually some people who don't even know that we have a human space flight program so I have got a lot of work to do here.

Bruce Tiller: Yes I understand.

Tish: But we don't have a connection in New York to Alabama or Mississippi work and we would like to be able to get proof besides video. Is there anything like a connection, an education person we can talk to down there that can give us some human space flight stuff?

Bruce Tiller: I am going to let Twila answer that one. I am certain there is but I can't answer that.

Twila Schneider: When you ask "human space flight stuff" do you mean like…

Tish: Handouts, models, things like that.

Twila Schneider: We don't have models - any handouts we have are going to be online. We don't stockpile hard copies of things. We are trying to be as electronic as we can. But if you – my email address for anybody who wants to email me is Twila, T-W-I-L-A.G.Schneider. It is S-C-H-N-E-I-D-E-R@NASA.gov and I can email you links to everything that is possible for you to print out online.

Bruce Tiller: And just to add to that. This test will be live on NASA TV certainly when it goes off. So you can get this one live and there will be video afterwards. But I think we will be on live probably 30 minutes before the test.

Twila Schneider: I think coverage starts around 7:30 Mountain Time and the test is at 8:05.

Bruce Tiller: Mountain Time.

Twila Schneider: Mountain Time. For Eastern that would be 9:30 Eastern Time and 10:05 would be the test. And I can send you links for where it will be carried live.

Tish: That sounds great. So you don't have anything physical.

Twila Schneider: No we don't have anything physical that we give away or that we send out.

Tish: Okay. All right I will see if we can get some money to do that. Thank you.

Bruce Tiller: Okay with that I am going to look a little bit more to vehicle here. This is the chart that says SLS Block 1 Crew Vehicle. And I will kind of talk about the components of the rocket.

As you know, when you first look at this it is very different from shuttle. This is not a orbiter that recovers. It is not an orbiter with wings that flies back to the ground. This one is more like the Apollo rocket with a crew capsule at the top. So I will point to the crew capsule just at the beginning. If you look all the way up to the top right you see something that says Crew Module. And it is that small thing right under the Launch Abort System.

And that is the Orion crew module and all those pieces there are labeled Orion Multi-Purpose Crew Vehicle. That is being managed out of JSC [Johnson Space Center]. That is really the spacecraft, so to speak. That is the thing that will fly in space, go around the moon and I believe it is going to be the longest duration human spacecraft we have ever made. In other words, it will go a lot longer than the Apollo spacecraft did.

Now everything below that is what Marshall [Space Flight Center] is doing. The Space Launch System which is a rocket. So the launch vehicle, our job is to get that Orion system up into space and that is the part I will be talking about here in a second.

So let’s talk about the propulsion elements and I apologize if you all know all this stuff. Some people I talk to know about rockets, some people don’t. I am going to assume you don’t.

And I am going to start in the middle, at the thing called the Core Stage. It looks like a long orange – it looks very similar to the external tank we had for shuttle. And what is included in there, if you kind of imagine, that is just a big cylinder and if you look at the little lighter orange band sort of three quarters of the way up, that is called the Inner Tank Region. Above that there is a tank in there and it is full of liquid oxygen. And below that is a much bigger tank and it is filled with liquid hydrogen. And those two fuels - every propulsion system, every rocket propulsion system has to have a fuel and an oxidizer and you mix those two and they burn and that is what creates the pressure and the thrust in order to get propulsion out. And I will talk about that here in a second. But the way this one works is those two big tanks feed - and now go down to the bottom left you will see something called the RS-25 Engine - there are four liquid rocket engines at the bottom of this stage that are fed by those two tanks. And those are actually the same engines we flew on the space shuttle, so we reuse those.

As a matter of fact, we have sixteen of those that actually flew. They are certified for flight and they are ready to go. The only modification we are making to them is putting a modern computer controller on them and that is a development underway now. So we are lucky to have those sixteen engines so for the first four flights we are good for those.

The other key part to this is - and us booster guys we say those engines are really cute but they don't really do much compared to what these boosters do - you will see these two solid rocket boosters. We produce 75% of the thrust to get this rocket off the ground, over 7 million pounds of thrust is what those two produce together and that is what will really lift this rocket up off the ground.

I won't go through all the various parts. The other thing I will mention, though, about this rocket that is different than shuttle and it was a key requirement in the development of this rocket. And that is it has a Launch Abort System.

And at the very top of this you see this little thing that looks kind of like a beanie cap, I don't know. There is actually a solid rocket motor at the very top of that spire up there. And that thing it attaches. It sits on top like a cap on top of the Orion crew module and what that does is if something goes wrong with the rocket below then they can abort the mission and they can fire these rockets and it will pull the astronauts away from the vehicle and it will actually steer them away at which time it'll disappear, and they have parachutes and they land wherever they have to be.

The normal flight of the SLS is that the boosters will burn for two minutes. So while the engines are burning as well two minutes, they fall away. Then the core stage burns for about eight minutes and then it falls away. Then you have an upper stage that burns a little more and then it falls away. And finally you have the Orion and its Service Module and they will do their mission whatever it is. We will talk about that in a second.

This Launch Abort System will actually leave it. If everything is going fine it flies away as well. And then once you have gone around the moon or wherever your mission is it returns to Earth. It goes through the atmosphere with the heat shield on the bottom just like Apollo, parachutes come out and it lands in the ocean and the Navy picks it up. So let's go to the – oh let's see do you have any questions about that?

Woman: I do have a question, actually two questions. I noticed one way of giving people context of how big this is to let them know how many crew members fit in that crew area.

Bruce Tiller: Yes.

Woman: How many people fit in there? And then my second question is if the solid rocket boosters are so powerful why do we also have liquid rockets?

Bruce Tiller: Very good question and I will address the second one here in a minute about why we have both. But there are four people, four crew members in the Orion is the current plan capability.

Now when we go to Mars they will have to add a what we call a habitat module. It has a lot of different names but you have to add more room to it when you are going for a long time like you would have to go for Mars. So we will add on to that vehicle for the longer missions.

But for what we will first do the Orion works great. Did that answer your question?

Woman: Yes thank you.

Bruce Tiller: All right so let's go to the next page and this is a video and I actually have it on a computer in front of me. So I am not sure how you make your work but I click and there is a little Play button there above the words.

And this is actually a little animation. It doesn't have any sound but it describes our first mission, we call it EM-1 - "Exploration Mission 1". And it shows us looping around the earth. This is the Orion Capsule loop around the Earth. Then it will go around the moon a couple of times and then take that big path back to Earth and land in the ocean. And that's – it goes pretty quick but that is as far as man has ever gone. We never went that far in Apollo. It will be pretty exciting.

Now, EM-1 doesn't have people in it. Let me back up for a second. EM-2 is the first crewed mission. But we will test out all those same systems. I don't know if you all kept up with Orion. They have actually had a flight where they launched on a smaller rocket than ours and we are able to reenter and test their parachutes and heat shields and such. But it wasn't at the full velocity they will get from coming back to a mission like this from a mission like this. So this will give them that first real test of all the systems and then we will be ready for a crewed mission on the EM-2. So let's go to the next page unless there are any questions about that.

All right so now I am going to talk a little bit about how we put together this thing. I have had people ask me, how do they put this thing together? And that is what this chart really tries to – I mean it is oversimplified, but it gives you some idea if people ask you.

For example, we will start at the top left. The engines, the RS-25 engines what that picture is is an engine test stand at Stennis Space Center and you are looking at an engine firing there where they were testing one of these engines probably for a shuttle flight though we did test some of these recently.

But that is a big cloud of steam that comes out of there. As I described, it burns oxygen and hydrogen and that makes water. So a big cloud of steam. At Stennis such where engines are there. They are actually manufactured both in West Palm Beach Florida and out in Canoga Park in California. But the 16 we have are living in Mississippi right now.

There to it there is the core stage is being assembled at the Michoud Assembly Facility which is right next to New Orleans called, MAF is what we call it. And that is GOCO. It is a government owned, contract operated facility. It is huge. It is an enormous place. We built the external tanks for shuttle in this facility. But they have revamped all the manufacturing facilities inside and we now have state of the friction stir welding. Some of the largest welding tools ever made.

It is really state of the art. It is very impressive, it will allow us to make these large, large tanks efficiently. And so that is where it is going.

Now once we have built the tanks we will actually take those tanks and we will take them over to Stennis, Mississippi there and we will put the engines on the bottom of them. We will do a green run test in the test stand and then we put them on a barge. And that is this picture to the top right. Well actually, this is shuttle external tank. But they've made that barge bigger to support the new stage.

But we will put the tank on a barge and we'll go across Gulf of Mexico and around the end there and back over to the Atlantic side and deliver it to Kennedy Space Center.

So then your boosters - down on the second row there on the left side it says "Five-segment SRM in Utah", that stands for Solid Rocket Motor. And our prime contractor I will mention all of these while I am thinking about it. Orbital ATK is our prime contractor who builds these solid rocket motors in Utah. Boeing is building the core stage at Michoud. Aerojet Rocketdyne is building the engine and so I will just mention those guys.

So anyway, Utah. Orbital ATK in Promontory, Utah builds these motors and this is where we test fire them as well. And that is what we are about to do next week. I will get into that more.

But we are going to get ready the flight articles we will put each segment - and there are five segment boosters - so each segment we will put on a rail car and pull by a train. We will pull all those segments from Utah to KSC and that is how they get there.

And finally, over here on the right you see something that says "Vehicle Stacking in the VAB". That is likely done the shuttle and the Saturn is in the same vehicle assembly building at Kennedy Space Center, though we are revamping all the platforms and everything to fit this new rocket. But that is where we put it together. We stack them. We actually stack the boosters first. We will put the boosters – we start with the aft skirts and then we put each segment one on top of the other until we have two boosters standing there. We'll pull them apart a little bit and then we will lower the core stage in and then we will proceed stacking up the Orion and everything until we have the whole vehicle on the top.

And then finally the picture at the bottom in the middle shows the mobile launcher rolling out of the VAB with the vehicle on it and that of course are just depictions because we haven't done it yet. Any questions on that?

Okay so the next one let's get a little focus on the boosters a little bit. As I described sort of, the boosters actually have five different motor segments. We have different names for them but there is basically the motor with its five segments and at the bottom you have a nozzle and then an aft skirt which has our thrust vector control system in it which actually steers the - it pushes the nozzle one way or the other and that steers the boosters which in turn steers the rocket.

And on the top we have the forward skirt and the nose assembly that is really for aerodynamics but also the forward skirt is where we house our computers, our avionics boxes and that is where the attach point is. It is hard to see from these pictures but the four stage actually rests on a little fitting, a little ball joint fitting and that is where all the load and mass is carried between the core stage and the boosters. The boosters actually sit on the mobile launcher and then the core stage hangs on the boosters and so when you light the boosters it pushes the whole vehicle up.

I did talk about here about 75% of the thrust is the boosters. Now you asked about why we have the engines as well? I will talk about that on the next page. So let's go to the next page. And I will pause there for a moment. Any questions on our booster before I talk about solid rockets in general?

Okay let's talk about – some people wonder why there are liquids and solids and what is the difference and this chart tries to talk a little bit about that. You can do it two ways. The picture on the left tries to describe a liquid engine stage which has the two tanks. You have got liquid oxidizer and liquid fuel. Then below that you have a rocket engine and it is a complicated beast with a bunch of valves and computers and it controls the flows of those pressurized liquid into a combustion chamber where it is burned and then it goes out the nozzle.

Liquid rocket engines are nice because one, you can turn them off. They have a valve and you can shut them off. They also, in general if it is an oxygen hydrogen engine, it is very efficient. You get more thrust per pound of propellant.

So when you get into higher altitudes and you are really more worried about your payload more so than your thrust. That is where these high efficient liquid rocket engines are really good.

Now if you just want to – and actually you are higher up so the thrust is – you don't require as much thrust to beat gravity. When you are right on the ground and you have got to fight against all of gravity you need the most thrust you can get and that is where a solid comes into play.

A solid rocket motor is solidified. You have taken oxidizer and fuel - not the same fuels and oxidizers, but it is different fuels. And you have mixed them in a big bowl and you have made this solid goop that is kind of a sludge and you poured it into each segment. You actually cast it. We have trucks that bring these big pots in and over a day's period they will pour a number of these pots full of this propellant into a segment where it is cast.

So then we stack them up and you have this rocket motor. So the advantage of that is - a lot of military uses solid rocket motors because they are storable for one thing. When you have liquids you have got to go tank that up. These are cryogenic. It takes a while to get the cold - these are very, very cold. It takes a while to load them up.

A solid if you have got something on a submarine or something a soldier has to carry on his shoulder. You don't have time to do all that. So if you have got to have an immediate response or you need to store them, solids are very handy.

So I guess I would say they are high thrust, long term storage or when this rapid readiness, when you really need to get it out of that silo in a hurry, that is where you use solid.

Any questions about that? And so my answer to your question earlier is I have the liquids on there. They will actually burn for eight minutes. My solids will be done in two. I got them the thrust. It didn't require the high efficiency. I got 7.5 million pounds of thrust. They [the liquid rockets] only put out - four of them is probably half a million apiece, 2 million pounds of thrust. But they burn for eight minutes.

So once mine have fallen off they are higher up in altitude. You are now well on your way. And they are able to push the whole vehicle now in a more efficient manner. So does that help with that answer?

[Unintelligible question]
They can but you would never do that once you start it. Twila asked me can you turn them on and off? And the answer is yes. And in fact we do that at every launch. Shuttle did it as well.

We will actually light those engines, wait just a second to make sure they are up to pressure and decide they are good. And if they are not good we will shut them off.

Once you light the solids you are going. You are going somewhere. You can't shut those off. Does that answer your question?

Woman: Yes that did. Thank you very much.

Bruce Tiller: You are welcome. Okay let's switch to the next…

Tish: Bruce I have got another question. This is Tish again.

Bruce Tiller: Sure Tish.

Tish: Some of our people are telling me that in the past some of this hydrogen and liquid oxygen produced so much water that it was a problem on launch. Can you tell us a little bit about that?

Bruce Tiller: No. You have got me on that one. Now I will tell you what I know about water on launch and maybe this helps. Let me see. When we launch a shuttle and we will have to do the same thing with this rocket. There is a – we actually spray a lot of water on the launch pad itself. We have things called rain birds we call them but they are big nozzles and we spray a lot of water on that pad. You have seen it if you watch the shuttle videos. And we will cover that whole pad with a bunch of water before we ever light the first rocket engine.

That is to help prevent an acoustic bounce back, so to speak. Noise from these rocket engines used to bounce off the pad and it would really affect the vehicle. The first shuttle launch almost got in trouble with that because we didn't know that in the first one.

But now we have this water spray. It is very helpful. That may, I am not sure if that is what you are talking about.

Tish: I guess I saw that last image with the steam and I thought that maybe that was the water they were talking about.

Bruce Tiller: Well it does certainly when you light the engines it creates an enormous amount of water. But I don't think that is a problem.

Tish: Okay.

Bruce Tiller: That I am aware of. So I may be missing that one. Now the rocket motors burn you don't get nice water coming out. You get some sort of nasty stuff. It is not real nice chemistry that comes out of a solid. It is much more complicated chemistry than just water. It is just different. So that may have been what they are thinking of. But the water part I can't think of damage there. Now I will say maybe…

Tish: I will make sure that they know that you said so. Thank you.

Bruce Tiller: Of course. And I will say this. Now everything that comes out of there, whether it is water or our solid rocket motor exhaust is extremely hot, extremely hot. So certainly that heat can cause a lot of damage on structures that are not cooled.

So for example, we had these big flame deflectors and big – we call them flame buckets. And we cooled those with water and any structure that is going to be hit by these rocket flumes we have to actively cool them with water to make sure they don't just burn right up. So I don't know maybe that has something to do with it. Certainly it is very, very hot. That is what I would say.

Tish: Okay so it is not from the engines. It is from the coolant.

Bruce Tiller: Well…

Tish: It is not a problem.

Bruce Tiller: I don't know the problem that your person is telling you about. But I will say both the exhaust from both the solid rocket motor and the RS 25 liquid rocket engines is very, very hot. And so it would burn things up if you didn't protect things. Does that make sense?

Tish: Okay. Thank you.

Bruce Tiller: So let's go to why we do a hot and cold static test. So now I am going to talk a little bit more about our booster and what we do to prepare for flights. So I am kind of wandering off my charts a little bit but that is okay.

A liquid rocket engine is kind of neat because you can test them in the stand and turn them off and then go refurb them and go put them back in the stand and test them again. They actually do lots and lots of engine tests with the same engine. It's a pretty quick turnaround. All you have got to do is tank back up again. It is not [really] that simple. You can only have so many starts, et cetera, et cetera. But it is easy to get a lot more tests out by just tanking up again and you turn around and test the engine again.

Not so with a solid because you had to bake all that in. You had to build that motor. So testing a full scale solid rocket motor test is a big deal. It takes about a year to build one of these so we don't do very many.

When you start a development program you decide up front. How many am I going to do to qualify for flight? In our case for this motor it is leveraged off the shuttle so we had a lot of shuttle experience because we flew a four segment version of this on the shuttle and we just added a segment. It is oversimplified but we just added a segment in the middle.

So given that leverage and it is the same propellant on the inside. It is the same metal cases. We were able to do this with only – we did three development tests and then we are doing two what is called, qualification tests and that is where you really go for score. That is where you are really certifying that yes, Mr. Vehicle, what I told you I would provide you is what I am going to provide you.

And we tell the vehicle they are kind of our customers. So we told them, hey we will give you this 7.2 million pounds of thrust and one of things they question is well wait a minute. I am down here at KSC somedays it is cold. Somedays it is hot.

And a liquid rocket engine doesn’t really care about that but a solid does. So if you look at the curve down there on the bottom right. I am not trying to get overly technical but it has - thrust versus time are those two curves.

And one of them, the red curve starts a little higher but ends sooner if you follow it over there it burns out sooner. The blue one starts a little lower but it lasts longer. Well those are two different temperatures and one of them is 40 degrees and one of them is 90 degrees. And that is the range of temperatures that we have said, hey we are good for those temperatures down at KSC.

Typically our launch days are in between those two somewhere. So we have to test both limits of that so that we can provide the vehicle with these curves. Because they have to know exactly how we are going to burn. They have got to know that curve and a bunch of variation around it so they will know where they are going to go.

I mean it is kind of a vehicle control thing and so it is important that they get the limits on the hot and cold performance of the solid rocket motor. So we do two. We do a hot one and a cold one.

Now this is kind of interesting how we do that. This thing has a million and a half pounds of propellant in it which is kind of like rubber. And if you can imagine it takes a very, very long time to change that rubber temperature at all.bSo when you want to do a hot test or you want to do a cold test it is going to take you a while. In fact it takes us about a month and a half of conditioning temperature to get this thing down to a temperature we want or up to the temperature we want.

And so the motor is built in this stand and I will show you another little bit picture or there is a video in here of that. But once it is built in there, there is a little house that rolls on wheels. The motor doesn't move but the house rolls on little train wheels and in this picture at the top it is actually to the left. You can't see it but it would roll to the right and cover that motor up.

And then we put these big air conditioners. You see these big blue refrigeration units in the picture at the bottom left. And they bring those in by truck. We lease them actually. And they will fire those up and get that building down about – boy I don't know 30 something degrees for a month and a half. And all the technicians are in there wearing these big old coats and still working. But they get it done and it gets it down to the temperatures we need.

Any questions on that? I have got another thing – I know I am running out of time. I don't know how much time we have got. But I can talk forever on this stuff.

Jeff: Yes I had a question. This is Jeff Nee at JPL.

Bruce Tiller: Hi Jeff.

Jeff Nee: Hi. Does that mean that launches are scrapped above 90 degrees Fahrenheit? Because it is Florida after all.

Bruce Tiller: It is Florida. No, but what that means when I talk about temperature let me clarify. What I am talking about is what we call Propellant Mean Bulk Temperature. So that is the average temperature of this entire motor.

The million and a half pounds I was talking about. So the chances that you are going to be 90 degrees for a month and a half, including at night, is not going to happen. It never happened during shuttle.

So yes we will have a hot day but you also have a cooler night. So on average, and remember I am saying it takes you a month to move this temperature a whole lot. I mean you will move it a few degrees but it doesn't move that rapidly, let me say it that way.

Jeff Nee: I see, thank you.

Bruce Tiller: Yes, it's a good question. Very good question. So we have more and I will talk about – we do have temperature limits especially if you all remember back in shuttle days. We were worried about our joint temperatures a lot. And so those we had heaters on. So those are more transient temperatures where there are temperature limits we are worried about that are quicker but not this one. This one is 40 to 90 on average. We are not going to bust that. We will be okay.

Earle Kyle: I have a question.

Bruce Tiller: Sure.

Earle Kyle: This is Earle Kyle Solar System Ambassador in Rochester, Minnesota.

Bruce Tiller: Hi Earle.

Earle Kyle: When it is on the pad, do they have internal thermometers embedded into the solid propellant material to actually monitor what its temperature is? Or do they just use an algorithm to calculate what it is based on the outside ambient temperature swings?

Bruce Tiller: Really good question. And the answer is no, we don't have temperature sensors inside embedded in the propellant. We do do it by analysis. You got it.

What we do on these ground tests we do have thermal couples on the inside - essentially pasted to the inside of propellant. We don't bury them down in the propellant. But we do put them on the inside. So like for the last month we have been measuring temperatures on the case, on the metal case on the outside and the inside of the propellant itself. So that is sort of the inside and the outside. And then we have a thermal analysis model, algorithm as you call it. Exactly right. And that thermal analyst will run a model and predict when he has those two boundary conditions what is the average bulk temperature. And that is exactly what we do at launch.

We know all the winds and temperatures of the air at night and during the day and they will take those transient temperature profiles and run them through the model. And they will tell the vehicle at a certain time before launch here is our PMBT we call it. The Propellant Mean Bulk Temperature. We will give them that and they will know –how to expect us to perform. Does that make sense?

Earle Kyle: Yes. I had one other quick question.

Bruce Tiller: Sure.

Earle Kyle: I was lucky enough to be right next to the vehicle assembly building for the launch of Apollo 11 and 17.

Bruce Tiller: Wow.

Earle Kyle: And since this beast you are building is much bigger than a Saturn 5 would that be dangerous to stand outside when that sucker lights up?

Bruce Tiller: I don't think so. I think the pad is still a pretty good ways away from there. You will be fine. But it will be pretty exciting. You will sure feel it, I'll tell you what. It will definitely put that chest rumble on you when it goes up.

Earle Kyle: Yes you bet. Okay thanks.

Bruce Tiller: Yes.

Steve Ainsworth: I have a quick question. Steve Ainsworth, Solar System Ambassador. Looks like on your burn profile that possibly the total impulses and a lot different between the temperatures of the grain. Is that what it pans out? And what is the total impulse?

Bruce Tiller: I don't have those numbers in front of me but you are exactly right. We are not creating energy here so you are exactly right. Total impulse remains the same and that is why one of them – for those that don't know what he is talking about that is sort of area under the curve of both of those curves.

And the area under the curve is the same. It should be. Because you haven't added any new propellant or any new fuel oxidizer. Its burn rate is different. That is kind of what has changed. So you are right. The impulse is the same. And I don't have the number in front of me.

Steve Ainsworth: Do you happen to know what the specific impulse is for these engines?

Bruce Tiller: You know I am going to say…I should know that number. But I am going to probably get it wrong, 297 seconds? I don't know but we can find that out.

Twila Schneider: If you will email me I will get that answer for you.

Bruce Tiller: We will get it to you.

Steve Ainsworth: Thank you.

Bruce Tiller: There is a number here for these motors and I don't know what it is. I also don't know if that is, well I don't know. I don't know but I will find out. It is not as high as those liquid rocket engines though. They have a lot higher $I_{sp.}$

So let's go to the next chart. So let's talk about QM motor 2 overview. This picture just tried to show some different motor pictures is what I am trying to do there. Talk about some of the different pieces.

The top left there is when we are putting a segment in the test stand. You can see the crane lowering the aft segment down. You can also see that –in that picture you can see what we call the aft skirt which is the thing to the right. And in there you will see a bunch of what looks like tanks and all sorts of stuff around the outside edge of that aft skirt. That is what we call the thrust vector control.

And what that ends up being is its own little hydraulic system that uses hydrazine as its fuel to run some turbines which then runs some pumps. Which then pushes these actuators with lots of force and it can drive the nozzle left or right. So that's what steers our boosters and we provide a lot of the controllability for the vehicle. The engine's gimbal as well, that is called nozzle gimbaling.

So it is in that aft skirt is where all that system is. Very complicated but very highly reliable. It came from shuttles and other leverage from shuttle we are using the same system that they had. In fact we have that hardware that flew on shuttle. A lot of these pieces flew on shuttles. It is kind of neat actually.

Okay the picture in the middle there is an insulation layout. You see a technician standing on a platform and he is rolling out big sheets of rubber. Again these are thin metal cases, relatively thin metal cases that contain this burning solid propellant. So of course it has to be insulated so the cases don't burn through. And that is what he is doing is putting that rubber in there. That is a whole another technology is getting that insulation right.

I would say the other picture I might show is down in the middle on the bottom you see a man on a platform looks like he is poking a stick at something. That is in the middle of the nozzle. That gives you an idea of the scale of the size of that nozzle. He is putting a plug in the throat of that nozzle. And it is actually made out of foam and the picture at the right shows that plug breaking into pieces right at ignition of the motor.

So we have a plug in the nozzle at launch time because when the engines light first. The engines light before the solids do. And we don't want those hot flumes from the engine to come up into the motor. One, to ignite the motor that would be bad if you didn't want it to. But also more than that it is an ignition overpressure that is kind of an transient acoustic thing. So to protect against that and keep that hot gas out of the motor we have put a foam plug in there.

Turns out it is a really big plug but it is one. So that is an issue for launch time because that thing is going to break up and send little pieces out all over the place. So it is a debris issue we are tracking. One of the things we learn from these tests is how will that break up? And we do some high speed video and really count the pieces. After a test the guys go out on the hillside nearby and actually pick up foam and they categorize how it broke up.

So lots of things we learn from these tests not just the – now I think it says at the bottom we have got something like 82 qualification objectives that are formal objectives. We are trying to - for our certification our real, you know, here is our specifications it has requirements in it. There are 82 of those requirements we are going to show we meet by this test. And then we have over 500 instrumentation channels, everything from temperatures to pressures, strains, stresses, we are measuring all kinds of things.

Lots of data. It takes a long time to scrub it all. Because like I said, we don't many of these tests but when we do it is a big deal. We try to get as much data as we can. Any questions from this page before I move on?

Man: Do these solid rocket boosters do they burn from the end like a cigarette? Or do they have a channel through the middle that burn all the way up the length?

Bruce Tiller: They burn through the middle. The grain geometry is cast such that you get that profile that I showed you. I showed you a hot/cold profile and it had a funny dip in the middle.

But that grain shape that you are talking about. The way, the size of the hole in the middle and the way that grain is shaped it actually has internal fins up in the very front of the motor. And the way that whole grain shape is creates that thrust profile. And so yes it has a hole in the middle. It is not an end burner. Does that answer that one?

Man: Yes thanks.

Bruce Tiller: Okay. Let's go to the next chart. So here are a couple of little videos you all can watch. The one on the – you can hit that one there. I will watch it too. You have probably seen them but the first one there is just a high speed video of assembly and the test stand.

The fun thing about these is if you haven't seen – it kind of gives you again a scale right? It kind of gives you a feel for how big these pieces are and how carefully you have to move them around. It is explosive stuff. So it is something you do carefully and slowly and you get it just right.

The hole you were talking about you can see that there. You can see that it has a hole right down the middle of that segment. And that is the gray part there is the propellant. The black part is actually – we call it an inhibitor. But we actually put rubber on the end caps to keep the ends from burning like you are describing. We want it to only burn down the middle.

And then the other video there over on the right, the QM-1 test. See if it will come up..

Woman: There it is.

Bruce Tiller: I can hit that thing to watch to see what it says. Yes it just a view on the test stand for just a piece of motor firing. But you get another view of the scale. This plume that this thing creates in the two minutes that it burns is something spectacular. It is high enough to where we have to alert the FAA. It is a big deal. We worry about our neighbors who are farmers. And we worry about the weather and which way the wind blows. It is a lot of stuff that goes in the air.

So let's go to the next page there. And this is finally just some dates. I want to talk about this picture for just a second and I will take some questions again. This is a nice picture of the motor and the stand. We are testing on 28th of June at 8:05 Mountain Time and it is in Promontory, Utah at Orbital ATK Test facility.

I wanted to talk a little bit about - you see it in the stand. When you do a test like this what you really want to – there are a lot of things you want to measure but if I want to measure that thrust, I really want to know how hard is it pushing?

If the hot stuff is coming out of the right side there into the mountain then I want to know how hard is it pushing to the left? And I don't want to impede that thrust by holding it somewhere else that would mess up that measurement if that makes sense.

So back here on the left it is hard to see but there are a bunch of steel structure that goes down to some load cells where we measure that thrust. And these two things in the middle are the interesting things to me. When we were doing these tests for shuttle, the four-segment versions didn't have those. We call them mid-span supports. We didn't have those and didn't need them.

But when we made a five-segment version the thing is so heavy it now sags in the middle. It actually droops in the middle. And a couple of bad things can come out of that. One, you could crack the case if it droops too much. The other is we think it changes the flow environments inside the motor and it is not flight-like.

In other words, when you have got these things vertical and you are flying straight up you don't have a big bow in it like you would have if you don't put these mid-spans in there.

So we did our first test with one of those. We decided we were still sagging too much for various reasons and we put two of them in. And that seemed to help us out a lot. So now we have two of them. And they are kind of unique features. It is hard to see but there is a band. It is like a – I don't know it is not cloth but it is some fancy material that is a strap that goes – that the motor actually hangs on a strap.

And then these things are free to move left and right. So they don't – again they don't constrict the motor from moving. And so you can watch that load as it is holding them during the test because actually the whole thing lights up. All that propellant is going out the back that will actually lighten up to the point where the case actually comes off the strap and it doesn't carry any load anymore during the test.

Anyway kind of the neat little test stand gee whiz thing there. So any questions about the motor and the stand here I can help with?

[Unheard question]

Lot of concrete. I wish I knew the number. It is a lot of concrete. To make sure that thing is what, 3.2 million pounds of thrust from one motor. Make sure it doesn't go anywhere. It is a lot of concrete. It is I don't remember the number but just imagine it is very deep and it is very wide. To hold it there takes a lot of stuff.

And I think that is all I have got. Any other questions I didn't cover? Anything anybody is interested in about boosters or SLS?

Jeff Nee: Yes I had a question. What exactly is the fuel for the solid rockets?

Bruce Tiller: It is called PBAN. P-B-A-N but that doesn't really tell you much. And I am not a chemist so I am not going to be helpful to explain all the chemistry. But if you were to Google up PBAN solid propellant that would probably get you some information there.

Jeff Nee: That is perfect thank you.

Bruce Tiller: There are other types of propellant but this one is called PBAN is what it is called.

You know one of the exciting things. We are really actually really fired up about this. This will be our last ground test before flight. So we are in the middle of building the booster for EM-1. We have got motor segments being cast. We are building that beyond this test already and parallel with this test.

We are building up the forward and aft skirts. There is a lot of work to be done there down at KSC is where that is done. We actually have a building there at KSC where we are doing that assembly so we are well on our way. We are building a lot of hardware for EM-1 and this is just one step in that big qualification. We have got a lots of things to qualify but the motor is one piece of it. And it is a big visible piece and that is what this second test will be.

The next time we light one of these up it will be EM-1. And we hope it is 2018 and we are pretty excited about that.

But you know is there anything else I can tell you guys? Happy to answer questions.

Man: The Ares flight used – was it just a four-segment motor like this?

Bruce Tiller: No we built a five-segment for Ares but as you recall that was a single stick rocket. We were going to go to a two booster version of that but we never made it. But we had a single stick version of that. In fact the first development motors that we fired were for Ares 1. And then we were actually able to switch to SLS pretty easily because our boosters were pretty much the same.

We just had to go to that – from going from that single stick where things were on top of us to go that side mount version which is the SLS. We had to bring in the forward skirts and the nose caps and add those features. But we had those from shuttle. Those were heritage so we were lucky there.

Man: There was an Ares test flight though.

Bruce Tiller: You are talking about Ares 1-X.

Man: Yes.

Bruce Tiller: Ares 1-X was a test flight using a shuttle four-segment solid rocket motor. It was one that was built but not flown. And so that wasn't an SLS configuration. It was a four-segment.

A lot of the avionics were tested on 1-X that are the same as we are testing on or we are using on SLS. So we have got a lot of the control systems were checked out there.

Man: How much can these rocket motors vary in thrust? I mean I imagine with two rocket motors they would have to be pretty well matched to work properly.

Bruce Tiller: Yes. They don't vary – well let's see how much do they vary? Good question. What I will say is this. When we model the performance we call it the ballistics of the motor. We vary all the parameters that might make a variation there and when we tell the vehicle how we are going to behave we give them two and three sigma on either side of the nominal thrust curve. So they know - plus the hot and cold we also have the variation you might get from all these other little things that might cause you to be different. But so yes there is some difference but it is not a lot. They are pretty much dead nuts on, but we have to give them a variation just in case.

And now the bigger concern for us is the variation between two boosters. One on one side and one on the other. Because obviously if you had a big imbalance, a thrust imbalance then that would be a problem for the vehicle. It would be hard to control.

But we have that as a requirement that the thrust imbalance can't be greater than some number. And so we watch that very carefully. Meaning that our variation for one motor can't be so high that you could get a thrust imbalance between them.

And so we worked that pretty hard, actually. And the vehicle works its ability to control with its software and how much it can steer. Because it steers each booster independently.

So that is a good question but it is a problem we work to – I mean we know it. It is part of the whole design set is to make sure we design to be controllable within the variation that is out there. Does that make sense what I just said?

Man: Yes.

Bruce Tiller: Okay.

Jeff Neww: And I had a question back on slide number seven, which was about the connection between the booster rockets and the fuel tank. There is only one point of contact?

Bruce Tiller: Yes. Isn't that amazing?

Man: That is.

Bruce Tiller: It is. It is called the – we call it the thrust post. It is the same design we used on shuttle actually. And literally like I said when you stack these things you build up the boosters just like you did on shuttle. And then you lower that tank down and it has the opposite side fitting. And it literally sits down on the booster.

Now we put something in there called a separation bolt. And that is how you bolt the two together. But it is a single fitting and that separation bolt is a bolt with explosives in it. So when it is time to separate - of the many things that happen at separation time one of them is you blow that bolt. And then the boosters – they have separation motors that pull the booster away from the main vehicle.

But yes, it is one connection. All that thrust goes through one post. If you looked at a forward skirt which is that metal casing at the top - and I'm going to get off in the dirt here, but if you look at that thing, that thrust post sits under – we have as you can imagine a beefed-up column of steel that comes under that post. And so it is a highly beefed-up area. We actually tested two of those to failure a couple of years ago as part of this new SLS rocket. We had the same structure we had under shuttle but since we added another segment so much more thrust. Would that same fitting handle that extra thrust?

So we put them in a stand. Put that extra thrust load down on that fitting and broke a couple of them. And we did it to prove that it wouldn't fail until well beyond the loads we expect with this configuration. Really good question. Highly loaded connection but we have tested it to failure with two skirts so we are very confident in its performance.

Jeff Nee: And just one more thing. The solid rocket booster is 100% reusable? Or are there parts that you have to replace after a while other than the fuel, of course?

Bruce Tiller: So it is reusable. We are not reusing them. Let me say that way. Under shuttle we did. You know we had parachutes and we landed them in the ocean and we drug them back to shore with some boats and we washed them out and we inspected them. And again I am oversimplifying that long, long process. But then we would take them back to Utah and fill them back up with propellant.

We had all those extra cases from shuttle days and that is what we are using for these boosters but these are not recovered. Now under Ares we were going to recover those and we had a new parachute system we designed for that because it was a lot heavier.

But under SLS we did not design for recovery for various reasons I can go into if you are interested. But it is not recovered and so it could be but it is not. Does that make sense?

Jeff Nee: Yes absolutely thank you.

Bruce Tiller: Okay.

Man: I am curious why did you decide not to recover these?

Bruce Tiller: Good question. Our plan for this booster was use what we got and use it up. And then we were going to – this vehicle was going to go to what is called a Block 2 version of the SLS vehicle which is going to be a more high performance vehicle to carry even more payload than this Block 1 vehicle.

And so that advanced booster is the next thing that would replace the booster we are using. So if that path takes place then we are going to use… I think we have enough motor cases to fly like eight flights. At least eight flights.

So the decision was made wow, we can get eight flight sets with the hardware we have got. We don't have to build a single another case or an aft skirt or a forward skirt. Because we have got it already. And since we are going to replace it all anyway, then we are not going to spend the money on parachutes, boats, infrastructure, all of the stuff that is required to – because it is very expensive actually to reuse this thing.

So for a dollar reason we decided not to do that because we didn't need to basically. That is the bottom line. We just didn't need to. How did I do with that answer? Did you get it?

Man: Yes thanks.

Bruce Tiller: We really have a building out there in Utah it is kind of neat to walk into with all these big metal cases just filling the halls. So it is pretty neat to see actually. And a lot of them, like I said they have all flown on shuttles. It is kind of fun.

Amelia Chapman: Do we have any more questions?

Bruce Tiller: Well if not, listen I appreciate you all listening to me ramble for an hour and I hope you got something out of it.

Amelia Chapman: Thank you so much for speaking with us today. I think it was a really great talk and I am looking forward to seeing this happen on TV.

I would like to thank everybody for joining us today and welcome you back this Thursday at 1 pm when we will be getting to know the first in A in NASA, Aeronautics with Tony Springer of NASA's Aeronautics Research mission directive. So I hope you will join us on Thursday at 1. And thanks again to Bruce.

Bruce Tiller: Thank you.

END