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Nondestructive Evaluation for the Space Shuttle's Wing Leading Edge

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The loss of the Space Shuttle Columbia highlighted concerns about the integrity of the Shuttle's thermal protection system, which includes Reinforced Carbon-Carbon (RCC) on the leading edge. This led NASA to investigate nondestructive evaluation (NDE) methods for certifying the integrity of the Shuttle's wing leading edge. That investigation was performed simultaneously with a large study conducted to understand the impact damage caused by errant debris. Among the many advanced NDE methods investigated for applicability to the RCC material, advanced digital radiography, high resolution computed tomography, thermography, ultrasound, acoustic emission and eddy current systems have demonstrated the maturity and success for application to the Shuttle RCC panels. For the purposes of evaluating the RCC panels while they are installed on the orbiters, thermographic detection incorporating principal component analysis (PCA) and eddy current array scanning systems demonstrated the ability to measure the RCC panels from one side only and to detect several flaw types of concern. These systems were field tested at Kennedy Space Center (KSC) and at several locations where impact testing was being conducted. Another advanced method that NASA has been investigating is an automated acoustic based detection system. Such a system would be based in part on methods developed over the years for acoustic emission testing. Impact sensing has been demonstrated through numerous impact tests on both reinforced carbon-carbon (RCC) leading edge materials as well as Shuttle tile materials on representative aluminum wing structures. A variety of impact materials and conditions have been evaluated including foam, ice, and ablator materials at ascent velocities as well as simulated hypervelocity micrometeoroid and orbital debris impacts. These tests have successfully demonstrated the capability to detect and localize impact events on Shuttle's wing structures. A first generation impact sensing system has been designed for the next Shuttle flight and is undergoing final evaluation for deployment on the Shuttle's first return to flight. This system will employ wireless accelerometer sensors that were qualified for other applications on previous Shuttle flights. These sensors will be deployed on the wing's leading edge to detect impacts on the RCC leading edge panels. The application of these methods will help to insure the continued integrity of the Shuttle wing's leading edge system as the Shuttle flights resume and until their retirement.

Nomenclature

CAIB	=	Columbia Accident Investigation Board
CT	=	Computed Tomography
FG	=	Fiberglass
KSC	=	Kennedy Space Center

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MLGD = Main Landing Gear Door
MMOD = micrometeoroid object damage
NDE = Nondestructive Evaluation
PCA = Principle Component Analysis
RCC = Reinforced Carbon-Carbon
SiC = Silicon Carbide
WLEIDS = Wing Leading Edge Impact Detection System

Introduction

After the Space Shuttle Columbia was destroyed in February of 2003, an independent accident investigation board (CAIB) was established to determine the cause of the accident and to suggest operation improvements for NASA's space program. The board made numerous suggestions for NASA to implement, two of which were that NASA:

> "Develop and implement a comprehensive inspection plan to determine the structural integrity of all Reinforced Carbon-Carbon system components. This inspection plan should take advantage of advanced nondestructive inspection technology." (CAIB recommendation: R3.3-1)[1]

and

> "For missions to the International Space Station, develop a practicable capability to inspect and effect emergency repairs to the widest possible range of damage to the Thermal Protection System, including both tile and Reinforced Carbon-Carbon, taking advantage of the additional capabilities available when near to or docked at the International Space Station. For non-Station missions, develop a comprehensive autonomous (independent of Station) inspection and repair capability to cover the widest possible range of damage scenarios. Accomplish an on-orbit Thermal Protection System inspection, using appropriate assets and capabilities, early in all missions. The ultimate objective should be a fully autonomous capability for all missions to address the possibility that an International Space Station mission fails to achieve the correct orbit, fails to dock successfully, or is damaged during or after undocking." (CAIB recommendation R6.4-1)[1]

This paper will review some of the progress and steps that were taken by NASA to address these recommendations.

To satisfy the first requirement, NASA investigated numerous NDE methods for certifying the integrity of the Shuttle's wing leading edge. It should be noted that RCC materials are very heterogeneous with significant porosity, therefore the detection of small flaws present a considerable challenge for NDE methods. Among the many NDE methods investigated for use on the RCC material were advanced digital radiography, high resolution computed tomography, thermography, advanced ultrasound, and advanced eddy current systems. Ultimately, NASA selected thermography to provide the first inspection step for the RCC panels. Its advantages are that it was a fast, noncontacting, one-sided application, easy to implement in the Shuttle's servicing environment, and it detects the critical flaws of interest. If any areas of concern were identified, then advanced eddy current or ultrasound would be applied to better define the indication identified by thermography. Eddy current is a single sided technique, has excellent resolution, can image flaws relatively deep in the RCC, and is also easy to implement in the Shuttle's servicing environment. Ultrasound is also a single sided technique, has decent resolution, and can image features through the entire thickness of the RCC, although it requires a couplant, which increases the need to control for contamination. Finally if these techniques are unable to resolve the nature of an indication, the panel would be removed and would undergo advanced computed tomography (CT) testing, which has excellent capabilities for assessing RCC integrity.

To help address the second CAIB recommendation, NASA implemented a monitoring system specifically designed to identify impacts to the RCC leading edge. The focus of the system is to detect impacts to the leading edge during Shuttle ascent and to also monitor for micrometeoroids impacts to the leading edge during orbital flight. Such information could greatly simplify the inspection requirements dictated by the above recommendations by helping to focus inspections to identified regions of interest and to warn the astronauts about MMOD impacts after inspections will have been completed. Equally important for the Shuttle launch system is that this system could possibly modify or remove the constraint to have a visual launch capability:

> (CAIB recommendation: R3.4-1 Upgrade the imaging system to be capable of providing a minimum of three useful views of the Space Shuttle from liftoff to at least Solid Rocket Booster separation, along any expected ascent azimuth. The operational status of these assets should be included in the Launch Commit Criteria for future launches. Consider using ships or aircraft to provide additional views of the Shuttle during ascent.[1]).

The visual launch constrains launch times to the space station to the daytime, limiting the launch window to a few weeks a month. If this system could provide the information the visual system requires, then it could relieve the constraint for daytime only launches. The addition of night launches would significantly expand the operational window.

NDE for RCC

Once the CAIB forewarned NASA that it was going to recommend that NDE be implemented on the wing leading edge, NASA promptly established a broad team of individuals representing government, industries, and universities to address the need. They reviewed a large number of advanced NDE techniques as well as existing well-established methods that were already in existence. The team developed a set of samples consisting of small plates of RCC materials with flaws that were sent to organizations to test. Also, at this point in time, NASA had two complete RCC panels that had foam impact damage for evaluation of NDE techniques. In addition, NASA continued testing RCC panels for impact sensitivity, which provided testing opportunities to test on actual hardware. Also, some of the recovered debris from the Columbia Accident Investigation was made available to the team for additional testing experience.

Any method ultimately selected would have to have several desirable capabilities. An important operational property was that the inspection method be applicable in the orbiter servicing environment. In that environment, highly desirable characteristics would be ease of use characteristics, such as single-sided application, noncontacting, noncontaminating, speed, and sensitivity to critical flaws. In the end, several advanced techniques were chosen that provided sensitivity to critical flaws and were adaptable to the Shuttle servicing environment. The methods were thermography, advanced eddy current, and ultrasound. If a panel was removed from the Shuttle, then computed tomography was also available.

A. Thermography

Thermography has been demonstrated on RCC materials to have many of the requirements that are desirable for application in the orbiter maintenance environment. Figure 1 demonstrates the relative capabilities of thermography compared to visual and through transmission ultrasound. The photograph indicates only a crack in the Silicon Carbide (SiC) coating of the RCC material. Both the ultrasonic and thermography images indicate significant amounts of subsurface damage, especially at the tip of the visible crack. The fact that the thermography image could be made single sided without couplants and relatively quickly were important issues in its acceptance by NASA.

Figure 2 shows thermography images made on an RCC panel number 6L and its adjacent T-seal. This panel had been impacted and a small crack was visible at the edge of the RCC panel. This damage was detectable by conventional thermography, whereas post processing with principle component analysis (PCA) highlighted additional subsurface damage at the crack location.

Figure 3 shows a photograph of the thermography system during acceptance testing. This system will ultimately be deployed in the Orbiter Processing Facilities at KSC. The system has a thermal hood to direct the energy from the high intensity flash lamps to the inspection surface in an efficient manner. The area of the hood's opening allows 0.9 square feet of RCC to be measured at a time. An image takes 14 seconds to acquire and an additional 15 seconds to process. The whole system is mounted on a cart that is confined to a track that follows the orbiter wing. The system can be rapidly and safely positioned along the whole edge of the orbiter wing. It is currently estimated that all the

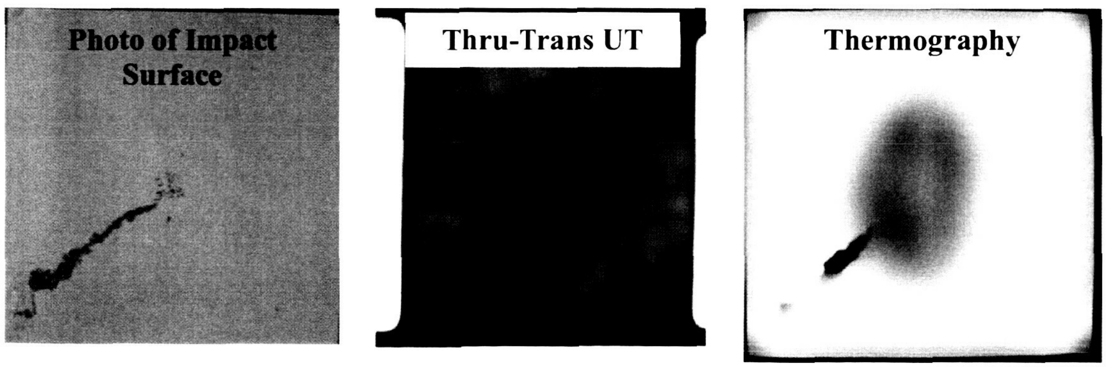

Figure 1. NDE images from an RCC impact coupon. *The left figure is a photograph of an impacted RCC test panel with a visible crack. The center view is a thru transmission ultrasound image. The panel to the right shows a thermography image. The ultrasonic and thermography images illustrate the hidden damage within the RCC panel.*

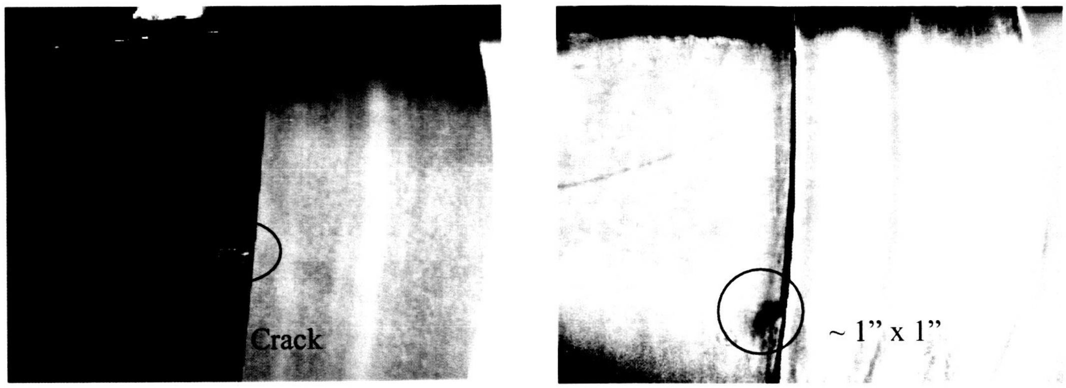

Figure 2. Thermography images from an RCC Shuttle panel 6L. *Figure on the left shows the thermography image of Shuttle hardware that was impacted, generating a crack visible on the surface. The right panel shows a similar thermography image after the data was post processed by PCA. This analysis shows more damage detail.*

RCC panels on the wing and on the nose of the shuttle can be scanned in about one week's time. In extensive testing, thermography demonstrated its ability to detect subsurface delaminations in the carbon-carbon, damaged SiC coatings, and erosion of the carbon-carbon material under the SiC coating. The system is required to detect a 0.375 inch diameter flaw through out the thickness of the RCC panel.

Figure 3. Evaluation of thermography system on RCC panel. *Picture illustrates the system mounted on a movable cart measuring an RCC panel during testing at Oceaneering Space Systems in Houston, TX*

B. Eddy Current

Once thermography, or information from the visual launch data system or from the Wing Leading Edge Impact Detection System (WLEIDS), identifies a region of interest that region can be further evaluated with eddy current techniques. Eddy current testing is a part of the acceptance testing for the RCC panels during manufacturing, where it is used to quantify the thickness of the SiC. The method is also very applicable to qualification testing of RCC with the panels in place on the Shuttle.

Figure 4 shows a scan of a RCC specimen that was recovered from the Columbia vehicle. The left figure is a image of the conductivity of the carbon-carbon. Midway on the right side of that figure a "red mark" highlights a crack in the carbon-carbon. The image on the left is a scan of the same region that represents the "lift off" of the eddy current probe. The "lift off" of the probe can be related to the thickness of the SiC outer layer.

Figure 5 helps to define the sensitivity of eddy current to hidden damage. This sample had a series of flat bottom holes drilled into the backside of the RCC material. The schematic on the right of Figure 5 shows the location, hole's diameter, and the remaining good material between the top of the hole and the outer surface of the RCC. The array system produces a unique signal where a circular flaw appears as a two lobed image within the figure on the left. Holes as small as 0.125" could be detected at a depth of 0.125". What is evident from these studies is that the detectability degrades as one tries to inspect for deeper and deeper flaws, which correlates with the penetration depth of the eddy current signal into the RCC material. Even with this limitation, the eddy current method can still detect flaws deep within a panel.

Figure 6 shows an eddy current array being used to rapidly scan an RCC panel. The panel has a thin layer of plastic laid over the RCC to eliminate potential contamination and wear to the surface and to delineate a scan grid. This system can produce nearly a four-inch wide scan of RCC material with one pass of the rolling carriage at one inch per second. The system can scan a one-foot square area in less than 60 seconds with a real time output display. The information provided to the operator includes information about the thickness of the SiC protective layer as well as the conductivity of the carbon-carbon substrate. That information can be translated into information about erosion of the SiC surface layer and damage or cracking of the carbon-carbon substrate.

C. Ultrasonic imaging

In addition to the use of eddy current methods, NASA has been qualifying conventional ultrasound for inspection of RCC materials at KSC to augment the thermography results if required. Figure 7 shows the ultrasonic testing results from the same panel that was shown in Figure 1. In this set of figures, the left most photograph shows a visual indication of a crack. The center and right panels show two types of images from ultrasonic backscatter data. These images have some additional information not visible in the thermography image in Figure 1. The center panel is a "C-Scan" image obtained by taking the amplitude of the signals that reflect back from the interior of the RCC

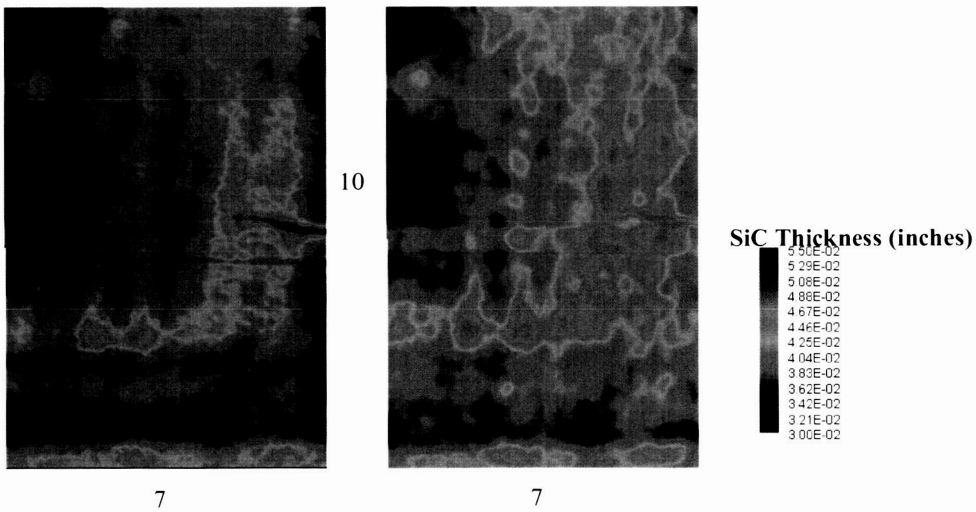

Figure 4. Eddy Current NDE images from RCC specimens. *The left hand figure is an image from an eddy current scan of an RCC test panel showing the conductivity of the panel. The red mark on the right hand side of that panel is from a crack in the carbon-carbon. The right hand figure is an image of the eddy current probe "lift off" which corresponds to the SiC thickness.*

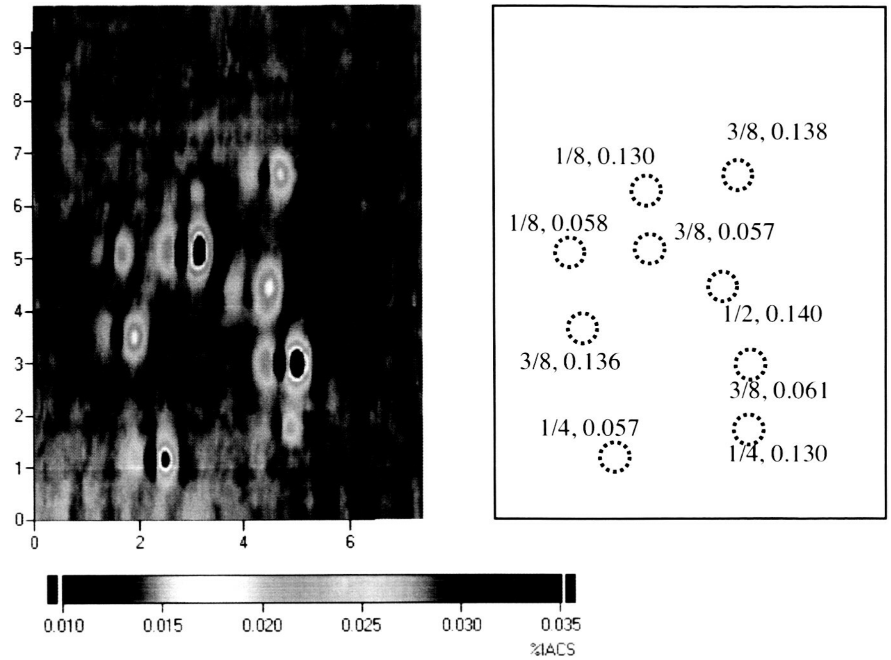

Figure 5. Inspection results and actual flaw diameter, depth from inspection surface. *The right hand figure is a schematic of the pattern of flat bottom holes that were drilled into the backside of an RCC panel. The left hand image gives indications of the sensitivity of eddy current to flaws in the carbon-carbon substrate.*

Figure 6. Eddy current array being used to rapidly scan an RCC panel. *The array system shown can produce a nearly four-inch wide scan of RCC material with one pass of the rolling carriage. Multiple passes will build up a coherent image of the in-phase and out of phase signals from the RCC material.*

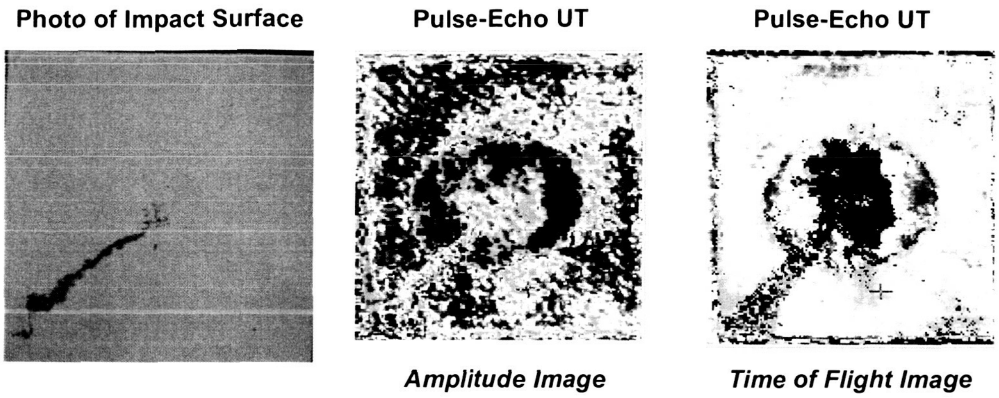

Figure 7. Ultrasonic backscatter images of damage in RCC. *The left hand figure is a photograph of a RCC panel with a visible crack. The middle panel is a "C-Scan" image of the amplitude of the ultrasonic signal from the interior of the panel. The right panel is a "C-Scan" image of the time of flight of the signal to the internal damage. That signal is related to the depth of damage.*

material. A strong reflection echo would be indicative of internal damage. The panel on the right shows a "time of flight" image in a "C-Scan" format. The "Time of Flight" image is indicative of the depth of the damage that can be detected. These images have significant levels of "noise" which arises from the significant heterogeneity of the RCC. One issue with ultrasound that is being addressed is the need for couplants. NASA has to decide how to deal with the potential for contamination to the RCC.

D. Computed Tomography imaging

If further questions about the quality of the RCC should be necessary, NASA has Computed Tomography resources available to investigate those questions. In this case, a panel would have to be removed for the test to be performed. Figure 8 shows an example of the results of a CT scan taken of an RCC sample. The figure highlights some of the regions where the SiC surface layers appear to be ill defined. Modeling has been used to help understand the types of distortions that can occur as a result of the large density differences between the carbon-carbon and SiC materials, especially when high levels of porosity are evident. The system has proven to very valuable for imaging defects in areas of complex geometry where other imaging modalities perform poorly. For example, digital radiography and CT can detect defects such as "tubular voids." (Tubular voids are long narrow voids, which are about 0.125" in diameter, several inches long, and occur at bends at the RCC joints.) These types of voids are hard to find with most

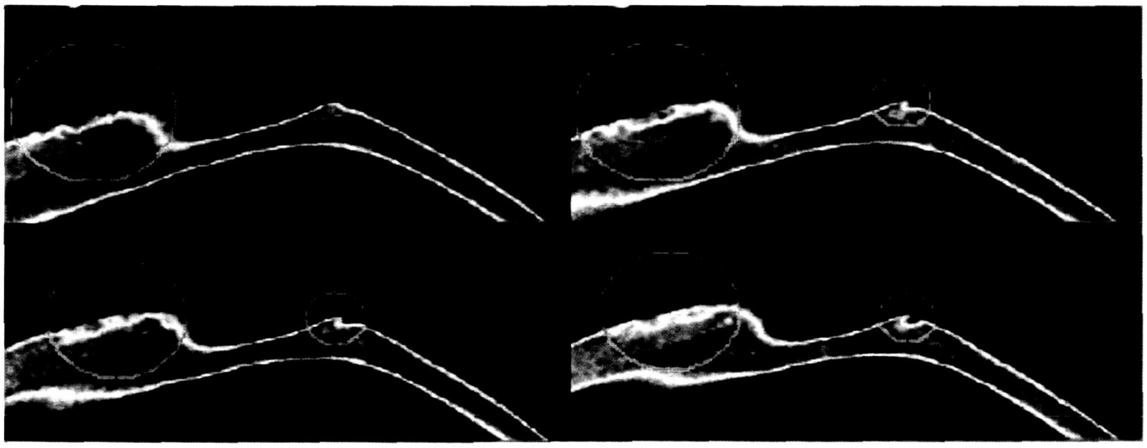

Figure 8. CT images of an RCC Sample. *CT Images of RCC materials showing some apparent coating anomalies of an RCC sample.*

conventional NDE methods because of the complex geometry where they occur.

Wing Leading Edge Impact Detection System

Shortly after the Columbia accident, plans were made to start testing Shuttle components for their resistance to foam impact damage. At the same time, measurements in the acoustic and ultrasonic frequency range were made to characterize the structure's response to these impacts. These measurements have the potential to form the under-pinning of an impact detection system for the orbiter's thermal protection system. If these techniques were to be practical, several questions needed to be answered. First, it needed to be demonstrated that acoustic and ultrasonic sensors could detect structure borne sound generated by foam impacts. Second, the capability of estimating the location of an impact source position needed to be demonstrated. Third, maximum distances from an impact point for which detection and localization via structure borne sound was feasible needed to be determined. Fourth, a determination of the variation in the measured signals as a function of projectile mass, material, shape, velocity, impact angle, and the level of damage in the impacted structure had to be acquired. Finally, all of these measurements had to be demonstrated in increasingly complicated but successively more realistic orbiter like structures. Test articles monitored included the wing leading edge with fiberglass (FG) replicas and then with real RCC panels, wing acreage (tiles), main landing gear door (MLGD) with tile, and an integrated test article, which included RCC panels, carrier panels, and tiles. These measurements also required tests where the sensors were simultaneously on the spar and wing structure and the need to determine the structure borne transfer function of the interconnecting intermediate structures. Finally, measurements on actual orbiter hardware needed to be made to relate all the test data to the real system.

Figure 9 shows a high-speed photo of a foam impact on an RCC panel and the resulting ultrasonic signals. The foam impact shown on the left represented a foam block (weight = 1.7 pounds, speed = 777 feet/second, shallow angle of impact) striking RCC panel 8L with enough momentum to fracture the RCC panel. The image on the left in Figure 9 shows eight individual graphs corresponding to the time response from eight ultrasonic transducers. Each graph represents a -0.5 to 0.5 volt signal level on the vertical axis and a 0 to 250 KHz frequency range on the horizontal axis. All the transducers detected the impact. Seven of those transducers were located on the bottom side of the leading edge of the wing, with an eighth transducer located on the topside of the spar. Each transducer was attached at a mounting point where neighboring RCC panels were attached. (These transducer locations would be protected from the extreme heat of the leading edge during an actual flight.) From the signals shown, the largest signals came from a transducer just aft of the impacted panel. The second largest signal was from the transducer just fore of the RCC panel. The time of arrival at each transducer could be used to locate the impact location as occurring on panel 8L. By comparing the signals from the transducers that were on the top and bottom of the wing, it could be ascertained that the impact occurred on the bottom side of the panel. Hence, impacts could be measured by transducers located several panels distant and the approximate impact location could be inferred by comparing

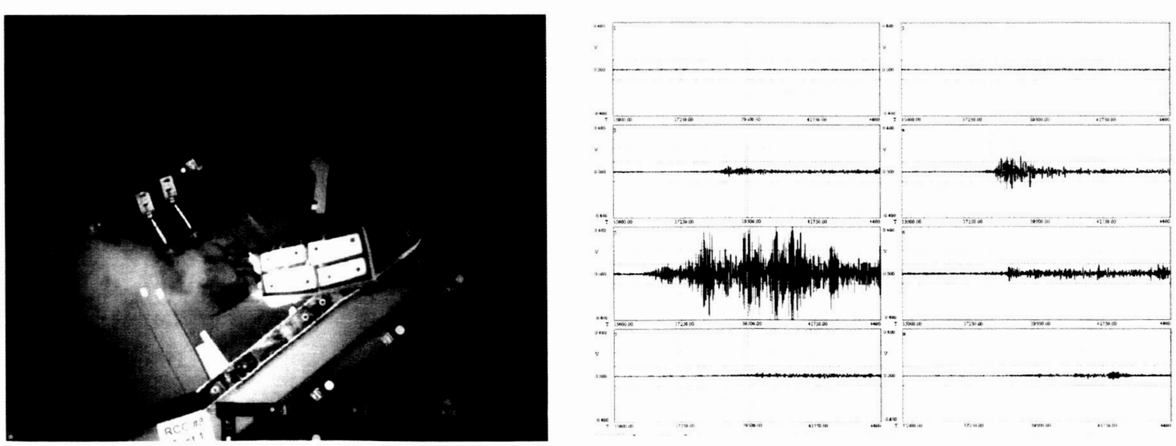

Figure 9. Shuttle wing test article being impacted and corresponding impact signals. *The photo at the right is a high-speed photograph of foam impacting RCC panel 8L. The figure on the right shows signals from eight transducers mounted on the wing spar.*

the time of arrival from several transducers.

Figure 10 shows some of the results illuminating the transfer function through the RCC attachment hardware. In the top left graph, the response from a transducer mounted on the RCC near the hardware attachment point is shown. In the figure on the top right, another transducer shows the response to the impact after it has passed through the RCC mounting hardware. That measurement is supposed to represent the point where the attachment hardware connects to the Shuttle's wing. The signals are both logarithmic and the frequency scale is from 0 to 250 KHz. In the top set of graphs it can be seen that a significant amount of the frequencies higher than 50 KHz are lost in transmission through the attachment hardware, while frequencies below 30 KHz are transmitted without much attenuation. A similar result is seen in another impact for the same set of transducer locations, which are depicted in the lower set of graphs in Figure 10. Again, the transducer mounted directly to the RCC panel (lower left panel in Figure 10) shows high frequencies in the range of 100 KHz while the transducer on the wing spar where the RCC is attached indicate that the signals are predominately below 50 KHz (lower right panel Figure 10).

Of the many types of impactors studied (foam, ice, ablator, and metal) one of the more interesting and important types are small hypervelocity impactors. These represent the class of impactors that simulate micrometeoroid object damage. In space these small objects can be traveling with a closing speeds of 15 km/sec. At that speed, even a small object is very destructive. The picture on the left of Figure 11 illustrates the level of damage that can be caused by a 2 mm (impact site at the left of the photo) and a 6 mm (larger impact site at the right of the photo) aluminum ball traveling at 6.82 km/sec that has struck a fiberglass plate. The graph on the right shows the relationship between the recorded ultrasonic signal corrected for distance and the projectile impact energy. The energy relationship is nearly linear until the energy becomes large enough that the projectile penetrates the plate and can no longer fully transfer its energy to the plate, hence the acoustic signal falls off.

Finally, to understand the relationship between our impact tests on test articles and the Shuttle wing, a series of tests were performed to characterize the relative similarities between the test article and the Shuttle's wings. Figure 12 shows the Shuttle's wing where a series of transducers were attached to the leading edge of the spar. At several

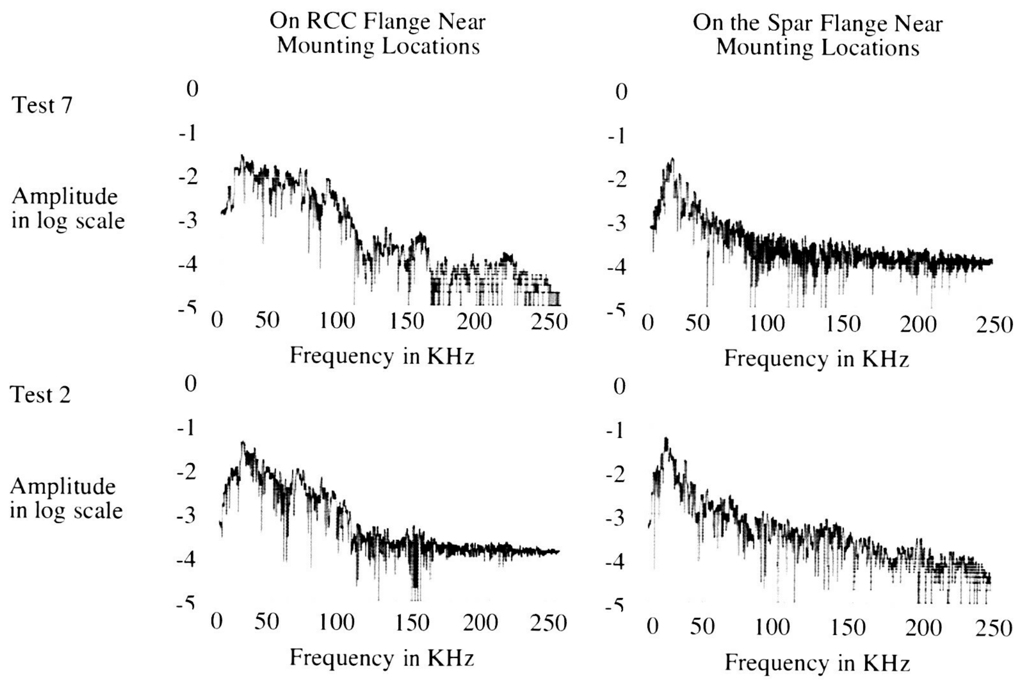

Figure 10. Impact Spectra recorded at different locations on an RCC panel. *The top two panels show the spectra from impact test 7. The left top panel shows the impact response of the RCC at the mounting flange and the right top panel shows the response at the mounting spar to the same impact. The bottom two figures show the spectra from impact test 2. The bottom left panel shows the impact response of the RCC at its mounting flange and the bottom right shows the response at the mounting spar to the same impact. The vertical scales are logarithmic and the horizontal scale is from 0 to 250 KHz.*

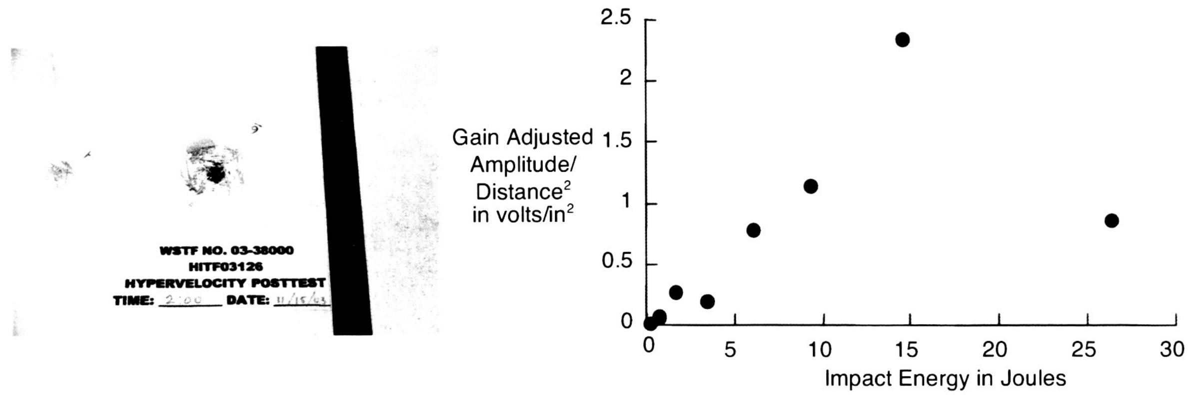

Figure 11. Hypervelocity impacts. *The right panel shows the results of a hypervelocity impact from a 2 mm and a 6 mm aluminum projectile traveling at 6.82 km/s. The left panel shows a plot comparing the ultrasonic output signal scaled for distance with respect to the impact energy.*

locations, an ultrasonic signal was injected with an ultrasonic transducer or an instrumented hammer was used to tap the aluminum surface in a controlled and recordable manner and the response of the various transducers were recorded. A similar experiment was performed on the test articles also using an ultrasonically injected signal and an instrumented hammer. Figure 13 shows some results relating the acoustic energy with the measured hammer loads. The acoustic energy is defined as the sum of the voltages squared over a unit of time and the hammer loads were recorded simultaneously. The difference between a small metal hammer tip and a larger metal hammer tip can easily be seen. The smaller tip concentrates the force into a smaller area, which produces a stronger acoustic energy signal at a lower hammer load. This emphasizes that the impactor's geometry is very important in the interpretation of the data.

These large series of experiments have demonstrated the feasibility of instrumenting the Shuttle's wing to try to detect impacts during the Shuttle's ascent and during orbital flight. NASA's Orbiter Project Office is supporting a test of the next three Shuttle flights to see how well impacts to the leading edge can be detected. The Shuttle will use existing space qualified instruments and accelerometers. These instruments have been installed on the leading edge spars of the Shuttle. The instrumentation will record the accelerometer's response during ascent and during on orbit operations until the systems batteries run out. During the Shuttle's orbit, data will be transferred to the Mission Control for evaluation. Any anomalous results will be reported to the Shuttle managers. Since a camera will be used to inspect the thermal protection surface after ascent on these first flights, the ability to identify impacts and estimate

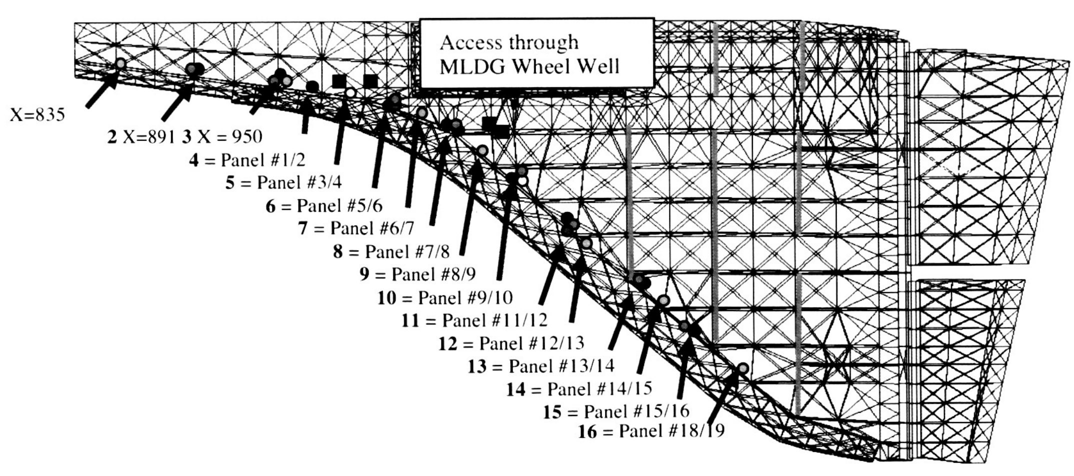

Figure 12. Shuttle tests. *The figure shows the location of a series of sensors for a test of the sensors' response to controlled excitations.*

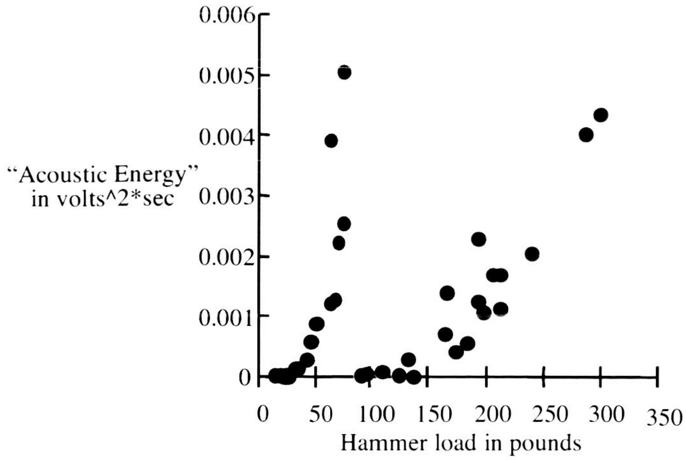

Figure 14. Impact hammer tests. *The figure shows a relationship between impact hammer load and acoustic energy (calculated as the voltage squared over a unit of time). The blue symbols are for a small metal hammer tip and the red symbols are for a larger metal hammer tip.*

the degree of damage on the leading edge RCC materials will be correlated.

Conclusion

This manuscript highlights NASA's efforts to implement NDE methods to certifying the integrity of the Shuttle's wing leading edge RCC system. Three NDE methods have been investigated and developed for use on the RCC material. The methods are advanced thermography, eddy current, ultrasound, and computed tomography. Thermography is used to provide the first inspection step for the RCC panels in part because of its speed, the fact that it is one sided, non-contacting, can be easily implement in the Shuttle's servicing environment, and it detects the critical flaws of interest. Advanced eddy current and ultrasonic methods are used to better define any concerns identified by thermography. Finally advanced computed tomography testing can be used further define a panel's integrity. Although CT has excellent imaging capabilities, it does require the removal of an RCC panel, which is very invasive, so that CT is a last line of defense in the qualification process.

In addition to the ground based NDE support system developments, NASA has implemented, after an extensive set of impact related tests, an impact detection system for the Shuttle's wing leading edge. The impact testing has covered a large number of parameters related to an impactor's size, shape, material, velocity, and angle of impact. The tests have covered the wide range of structures and materials that represent the Shuttle. It is hoped that this orbiter flight system will be able to help alert Shuttle managers to critical flight safety problems prior to reentry and to possibly mitigate the need for a visual launch constraint that currently limits launch times to daytime only.

References

[1]Gehman, H., Adm. USN, Chairman, Columbia Accident Investigation Boar Report, v3, US Gov. Printing Office document no. 033-000-01260-8, Aug. 2003.