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Retrospection of STS107 Crash: A Review From Forensic Engineering Perspective

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ABSTRACT:
On February 1, 2003, the Space Shuttle Columbia shattered into pieces while descending to Earth after its space mission and it resulted in loss of life of all its 7 crewmembers. After the incident, a large scale investigation mission and committee was setup to investigate and establish the reason behind crash of the Space vehicle. The leading investigating teams included experts from various technical disciplines, NASA (National Aeronautics and Space Administration), space industry and academics.
An investigation team, other than that of NASA, was formed, called the Columbia Accident Investigation Board (CAIB), which worked independent of NASA and conducted an investigation to understand the cause of Columbia crash. The reason behind the accident was the fracture in the left wing leading edge RCC (Reinforced Carbon-Carbon) thermal protection system of the Shuttle which was commenced by the impact of thermal insulating foam. This foam broke loose from external fuel tank of the orbiter merely after 81 seconds of the launch of the Shuttle from Earth. While re-entering into the Earth's atmosphere, the superheated air entered gushed in behind the leading edge through the fracture and eroded the left wing structure made up of Aluminium and ultimately lead to shattering of the orbiter.
This review paper includes the timeline of the major events of the flight during its return to Earth after its 16 day scientific research mission and aims retrospect the crash event forensically which includes both mechanical and human error factors that could otherwise have been avoided had the corrective measures been taken timely to tackle the problem that was diagnosed during the early stage of launch of Columbia.

KEY WORDS: Columbia Space Shuttle, CAIB, NASA, RCC thermal protection system,

INTRODUCTION
Columbia was the first Space Shuttle and its first flight (STS-1) for space shuttle program dated back to April 12-14, 1981[5]. Columbia carried out in total of 28 mission flights during its service time. On January 16, 2003, the National Aeronautics and Space Administration (NASA) launched the space shuttle Columbia on its STS-107 mission, becoming the last flight for the Space Shuttle. After completion of its 16 day scientific research mission in space on February 1, 2003, as Columbia re-entered the Earth's atmosphere, it disintegrated over north-eastern Texas, decimatingall seven astronauts aboard. The crew-members that were aboard were: Commander Rick Husband, Pilot William McCool, Mission Specialists Michael P. Anderson, David M. Brown, Kalpana Chawla, Laurel Clark and payload specialist IlanRamon[5].
In order to review the details of failure (both technical and organizational) and disintegration of the Shuttle and loss of lives of its crew members, NASA had commissioned the Columbia Accident Investigation Board (CAIB)[1]. The industrious and diligent work of the CAIB team identified the cause of misfortunate event that suggested more of a murderous mishap due to negligence of the ground team at NASA. The investigation showed that a large piece of insulating foam had disintegrated from the external fuel tank of the orbiter during its take off from Earth and it later struck the RCC (Reinforced Carbon-Carbon) thermal protection

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system at very high speed which lead to development of fracture in the left wing of the Shuttle. The damage remained undetected by the crew during their stay in space.

Sequence of Events[1]

To develop a better understanding on the disintegration of the Shuttle and what possibly went wrong, a careful review of the sequence of the events needs to be. Following is the timeline of events from the start of the return journey of Columbia back to the Earth:

- 8:10 AM: Mission Control notified Columbia's crew they were ready ("go") for de-orbiting process. Columbia was flying upside down and in tail-first position.
- 8:15:30 AM: De-orbit burn was executed by Commander Rick Husband and Pilot William McCool, which lasted 2 minutes and 38 seconds. Husband then turned Columbia on its belly, turned the nose to face forward, and slightly pitched the shuttle in nose-up position.
- 8:44:09 AM: The shuttle entered perceivable atmosphere about 400,000 feet from the Earth: Entry Interface (EI 00 seconds).
- 8:48:39 AM (EI+270 seconds): indications were given by a sensor inside the leading edge of the left wing, showing that the wing was under strain higher than normal. This data was not meant to be sent to the crew aboard the shuttle or to the Ground Control. One of Columbia's internal data back-up units recorded the data (and, luckily, the unit survived the crash).
- 8:49:32 AM (EI+323):As per the plan, Columbia executed its roll to the right. This action banked the spacecraft, decreased the rate of descent of the orbiter and also reduced heating on the spaceship's surfaces.
- 8:51:16 AM (EI+427): The damaged RCC tiles on the left wing failed and the wing was breached. Superhot plasma, as hot as 8,000 degrees Fahrenheit, now began to flow into the wing. Aluminium melts at 1,200 degrees Fahrenheit, and the interior aluminium struts inside Columbia's wing began to heat toward the melting point.
- 8:51:46 AM (EI+457): Columbia began to yaw {sideslip) to the left as the damaged front of the left wing created drag.
- 8:52:00 AM (EI+471): temperatures on the leading edge of Columbia's wings reached 2,650 degrees Fahrenheit.
- 8:52:05 AM (EI+476): Columbia's yaw became so pronounced that the shuttle's computers were forced to automatically trim the aileron to compensate. The Mission Control or the crew could not observe the either the yaw or the trim change.
- 8:52:17 AM (EI+488): The left main landing gear brake line present in the wheel-well began to show a rise in the temperature. This indicated that a significant internal damage had occurred to the wing struts.
- 8:53:10 AM (EI+541): Failure of the four hydraulic sensor cables(running from the aft part of Columbia's left wing through the wiring bundles outside the wheel-well).
- 8:53:38 AM (EI+569): Columbia's yaw exceeded all previous flight experience.
- 8:53:44 AM (EI+575): The first debris was shed by Columbia. This eight-pound piece became visible from the ground two seconds later.
- 8:53:46 AM (EI+577): People in California watching and filming the shuttle's flight from the ground saw debris being shed from Columbia. During the next 23 seconds, observers witnessed sudden brightening of the superheated air surrounding the orbiter, causing a streak in the shuttle's trail, followed by four distinct events as chunks of debris came off the shuttle. Innext 15 seconds that followed this event, temperatureof the left Orbital Maneuvering System pod and the fuselage sidewall (the housing for one of the main engines) began rising. Tests suggested that the yaw changes and increased heating on the

roll and the Orbital Maneuvering System pod resulted from substantial damage around RCC panel 9.

- 8:54:13 AM (EI+601): Temperatures in Columbia's wheel-well hiked expeditiously, indicating that the superheated air coming through the wing leading edge had breached the wheel-well wall. Simultaneously, observers on the ground noted additional shedding of debris. One of these objects probably weighed about 190 pounds, which means Columbia's physical integrity was now seriously compromised. There was no indication that either Mission Control or the crew knew the shuttle was breaking up.
- 8:54:14 AM (EI+602): As the left wing deformed due to loss of structural integrity, it exhibited increased lift. Columbia began rolling to the right to compensate. Left wing drag was also worsening, causing additional leftward yaw. Additional significant debris had shed over the next 30 seconds. There was no indication that suggested that either Mission Control or the crew had any hint that the shuttle was breaking up.
- 8:54:24 AM (EI+613): Technicians in Mission Control told the Flight Director about the failure of the hydraulic sensors.
- 8:54:25 AM (EI+614): As Columbia travelled from California into Nevada, a bright flash was visible from the ground. There was no indication that either Mission Control or the crew knew the shuttle was breaking up.
- 8:54:32 AM (EI+623): Several hundred pounds of debris broke free from Columbia. Visible from the ground four seconds later, this is the brightest debris shedding seen by the public. There was no indication that either Mission Control or the crew knew the shuttle was breaking up.
- 8:56:30 AM (EI+741): As per the plan, Columbia initiated a roll to the left.
- 8:56:55 AM (EI+766): Columbia completed the planned roll to the left.
- 8:58:03 AM (EI+834): the aileron adjustment exceeded all previous flight experience. This was likely due to additional, severe wing deformation. Ground observers saw more debris break from the shuttle. There was still no indication that either Mission Control or the crew knew the shuttle was breaking up.
- 8:58:20 AM (EI+851): Columbia shed a thermal tile. This was the most westerly piece of debris that was recovered during search operation.
- 8:58:39 AM (EI+870): An alarm light flashed in Columbia's crew cabin and an alarm tone sounded which indicated a loss of pressure in the left main landing gear tires. Mission Control received the same alarm. Husband and McCool called up the fault page in the shuttle's computer to review the information.
- 8:58:48 AM (EI+879): the shuttle crew contacted Mission Control. "Roger, uh, Hou --" That was not unexpected, as garbled messages were common during re-entry as antennae adjusted to track the shuttle.
- 8:58:49 AM (EI+880): An alarm flashed and sounded in Columbia's crew cabin, indicating low inboard tire pressure. Mission Control received the same alert.
- 8:58:56 AM (EI+887): An alarm flashed and sounded in Columbia's crew cabin, indicating low outboard tire pressure. Mission Control received the same alert.
- 8:59:06 AM (EI+897): An alarm flashed in Columbia's crew cabin which indicated that the left main landing gear was down. The Mission Control also received the same alert. This false indicator was due to a failure in the landing gear sensor system. This is the first indication the crew has that something is seriously wrong. Columbia's crew has just 1 minute and 12 seconds left to live.
- 8:59:15 AM (EI+906): Pressure was lost on both left main landing gear tires. Mission Control began to evaluate the indications as soon as they saw the message. Flight Control then radioed Columbia that it could not interpret the crew's last transmission.

- 8:59:26 AM (EI+917): an abrupt change in Columbia's aerodynamics occurred as the left wing suddenly deformed significantly. Yaw right and left began to occur, and the left wing's drag worsened even as its lift increased.
- 8:59:29 AM (EI+920): Columbia started yawing and rolling which was beyond the ability of the aileron to compensate. Two of the control jets of the shuttle began to fire continuously to compensate. It was not unusual for the jets to pulse as needed throughout re-entry. But continuous firing indicated a severe problem. Although a light on Commander Husband's control panel lit up, this light was not easily noticed.
- 8:59:32 AM (EI+923): As per the last communication from the crew, Commander Husband was heard saying "Roger, uh [cut off in mid-word]." Telemetry was lost at the same moment by Mission Control, as expected, as the shuttle was switching from western antennas to eastern antennas. At this point, sensors inside the shuttle indicated that all but one crew member was in their seat and strapped in. The final crewman were just egressing their seat. Several crew members did not have their gloves on, and none had their visors closed.
- 8:59:33 AM (EI+924): Columbia's Master Alarm sounded and flashed, indicating the failure of a wire bundle. The crew probably reset the alarm and called up a page in the computer to begin assessing the problem.
- 8:59:36 AM (EI+927):The third control jet began firing continuously.
- 8:59:37 AM (EI+928): The fourth control jet began firing continuously. Ground observers saw a massive brightening of the shuttle. The crew lost all hydraulics and control of the shuttle, and the flaps and aileron began to "float" without power, moving randomly.
- 8:59:46 AM (EI+937): An alarm sounded in Columbia's crew cabin as the nose of the shuttle pitched up uncontrollably. The shuttle's nose was now vertical in the air. As the shuttle began to corkscrew, the crew saw shadows move inside the cabin and saw the horizon disappear. The crew was tossed from side to side, their upper bodies moving forward as they simultaneously sank into their seats. Over the next 34 seconds, the crew experienced ups and downs in G-forces, up as much as 3Gs. A bright piece of debris was also shed at EI+937, followed by a second, dimmer piece two seconds later. More and more debris is shed from the shuttle, visible from the ground as brightening, shining objects separating from the main glow, puffs in the trail, and splitting of the trail.
- 8:59:49 AM (EI+940): Pieces of Columbia's left main engine pod began to be shed.
- 9:00:03 AM (EI+954): Columbia's autopilot was turned on. This indicates that either the commander or the pilot was still executing commands.
- 9:00:04 AM (EI+955): The left wing separated from Columbia. The orbiter began to fall out of control at 10,000 mph.
- A short time after 9:00:05 (EI+956): The Pilot McCool attempted to restart the auxiliary power units (APU). He must have naturally assumed that the loss of control was due to an APU failure, when in fact the hydraulic system itself had ruptured due to the heat.
- 9:00:18 AM (EI+969): Columbia began disintegrating. People on the ground heard a loud sonic boom. A major brightening occurred, indicating the shuttle was breaking up. The fore-body (including the crew cabin and nose) separated from the mid-body, causing all power to be lost in the crew cabin. The shuttle's break-up occurred not because of stress, but because heat had significantly damaged the shuttle aft of the crew cabin. The first crack appeared on the right. The crew cabin remained attached to the mid-body for a few seconds before finally pulling free.
- 9:00:25 AM (EI+976):The two major pieces of Columbia became discernible from the ground. As the crew cabin must have pulled free from the rest of the shuttle, they might

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have experienced a jolt. But in breaking free, the cabin was also damaged, and a number of small breaches above and below the crew deck occurred. The crew cabin depressurized in two or three seconds. None of the crew had their helmet visors down and locked. So although their spacesuits were feeding them air, the air was being sucked away. At least two crew members did not have their gloves on (which would have exposed them to more decompression effects), and one did not have their helmet on.
Autopsy data showed that[6]-

- None of the crew managed to close their visors.
- All of the crew suffered from depressurization effects, which would have rendered them unconscious within just a few seconds.
- Their breathing would have stopped as well, although heart and brain function would have continued for another two to four minutes.
- The crew cabin also began tumbling.
- Whenever a crack in the cabin faced forward or downward, superhot plasma invaded the crew module at breach-points.
- Melt near the cracks melted, and globs of molten metal were found on the crew's spacesuits, seats, and restraining straps.
- There was no indication that the interior of the crew module was hot enough to cause death.
- The crew module's rotation increased to one every two seconds, with internal stresses as low as -1G and as high as 5Gs.
- Crew harnesses either failed to lock, were blocked by debris, or improperly functioned.
- If any crew were still alive, they now suffered lethal neck and upper-body injuries as their heads and torsos snapped around in the spinning capsule.

- 9:00:53 AM (EI+1004): a significant brightness was observed around Columbia's fore-body, which indicated that it was breaking up. First, the nose came loose from the crew module which exposed the crew's bodies to air and fire. Within 10 seconds, the crew module itself began to come apart. The upper flight deck stayed intact for five more seconds as compared to the lower deck. The crew capsule completely disintegrated by EI+1019. The terrific speed of the air stripped the spacesuits from the crew's bodies, causing additional injury. The wind and stress then dismembered the crew.
- 9:01:10 AM (EI+1021), Columbia's crew module and mid-body disappeared from video, as they had slowed enough for the plasma around them to dissipate.
- 9:35:00 AM (EI+3051), all debris from Columbia reached the ground. It had taken half an hour for the debris to fall the 39 miles to the Earth.

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Vol-22-Issue-17-September-2019

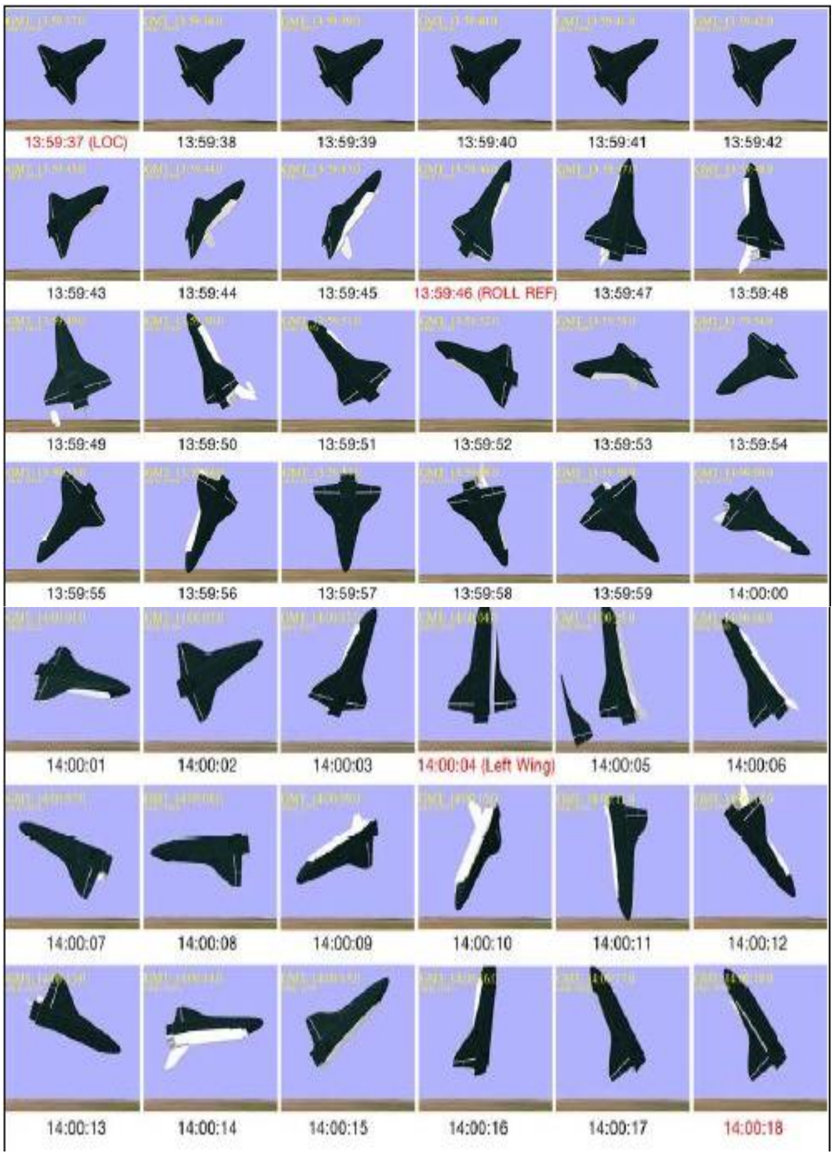

Figure-1: *Entry simulation snapshot sequence*

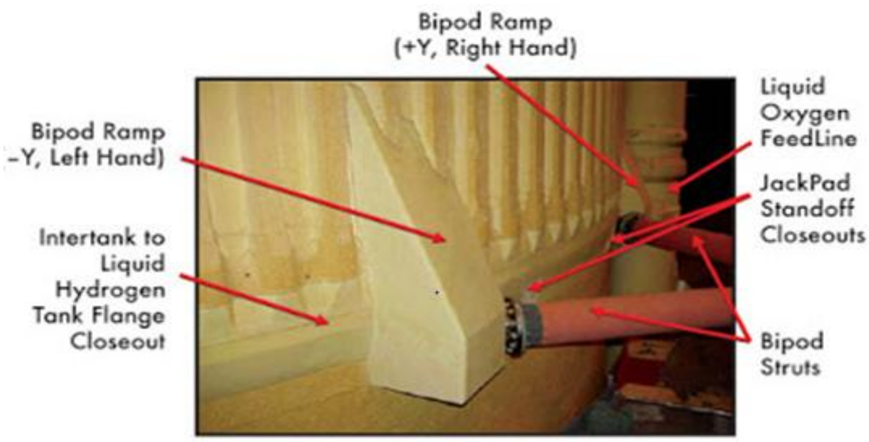

Figure 2: *Figure showing bipod struts and its connection to external fuel tank*

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Vol-22-Issue-17-September-2019

Earlier missions: lessons not learnt

NASA had a prior history of Space Shuttle mishaps that indicated a loophole in designing and planning of the space program that had resulted not only in loss of Space Shuttles but also valuable human lives. Some of the accidents and their failure reasons were:

1. STS-1

The shuttle's maiden flight in 1981, more than 300 tiles on Columbia were damaged by foam, ice, and launch pad debris and had to be replaced. A whopping 16 tiles came lose and were lost (although none of them were in critical areas). Engineers were shocked; some even said that, had they known that such a large amount of foam could be shed, they would not have cleared Columbia for flight.

2. STS-7

This was Challenger's second mission. The flight was launched on June 18, 1983. The bipod ramp foam had come loose. NASA declared the event an "In-Flight Anomaly", which meant the problem needed to be resolved before the next shuttle launch, or it had to be proven to pose no risk to the crew. There wasn't much time to resolve the issue: Challenger was due to launch again on August 30, 1983. At Challenger's Flight Readiness Review, the anomaly was declared "not a flight or safety issue." Astonishingly, no one had yet figured out the cause of the foam shedding, and no hazard analysis or engineering attention had been given to the problem. The Flight Readiness Review made its declaration without any evidence to back up its claim. The rationale- the shuttle came back safe, so loss of foam must be safe. This was a blatant breach of NASA's safety norms. And no one said anything.

3. STS-27

The third flight of Atlantis (launched December 2, 1988): Foam from the right-hand solid rocket booster nose hit the orbiter's nose 85 seconds into the flight. This debris then struck the orbiter's window, blocking the crew's view as they ascended into space. There was clearly heat shield damage from the impact. But because of the location of the damage, it could not be completely seen using the shuttle's robot arm. The images that did exist were downloaded to NASA.

But this was a classified Department of Defence mission, which meant that the shuttle had to encrypt all its communications. This degraded the images, and left NASA convinced that the thermal protection system was intact. Mission Control told the crew not to be worried. A post-mission damage report warned NASA that attention to foam varied with the amount of damage the foam made. The report warned that foam was a major concern for safety, and demanded better monitoring of tile damage to identify any trends. No such improvements were made. The report also recommended that a thorough investigation of foam shedding be conducted. No investigation was made.

4. STS-32

On January 9, 1990, Columbia had suffered the loss of bipod foam.

5. STS-35

On December 2, 1990, Columbia suffered a significant foam shower. In the Flight Readiness Review for the next shuttle mission, NASA declared foam a "re-use or turnaround issue" for the first time, downgrading the risk from Safety of Flight.

6. STS-50

On June 25, 1992, a bipod foam was lost on a Columbia mission. A Hazard Report issued by NASA after the event called the loss an "accepted risk". It did so without any evidence to support the downgrade from Safety of Flight.

7. STS-52

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On October 22, 1992, a bipod foam was lost on a Columbia mission. The loss of foam was the fourth bipod event, and went undetected. NASA would only discover the incident in the post-Columbia disaster investigation in 2003.

8. STS-87

On November 19, 1997, Columbia suffered 90 hits to its thermal protection system. Among them were 12 holes one inch or larger. NASA characterized the damage as "less than average", even though it wasn't. In fact, the agency was so alarmed that it began testing ways to make foam sturdier. NASA knew it had a huge problem, but refused to reclassify foam shedding a Safety of Flight issue. NASA knew it had a problem, but refused to fix it before the next shuttle flight. Instead, NASA tried one solution after the other over the next nine flights. None worked. Frustrated, NASA simply declared issue resolved: Foam shedding was an "acceptable risk" as of STS-101 (May 19, 2000) when Atlantis flew.

Forensic Analysis: What Went Wrong?

Early tests conducted by the investigation team suggested that as the shuttle launch system lifted off, the nose of the external tank remained relatively unaffected by the compression heating and stress. But just behind the nose of the tank, nearly around the point where the bipod strut connected the tank to the nose, immense shock waves were formed that created one of the major stressful environments and heat around the tank. Furthermore, airflow around the struts was complex and was capable of causing heat and stress. Initially it was assumed by NASAthat the usual foam insulation around the struts would protect them but additional testing disapproved this notion[2][5].

After launch of STS-107 (Columbia) on January 16, 2003, a foam from the left bipod strut separated from the external tank and struck its left wing 81.9 seconds just after its lift-off. The cause of the left bipod foam ramp braking free still remains a mystery. Later image analysis showed that the piece of foam ranged roughly from 21 to 27 inches in length and 12 to 18 inches in width, and relatively thin[3]. The foam travelled with the shuttle at about 1,568 mph. When the foam detached, it began to slow down (in part, because it was no longer powered, but also because its low density and shape shed energy and thus reduced its speed). Essentially, the orbiter ran into the foam at a relative velocity of about 545 mph. It is estimated that the foam made about 18 revolutions per second as it fell. Its trajectory was parallel to the shuttle's fuselage, at a 5 degree angle away from the external tank, and with a slight outboard movement. The actual orientation of the panel of foam to the wing at impact cannot be determined. The foam hit RCC panels 6-left through 9-left. As the shower of post-impact fragments could not be seen passing over the top of the wing, analysts later concluded that the debris had impacted the left wing below the leading edge[3][4]. The debris impact was identified on January 17, the second day of the mission. That same day, an object - probably a piece of damaged RCC tile - drifted away from the orbiter. Although military radar observed the piece floating off, this was not discovered until after the accident.

CONCLUSION

The crash of Columbia was preventable had the timely actions been taken. The mishap was indicative of list of pure human and technical errors that lead to series of devastating events.

The technical and manual errors were intertwined, though majority of the fault is credited to the casual approach of the members of the STS107 mission program.

The visual inspection of the Shuttle was not sufficient enough to permit the Shuttle to fly. After carving, the foam was visually inspected for holes, cavities, or other related manufacturing defects. The foam was not cut open to look for any defects. NASA never conducted enough tests and experiments to check or lookout for minor changes like hand-spraying technique. This technique introduced minute but critical and significant faults, fractures and voids into the foam. As per the reports,[1][3][5]not sufficient tests or drills were conducted by NASA to ensure that the spraying equipment was cleaned, prepared, used and functioned properly. Furthermore, other tests demonstrated that the physical shape of the bipod strut made application of the foam difficult. The hand-spraying technique and the requirement of emission of an exact ratio of elements by spray-gun introduced subsurface defects on the foam surface. Some of these defects included fracture lines (points where the foam could shear into two or more pieces under stress).

The foam broke loose from the external tank during lift-off of STS107; it stroked the thermal protection system and damaged a tile. NASA had previously established a fundamental design requirement for foam: it could never come loose from the external fuel tank. Working under this assumption, the heat-resistant shielding didn't need to be very strong. After all, it had to be heat-resistant, not impact-resistant[1][3].Engineers subsequently designed the thermal protecting tiles that could withstand impacts from any object with kinetic energy of less than 0.006 foot-pounds. A foot-pound is a unit of energy equal to the amount required to raise one pound a distance of one foot. This meant that just pressing your fingernail into a tile could damage it. By every standard of the day, NASA's engineering of the bipod strut and foam ramp was acceptable. At the time, engineers worked on the mechanical aspects of the strut first then turned this over to the thermal team, which turned it over to the de-icing team. This approach meant that the strut was designed for optimal mechanical performance, but its design hindered the application of the insulating foam. By every standard of the day, NASA's testing of the foam ramp was also acceptable. NASA engineers sprayed foam into a solid block, cut it into shape, and then subjected it to wind-tunnel and heat tests. It passed with flying colour[2].

"Test what you fly, and fly what you test." This rule of aeronautics and rocketry stems from the fact that ground tests, wind-tunnels, flamethrowers, and the like cannot even come close to the speeds and heats and stresses of actual spaceflight. Ground-test results must be extrapolated to real conditions. But this extrapolation isn't always correct. That's why sensors are always applied to the test vehicle in every conceivable way, to see if in-flight experience confirms the ground-test data. NASA never did this, so it never knew how the foam was acting in the real world[5].

The debris impact was identified on January 17, the second day of the mission. A series of organizational snafus, informal analyses and messages, poor communication, and other errors now deeply compromised NASA's ability to determine if the impact had caused any damage. Managers repeatedly assumed "no damage", even as lower-level engineers became almost frantic with concern. Use of informal channels led upper-level managers to assume there was nothing to worry about.Managers also relied on informal advice from one engineer who was a non-expert in the RCC tiles - and this engineer gave plenty of advice about how there was "no damage" (feeding their own ego while speaking about issues they were unfamiliar with). Top shuttle program managers focused on sticking to schedule rather than worrying about safety, and repeatedly dismissed attempts to assess damage by saying "there's nothing we can do about it now". In fact, NASA had plenty of opportunity to determine if Columbia was in danger. Although no launch pad footage of the bipod ramp existed, a Columbia crew member had filmed the bipod ramp from inside the shuttle.[6] NASA could have asked for the complete footage to be downloaded, and did not. NASA could also have asked the Department of Defence to image Columbia using ground-based telescopes or satellites. It never did.

NASA could have ordered a spacewalk, during which the crew would have attempted to pack the damaged area with insulation, metal, and other items. Although this stuff would be burned away during re-entry, Columbia's own internal structures would be saved and the shuttle might - might - land safely. NASA later judged this to be an "extremely high-risk" solution, however. Much more likely, NASA would have sought to send Atlantis into space to rescue Columbia's crew. Atlantis was almost ready to move to the launch pad. NASA would have to rush its refurbishment and safety checks, and had a flawless countdown. Columbia carried enough carbon dioxide filters (and more than enough food, water, and oxygen) to allow Atlantis to reach it, with even a few days to spare. But since NASA never knew about the damage to Columbia, no rescue mission was attempted.

The unfortunate event was preventable had the program team paid more attention and invested more time on testing and verifying each particular related to flight.

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