Danielle (00:00):

I would like to now introduce our first speaker, Dr. Panerai. Dr. Panerai is an assistant professor in aerospace engineering at the University of Illinois, at Urbana-Champaign. Prior to Illinois, he was a research scientist at NASA Ames Research Center in California. His research covers advanced materials for extreme environments, transport in porous media, and hypersonic aero thermodynamics. Dr. Panerai received his PhD in aeronautics and aerospace from von Karman Institute for Fluid Dynamics in Belgium, and a Master's in science. As well as a Bachelor's in science, in mechanical engineering from the University of Perugia in Italy. He is recipient of the 2019 air force young investigator award. Today, dr. Panerai will be speaking about the seven minutes of terror with a heat shield.

Dr. Francesco Panerai (01:22):

All right, thank you very much for the kind introduction, Danielle. Let me tell everyone that it's a great pleasure to be here. I would like to thank the Illinois Space Grant Consortium, for putting together those events. I feel blessed to be able to talk to this audience about a very exciting topic in space technology, which is the topic of entry in the atmosphere. So many of you have read the news about the March 2020 spacecraft who delivered the Perseverance rover to the surface of Mars, just about, and now's approximately a couple of weeks ago. If you see the picture here in my first slide, I think this is one of the most beautiful picture of this event. It doesn't maybe tell us much, but you see two bright dots at some point in this location, which are magnified here.

This is entry system that deliver, this is the entry system actually, that delivered the Perseverance rover, down to the surface of the planet, on a parachute. So it was an image that was taken by one of the orbiters, that is orbiting around Mars, and is monitoring the surface of red planet, and is patent, the vehicle during the entry. Now, the entry and the descent. Now this entry, descent and landing is what many people at NASA have referred to as the seven minutes of terror. I try to give you at least my version of where the terror comes from, and eventually, how do we protect from it. So we are going to discuss one of the materials that helps survive actually, the harsh conditions that we find during the entry into the atmosphere. All right. So this gives you a little bit of picture, of this seven minutes, and what happens, you have the surface of Mars, you have a crater where you really want to usually deliver a payload, in this case, this little robot here.

So there is a series of very challenging, very well timed operations that need to happen for this rover to be delivered. Everything starts off with this capsule here, that is undergoing long journey, of many months in space. All of a sudden is going to approach actually, the red planet and is going to find an atmosphere. So this capsule is traveling at extremely high speed. So when it starts entering the atmosphere, is going to interact actually, with the gas of the atmosphere and produce a lot of heat. I give you a sense in a minute, of how much this heat is, but it's so intense that actually we need to find a way to protect for that.

We protect from it, using what we call the heat shields, which is what I'm going to discuss in details today. In particular, I'm going to talk about one of the ablative heat shields, and I'll explain what an ablator is. That is being used actually for this Mars 2020 missions, and is being one of the most successful technology that NASA has developed for entry, descent, and landing.

So I want to start with, since probably we have some engineering students in the audience, I want to start with a little calculation here. So if you look at velocity, this spacecraft is arriving at the orbit around Mars at about 12,500 miles per hour. That's very fast. So it needs to cross the atmosphere a few tens of kilometers, from orbit all the way down to the surface where it needs to arrive to zero velocity, Otherwise you would crash this robot to the surface. So for, for those of you who have taken engineering class, you know that when you hire above the surface of a planet at a certain orbit, you have different kind of energies, but essentially you have two main components. One is a component of kinetic energy, and one is a potential energy component. So the kinetic energy is proportional to the mass of the spacecraft, which in the case of Mars, like a big car. So it's not very large, but you see that's proportional also to the square of the velocity. So this term of the kinetic energy becomes extremely large. In addition, you have an extremely large potential energy that comes because you're sitting above the surface, and actually at a certain distance from the center of the planet.

So during this entry, so during this trip into the atmosphere, you need to lose all the energy, and arrive to the ground at zero energy, where the velocity is going to be zero, and the altitude is going to be zero. So the question is, what happens to this energy? That energy is always conserved, so we cannot destroy it. So it needs to go somewhere. Well, it turns out that this energy into this process is converted into heat. So I did a small calculation this morning, and if you look about the energy that you need to dissipate, this is about a hundred thousand megajoules, that need to be dissipated during this phase. You compare it with an average household consumption in Illinois, that's about 10,000 kilowatt hour per year, so that's almost 36,000 megajoule per year.

So if you compare it with the energy that needs to be dissipated by the spacecraft, you can see that, in about seven minutes, this spacecraft needs to lose the entire energy that you could use to power your house for about two and a half year. This might not seem a lot, but there are some conditions, for instance, when you're coming back from Earth, or whether you're coming back to the Earth from the Moon, or even from Mars, where this number can go as high as two or 3000. Okay. So how do we protect the spacecraft from this energy? Well, we use what we call heat shields, or thermal protection systems, which are very high performance materials that we put at the front of our spacecraft. They're going to be able to meet the atmosphere and dissipate a lot of this, or handle a lot of the heating that is being produced while also protecting everything that is contained inside this little system. Take into account that these are approximately the dimension of a small car.

So I'm going to talk about this very material. Before going into that, I would like to give one further overview about two different classes of materials, that we can use to perform this protection from the hot environment. The first class is the class that we call ablative materials. The second class is the class that we call of reusable materials. So most of you are probably familiar with this type of materials, those where the tiles that were used in the space shuttle varied, also successful and well known technology that NASA created. But in terms of the space shuttle are good only for very benign conditions and cannot be always used. In fact, there are vehicles that come back from Mars or from far the solar system, or even from the Moon, where if you would put this technology, the material would actually get destroyed during entry, and you would lose astronauts, you would lose payload, you would lose anything that is contained inside your entry system. So for this class of trajectories, we use what we call ablators.

The most successful of those, I'll give you in a second example of how the ablators behave, the most successful of those is that technology that NASA inventor is called the Phenolic Impregnated Carbon Ablator. This is the way it's made, you start from a brick, which is essentially carbon fibers, is very lightweight, brick. That is mostly composed by air, and carbon fibers. In fact, air is approximately 90% of the volume of this tile. Then you add to the pores of this carbon fiber bricks, some resin, you do some magic, and you process it into a very high performance material, [inaudible 00:11:20] call it PICA. That's the name that NASA uses. This stands for Phenolic Impregnated Carbon Ablator. So this is the very material that was used in the front shield of the Mars Science Laboratory, was used in March 2020, just two weeks ago, as it landed on Mars, it was also used in Stardust, which was a spacecraft that scooped actually, the tale of a comet and brought back part of the comet dust, back to the Earth. This was the fastest manmade object that ever returned to Earth. Entry velocity in this case was about 12 kilometers per second.

Actually, so much of a good material that NASA made, that actually the commercial industry decided to adopt it. SpaceX, put an X in front. It calls it PICA X, but is a very similar technology that is used for their Dragon capsule to bring back astronauts from the international space station.

So how does the ablation phenomenon work? So we have wind tunnels. We are in the process actually of commissioning two here, at the University of Illinois that can reproduce the hot environment that this material is experienced during atmospheric entry. They do that, or we do that actually, by producing a plasma plume, that represents the flow that you would experience during entry. This flow, just to give you an idea, is approximately 10,000 Kelvin at this location. So the temperature is about twice the surface temperature of the Sun. So we use this flow to bring in a sample or, a specimen of this materials. This is going to interact with the environment and undergo a series of chemical, mechanical, and thermal processes, that we know as the process of ablation. So essentially what this is, the material is burning, under the effect of oxygen, and this dissipating all this heat that is receiving. This dissipation process is what helps whatever is sitting inside here to survive those extreme temperatures.

So just to go a little bit more in details, this ablation phenomenon is composed by many different type of processes. So you have transfer of gases, inside those materials that are porous, you have radiation that is heating the material from the gas, you have a process that is called pyrolysis, is a process that actually burns the resin that is contained inside the material, so as to create gases that are pushed outside and serves as a farther shielding from the hot environment. One of the main processes is, this one of the main phenomena that occurs, is this interaction of oxygen and nitrogen that are contained, into the atmospheric gas in Mars it would be CO_2, but it would be eventually the same, that interacts with the carbon and produces gasifies the carbon, and determines the material to lose mass and to recess.

This is the process, the essential process, that takes most of the heat away from whatever is sitting inside those materials. Now, what I'm showing here is a very magnified picture of the fibers that are composing this ablator. This is a picture that is taken with a very powerful microscope. So you see a certain organization, when NASA produces the materials, they try to tailor the position of those fibers, to achieve actually a certain performance. So we are involved in many projects with them, among others, we have activities that help them to model the way those fibers respond to actually the very high temperature environment. When we started those activities, I tried to model this material with conventional tools. We didn't really have a good way to represent.

So what we were using, we were using virtual materials that are made by cylinders that are supposed to represent these fibers. But you see that, there are details, but of course we are missing a lot of the features that you observe in very old material that is being used. So I'm going to discuss a technique that can be used to get better images, than the one that you are seeing here. And is a very powerful technology in material science that we can use to understand first, the properties of these ablators, and then we can also use to model the response of those ablators to the high temperature environment. This technique is called X-ray Micro-Tomography. So we use x-rays like in a CT scan at the hospital, where you have a patient that is going inside at [inaudible 00:17:06] x-ray source.

This x-ray source is spinning around you and is taking a 3D image of the body. Since we are in COVID era, you probably have seen many images of lungs that are taken with this technique. Well, we can use very powerful x-rays to do the same for materials. So we can take images at different angles, and penetrate the material with the x-rays to reconstruct a 3D object. So most of the work that I'm going to show has been done in this facility, which is a powerful x-ray source, hosted at the Synchrotron Light Source at Lawrence Berkeley National Lab, in Berkeley, California. This was close to the NASA center, actually in the Bay Area, where we started most of this work back in 2013. And so this light source is what produces the x-rays that are used to penetrate those materials.

So it's just a big building with a particle accelerator where electrodes are being bent close to the speed of light. And as you bend them, as close to the speed of light, that produce x-rays at a certain energy that we can use to take three dimensional pictures of these materials. So if you do that for the Phenolic Impregnated Carbon Ablator that I've showed at the beginnings, the material that is used in March 2020, you get these kind of images, where you can really resolve all the features of the fibers that are composed. And we get down to details that, just a few years ago, we were not able to achieve. So just to give you an idea, one of these fibers is probably a fraction of what is a human hair. So we can really get astounding resolution and understanding of how the material behaves.

Now, these are not just pretty pictures, are a lot more than that. In fact, there are three dimensional images where the material is described, into a series of two dimensional images that are stacked on top of each other. So essentially what they are, are representation of the material into a three dimensional grid. So since the material is represented into a three dimensional grid, we can use those images to make calculation of different phenomena that are relevant to the atmospheric entry that I discussed at the beginning, including transport of gases. So imagine this where those pyrolysis gases that I mentioned that are traveling inside the material, and are helping to shield us from the hot environment, we can simulate thermal transport. So typically, how the heating that we have at the front is being conducted to the back where our robot, or the astronauts would sit.

We can also use it to simulate chemical phenomena, especially like the way oxygen is heating the carbon fibers. As I explained before, during the ablation phenomenon. This is a further example of the gases that are moving inside those images. Those are extremely complex simulation that we do with particle methods, and that we have extensively actually verified with experimental measurement in the laboratory. So this provide information that then we need, we feed actually to NASA engineers that are going and deciding the thickness of the material, how to distribute it around the spacecraft, and another important data that help for the design process of those ablative heat shields. Another exciting thing that we can do with those images is to simulate the oxidation phenomenon, is what I've shown before. So we have carbon fibers that react with oxygen and form either carbon dioxide or carbon monoxide.

So you see that the material goes from a solid to a gas. So what we have is a gasification of the material that loses mass and dissipates the energy. Now, perhaps I'm not going to go into the details here of those regime, but what you see in here are, simulations of this ablation phenomenon, at different conditions. So when the oxygen is very reactive, so when the temperature is very hot in point of the trajectory, where the vehicle goes faster, most of the oxygen is going to react at the surface without penetrating into the material. At the opposite hand, at the low temperature condition, the oxygen is going to penetrate inside the material, and is decomposing the heat shield underneath. And then you have the other portions of the trajectory of this entry trajectory, where instead you have an intermediate phenomenon, where you have some penetration into the material, and some consumption of the material at the surface.

So since we have access to x-rays, and to this powerful light source here, we used a similar one. This one is actually at the Swiss Light Source, close to Zurich in Switzerland, is similar to the one that I showed you at Berkeley. And what it has in addition to that, is a very fast camera, where not only we can take three dimensional images of the materials I showed here, but we can take three dimensional images of the material as it decomposes. So we can try to capture in the lab, in an experiment, this behavior that you see simulated here in those images. This is a video of how the setup works, or how the experiments are being performed. So what we have is our reactor, where we illuminate the material with lamps, the lamps are providing heat, that is comparable to that experienced by the spacecraft during entry, in the middle of this, there is one of the samples that we want to investigate of the ablator. And then this is sitting into a reactor that is spinning very fast, and with each rotation of this experiment, we take a full three dimensional image of the material. Now, we can look at how the material decomposes and evolves in time.

So this is a farther picture of the setup. Our carbon material is sitting in the middle of this reactor, this reactor spins, and then we take three dimensional images. So if you do that, this is the kind of data that you can get. And this is, I believe is, the first ever observation of high temperature carbon oxidation in four dimensions. So not only you see the material now to fine scales, but also you see the material as it is reacting with oxygen, and the composing under the effect of those high temperatures. Now, if I go back to the three regimes, that I've shown before, where you see that now, for the real experiment, we are trying to capture the same effect. So this is a condition where the temperature is very high, 1400 Kelvin. This is an intermediate condition, where the material is going to impart, be consumed at the surface in part inside.

And then you have this case, which is lower temperature than the others, with the oxygen penetrating depth. It decomposes the material in depth, so that at a certain point, a material loses structural strength, and collapses onto itself. This is very recent data that we have collected. And some of the students in my research group are still analyzing. But they're kind of surprising, because it's the first time we can observe an ablation phenomenon at such highly resolved scales. And also, it's very surprising to see that conditions, that apparently look a lot more benign, or a lot less severe actually, than high temperature conditions, can endanger the survivability of the material, a lot more, in lot more pronounced way, compared to those conditions. So those are information that we are investigating, and we are providing to NASA as we collect them, and are really experiments that are able to help us understanding how the material behaves.

I think this is the last slide that I want to give you. And I want to leave you with a message. So this material that I've talked about, and we are trying to understand, is again, this very successful technology that NASA is using for all their exploration missions to planets. And you might have read in the news in like late 2019, about a year and a half ago, that NASA selected a new mission to go to Titan and is actually a mission to deliver a quad, or octocopter here, to the surface of Titan, is one of the largest moons of Saturn. Well, this mission is going where we have, heating is going to behave very similarly to the entry that I've showed into Mars, and is going to use exactly the same material that we have discussed today.

This is a plot that shows the altitude of the spacecraft, as a function of time, where we see maximum deceleration, deployment of the parachute, the deployment of a second parachute, and the land release of the lander. Well, just to give you an idea, those were the seven minutes of terror, that happened in March, where we needed to protect the spacecraft from this hot environment. And so those are going to be a hundred minutes in Titan. So I call those the hundred minutes of terror of Titan. So this is a very exciting time because this mission is just about to start and NASA engineers, with the help of academia, trying to understand the behavior of this material for this type of missions. And of course, this type of undertaking will it other similar challenges.

And, of course, a lot of exciting discoveries. That's really what I have, I'll be happy to take questions. I want to acknowledge a few people here, especially my students, which is an amazing group, and they're doing most of the work, and my collaborators at both at NASA and at the Advanced Light Source at Berkeley National Lab. I want to also to thank the agencies that are sponsoring our research in this area, and the colleagues at the Center for Hypersonics and Entry Systems Studies here at Illinois. Thank you very much.

Heidi (29:38):

I actually have a question. This is Heidi from the University of Illinois, Illinois Space Grant. It's a hundred minutes of terror, is it because of the time that it's going to take for us to get the information back?

Dr. Francesco Panerai (29:53):

So it's both. So information, of course are going to travel slower because we need to reach out further. So the mission is going to be launching 2026, and it's going to arrive to Titan, 2034. So it's going to take about eight years to get there. So, can imagine that information to travel back, it takes a lot. It also is longer for the [inaudible 00:30:26] cause of the characteristics of the mission, and the way we are going to land to that planet. So, in fact, if you look here is going to, so the spacecraft is going to spend most of its time onto a parachute was lowering descending to the atmosphere. Parachute for this type of missions are another, extremely challenging undertaking. There is a say at NASA at every mission with a parachute is a problem, with a parachute. We're just actually about to start a project on that, in collaboration with NASA, to study parachutes that used for this purpose. Take into account, that parachutes for entry systems are, are the largest parachutes ever built. And so they have significant challenges in terms of materials, in terms of development, the way they deploy at super Sonic conditions, and other things.

Heidi (31:38):

Thank you.

Speaker 4 (31:38):

Yes. I have a question.

Dr. Francesco Panerai (31:41):

Sure.

Speaker 4 (31:42):

Yes. I had a question, is this just for unmanned missions, or could this also be safe enough to be used in man missions in the future?

Dr. Francesco Panerai (31:54):

The material that I've discussed today has been used only for robotic missions to date, except, SpaceX is going to be the first one, actually that uses the X version of these materials for bringing back astronauts from the space station. But the materials, so highly and well performant that could be used for many man mission. What NASA uses at the moment, for their man capsule, the Artemis program or the [inaudible 00:32:34] program, if you want, is a slightly different technology, where it is actually is the same technology, but slightly different material that has a different recipe, if you will. But it behaves in a very comparable way to what I've showed that. And the material that I use is the heritage from the Apollo program that was very successful to bring astronauts back from the Moon. And so that's the technology that NASA is adopting.

Speaker 4 (31:54):

Okay, thank you.