Fracture, Fatigue and Failures of Materials
Professor Indrani Sen
Department of Metallurgical and Material Engineering
Indian Institute of Technology Kharagpur
Lecture 59
Failure Analysis – Case Study – Columbia

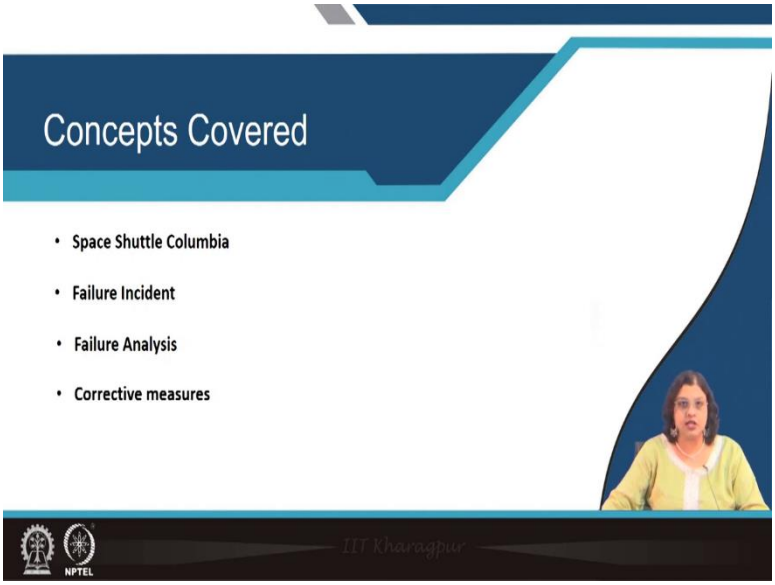
(Refer Slide Time: 0:29)

Hello everyone. We are at the 59th lecture of the course Fracture Fatigue and Failure of Materials and as we have come towards the end of this course. We will discuss about one more case studies and failure which is on a completely different space altogether.

So, so far we have discussed about the failure incidents on the sea levels like in Titanic, even below the sea level for the oil rig and then we have moved towards the sky for the air crash and today we are going to move even farther beyond. Yes, absolutely right, we are going to talk about the Space Shuttle Columbia.

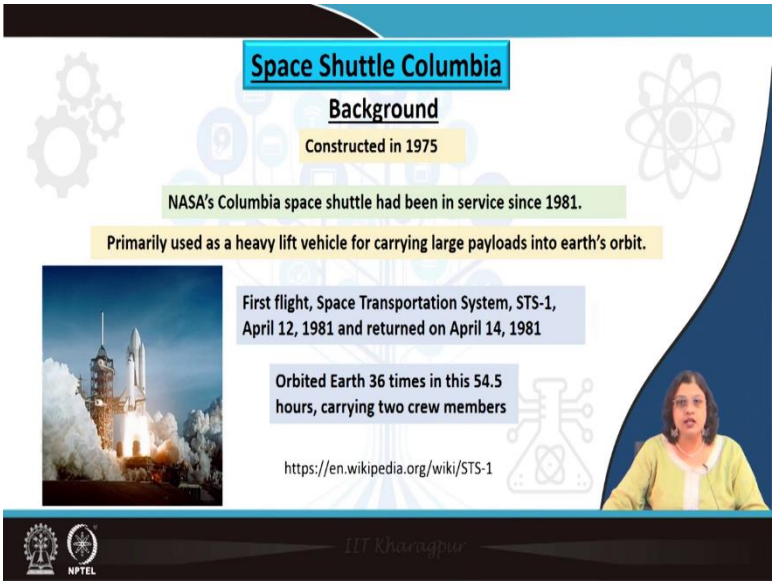
Many of you are aware of the fact that how this has met with an accident and what has actually happened. So, in this lecture we will look on to the materials aspect what were actually the reasons for the failure of the space shuttle Columbia and what could have been done to avoid that.

(Refer Slide Time: 1:30)



So, the following topics will be covered in this lecture about the space shuttle Columbia in general and then the failure incident will be talked about in details. Of course, this should be followed by a failure analysis and what are the corrective measures that had been taken based on this failure analysis and this incident.

(Refer Slide Time: 1:51)

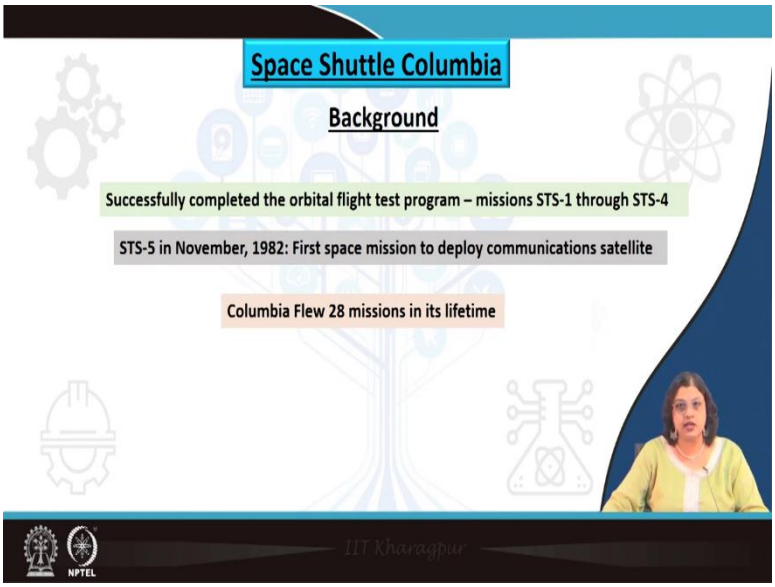


So, the space shuttle Columbia is a very special space program for the National Aeronautics and Space Administration commonly known as NASA, USA. And it is constructed in 1975 but space shuttle Columbia is in action since 1981.

Actually, it is primarily used as a heavy lift vehicle for carrying large payloads into the Earth's orbit and the first flight which is known as the space transportation system or STS-1 has been launched on April 12, 1981 which after a travel for almost 55 hours returned back on April 14, 1981.

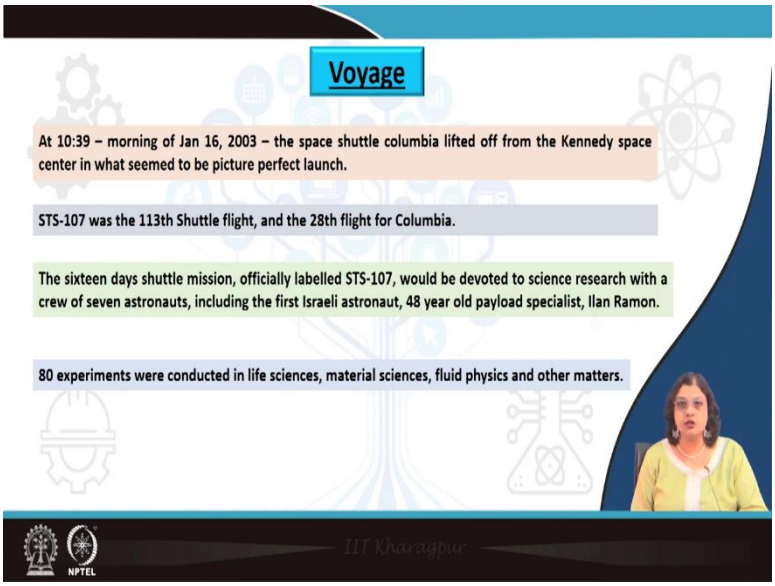
So, over this almost 54.5 hours actually it has orbited the Earth 36 times and carrying two crew members.

(Refer Slide Time: 2:48)



Following that it has successfully completed the orbital flight test program missions STS-1 through STS-4 and then STS-5 has been launched in November 1982 and this one is having a significance in terms of this is the first space mission to deploy communication satellite and after that Columbia flew for 28 number of times, 28 missions in its lifetime and this incident has happened on the 28th flight itself.

(Refer Slide Time: 3:21)



So, during this particular incident the launch seemed very successful and all the NASA officials and engineers who were involved in this as well as the common public were relieved and happy to see how the spacecraft has been launched and this particular program is named as STS-107 and it has been launched from the Kennedy Space Centre at around 10:39 in the morning.

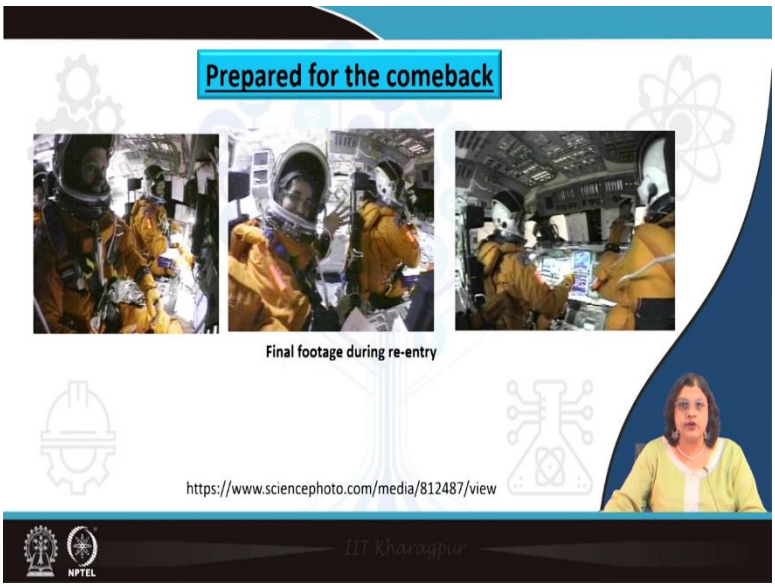
STS-107 was actually the 113th shuttle flight and the 28th flight for Colombia as mentioned. It is meant for a 16 days mission which is officially named as STS-107 and the main purpose of this mission is to do some scientific research and with a crew of seven astronauts including the first Israeli astronaut of 48-year-old payload specialist Ilan Ramon.

So, overall, 80 experiments has been performed on space and these were conducted in a life sciences, material sciences, fluid physics and other important topics. So, as you can understand that this particular mission was very very important for us the material scientist worldwide.

(Refer Slide Time: 4:46)

So, following other crew members and of course Colombia was also known for the crew member Kalpana Chawla who is of Indian origin and she was also in her second space mission in this Columbia for doing some scientific research on this apart from the other crew members there.

(Refer Slide Time: 5:04)

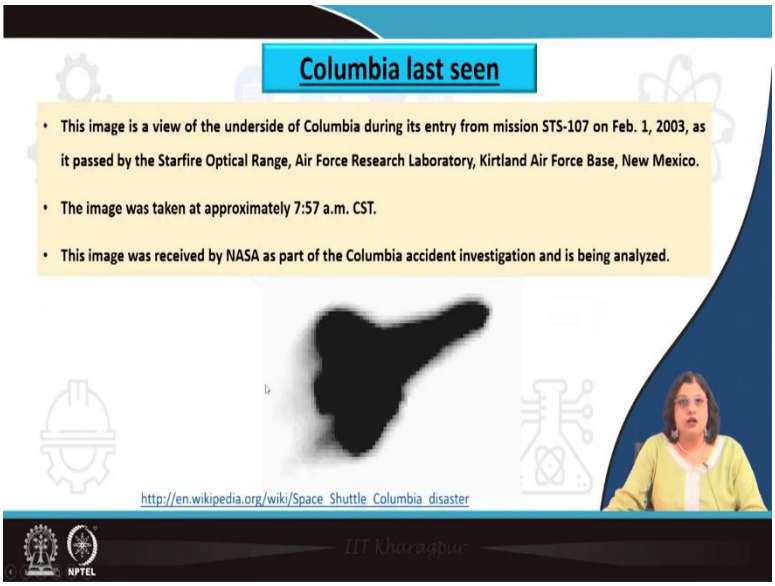


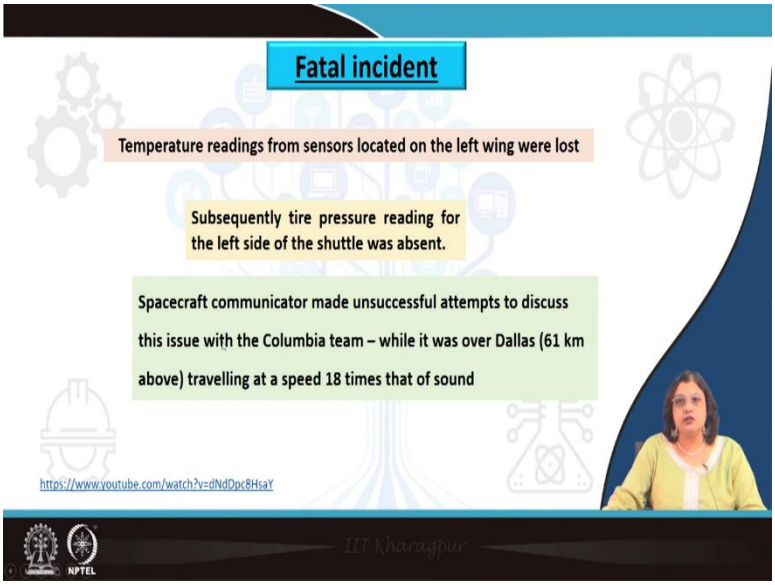
Now you can see here, how the flight was there on space and of course this is a simulated video one, just to give you a glimpse of what actually happens there. So, these are the crew members as I mentioned the seven crew members who were there in the Columbia Space Shuttle.

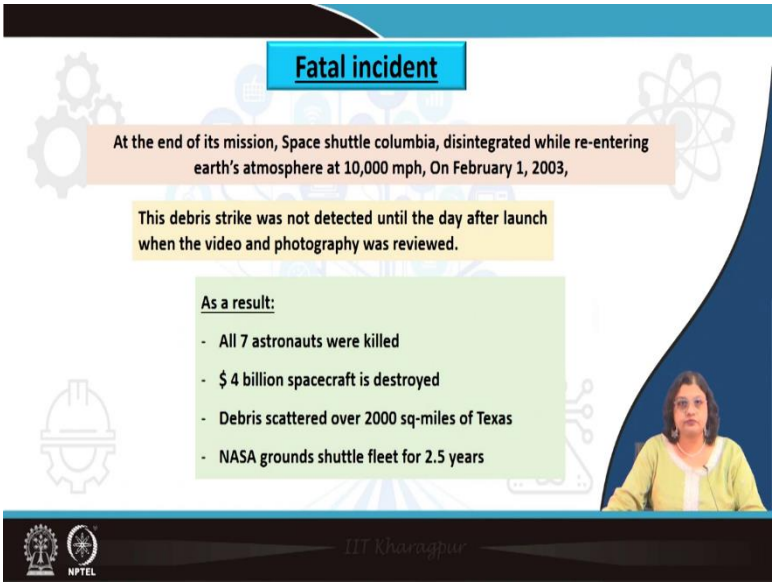
So, this image has been captured during the mission itself and later on recovered from the wreckage inside an undeveloped film canister and you can see all the happy faces and they were successfully doing all the experiments they were meant to do on the space shuttle.

And everything was fine so far for all those 16 days everything went as far as planned and they have already prepared for the comeback. So, this is the final footage during the re-entry and once again you can see the happy faces. You can actually identify Kalpana Chawla in the middle image who were ready to come back home and obviously they look pretty happy.

(Refer Slide Time: 6:11)







But then the Columbia was last seen actually on February First 2003 that was the day they were supposed to arrive as it passed by the Starlight Optical range which belongs to the Air Force research laboratory for Air Force base New Mexico.

This image was taken at around 7:57 AM for the local time and this image was received by NASA as part of the Columbia accident investigation and is being analysed. So far many of you might be wondering that what happened to them, so when they were about to come back and they were entering the Earth's atmosphere from the space something else has happened which is a fatal incident.

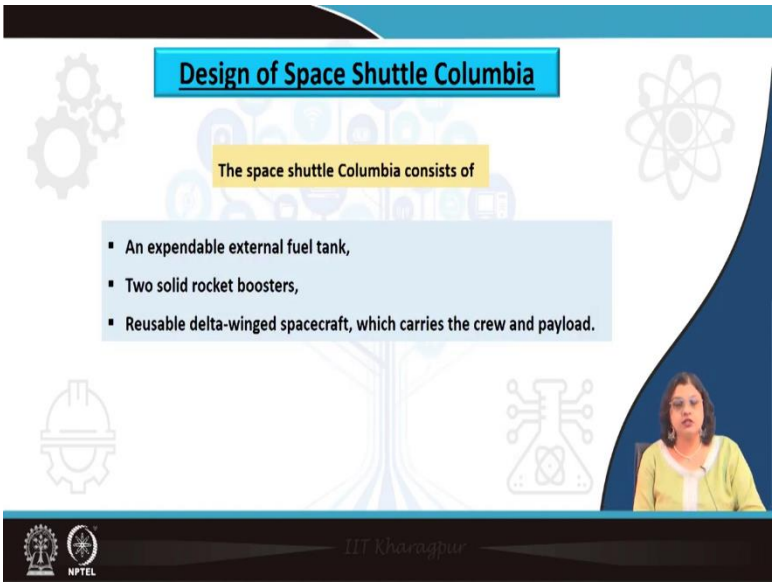
Typically, what they have undergo and what the ground engineers have received is the signal from the temperature readings from one of the sensors located on the left wing was completely lost and subsequently the tire pressure reading for again the left side of the shuttle

was also absent. So, finding that something is wrong with the spacecraft they tried to communicate with the Columbia team, the astronauts but that was unsuccessful.

So, Colombia was last seen over Dallas at around 61 kilometre above the ground level traveling at a speed of 80 times that of sound. So, at the end of this Mission when it was about to reach back to Earth on February First, 2003 space shuttle Columbia actually disintegrated while re-entering the Earth's atmosphere.

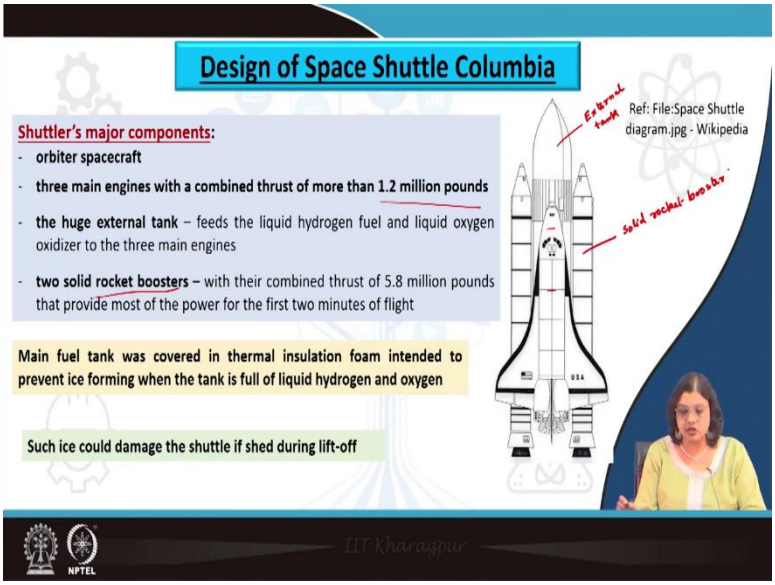
This debris strike was not detected until the day after launch when the video and the photography were reviewed and as a consequence to this fatal incident all the seven astronauts were killed. The spacecraft is completely destroyed and debris was scattered all over around 2000 square miles of Texas and again as a result of this, NASA had to ground the shuttle for almost 2.5 years to do further investigation.

(Refer Slide Time: 8:28)



So, before we go to the investigation part and do the failure analysis it is important to understand about the design of the space shuttle Colombia. So, the space shuttle typically consists of an expandable external fuel tank and then there are the two solid rocket boosters and the reusable delta winged spacecraft. Of course, that is the main part which carries the crew and the payload.

(Refer Slide Time: 8:57)



So, let's see here how it looks like the shuttles major components are the following, the orbiter spacecraft. So, this one here, you can see the spacecraft here and then there are three main engines with a combined thrust of more than 1.2 million pounds so that was quite large to generate the required energy. The huge external tank fits the liquid hydrogen and the liquid oxygen to the three main engine. So, this is the external tank that we can see, this is really really very much huge compared to the other parts.

And then there are two solid rocket boosters with the combined thrust of 5.8 million pounds that provide most of the power for the first two minutes of the flight. So, initial launching is the most critical and for that part the solid rocket boosters are very very helpful. So, these are the solid rocket booster and there are two in numbers.

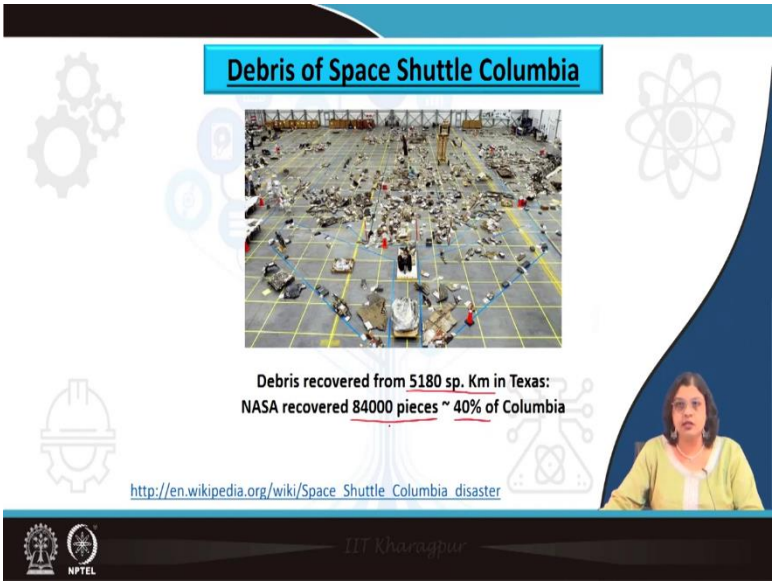
So, actually the main fuel tank is covered with thermal insulation foam and that is intended to prevent ice forming. When the tank is full of liquid hydrogen and oxygen, so of course the temperature is much much lower and below the freezing point and that may lead to formation of ice.

Now once this ice forms, ice typically is having very very high hardness, as a result such ice chips if it comes out and shades off during the lift up. There are possibilities that wherever it hits that may lead to some kind of damage. So, ice formation should be completely prevented and that is why there is this insulation foam that are typically being used for the space shuttles.

(Refer Slide Time: 10:53)

So, this is the particular design of the Colombian, you can see the external fuel tank is really really big compared to the human standing here you can see such a big dimension of this and everything is designed properly and the sitting arrangements of all the crew members are well planned and positioned and you can see how the spacecraft or the orbiter is connected with the main fuel tank and then there are the rocket boosters on the two sides to associate that.

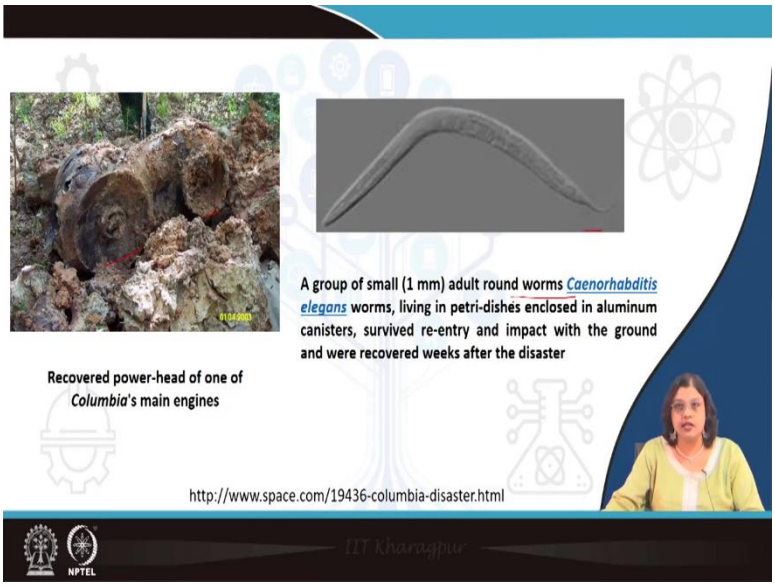
(Refer Slide Time: 11:28)



So, after the incident, after the fatal accident the debris were located and it had been found and they have tried to recreate the structure as you can see that only around 40 percent of the entire structure has been recovered which was recovered from actually more than 5000 square kilometre in Texas and almost 84,000 pieces were recovered.

So, you can understand that major part has been lost 60 percent is already lost and whatever has been recovered they have been deformed extensively many of this has been has lost its typical signatures of deformation but still a lot of information could be gathered from this debris as well.

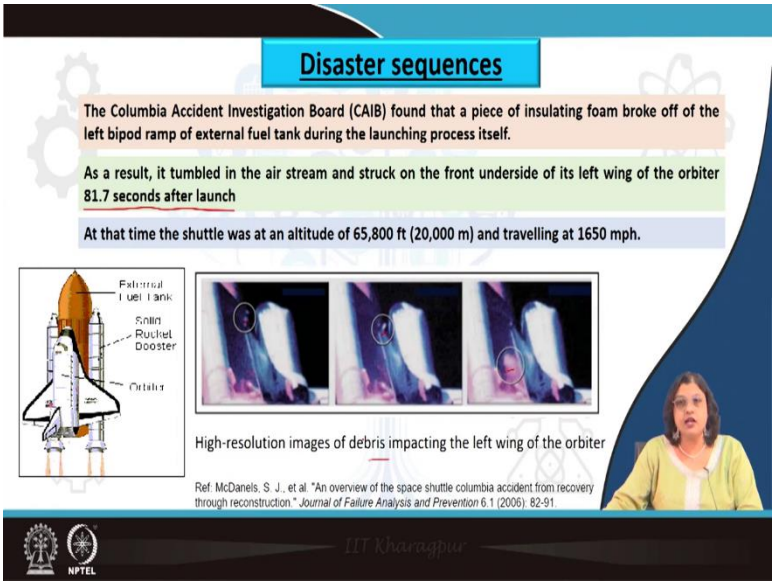
(Refer Slide Time: 12:23)



So, this picture here is the power head of one of the Colombia's main engine that you can see, so that has been recovered from the debris and several other studies has been performed and the image on the right side is very interesting. So, this is actually a group of small round worms. So, these were in the petri-dishes enclosed in aluminium canisters. However, this little worms survived the re-entry and the impact with the ground and were recovered weeks after the disaster.

So, once again they have been found very very useful for all the, so this has been carried to perform some biological experiments and later on some more information about the accident had been gathered from all the debris that has been collected.

(Refer Slide Time: 13:15)

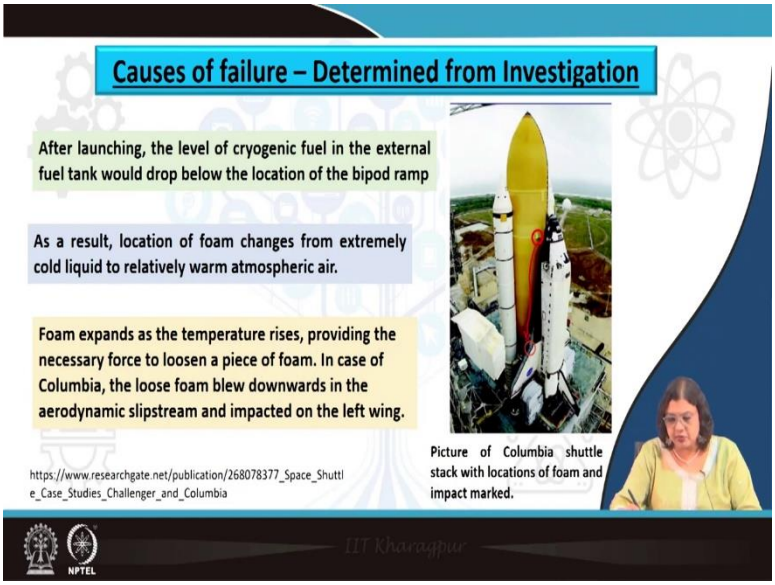


So, following are actually the disaster sequence that people have understood after the thorough failure analysis. So, initially the Columbia accident investigation board has been formed just after the incident and their detailed investigation found that a piece of insulating foam broke of the left bipod ramp of the external fuel tank during the launching process itself. So, this kind of went unnoticed at the time of launching.

So, as a result it tumbled in the airstream and stuck on the front underside of the left wing of the orbiter. So, one of the wing of the orbiter got hit by this foam. So, this entire incident happened almost 82 second after the launch. So, at the very initial period itself. As you can see here these images has been carefully analysed after the incident has happened and it has been noted that how the foam is coming out at the different time frames and how it has hit the left wing of the orbiter.

So, this were actually images of the debris that impacting the left wing of the orbiter. At the time the shuttle was at an altitude of around 20,000 metre and traveling at a speed of 1,650 miles per hour so that is really fast and at that point this foam has broke off and it hit the left wing.

(Refer Slide Time: 14:54)

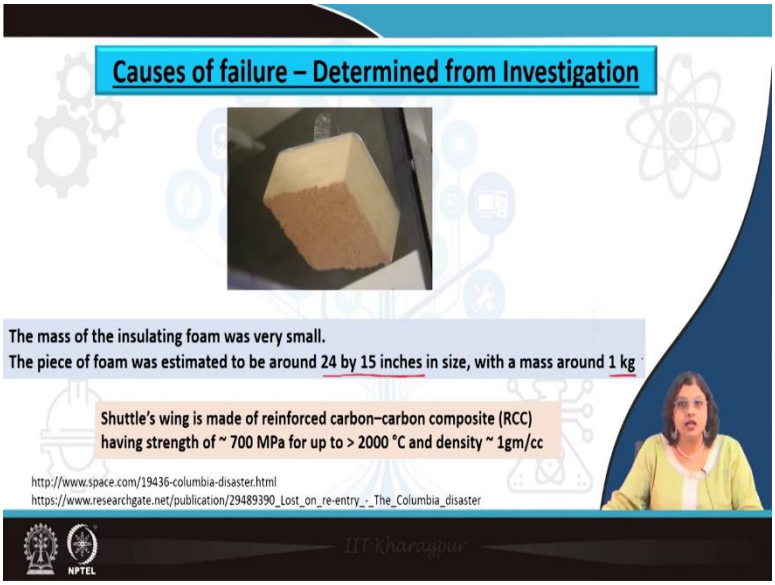


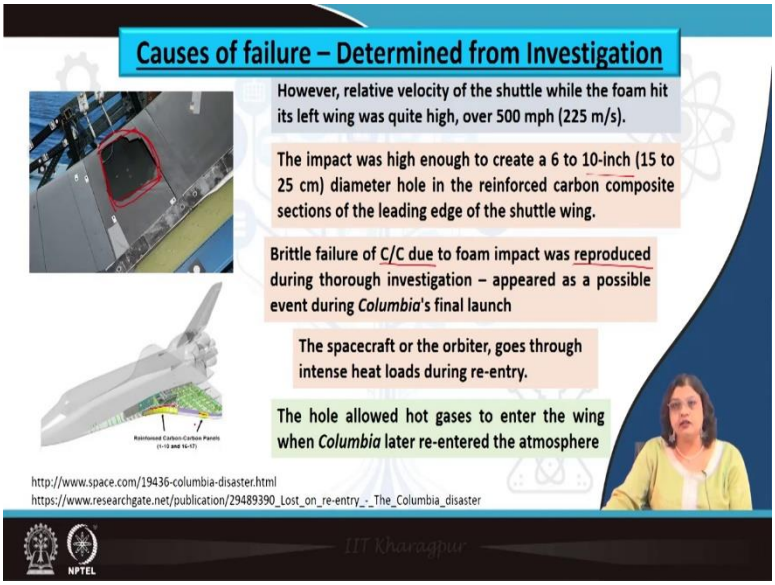
So, what would be the reason for that? Actually, after launching what happens is that the level of the cryogenic fill in the external fuel tank drops below the location of the bipod ramp and as a result of this the location of the foam changes from extremely cold liquid to relatively warm atmospherical air.

So, there is some temperature changes that happens. So, as a result of which the foam expands as the temperature rises providing the necessary force to loosen a piece of foam. So, there is some mismatch in the strain because of one of the foam gets expanded.

Now in case of Columbia, the loose foam blew downwards in the aerodynamic slip stream and impacted on the left wing. So, this is exactly what has happened, you can see that the foam has been broke off loose from such a region and then it has simply, as the flight is moving it is simply pointing downward and hit the underside of the left wing of the orbiter.

(Refer Slide Time: 15:58)





Now, you may also wonder that this is named as foam and when we heard of a foam we automatically think that this is very lightweight and that is also true for the case of Columbia also. You can see that this is more or less the size of the foam and it is once again not very heavy. So, the mass of the insulating foam is actually very small it has a size of 24 by 15 inches and mass of only 1 kg. So, that is certainly not much compared to the entire volume and the entire size of the structure that we are talking about.

And most importantly the shuttle swing is made of reinforced carbon carbon composite. So, this RCC are actually having pretty high strength of 700 MPa and that to up to a high temperature as high as 2000 degree centigrade. It has a very low density as well which helps it to fly. So, that way since it has quite high strength and that the foam is not very heavy

weight, there should not have been any damage at all but there is one more thing to this that we should pay attention to, which is the fact that the relative velocity of the shuttle while the foam hit its left wing was very very high.

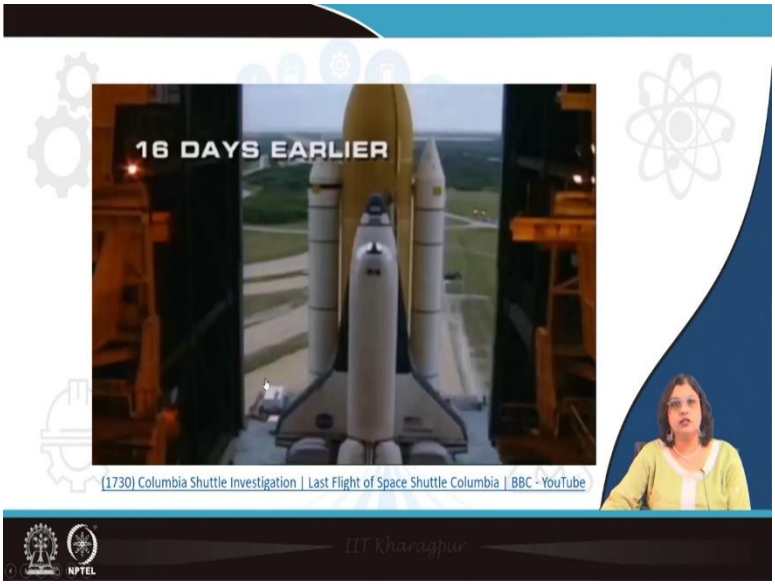
It is almost 500 miles per hour, so that is quite high and as a result the impact was very high. So, the foam was lightweight, the strength of the wing is also quite high but since it has been impounded at a very very high strain rate that is sufficient to create a hole which is of size of around 6 to 10 inch in the reinforced carbon composite that happened at the leading edge of the shuttle wing.

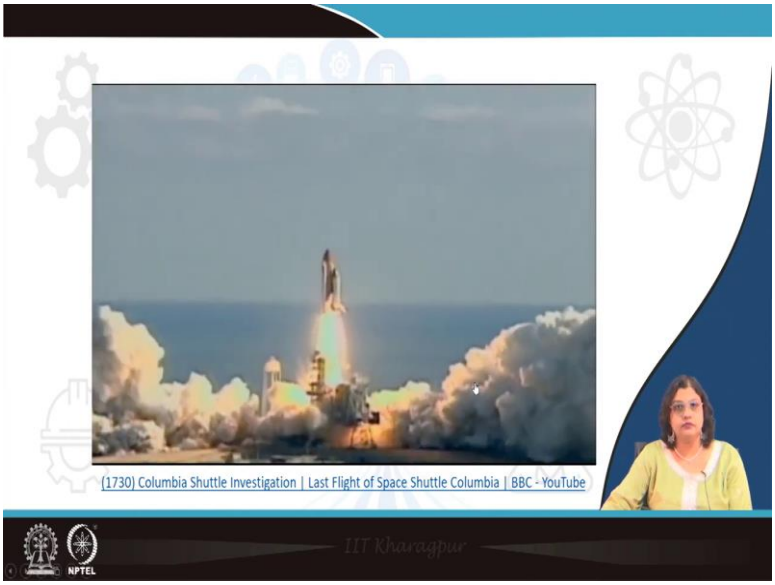
So, you can see that such a big hole actually formed and to that matter comparing the overall size of the shuttle, the size of the hole is also not that dramatically high but even that may lead to the failure as we have seen. So, this kind of brittle failure of the carbon-carbon composite for the wings has been reproduced or simulated and experimentally performed after the incident separately. So, to understand that what actually might have happened and they figured out that such a big hole have been formed which is having a size of around 6 to 10 inch.

So, you can see the position of the carbon panel at which the hole has been formed. The spacecraft or the orbiter goes through intense heat loads during the re-entry. Now that is the main part here.

So, so far at the time of launching this has happened and that was not an issue when it was on the space but while the comeback during the time when it is entering the Earth's atmosphere, because of all the air friction and the influence of the atmosphere there is a very intense heat load that generates and this hole allowed the hot gases to enter the wing when the Columbia entered the Earth's atmosphere.

(Refer Slide Time: 19:25)

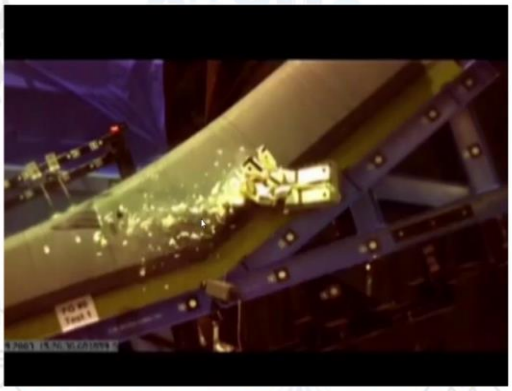




(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

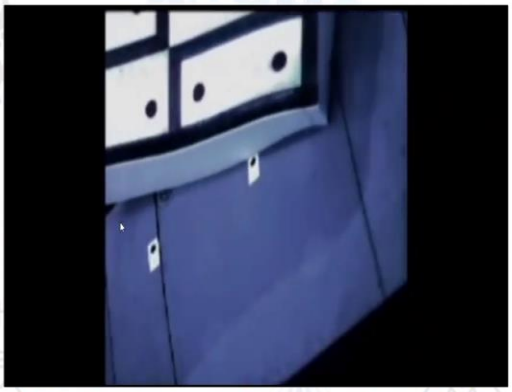
(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube



(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

IIT Kharagpur



(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

IIT Kharagpur

(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

IIT Kharagpur

(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

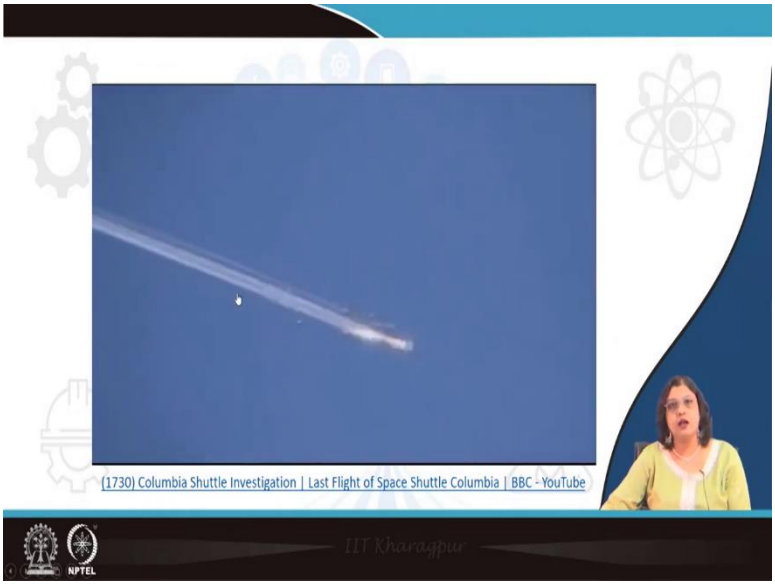
IIT Kharagpur

(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

IIT Kharagpur

(1730) Columbia Shuttle Investigation | Last Flight of Space Shuttle Columbia | BBC - YouTube

IIT Kharagpur

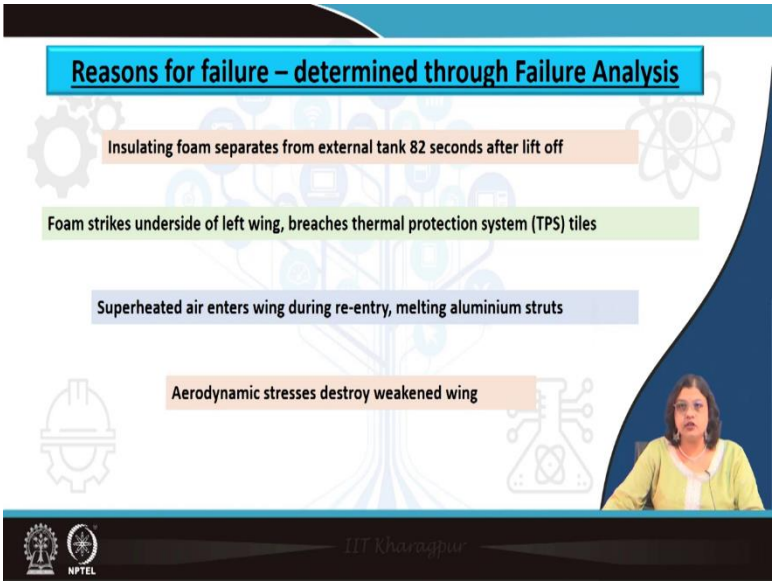


So, here is a video to understand what actually might have happened so you can see that the launching was quite good and it appeared very very successful launching and that was the pilot Rick Husband and you can see the foam coming out and striking the left wing very clearly.

Now this has been repeated in the simulation for you to understand more and you can see the same frame was actually being shown that how it is, so this part is a simulation one. To understand that what kind of force it might have generated, how much the damage are there and what is the size of the hole that has been formed that has been very very carefully analysed and determined and experimentally validated as well.

So, this has been shown from different angles for you to understand that what is actually the impact of the foam falling on the left wing of the aircraft. So, the spacecraft however has performed all it is intended to do and everything looked quite successful up to that level and nobody was actually aware that something has happened to the structure and now you can see that the point the time at which it was supposed to land, at that point there are has been just some fragments which has been noted on the skyline.

(Refer Slide Time: 21:16)



So, the reasons for the failure if we just sum it up these are the following this insulating foam separates from the external tank almost 82 seconds after the lift-off and this foam strikes the underside of the left wing. It breaches the thermal protection system tiles.

As a result the superheated air enters the wing during re-entry and that is capable of melting the aluminium struts. Aerodynamic stresses destroy the weakened wing and once one part is destroyed obviously the rest of the aircraft will be completely destroyed.

(Refer Slide Time: 21:56)

So, what was the effect of the risk management, how has been actually dealt? So, actually this disaster is has happened because of both the failure from the physical factors as well as

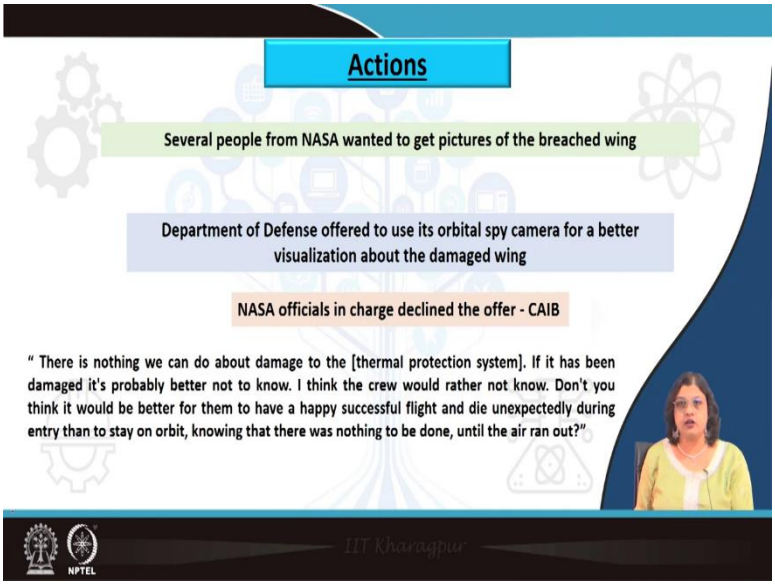
the human factors. Now many times these chunks of the insulating foam broke off at a launch and dinged the thermal protective system.

So, this is not the first time those of you who are thinking that the foam has been the first time that it has hit the spacecraft wings this is not the first time that it has happened. In any other previous missions also officials have seen that many time this chunks of the insulating foam breaks off and that hits some part. In most of the cases it has not hit some part which is very much crucial like the wing in this case most of the cases it has just simply fallen back to Earth.

So, that has not damaged the spacecraft in any way but this particular time however that is the fate that it has hit, this foam has hit the left wing and created a hole. So, NASA observed this failure of the foliage of the chunks of the insulating forms many times on orbiters and those orbiters actually had returned safely.

So, they did not consider it as a serious problem. They were aware that such can happen but they also understand that that may not be crucial for any kind of fatal incident. Each successful mission with the foam breakage actually reinforced the perception that foam shielding was unavoidable. So, it often happens that a few bricks or few forms just fell off and that has not so far led to any fatal incident. So, they are were not supposed to jeopardize the safety or had an acceptable risk.

(Refer Slide Time: 23:52)



However after this incident later on, after the failure has already happened and when they looked into the launching video very very carefully and they could realize that there were

some foam that has fell off, people from NASA actually wanted to get pictures of the bridged wing more through a more careful analysis and they would have understood what actually how much was the damage and the Department of Defence offered to use their orbital spy camera for a better visualization of the damaged wing.

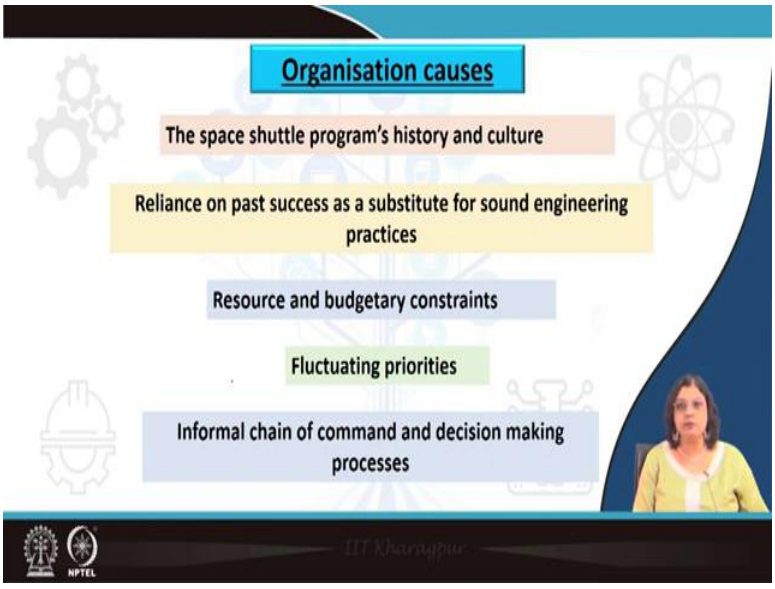
But however, the NASA officials in charge declined the offer as mentioned by the CAIB source. So, their logic was, there is nothing we can do about damage to the thermal protection system. If it has been damaged, it is probably better not to know, better for the astronaut not to know that it has undergone some kind of damage.

So, what he mentioned is that that I think the crew would rather not know. Do not you think it would be better for them to have a happy successful flight and die unexpectedly during entry than to stay on orbit knowing that there was nothing to be done until the air ran out?

So, this is certainly a very very philosophical thought, so what they meant is even if something went wrong, something which is very much critical nothing can be done at this point since the vehicle has already been launched and they have performed their scientific research.

So, even if knowing that the damage can be fatal there is no way that they could have been rescued. So, it is better that they not knowing the situation will be actually happier for them than to just simply know and wait for the oxygen to run out.

(Refer Slide Time: 25:49)



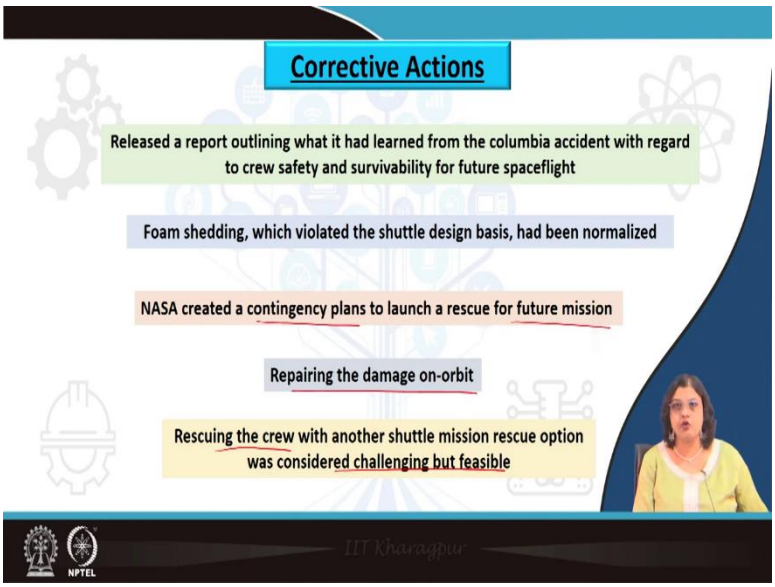
Now there were several organizations causes also. As I mentioned the failure analysis often comes with some legal bindings as well. So, the space shuttles programs history and culture

were such that it has been observed several times at the foam fell off but so far nothing has happened and this time when they were carrying the live crew members, this time only because of luck that this foam hit the wings and there was a hole and that lead to a fatal incident.

Now since they have relied on the past success as a substitute for sound engineering practice, they did not pay attention to make any changes to make the design better such that the foam should not come out. There were also some constraints based on the resource and the budget. Of course, there are a lot of other issues which are already involved in such kind of big missions and they did not consider the foam failing as the prioritized one.

So, there was an informal chain of common and decision-making process someone who pays more attention to even the political part which are not much related to the actual engineering part. So, those were some organization causes which were some of the reasons that this had not been paid proper attention to.

(Refer Slide Time: 27:20)



And after this incident of course there are some corrective actions that has been taken, NASA released a report outlining what it had learned from the Columbia accident with regard to crew safety and survivability of for future space flight. So, one of the thing to clarify here is that when we talked about the oil rig incident, the Alexander L Keyland we have seen that how the safety of the workers had not been paid proper attention to.

Of course, this has happened much earlier than the Columbia incident. In Colombia was a space shuttle where the crew safety were at the highest priority of course, but still they have

not understood that how even a minor defect can lead to such catastrophic event and loss of the seven crew member, seven astronauts, world-class astronauts were actually cannot be expected.

Foam shedding which violated the shuttle design basis had been normalized as a corrective actions and once again I would like to highlight another incident for the case history of Titanic, when we have seen that how the ship has being impacted by the iceberg and that led to failure of the first few compartments, the watertight compartments and that led to sinking of the entire ship.

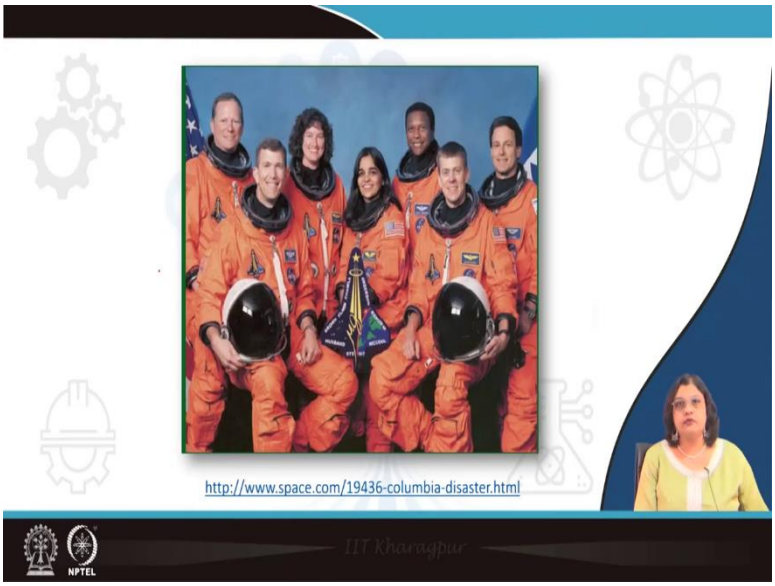
So, that was the impact loading which was very critical and people were not much aware of the ductile to brittle transition temperature at that time and they were not aware of the role of high strain rate testing. But that had happened in long back or more than a century back, the incident of Titanic and when we are talking about the Columbia incident this has happened in 2003. So, people were much more aware of the impact testing and all the details associated with it.

Of course, there has nothing to do with the ductile to brittle transition in case of the Colombia but there were impact loading. Had this foam has hit the wings not at such a high rate at a high velocity nothing would have happened. So, impact really played a big role even after a century later so this kind of fatal incident has happened.

So, as a corrective measure, NASA has created a contingency plan to launch a rescue for future mission. Actually, there were provisions that repairing can be done on orbit while if something went wrong on the spacecraft, there could be some way of repairing this at the International Space Station.

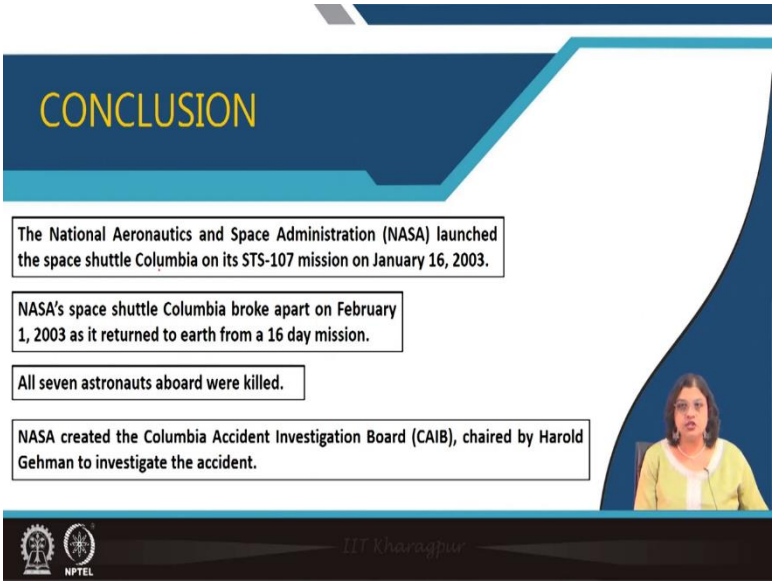
And there could be also possibilities where the crew can be rescued by sending a separate spacecraft by which they can return back to Earth safely. So, those although were considered challenging but they were made feasible so that such kind of incidents could have been avoided in future.

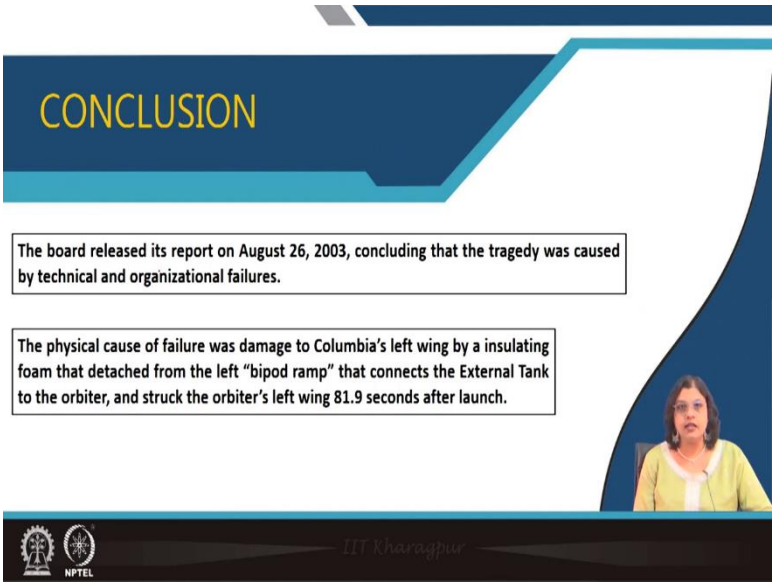
(Refer Slide Time: 30:30)



So, these are the memoirs of Columbia incident and you can see the window frame of the spacecraft has been put together in the museum for remembering the incident. So, these are the tribute to the crew members.

(Refer Slide Time: 30:49)





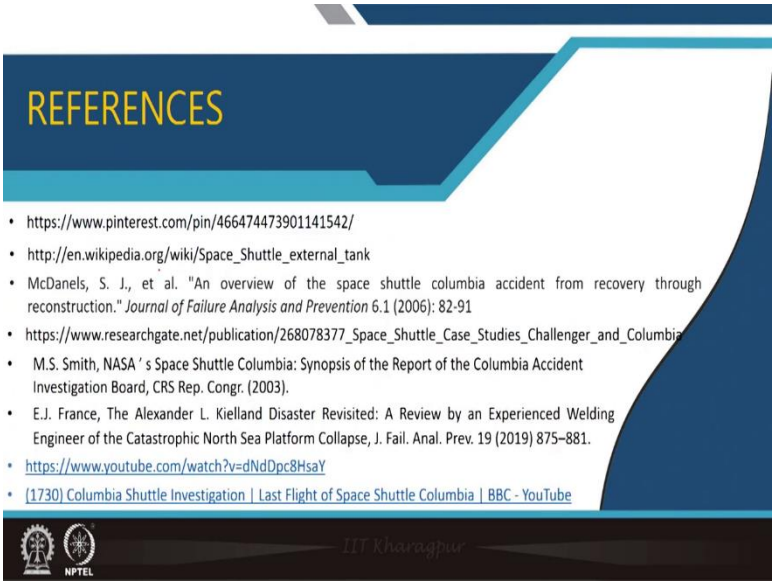
And the conclusion of this lecture are the following, National Aeronautics and Space Administration launched the Space Shuttle Columbia on its STS-107 mission on January 16, 2003. So, the space shuttle however broke apart on February First, 2003 as it returned to Earth from its 16-day mission and as a result of this all the seven astronauts aboard were killed.

And NASA created the Columbia accident investigation board chaired by Harold Gehman to investigate the accident, actually NASA was very badly criticized for this kind of failure which many part has been based on the ignorance of NASA in controlling the engineering features of the spacecraft.

The board released its report on August 2003, concluding that the tragedy was caused by technical and organizational failures. Technical failures in the sense that as we have seen that the foam has fell off and it bridged the left wing of the orbiter and the organizational failure is that previously also such kind of foam failure has happened but so far that had not breached any part of the aircraft and as a result nothing serious or nothing fatal has happened and they have completely ignored that as a critical event so that was the organizational failure.

And the physical cause if we are talking about the as a materials engineers or failure analyst expert, we could say that the physical cause for failure was damage to Colombia's left wing and that happened due to an impact from the insulating foam that get detached from the left bipod ramp and that connects the external tank to the orbital and stuck to the orbiter's left wing almost 82 seconds after launching.

(Refer Slide Time: 32:59)



And following are the references that has been used for this lecture. Thank you very much.