DRAFT

COLUMBIA ACCIDENT

Appendix to An impossible dream

Hans van der Zanden

June 2009

COLUMBIA ACCIDENT
Appendix to An impossible dream

Draft published on Lonenlyscientist.com for comment June 2009

COLUMBIA ACCIDENT

Also the astronauts boarding Space Shuttle Columbia flight ST-107, January 16th 2003, had no idea that their flight would end in disaster during re entry - February 1st - because of a known impact of a large piece of foam that broke away from the External Fuel Tank shortly after take off and damaged one of the reinforced carbon-carbon panels of the Thermal Protection System. What adds to the drama is that the accident could have been avoided when numerous requests for imageing the shuttle on-orbit had not been refused. Worse even, the U.S. Strategic Command (USSTRATCOM) at Colorado's Cheyenne Mountain Air Force Station were already preparing for such imageing when the manager who had made the request was overruled by Shuttle Program Chief who personally cancelled the request - the imagery request was made outside the official chain of command and without first gaining permission from management. But the underlying cause of the accident was that NASA paid no attention – whatsoever – to the poor impact performance of the heat shield materials.

After the accident the remaining space shuttles were grounded and the Columbia Accident Investigation Board (CAIB) conducted a lengthy investigation that is described in great detail in their excellent final report. NASA conducted a lengthy and costly return to flight program based on the recommendations included in the CAIB final report. After a delay of two years, the first Return to Flight mission - Discovery ST-114 - was launched July 26th. During launch it was immediately clear that the problems that caused the Columbia accident had not been solved. *'Imagery during launch showed* *a piece of foam being shed from the external tank, as well as smaller tile and foam dings. Imagery of the tiles showed two areas where gap fillers were protruding'.* Indeed the main improvement is that better imageing is conducted.

Flight ST-117

Columbia was the first Space Shuttle - flight ST-1 - launched on April 12th 1981. Although the Orbiter was originally designed not to be subjected to any significant debris strikes, Columbia sustained heavy damage on its inaugural flight from debris strikes during launch. More than 300 tiles had to be replaced, but this was no surprise to the engineers who later acknowledged to the Investigation Board that they had known in advance that the External Tank *'was going to produce the debris shower that occurred".* All later flights experienced damage, sometimes much worse. For NASA these problems soon became a simple maintenance, so-called *'turnaround issue'* and nobody recognized that one day an accident was bound to happen.

January 16th 2002, Columbia flight FT-107 took off for its 28th mission, the 113th Space Shuttle flight. 81.9 seconds after launch, a large piece of foam broke away from the External Tank and struck the left wing, when the Orbiter was travelling at about 65,700 feet, at 2300 ft/s or 700 m/s. Engineers estimated within days - with the Shuttle still in orbit - that the piece of foam was probably 19 inches by 11.5 inches by 5.5 inches, weighing 1.67 pounds with a density of 2.4 lb/cu ft. Transport analyses revealed that it took the foam about 0.2 seconds to travel to the left wing. Because of a large drag, the foam slowed down to about 1500 ft/s and struck the Shuttle at a relative speed of about 800 ft/s (45 m/s) and damaged most probably Carbon-Carbon panel number eight that protects part of the wing edge.

On the 1st of February at 8:44:09 am Columbia crossed Entry Interface, at

400,000 feet travelling at approximately 17,500 mph. Re-entry appeared normal until 8:54:24 when temperature indicators started to fail. Superheated air entered the wing, which may have been as hot as 8000 degrees near the breach. This led to total destruction of Columbia at a height of about 200,000 feet over Texas. Last communication with the crew was broken at 08:59:32.

A history of trouble

The Space Shuttles flew 113 missions during the period 1981 to 2003. It is common knowledge that *'the heat shield of tiles, the reinforced carbon-carbon panels and thermal blankets were not designed to be damaged in any way for any reason. That's why the Orbiter isn't allowed to fly through rain, stay outside when it hails or risk having workers drop tools on it'*. It is therefore surprising that Columbia, on its inaugural flight in 1981, sustained heavy damage from debris and more than 300 tiles had to be replaced, and the engineers apparently knew in advance that the External Tank *'was going to produce the debris shower that occurred'*. With the 79 flights of which imagery was available, foam shed 70 times and impacted the Thermal Protected System, together with lumps of ice. No serious action was taken. Tiles came back damaged every time with on average 143 divots with 31 divots averaging over an inch in dimension. When Atlantis flight ST-27 returned from its mission in 1988 damage was massive - *'looked like it had been blasted by a shotgun'* - the Orbiter had 707 dings, 298 of which greater than an inch. Also serious damage occurred to the reinforced carbon-carbon panels on previous flights. Then, just three months before the Columbia accident, with flight ST-112, a particular big block of foam separated 33 seconds after launch of Atlantis and damaged the External Tank Attach Ring of Atlantis.

With the Columbia FT-107 video captured quite dramatic pictures of a heavy foam impact to the left wing 81,9 seconds after launch when travelling at Mach 2,46 (2300 ft/s or 700 m/s) at about 65,700 feet. This was actually the seventh recorded left bipop ramp foam loss. Also an object was seen via military radar floating from the Space Shuttle during the second day of the mission, but this recording was not discovered until after the accident. As mentioned before, the accident could have been avoided when orbit imageing had been performed - and more important - when the heat shield materials had been properly tested.

A turn around issue

The cause was just total neglect - multiple total neglect to be more precisely. Much has been written about why the alarm bells were not ringing at a much earlier stage, why no photos were made in orbit to assess possible damage or, even better, to order the crew to inspect the shuttle in space which is always possible in case of emergency. Did engineers got used to the problems and did managers convince themselves there was no safety of flight issue, as is suggested in so many analyses and is described in great detail in the excellent final report of the Columbia Accident Investigation Board (CAIB). NASA engineers got indeed used to foam debris that was no longer regarded a safety-of-flight issue from 1990, when it officially became to be known as a *'turnaround'* or maintenance issue, and less as a hazard to the vehicle and crew. But based on what? And there is another important contributing factor in that impact response of materials at higher velocity is not well understood. The reason for this is – bizarre as it may sound - that no suitable method is available to test impact response of materials at high velocity.

For anybody familiar with high velocity impact imageing, the apparent force and magnitude of the rebounding debris at that velocity that showed on the video taken during take off revealed for certain that most probably something terribly had gone wrong.

Researching impact performance of rock with the aid of high speed video recording at that time – this author watched the impact on CNN in Holland and was horrified but what could I do. I knew an accident was bound to happen on re entry and felt terrible when it happened. This led me to follow developments closely and now the author trier to prevent another possible disaster again involving impact - the purpose of this study.

That Shuttle Program Management declined the requests on orbit imageing - the CAIB report summarizes nine missed opportunities during the flight that could have prevented the accident from happening - and ultimately discounted the possibility of a burn-through, was a mayor management blunder. But also engineers contributed to this decision through inexperience and ignorance, keeping the main focus on the tiles, the use of out of date models, incorrect interpretation of the results and so on.

But it has to be stressed that all engineers were concerned about the foam impact and wanted closer inspection of the Columbia; that is, except for one with *'close connection to Shuttle management'* who regarded him as the top expert on the Thermal Protection System. Somehow, this expert was *'convinced'* that there was no problem and advised management repeatedly that there was no safety-of flight-issue and they followed his advice - apparently blindly.

Tile or panel

Analysis of lift-off imagery on the second day of the mission revealed that the Orbiter's left wing took a heavy blow 81.9 seconds after launch. The *Intercenter Photo*

Working Group, being familiar with such images from earlier impacts, was immediately concerned about the large size of the impactor and the apparent momentum of the impact, as revealed by resulting shower of rebounding fragments, and believed that the Orbiter might have been damaged. They put in a request for on-orbit imagery of the Shuttle and distributed the video and photo images for further review. The request for imagery was soon to be supported by the *Debris Assessment Team*. Then, analysis by Boeing engineers on flight day three and four indicated that the size of the impactor was rather large indeed; some 20” by 20-16” by 2-6” and they estimated the apparent impact velocity to be approximately 750 ft/s (229 m/s), and the incidence angle of impact less then 20 degrees, which later proved remarkably true.

Transport analysis that were made during the flight identified 15 possible strike regions, 12 predicted an impact in the regions of the Shuttle tiles and only one on the Carbon-Carbon leading edge at a 21 degree angle that was regarded a ‘safe’ angle of impact as will be discussed later. Concern focused therefore mainly on the ‘fragile’ tiles - within NASA there was *‘this long-standing belief that foam was not a threat to Carbon-Carbon panels,’* although no reliable test results were available - what so ever - to support this view and serious damage had already occurred to a Carbon-Carbon panel during a previous flight.

Believing Crater

Being uncertain often leads engineers to either more or less ignoring a problem or take refuge in mathematical models. In many instances insufficient data can be made available for the proper development, validation and the running of such models, and this is certainly true for impact - as NASA learned the hard way when the available Crater simulation model suggested that damage might have occurred to Columbia’s

Protection Heat Shield.

For modelling of foam impact against the tiles only the *'Crater-model'* was available to assess possible damage. Crater is no more than a very simple mathematical equation designed back in 1966 during the Apollo Program to assess impact damage by micrometeorites. But it was all that was available at the time of the accident - that is of course except for the possible request for on orbit imageing. The equation had been modified between 1979 and 1985 to enable the analysis of impact to the tiles by small size objects up to 3 cubic inches in volume -however, with no physical validation. But the volume of the actual piece of foam that caused the accident was initially estimated to be some 640 times larger - later estimates put the size at approximately 400 times larger. Furthermore, Crater had the reputation to be a *'conservative tool'*, in that it normally predicted more damage than will actually occur. This is a remarkable view since the model was not validated, at least not with reliable physical test data.

It happened that the engineers on duty were new and not really familiar with the model. With an impactor that was some 640 times *'too big'* for Crater, the engineers tried to translate the results from the model to the actual accident conditions, with correction for size and extrapolation for density. Somehow, this interpretation led engineers *'to judge that the actual damage from the larger piece of foam would not be as severe as Crater predicted, and to assume that the foam did not penetrate the orbiter's skin',* although it was not known were the actual impact took place and virtually nothing was known about heavy foam-tile impact performance.

When the engineers focused on potential Reinforced Carbon-Carbon damage, they used - or tried to use - a Crater-like model that was calibrated in 1984 by impact data from small ice impactors. This exercise indicated that impact angles greater than 150 would result in Carbon-Carbon penetration. The results were qualitatively extrapolated for lighter foam impact and this led *'engineering judgment to conclude that foam impact up to an angle of 21⁰ would not penetrate the Carbon-Carbon'*.

Although some engineers were uncomfortable with these extrapolations and interpretations, no further analysis were performed to assess tile damage or Carbon-Carbon damage. The engineers informed management that Crater indicated that the foam most probably did not penetrate the Orbiter's skin. This illustrates, in an unfortunate dramatic way, how modelling can become the cause of accidents, instead of preventing them. But the bottom line here is that when *'something the size of a large cooler strikes the Orbiter at 500 miles per hour'* as one engineer put it, nobody, neither engineer nor management, should have even questioned - or try to verify by modelling - the request to take a close look at the Orbiter, which Thermal Protection System is known to be fragile.

Expert advise during the flight

But a number of engineers felt uneasy about this outcome of the modelling and decided to put in a request for closer inspection, but this request was more or less *'overruled'* by the previous mentioned 'expert'. On flight day six our expert send an e-mail to Shuttle Program Management *'for your information -Thermal Protection System took a hit-should not be a problem-status by the end of the week',* that essentially down played the possibility that foam damaged the Thermal Protection System. Apparently unknown to the managers was, that this expert was specialized in the tiles only and had no expertise on Reinforced Carbon-Carbon what so ever. Moreover, after the accident the investigation revealed that essentially nothing was known at the time about impact response of the tiles other than damage assessment on return. The expert himself probably did not realize his awful position - there was not really very much to expertise on and consequently not much to refute him.

During the third *Debris Assessment Team* meeting on flight day eight a heated discussion took place when our tile expert was called to ask about their rationale for pursuing on orbit imaginary – that he deemed not necessary. Pressed for additional reasons and not fully understanding why their original justification was insufficient, the Boeing analysts reasoned *'that at least they would know what happened if something were to go terribly wrong'* and challenged the expert, that when *'something the size of a large cooler had hit the Orbiter at 500 miles per hour'* further investigation should not be questioned. The tile expert remained confidant and reassured '*that the analysts were new and would learn from this exercise'.*

On flight day nine the *Debris Assessment Team* presented it's findings to the management. The engineers still *'shared a high level of concern'.* Five scenarios for debris damage were presented which focused primarily on the tiles and not on the RCC panels. Each case predicted thermal and structural effects for Columbia's re-entry, however, uncertainties remained about where the debris had struck and about Crater's reliability. *'Engineers ultimately concluded that their analysis, limited as is was, did not show that a safety of flight issue existed'.*

Also on flight day nine, our tile expert stated again his belief *'that no safety-of-flight issue exists'* during the final *Mission Management Team Meeting* and this *'conclusion'* was entered in the *Mission Evaluation Room* console log. Case closed. But till flight day seventeen when the accident happened, the impact was further analysed and discussed by the engineers but the safety-of-flight status remained, although most of the engineers felt very uncomfortable about this and still wanted images of the left wing but *'had given up trying...'*

An environmental issue

At the time of the Columbia accident, results of an incomplete test program, performed in 1999, was essentially all that was known about foam impact response of the tiles. But as always, NASA paid attention to environmental issues. Due to environmental concerns it was decided, in 1995, to replace the original (SOFI) foam material because it contained CFC's (chlorofluorocarbons). Loss of foam has always been a problem, but the first shuttle provided with the new (NCFL) foam material experienced more heavy loss of isolation material then NASA was used to so far - and that means really a lot and damaged increased. But now the environment was involved there was of course no way back for NASA on the chlorofluorocarbons – apparently regarded more important than the safety of the crew. Modifications of the foam chemistry showed some improvements, but did far from eliminate the problem. Then, in 1999, NASA decided finally to have the tiles tested for foam impact in what later appeared to have been 'a rudimentary program' only. The report can be downloaded from the web. Three small types of NCFL 24-124 foam projectiles – blocks and cylinders with volumes from a quarter to three cubic inches weighing 0.1 to 1.77 grams - were shot at 18 engineering tiles and at 37 used flight tiles at velocities ranging from 400 to 1600 ft/s and at angles of 10^0 to 60^0. Due to the limited number of experiments, the tests showed *'a degree of mixed results where definitive conclusions are difficult to make'* and it was concluded that *'As expected, tests conducted with large fast moving projectiles fired at increased incidence angles produced the largest crater volumes',* confirming common household knowledge only.

However, a closer look at the test results reveals a more alarming picture. Crater depths up to one inch and more - in one case *'the damage was too extensive to accurately measure volume'* - require at least more serious follow-up testing, taking into account what is at stake. It is therefore difficult to understand – actually astounding - that for reasons not clear to us, this program was somehow suspended halfway, when it appeared that the small pieces of foam damaged the tiles more heavily than expected. The test report mentions that *'During the initial stages of this study the decision was made by the sponsor to eliminate all tests with the 1.0"x3.0"x6.0" (11.5 grams) projectile due to the levels of damage created by the smaller projectiles',* although in reality the pieces were known to be up to hundred-fold larger…. It is therefore incomprehensible when we read that *'No tests were performed with larger debris objects because it was not believed such debris could ever impact the Orbiter'.* We wonder whether our expert has been involved with this test program.

Much remains unclear – and one can only wonder in disbelief – but the way this test program was executed contributed in a significant way to the destruction of the Columbia – in that it shows total neglect about the impact performance of the tiles. Had these tiles been investigated properly this would have revealed their real vulnerability and most probably someone would have asked also to study the carbon-carbon panels.

A sceptical community

After the accident there was no agreement among investigators that the foam impact could cause sufficient damage to precipitate the accident, despite the dramatic video images of foam striking Columbia's left wing short after lift-off. To find out, NASA planned a full- scale test. This was going to take some months and in the meantime NASA asked Sandia to prepare first computational models, based on the recorded foam impact. Early results indicated that such impact would not cause much damage to the lower wing tiles. But the analysts at Sandia found that impact to the wing's leading edge could actual have damaged and potentially penetrated the reinforced carbon-carbon material. For many at NASA this was hard to believe - as one Sandia analyst put it *'We faced a very sceptical community'* - and this scepticism would remain until the full-scale test was performed.

In the blink of an eye

The full-scale test was performed at Southwest Research Institute in San Antonio, Texas, July 7th 2003. Although it had never been done before, it proved not too difficult to shoot a rectangular impactor of foam about the size thought to have caused the accident at the estimated relative velocity (777 ft/s or 237 m/s), at the estimated angle of incidence (25.1degrees with correction for self rotation) and at the estimated clocking-angle against the reinforced carbon-carbon panel number 8 of the leading edge where the actual impact was thought to have occurred. To the total surprise of many – a previous test involving another panel did reveal no damage - this test confirmed that such impact produces indeed enough power to break up the panel. *'I don't think anyone expected to see a 16-inch square hole',* one of the engineers reported later, *'In the blink of an eye, there it was, and hundreds of people immediately came to terms with how much damage a piece of foam can do'*. From the force with which the shower of debris rebounded after the actual impact we estimate that it is possible that the damage to the Shuttle was even larger. On the other hand, arc testing performed later revealed that much smaller damage to the panels can already cause an accident as it occurred.

Return to Flight program

The problem for NASA is that the Thermal Protection System was not designed to be impact resistant during launch, but to be temperature resistant during entry; that is up to at least 2500 F (1400 C). The Shuttle was designed not to fly through rain, nor to stay outside when it hails. But already during the first flight it appeared that the Thermal Protection System had to be also impact resistant, due to the heavy loss and subsequent impact of foam and ice. It was already noted that not too much attention has been paid to this problem until the accident with the Columbia happened. But now the problem had to be solved – at least that was the idea.

Before long it became clear that it was much more difficult to study in detail the impact response of foam, ice and ablator materials against the reinforced carbon-carbon panels, ceramic tiles and window glazing at high velocity. With not much know how '*Little was known at the time of the accident about the impact characteristics of either the foam isolating the external fuel tanks or the reinforced carbon-carbon thermal protection system*,' only limited experience - '*I was amazed that a 2-gram piece of foam could break a reinforced carbon-carbon strip*' - as one engineer puts it and results from previous tests incomplete, engineers at NASA realized that they had to start essentially from scratch. With the heat shield materials there were not even reliable data available about tension, bending and compression behaviour and other measures of failure were incomplete.

NASA's Return-to-Flight Program focused in particular on preventing damage to the Thermal Protection System from happening again. Therefore engineers concentrated on eliminating or significantly limiting the shedding of foam and of ice build-up, for which numerous improvements and modifications were made to the External Fuel Tank isolation system – modelling played an important role up to a level that at some moment virtually all computers at NASA were preoccupied with damage assessment. Regardless all these efforts, the first return-to-flight - ST 114 - experienced again multiple foam loss during launch, July 28th 2005, and '*the large size of some of the foam loss caused concern because they were much larger than analysis had predicted was* *likely'* - that for the models. Damage to the heat shield was however limited, probably because a number of the foam losses occurred later than 135 seconds after launch at a height where lower aerodynamic pressure limits drag and consequently the impact velocity to a level too low to cause critical damage as was already pointed out before.

The focus was also on possibly 'hardening' of the Thermal Protection System. Orbiters have continuously been provided with more impact resistant tiles the Shuttle program and recently again stronger tiles - BRI 18 - have been developed. As was pointed out before, hardly any attention was paid to these panels during the Shuttle program and also now engineers did not find a way to increase on the impact resistance of the reinforced carbon-carbon. The probably easiest way out is to redesign the panels such that it provides two and for the most critical area's three protective shields behind each other. Suggestions in this direction have already been made. But for the moment the existing panels remain in place and these pose a repeated risk for similar damage to occur.

It is therefore of utmost importance that much more imagery is obtained of the heat shield as is now the case during launch – and for detailed inspection in space the Orbiter is now provided with a robot-arm with sensors. Photo imagery is also taken by the crew of the International Space Station, ISS, of the acreage tiles across the bottom of the Orbiter before docking, as will be discussed later.

A problem that remains is repair when damage is detected. Several techniques have been developed for possible repair in space but *'Despite comprehensive efforts to develop TPS repair materials and techniques; the state-of-the-art technology in this area has yield modest technology to support the capability. As a result, continued efforts do not hold promise of significant capabilities beyond those in hand'.*

Rocket science

What caused the accident with Columbia accident cannot be answered in a straightforward way as with the Comet and The Concorde. The cause is here more alarming because it concerns the by far largest scientific organization in the world with thousand of top scientists and engineers with resources available to them beyond belief. It is therefore also beyond belief when the causes of an accident with such a prestigious project include that no attention was paid to impact response of the heat shield materials – again whatsoever – while all flights endured impact damage, in many cases very heavy damage. The only thing they could apparently come-up with was to term it a *'turnaround'* issue - and of course there was Crater. But the vulnerability of shuttle concept could have been foreseen – this requires no rocket science – and was foreseen.

As indicated, NASA engineers did already know before the first Space Shuttle was launched that essential mistakes had been made with the design – in particular that the vulnerability of the concept was largely underestimated. When the design was worked out, the idea was to have a reusable shuttle that could land like an aircraft. For that the main engines had to be part of the Shuttle, and therefore the engines had to be designed in a way that they could be reused - contrary to rockets were the engines are used only once. This concept required the Shuttle to be equipped with a separate tank that contains the liquid oxygen and liquid hydrogen. If that was not enough, it was decided that this tank would also have to be reusable. This led to a design were the tank was attached alongside the Shuttle. It was recognized that this posed an impact threat to the shuttle from debris falling of the tank in particular ice that would build up along the tank surfaces. The tanks were therefore provided with a thick coating of foam to prevent such ice formation with a new coating to be applied each time. With this decision it went wrong, the behaviour of the foam had not been well thought through.

What is the case? The foam is sprayed on the tanks in layers manually but even with robots formation of air voids in the foam cannot be avoided, in particular where the surface is irregular and near corners and edges. As foam heats up it softens, as is the case during launch due to friction with the air. The Shuttle is very fast gaining height and this causes a very fast drop in atmospheric pressure but the pressure in the foam does not drop so fast. Together the higher temperature and the pressure variation cause possibly loosen of parts of the foam. Furthermore, liquid nitrogen filled voids can arise between the foam and metallic surfaces of the tank because the balance is here disturbed when the tank empties during take off and this goes at rather fast rate. This means that the liquid nitrogen heats up and evaporates and that can damage the foam and cause parts to break away. And probably other physical and chemical processes are involved.

Could this have been foreseen? Of course, this is elementary science – doesn't need rocket science - may be too elementary for the scientists involved. And even if the processes that caused the damage are ignored it could have been easily demonstrated by relative simple research. Moreover the foam did not prevent ice formation, at least far from completely - which involves also elementary science - and considerable amounts of ice did build up and lumps of ice did break away during launch together with foam.

As discussed before, this debris caused damage to Shuttle each time, often heavy and in case of the Columbia with fatal consequences. But it was not only the foam, the whole design was wrong in that the crew should always be positioned on top. The traditional capsule is again the design of choice - as the Russians and also the Chinese can tell you by now. Future manned spacecraft are going to be much smaller with the payload brought into orbit with unmanned rockets.

During the return to Flight Program much attention was paid to modelling. This is extremely difficult with impact and not too much relevance should be paid to these models. It is, however, recognized that these models provide a very important tool with physical research but are still far from mature to be relied upon for predicting whether a particular impact has to be regarded as a safety-off-flight issue - whatever the mathematicians, who often seem to have blind fate in their models, want to insist that this is the case.

The 200 millions or so computer impact simulations that were deemed necessary to calculate during the return to space program did hardly contribute to safety improvement - they did help with better understanding of the problem. The real contribution came from the engineers who managed to improve on the gas gun method of full-scale impact testing - they discovered the cause of the accident in the first place - and enabled to characterize impact response of the tiles, carbon carbon and the foam. Real physical test results, that's what impact safety is all about, as well as real imageing in space – and beyond.

The outcome

What improvements have been made during the Return to Flight Program. The most important no doubt is that it brought back NASA 'back from the future' and to deal with real issues. Mentality has changed and warnings from engineers are again taken seriously and the same applies for the attitude of those engineers. The second most important improvement is that now detailed imageing is obtained as has been discussed before. But the return to flight Space Shuttle is still largely the same 'old' structure. Improvements involve mainly details, in particular modifications with the foam isolation layer, but the problems with impact damage still occurs and is now also closely monitored by CNN.

At least damage can be seen now, or can it? Visual inspection of a tile is not such a problem, but there are many tiles, about 24,300 to be exactly. More difficult is visual inspection of the Carbon-Carbon panels that caused the Columbia accident, since even minor damage can here have fatal consequences and hidden damage might be involved. The reinforced carbon-carbon provides a great thermal barrier – up to 2300 F. However, in the presence of oxygen and high temperature, the material is highly susceptible to oxidation. To protect the material against hot oxidation, a silicon carbide coating is provided on all surfaces with a thickness of 0.02 to 0.04 in. This layer is again covered with a coating of silica to further harden the front surface. Such coatings are extremely fragile and prone to craze cracking. As said before, arc jet testing has now shown, that relative small damage to these coatings can lead to fatal burn through! This means that the real damage to the Carbon-Carbon panel that is thought to be the cause of the accident might have been minor.

That brings us back to the fuzz about the refusal to allow for imageing by the military, that is with cameras from earth. Rumour has it that these guys can see a fly on a spacecraft in orbit. But recent research has it that flies do not exist in space. It is therefore questionable whether such imageing would have revealed the danger. Whatever it does not bring back to us those brave astronauts. Their contribution to safer spacecraft and aircraft and all other areas where impact poses a safety threat has been immense and hopefully will be taken seriously in time by Boeing and Airbus - amongst others.