Volume III

Appendix E.3

An Assessment of Potential Material Candidates for the "Flight Day 2" Radar Object Observed during the NASA Mission STS-107

This Appendix contains the Air force Research Laboratory Technical Note, AFRL-SNS-2003-001, An Assessment of Potential Material Candidates for the "Flight Day 2" Radar Object Observed During the NASA STS-107 (*Columbia*), Final Summary Report, 20 July 2003.

Air Force Research Laboratory
Technical Note
AFRL-SNS-2003-001

An Assessment of Potential Material Candidates
for the "Flight Day 2" Radar Object Observed
During the NASA Mission STS-107 (Columbia)

Final Summary Report

20 July 2003

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Report Documentation Page

This report describes the results of an investigative analysis performed by the Air Force Research Laboratory Sensors Directorate at the specific request of the Defense Columbia Investigation Support Team (DCIST) who was supporting the Columbia Accident Investigation Board (CAIB). The work was performed during the period February 20, 2003 through 20 July 2003. An interim release of measurement findings was provided the CAIB on 24 April 2003, and the information was released in public testimony to the CAIB on May 6, 2003 at the Hilton Hotel, Houston, Texas. The overall assessment and conclusions of this report are consistent with the CAIB 6 May 2003 testimony, with one notable exception discussed in Section VI.

This report has been reviewed by the AFRL/SN "Flight Day Two" DCIST appointed assessment team, and is hereby released to the CAIB and DCIST for final disposition.

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Acknowledgements

The author wishes to recognize the many collaborators and co-workers on this project, without whose help this task would not have been successfully completed. First, I would like to thank AFRL co-workers Mr. Dan Turner and Mr. William Brandewie. Mr. Turner skillfully scheduled all radar signature testing of the various radar objects in AFRL's advanced compact range, and wrote up many of the test reports. Mr. Bill Brandewie is commended for his role in arranging the shipping, receiving, and disposition of the many NASA parts tested throughout this project, including flight qualified assets that needed extremely careful handling and shipping. AFRL Co-workers Dr. Kueichien C. Hill and Captain John Gulick are credited for their in-depth assessment of the UHF RCS of the Tee-Seal, and are the primary authors of Appendix I. Next, the author recognizes the efforts of Mission Research Corporation employees Mr. Bill Forster, Mr. Christopher Clark, Mr. Frank Fails, and Mr. Travis Mensen. These collaborative on-site contractors supported over 1,000 hours of range testing during the months of March through May of 2003, and their crucial data was the key in narrowing the mystery of the flight day two object. Mr. William Griffin of MRC is credited with the creation of the geometry files through laser collections for the Tee-seal 21 RCS calculations. Next, the author wishes to recognize Mr. Robert Morris and Mr. Taft Devere of US STRATCOM, Peterson AFB, CO, who thoroughly assessed the "area-to-mass" ballistic coefficients for the flight day 2 assessment. Last, I am deeply indebted to Mr. Steve Rickman, NASA's Chief of the Thermal Design Branch, Johnson Space Center. Mr. Rickman tirelessly educated me about the composition and location of the myriad of materials on the Shuttle, obtained representative samples of each, and greatly assisted in coordinating NASA's support of radar signature testing. This assignment would not have been accomplished without your collective assistance, and I am professionally indebted to all of you for your tireless help and support.

Finally, I wish to recognize working members of the Columbia Accident Investigation Board who moved mountains and enabled unparallel access to the NASA Orbiter flight worthy materials, as well as access to the debris recovery hanger at Kennedy Space Center. The author specifically recognizes USAF officers Lt Colonel Pat Goodman and 1Lt Steve Clark. Finally, I would like to add my thanks for the time, attention, and commitment of Major General John Barry who provided our team with everything we needed to successfully complete this assignment. On behalf of all members of the technical community involved with this effort, we salute the professionalism and commitment of the CAIB board members who have dedicated their time and talents to identify the root causes of this most unfortunate national tragedy.

Brian M. Kent
11 June 03

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Section I - Introduction and Background on the STS-107 (Columbia) "Flight Day 2" Object

On February 1, 2003, The National Aeronautics and Space Administration (NASA) Manned Mission STS-107 (Columbia) tragically ended when the Orbiter broke up upon reentering the atmosphere, killing the entire crew. The Columbia Accident Investigation Board (CAIB) was established to launch and execute a thorough and exhaustive investigation to establish the likely root cause of the accident, and to make recommendations to prevent a reoccurrence in the future.

Within a few days of the accident, NASA requested the United States Air Force (US STRATCOM) to carefully review the automated track records from the US space tracking network during the period the Columbia was in orbit on mission STS-107. US STRATCOM operates a very sophisticated network of radar systems to track nearly every know piece of space debris and satellite in orbit around the earth. Most objects tracked include known artificial satellites as well as various pieces of debris leftover from nearly 50 years of launching objects from earth into space. These radar systems have the necessary angular coverage and sensitivity to track even small objects in orbit around the earth. The CAIB wanted to know if this network detected and tracked any unusual radar events related to the STS-107 mission.

Within a few weeks of being tasked, an exhaustive analysis by US STRATCOM reported back that a new space object designated "2003-003B" was detected in orbit on January 17^{th}, 18^{th}, and 19^{th}, 2003. The object had confirmed tracks by the PAVE PAWS UHF Phased array tracking radar at Beale Air Force on January 17^{th}, as well as the Cape Cod PAVE PAWS UHF Phased array radar on the January 17^{th}, 18^{th}, and 19^{th}. In addition, other fragmentary VHF radar track files were recovered from Eglin AFB, Florida and the Kwajelien Atoll "Altair" radar. The collective tracking information from these radars was used by US STRATCOM to re-construct the orbit of object "2003-003B". When the orbit was traced backward in time from its measured orbital parameters, the resultant object orbit merged precisely with the orbit of STS-107 in the mid- to late-afternoon of STS-107 flight day 2 on 17 January 2003. Figure 1 shows the tracked orbit of object "2003-003B" and where in time it appears to originate from the Shuttle.

Though the part was never visually "observed departing the Shuttle", the radar data unequivocally shows the object originated from the Shuttle on the 17^{th} of January, and departed the Shuttle at a very low exit velocity of under 1 meter per second. In addition, the radars tracked the object until it reentered the atmosphere approximately 60 hours after it originated from the Shuttle and the object was subsequently destroyed on re-entry. In order to simplify nomenclature, from this point forward, the author will refer to object "2003-003B" simply as the "flight day 2 object", or FD2 for short.

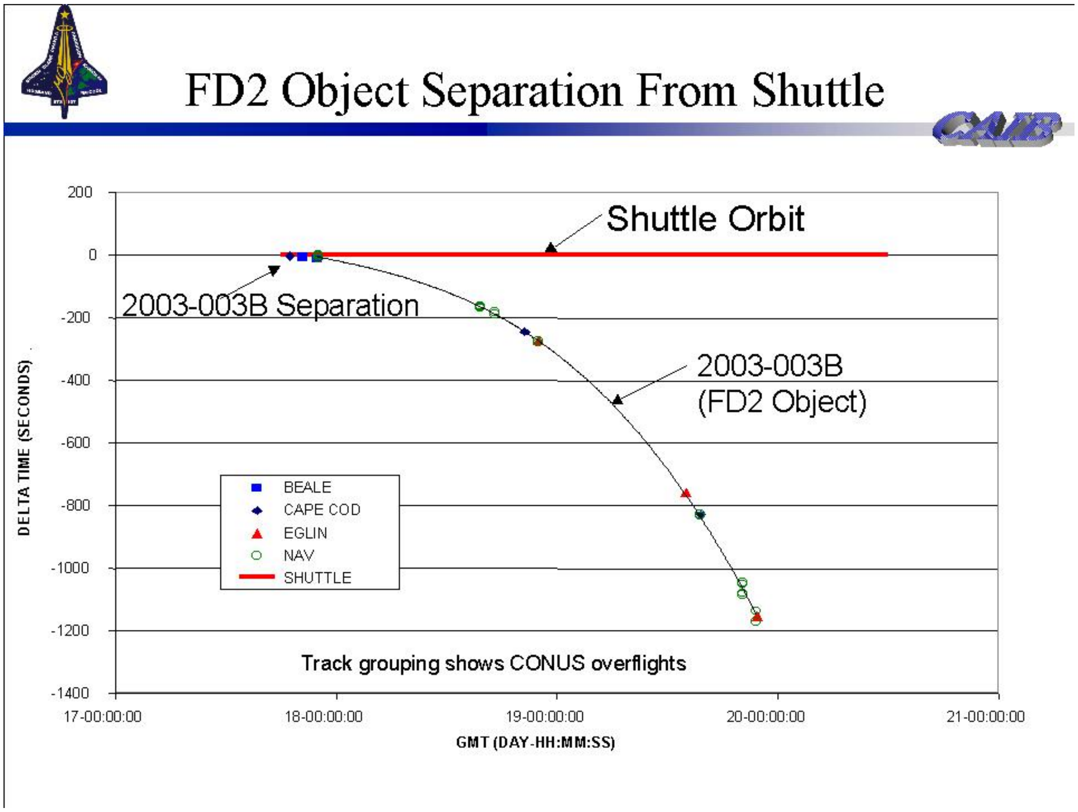

Figure 1 – Flight Day 2 (FD2) Object Orbit Relative to Shuttle

Many questions obviously arose after this discovery. How did the FD2 object come to separate from the Columbia in the first place? Did some "on-orbit" hypervelocity event dislodge a piece of material, or did the piece dislodge after some earlier event as the Orbiter was propelled into orbit? Was it possible to identify the make-up of the FD2 piece?

Although these questions are all related to the FD2 piece, this report solely concentrates on the third question, namely would it be possible to identify the origin and nature of the FD2 piece. The other aspects of what could have caused the FD2 piece to depart the Shuttle in the first place is the subject of an entire separate investigative team lead by NASA-JSC, and will not be discussed further. However, I will point out that the Orbiter made 2 minor and benign attitude changes using the 25 lb vernier jets on flight day 2. The Orbiter, oriented in a bay-to-earth, tail on velocity vector orientation, maneuvered to a biased starboard wing on velocity attitude at mission elapsed time (MET) 23 hours and 7 minutes and returned to the bay-to-earth, tail on velocity vector attitude at MET 23 hours and 42 minutes. There were no other maneuvers performed in approximately sixteen hours prior to this maneuver nor were there any additional maneuvers performed until approximately one day after. While it cannot be confirmed, it is possible that this maneuver imparted the departure velocity to the FD2 object.

From this point forward, this report will concentrate on establishing a methodology for identifying candidates for the FD2 object, and to use engineering tests and data to reduce the potential candidates for the FD2 object to the smallest number feasible based on observed on orbit data as well as follow-on ground test data.

Section II - Measured Radar and Ballistic Properties of the "Flight Day 2" Object

Since the FD2 object burned up upon re-entering the atmosphere, it obviously could not be physically recovered. Without physical evidence, unequivocally identifying the FD2 object appears initially to be an intractable problem. However, the CAIB suggested that any information provided that *eliminated* potential material candidates was nearly as valuable as knowing precisely what the object was. Based on this direction, the team devised a methodology for eliminating candidates from consideration. The basis for eliminating candidates relied very much on knowing certain physical properties of the FD2 object, and measuring those properties for various candidate materials to methodically eliminate possibilities. Before describing this process, however, we need to know precisely what is known, with high certainty, about the FD2 object.

As mentioned earlier, US STRATCOM radars were able to track the FD2 object on three separate days from 17-19 January 2003 (Figure 1) and in the process were able to measure a physical property of the object called the "radar signature" or "radar cross section (RCS)". The RCS of an object is a property that relates how much incident radar energy is reflected from an object or target. The RCS is a complex function that depends on the SIZE, SHAPE, and MATERIAL COMPOSITION of the object in question, as well as the operating FREQUENCY of the radar and the ANGLE or orientation of the object relative to the observing radar. RCS is usually expressed in either square meters (m^2) or in decibels per square meter (dBsm), and is represented by the Greek lower case letter sigma (σ). The relationship between RCS in dBsm and RCS in m^2 are shown in Equation 1 below.

$$RCS(dBsm) = 10Log\{(\sigma)m^2\} \qquad (1)$$

The radar frequency is a known quantity, as both the Beale and Cape Cod PAVE PAWS radar systems operate at a frequency of 433 Megahertz (MHz). For those who think in radar "wavelengths" instead of frequency, this represents a radar wavelength of 69.28 cm (27.28 in). The FD2 object appeared to tumble in space, resulting in a time varying RCS value whose rotation rate gradually increased over the three days it was tracked on orbit prior to re-entering the atmosphere. On-orbit RCS data from the 17^{th} – 19^{th} of January showed the unknown object's RCS varied between –1.0 and –20 dBsm with a confidence level of +/-1.3 dB. The object appeared to be initially tumbling approximately once a minute on the 17^{th}, increasing to once every 3 seconds by January 19^{th}. It is thought aerodynamic drag caused the object to increase its tumble rate with time, and this increased tumble phenomena was extensively studied and reported by another investigative team from Lincoln Laboratory and will not be discussed further here. The main point to understand is that the object's RCS variation (a measured physical property) at the radar frequency of 433 MHz is known over a tumble period, and this important physical property is essential to screen potential candidates for the flight day 2 object.

In addition to the RCS information, the various US STRATCOM space tracking radars also provided another very important piece of information. From the orbital decay parameters measured from the FD2 trajectory, US STRATCOM was able to quantify the object's "ballistic coefficient" or "B-Term" for short. The B-Term is a physical property related to the object's area to mass ratio, and is expressed in metric units as meters squared per kilogram or m^2/kg. In the case of the FD2 object, US STRATCOM calculated the FD2 object's B-Term as 0.1 m^2/kg +/- 15%.

Therefore, there were now two physical quantities known for the FD2 object; its RCS at the UHF frequency of 433 MHz was known to lie between –1.0 and –20 dBsm and its B-term was known to be 0.1 m^2/kg. Armed with this information, a joint team drawn from NASA-JSC, US STRATCOM, and the Air Force Research Laboratory (AFRL) was formed. NASA-JSC identified potential Shuttle Orbiter material candidates to examine. US STRATCOM evaluated those candidates by calculating the B-term for each candidate, and AFRL's Sensor's Directorate measured, in a controlled ground test environment, the RCS of the various candidate objects. In parallel, another small team performed a computational UHF RCS assessment of various reinforced carbon-carbon tee-seals and tee-seal fragments, in order to narrow down possible variants of tee-seal fragments. It was hoped that the information gleaned from these tests could provide insight into the nature of the FD2 object.

Section III - Brief Description of STS-107 External Orbiter Materials

If one agrees with the scenario that the FD2 object originated from the Orbiter, it is possible to quickly identify candidate Orbiter materials to study. Since we have no insight at this point on the origin of the material, the process of elimination begins with all known and reasonable Orbiter candidate materials. For those not intimately familiar with the composition of the Shuttle Orbiter, this section will briefly list the materials one finds on the exterior surface of the Shuttle, as well as materials that could originate from the payload bay while on orbit.

In the most general sense, the Shuttle Orbiter consists of two general classes of materials. The first class is the "Thermal Protection System or "TPS". These materials compose the largest share of the exterior of the Orbiter, and are responsible for protecting the Orbiter during the searing heat of re-entry. The second class of materials makes up the "Thermal Control System" or "TCS" materials. These materials protect elements of the payload bay, payload bay interior, and various experiments that may be present in the Orbiter payload bay while on orbit. Since the Orbiter essentially goes through an entire day/night cycle in a roughly 90 minute period, the TPS and TCS materials must survive the several hundred degree change in temperature in space from full sun to full shadow.

First, let's describe the Thermal Protection System or TPS materials. Figure 2 below shows a schematic of the materials composing the TPS system. Clearly from Figure 2, the silica-based tiles make up a large majority of the Shuttle exterior real estate. The Shuttle tiles come in a variety of densities, 9 lb/ft^2, 12 lb/ft^2, and 22 lb/ft^2, respectively. These are referred to as LI900, FRCI 12, and LI2200. Additionally, there are a very small number of 8 lb/ft^2 tiles (AETB 8) on the base heat shield near the main engines. With the exception of the Reinforced Carbon-Carbon (RCC) edges, the tiles cover most of the lower half of the delta wing structure. Since the Shuttle re-enters the atmosphere at high angles of attack, the majority of the upper surface of the Orbiter sees far lower temperatures than the lower tiles and leading RCC edges. In these areas, blanket insulations such as Advanced Flexible Reusable Surface Insulation (AFRSI) and Flexible Reusable Surface Insulation (FRSI) are used. Closeout of the RCC panel attach regions is accomplished using "carrier panels". There is a row of "carrier panels" just beyond the RCC edges on both the top side and bottom side of the edges. These are referred to as "upper carrier panels" and "lower carrier panels". Carrier panels consist of either 3 or 4 high density LI2200 tiles bonded onto Nomex felt, and subsequently, aluminum structure using Room Temperature Vulcanizing (RTV) adhesive. Each carrier panel, in turn, is bolted onto the Orbiter using two attach bolts. A "horse collar" seal, comprised of Inconel over Nextel fabric, is used to preclude the flow of hot gases into the wing leading edge cavity.

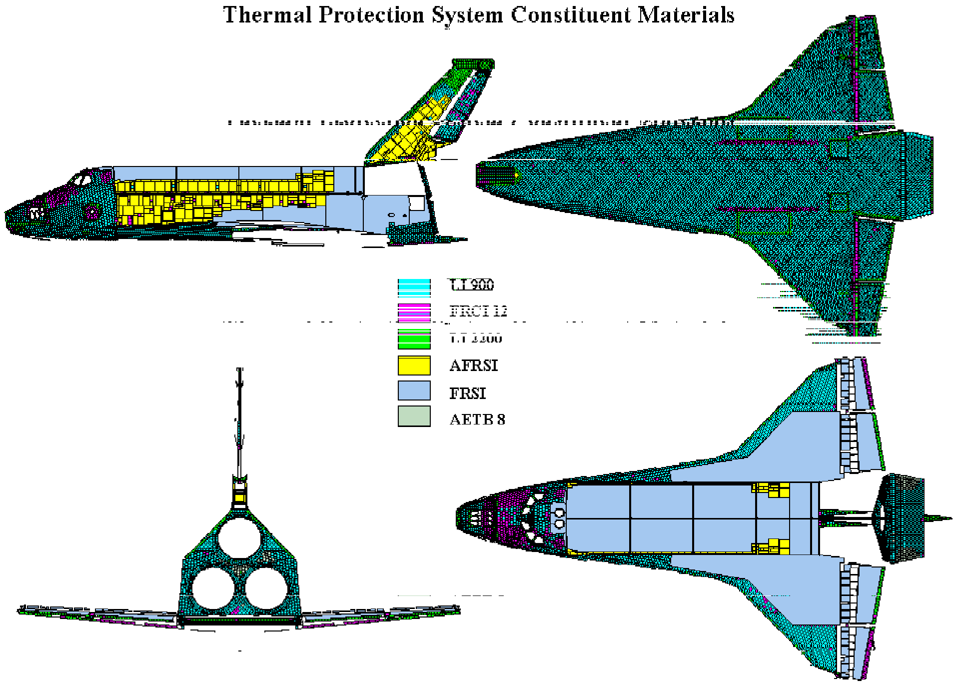

Figure 2 – Thermal Protection System on the Orbiter Exterior

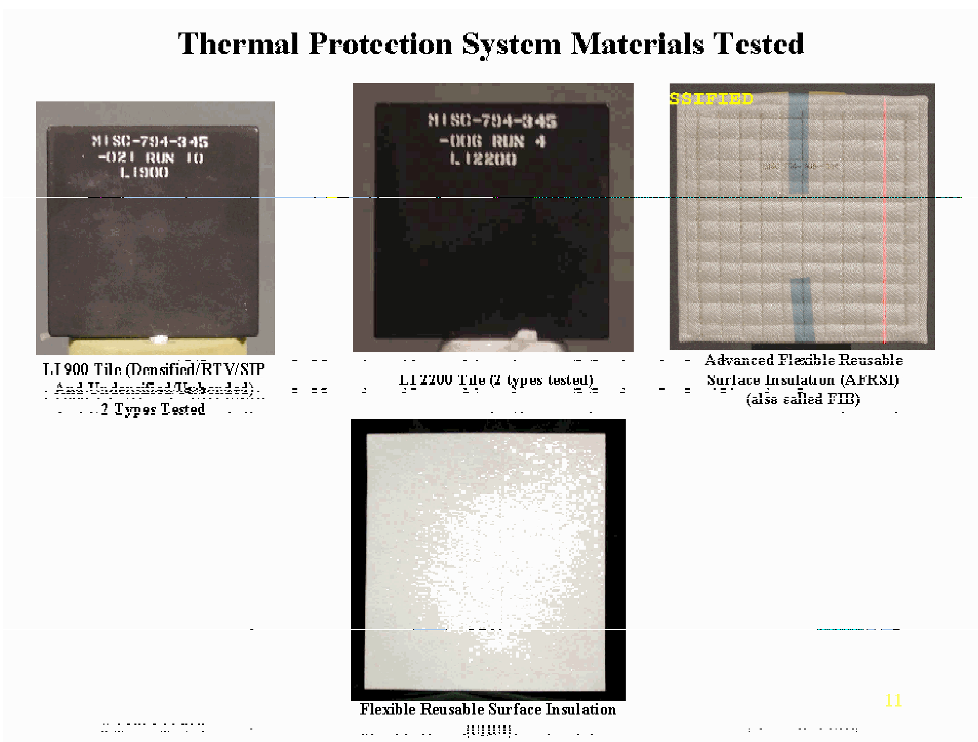

Figure 3 – Shuttle TPS Materials LI900, LI2200, AFRSI, and FRSI

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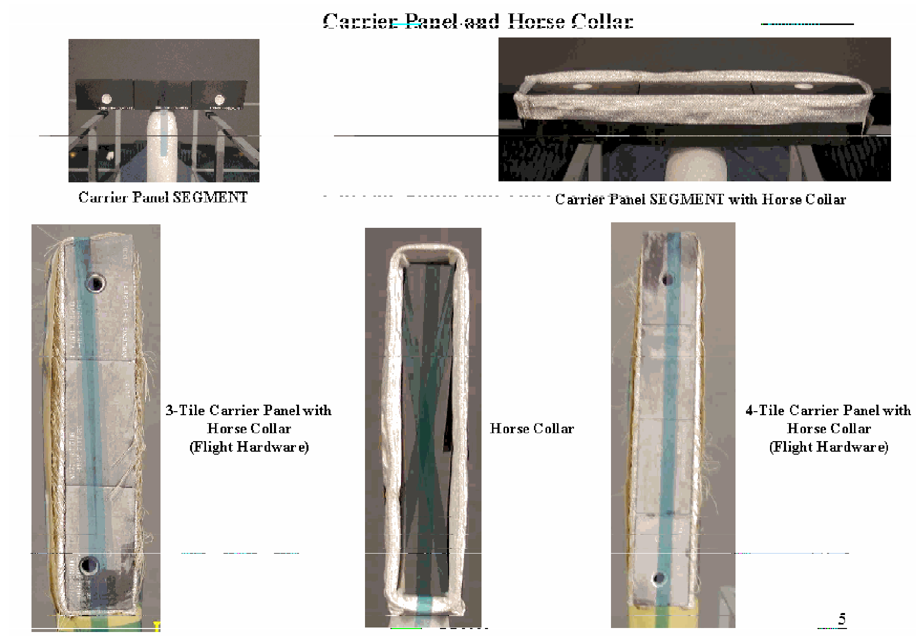


Figure 4 – Shuttle TPS Materials Including a Lower Carrier Panel, Horse Collar, and Carrier Panel with Horse Collar

The reinforced carbon-carbon (RCC) materials consist primarily of leading edge panels with Tee-Seals between adjacent RCC panels. Figure 5 below shows an entire RCC panel with the Tee-Seal clearly visible on the end. The rightmost picture of Figure 5 is the tee seal alone without any edge attached. The center picture is called the Incoflex spanner beam insulation piece, though NASA engineers commonly call it the "ear muff" seal. This insulation is typical of that found in the wing leading edge cavity and is used to protect the structure from high temperatures during reentry. Taken together, Figures 3,4, and 5 comprise the suite of materials of the TPS system.

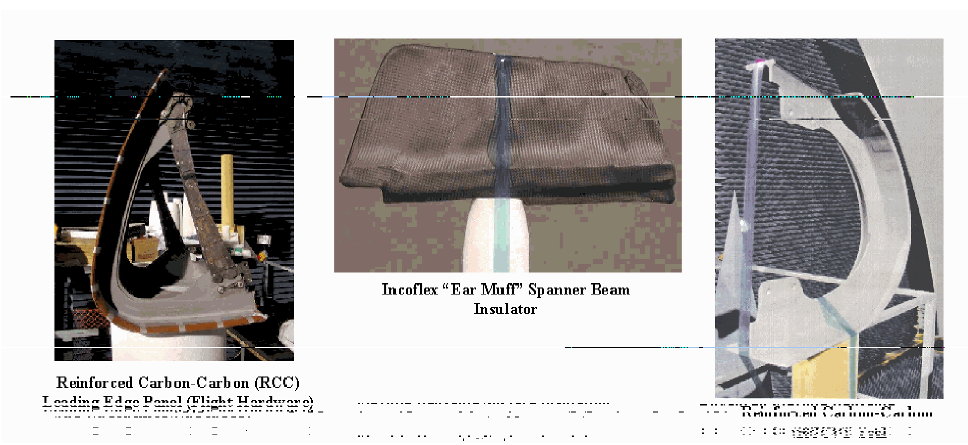
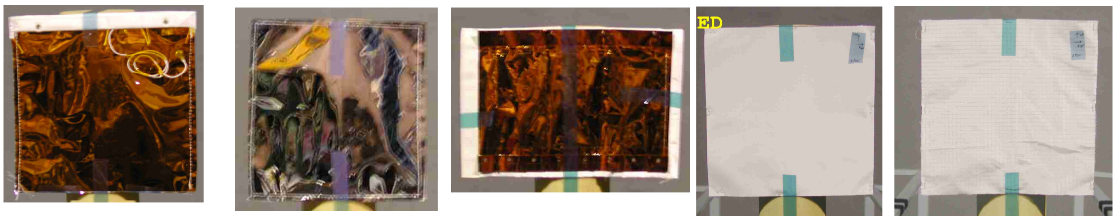


Figure 5 – Elements of the Reinforced Carbon Carbon (RCC) Leading Edge Thermal Protection System (TPS)

Next is the Thermal Control System (TCS) materials. These materials are altogether different from the TPS materials, and primarily reside in the payload bay of the Orbiter. Most are highly reflective (silver or white) and lightweight, as they are not exposed to re-entry heating since the payload bay door is closed during re-entry. Figure 6 depicts samples of multi-layer insulations used on STS 107 payloads in the cargo bay.



Freestar A2 **Freestar B** **Freestar C** **Blanket 1** **Blanket 2**

Figure 6 – Samples of the Orbiter TCS Materials

The "Freestar" samples are all lightweight highly conductive thermal blankets, while the rightmost two are beta cloth covered thermal blankets. Although not shown, we also examined TCS components consisting of plain beta cloth with and without its ground wire quilting. Orbiter TCS materials are shown in Figure 7, which also includes a common tool, used to snap the thermal blankets in place or to one another. Looking at these materials, one quickly comes to the realization that most look very much like a metal conducting plate from a radar signature standpoint. This meant the blankets were relatively easy to evaluate in the laboratory.

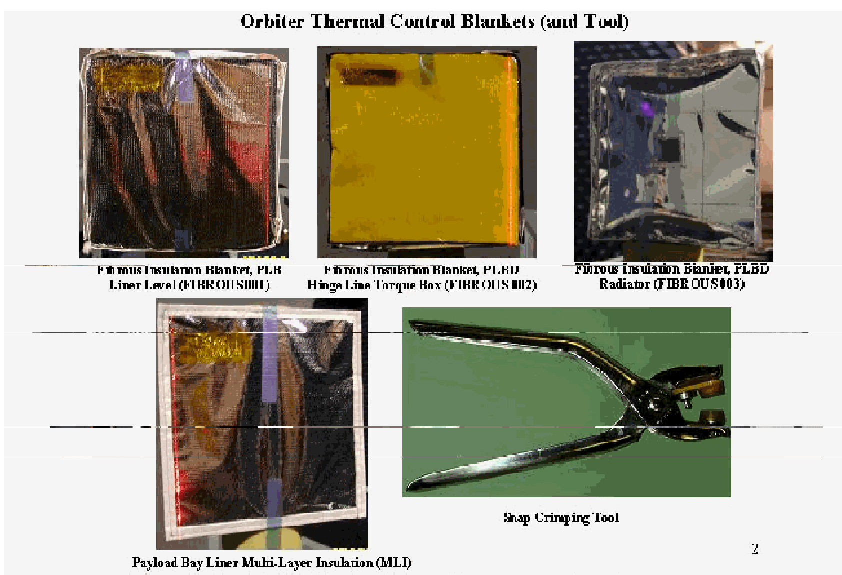


Figure 7 – Orbiter TCS samples including metalized insulation blankets and a typical "crimping" tool

In all, NASA ultimately identified 31 distinct material samples to assess their potential to match the known characteristics of the FD2 object. In addition, several specialized items were postulated as possibilities for the FD2 object, including various tools that could conceivably have been left in or "lost" in Columbia's payload bay during one of its normal pre-flight maintenance period. Although NASA attempted an in-depth 2-year audit of missing tools in any facility used by Columbia up to its final STS-107 mission, the handful of tools that came up as "unaccounted for" were not likely matches for the physical and radar characteristics of the FD2 object, and therefore were not pursued further by this team. [Note that there was no evidence provided to the WPAFB FD2 team that any of these lost tools were likely in the Columbia payload bay, though it is impossible to totally discount the possibility that some tool or part was left in the payload bay unknown to all.] Having identified candidates, the next step was devising a scheme for assessing the potential FD2 candidates.

Section IV - "Flight Day 2" Candidate Elimination Process

Having exhaustively examined the exterior of the Shuttle Orbiter and payload bay in depth, NASA-JSC identified 31 different potential candidate materials and/or exterior parts to assess for potential as the FD2 object. The next step was to come up with a systematic method for examining these candidates in the context of the known physical properties of the FD2 object. It is emphasized that the nature of the physical information available about the FD2 object requires that exclusionary logic must be applied to eliminate potential candidates.

The process for excluding potential FD2 candidates involved three separate test conditions:

(1) The measured Circular Polarization (CP) UHF RCS of the candidate object had to equal or exceed –1 dBsm over some angular coverage of target orientations, within the stated measured on-orbit uncertainty of +/- 1.3 dB at the measured frequency of 433 MHz. Note that the uncertainty values were obtained based on a fairly extensive set of on-orbit RCS calibration measurements performed by both the Beale AFB and Cape Cod PAVE PAWS radar. In addition, common sense dictates that the maximum value of RCS needs to occur over a fairly broad set of angles relative to the target orientation, since the FD2 part tumbled in space and therefore presented a somewhat random orientation relative to the radar. Fortunately, since the radar wavelength is fairly long (27.28 inches), and since many of the parts examined are shorter than the radar wavelength, their scattering behavior exhibits the large angular coverage that makes the alignment between the tumbling FD2 piece and the radar line of sight less problematic.

(2) The calculated ballistic coefficient or "B-term", based strictly on the geometry and aeronautical drag coefficients of the candidate parts, must fall within 15% of the measured FD2 value of 0.1 m^2/kg.

(3) The candidate part is not refuted by the forensic evidence recovered from the Columbia debris field. For instance, if an item appears in the debris, it can't possibly be the FD2 object, since the FD2 object burned up on re-entry. Another example may be a part that might match the B-term and RCS data, but which mechanically is excluded from having come off the Orbiter for other reasons.

Therefore the approach taken for each candidate material was to perform the requisite RCS test and/or B-Term analysis to assess the viability of the candidate in question. Early on in this process, the B-Term analysis and RCS testing occurred in parallel, meaning US STRATCOM and AFRL conducted their analysis nearly simultaneously in time, in order to produce the results as quickly as possible. As both organizations refined their approaches, and as new material candidates emerged, the team shifted to a "serial" test hypothesis approach, meaning we would evaluate potential candidates for "B-term" compliance first, and then perform the more expensive and extensive UHF RCS tests on the successful B-term candidates only, rather than perform RCS tests on every piece imaginable. This "serial" approach helped reduce the needed UHF RCS test time to down-select candidates from potentially many thousands of test hours to about a thousand test hours. In addition, this assessment approach freed up AFRL RCS range time that NASA requested for higher frequency RCS testing needed by the CAIB and DCIST for other purposes. Specifically, NASA requested extensive AFRL RCS measurement support for L-Band (1.2-1.4 GHz), S-band (2.7-2.9 GHz), and C-Band (5.6-5.7 GHz) to assess the Shuttle ascent debris shedding analysis (C-Band) as well as the NASA Early Sighting and Assessment team (ESAT) at L and S bands. Both of these efforts were focused on debris recovery efforts. None of the L, S, and C band RCS data and information was necessary or relevant to the FD2 assessment, and won't be reported here as it has been extensively documented in other NASA technical reports related to the Columbia investigation. [1,2]

At this point, a brief "top level" technical description of the specific technical down selection approaches is in order. Let's begin with the B-Term analysis performed by Mr. Robert Morris and Taft Devere of US STRATCOM. Given the plotted trajectory of the FD2 piece, and information on the state of the atmosphere at about the time of the FD2 event, Mr. Morris and analysts from US STRATCOM oriented the candidate parts in one of two orientations hereafter referred to as pure "spin" and "tumble". The "spin" axis refers to rotation about the shortest axis (dimension) through the part's center of mass, while the "tumble" referred to rotation about the longest axis (dimension) through the part's center of mass. For example, if the part was an ordinary writing "pencil", pure "spin" would refer to rotation of the pencil about an axis along the length of the pencil including the center pencil lead, while pure "tumble" would refer to rotation of the pencil "end over end" point to eraser. Naturally, a part tumbling in space would likely consist of some element of both rotational planes, so any number of states between pure "spin" and pure "tumble" are possible. However, for simplicity US STRATCOM concentrated on the pure "spin" and pure "tumble" cases as bounding the possible complex tumble state in space.

Once the part geometry is known, and its center of aerodynamic mass is identified based on the part geometry, a very complex model of the atmosphere is used to estimate the density of the very sparse atmosphere encountered by the part as it proceeds in low earth orbit. It is a highly sophisticated computational model, which has been used for many years by US STRATCOM to predict orbital dynamics of satellites and debris in low earth orbit. Using this model to help establish estimates for the coefficient of drag, the candidate part's B-term or area/mass ratio is computed for the spin and tumble orientation. (In some candidate cases, B-term calculations are only done in the tumble orientation, since the spin axis is very short and is very unlikely to occur. For instance, the B-term of flat square pieces were only calculated in the tumble axis.)

The second down selection criteria is the UHF RCS test properties. Numerically modeling the UHF RCS for a complex body with non-metallic properties is an extremely difficult RCS computational problem. In fact, in the area of computational electromagnetics, it is the most complex problem being studied by electromagnetic specialists today. Though it is possible to get reasonably accurate RCS predictions for simple flat conducting shapes (like flat metallic plates) or for simple bodies of revolutions (like spheres or cylinders), more complex parts like RCC edges, spanner beam insulation pieces, and RCC Tee-seal represent a far more difficult RCS prediction problem. Though attempts to model a few isolated cased with RCS predictions were reasonably successful (See for instance the Tee-seal RCS calculations in Appendix I), the team decided that the most accurate and fastest way to complete the RCS assessments for the myriad of other complex parts were through direct RCS measurements performed in a very controlled ground based RCS measurement environment. Fortunately, the Air Force Research Laboratory in Dayton Ohio had precisely the facility needed to perform the required UHF RCS measurements, namely the Advanced Compact RCS range or ACR.

The AFRL ACR is a large laboratory room of lined with radar absorbing or "anechoic" material. The large anechoic main chamber room is 65 ft wide, 45 ft high, and 96 feet long. The room is dominated by a "dual reflector" compact range reflector system, shown below in Figure 8. Only the main reflector is shown in the large chamber, as the feed antennas and sub-reflector are located in a smaller anechoic room below the main chamber. Much like the optics in a telescope, the dual reflector system converts the spherical wave originating from the feed antenna into what is called a "plane wave" in radar terminology. A "plane wave" is an electromagnetic wave whose amplitude and phase properties are nearly constant in a plane sliced perpendicular to the direction of propagation. As a result, the advanced compact range very accurately simulates the very large separation that normally occurs between the source radar and the target under test. In technical terms, we say that the compact range simulates the "far field" conditions from an electromagnetics standpoint. Since the FD2 object was 300-1200 km away from the radars at points through its orbit, the FD2 was considered to be in the "far field" of the earth based radars. Therefore, the ACR accurately simulates these conditions.

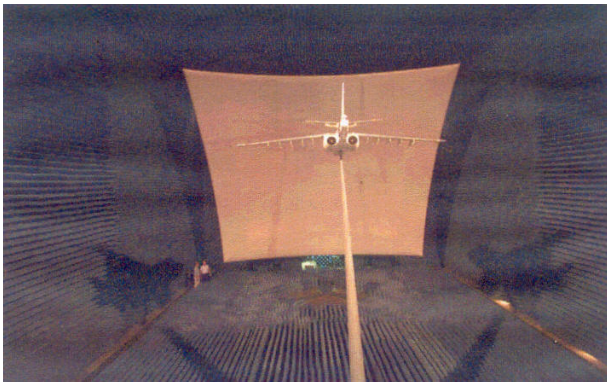


Figure 8 – The AFRL Advanced Compact RCS Measurement Range (ACR)
(This test facility is located at Wright-Patterson AFB, Ohio)

In order to support the targets under test, AFRL uses very low radar cross section mounting structure. This consists of a tilted metallic wing-like structure referred to as a target support "pylon". Since most of the pieces in this assessment were fairly light (the largest was well under 20 kilograms, and some as light as 0.5 kg), we use a lightweight foam cylinder to support the test objects. Figure 9 shows one of the very lightweight space thermal blankets held in place for RCS testing. Note that the tiny RCS contribution due to the mounts can be coherently subtracted out of the RCS test so that they do not contribute measurably to indoor RCS measurement uncertainty. The steel platform that surrounds the sample in Figure 9 is the target placement work platform, which is

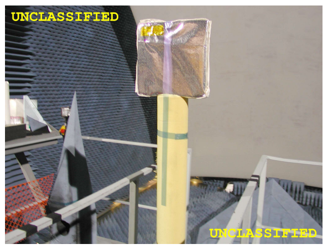


Figure 9 –Thermal Blanket on Low RCS Support at the AFRL Compact Range.

removed from the facility during the actual RCS measurement. The sample, as mounted in the range, can be seen in Figure 10 below. For scale purposes, the sample in Figure 10 is roughly 30 cm (12 inches) on a side. The reflector is 19 m forward, and its dimensions are roughly 14 m x 14 m.

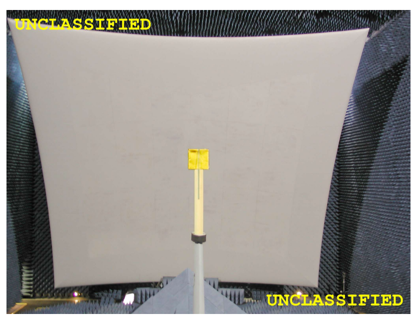


Figure 10 – ML-004 TPS Blanket in the AFRL ACR for UHF RCS Testing

There is one other aspect of the radar testing worth mentioning. The earth based radar systems transmit an electrical field whose orientation constantly revolves with time perpendicular to the axis of propagation. This is technically referred to as "circular polarization", and used by space based and weather radars because of its superior ability to penetrate clouds and rain. Although RCS is not a function of weather and rain, it is a function of the orientation of the electric field. In the AFRL ACR, we measured the two linear polarizations, horizontal (or HH) and vertical (or VV). We then combined these results mathematically respectively to re-create the equivalent on-orbit circular polarization (CP) results. (The PAVE PAWS results previously mentioned in earlier sections report CP RCS results.) The "linear to CP" conversion routine was tested theoretically and experimentally with a known 12 inch by 12 inch flat metallic plate, and is shown in Figure 11. The green trace shows the UHF RCS for HH polarization, the red trace for VV polarization, and the blue trace show the results for circular polarization.

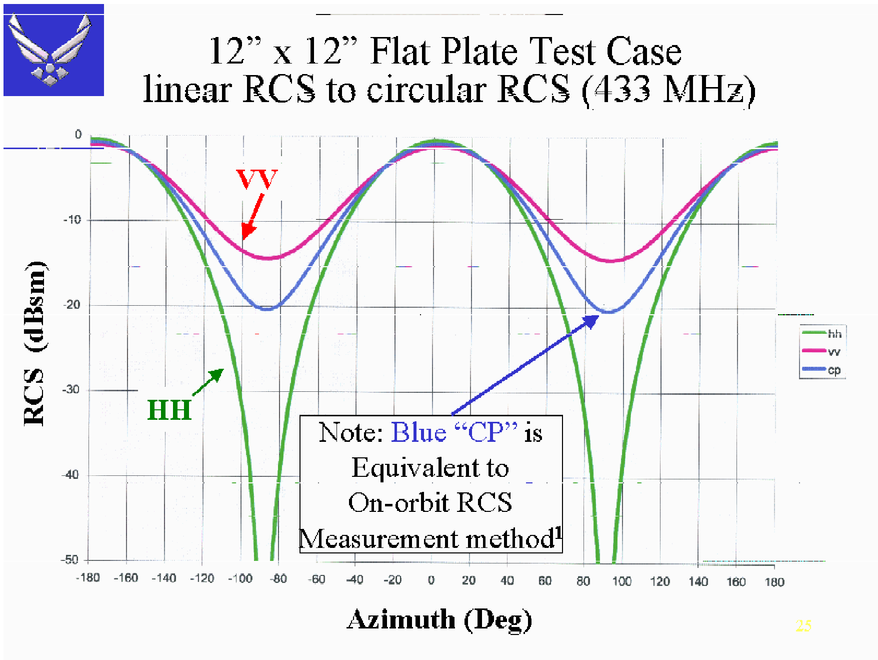


Figure 11 – Linear and Circular Polarization UHF RCS Results for a Simple 12" by 12" Flat Metallic Plate

This leads me to the final comment about this section. Of the 31 items identified by NASA for consideration in the FD2 identification process, some of these items had very simple geometries and others had very complex geometries. In the simple cases, notably the flat plate-like samples, we only needed to mount the test article once and rotate the object 360 degree off a single axis. We chose orientations we were reasonably certain would present the minimum and maximum RCS to the direction of the radar. For the complex targets like the carrier panels, spanner beam insulation pieces, and RCC tee seal and edge samples, we mounted the device in up to three different "near orthogonal" orientations. (Because of the complex shapes, precise 3 axis orthogonal mounts were impractical and unnecessary). We chose the three axes to present the minimum and maximum RCS in the various rotational planes. When you added the multiple configuration mounts to the 31 materials considered, we reported over 40 different target mount results. Therefore, the reader should not get confused when more RCS "results" are reported than candidate materials, since several candidates were measured in several orientations.

Before we move into the final down selection process, it would be appropriate to use some of the actual UHF RCS measurements to illustrate our down selection process in detail. Figure 12 shows the measured linear and CP UHF RCS results for the AFRSI example. The sample plot shows the item tested photographically, the actual linear and circular RCS data, and a square "box" that represents the range of the on-orbit RCS measurements of the FD2 object. Remember, in this data display, the RCS in blue must exceed or "break" the top of the observed on-orbit RCS limits to be a viable candidate. RCS values that are several decibels below the peak are not viable candidates for the FD2 object. Since this is a decibel scale, it is clear that the RCS of AFRSI is 2 or more orders of magnitude too small. This object would be quickly rejected as a potential candidate for the FD2 object based solely on the RCS data. If we perform the same measurement of one of the payload bay TCS blankets, namely MLI-004, the UHF RCS results are shown in Figure 13. Based solely on RCS test results alone, one would have to consider the MLI-004 a very viable candidate for the FD2 piece.

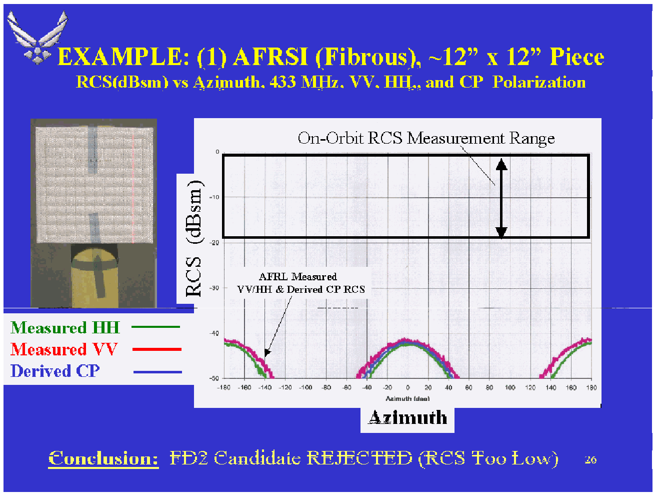


Figure 12 – AFRSI CP UHF RCS Measurement of a 12" by 12" Sample

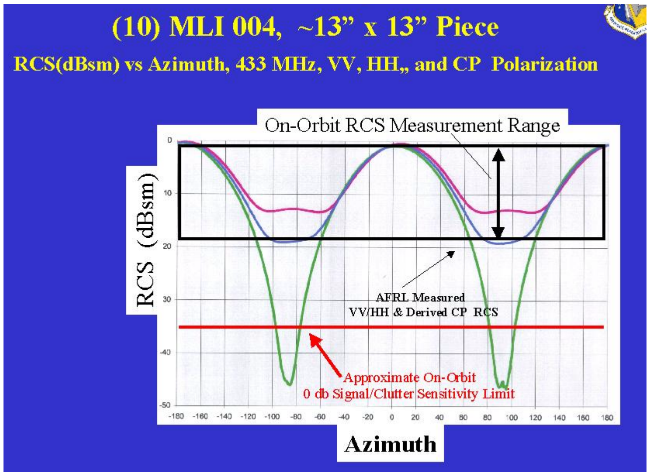


Figure 13 – MLI-004 TPS UHF RCS Measurement of a 13" by 13" Sample

Looking at the results of Figures 12 and 13 the RCS test and elimination process looks fairly straightforward. When we combine our knowledge of the ballistic coefficient or "B-term" for these cases, the situation becomes much clearer. A "B-term" analysis shows the MLI-004 (and other similar thermal blankets of the TPS system) are a factor of 7 or more too light to exhibit the B-term properties of the FD2 object. The MLI-004 object above, for instance, was rejected as a FD2 candidate based on the exclusionary B-term analysis. The AFRSI blanket failed both the "B-term" test, and the RCS test, and therefore was also rejected as the FD2 candidate. In a similar fashion, the team methodically proceeded through all the configurations and materials NASA identified as potential candidates.

Section V - Best Assessment of the Flight Day 2 Object Composition

Since the nature of this report is to produce an overall description and working summary of the results, the readers will be spared a detailed description of every B-term calculation and UHF RCS measurement performed under this study. The interested reader can refer to our originally reported UHF RCS results on the CAIB web site at WWW.CAIB.us, under May 6, 2003 public hearing, to see a complete summary of the UHF test results produced under this effort. At this point, it would be advantageous to create a table summarizing all of the materials screened, and then present relevant RCS and ballistic coefficient data for only those items that survived the dual screening criteria.

Table 1 shows the complete list of candidate materials evaluated by the FD2 assessment process. Glancing over the table, it is evident the RCS tests eliminated 14 of the tested components, while the B-term analysis eliminated 18 candidates. The thermal protective materials making up the TPS system are generally lightweight and are very inefficient scattering devices. Most of the results exhibited exceptionally low RCS, especially the Shuttle thermal tiles, FRSI, and AFRSI materials. Looking over many of the Thermal Control System (TCS) samples, many of them exhibited good RCS levels at UHF frequencies. This should be no surprise since most of the TCS systems consist of metalized Mylar or Kapton, so many of these samples scattered similar to the 12” by 12” flat plate test case presented earlier. However, these classes of objects are very lightweight, so their area to mass “B-term” calculations were far above the observed on-orbit quantity of 0.1 m^2/kg. Figure 14 shows representative values for the area-to mass for some of the components listed in Table 1 as “excluded” under the B-term analysis. Specifically, it is seen that the TCS samples are generally too light to meet the observed B-term value for the FD2 object.

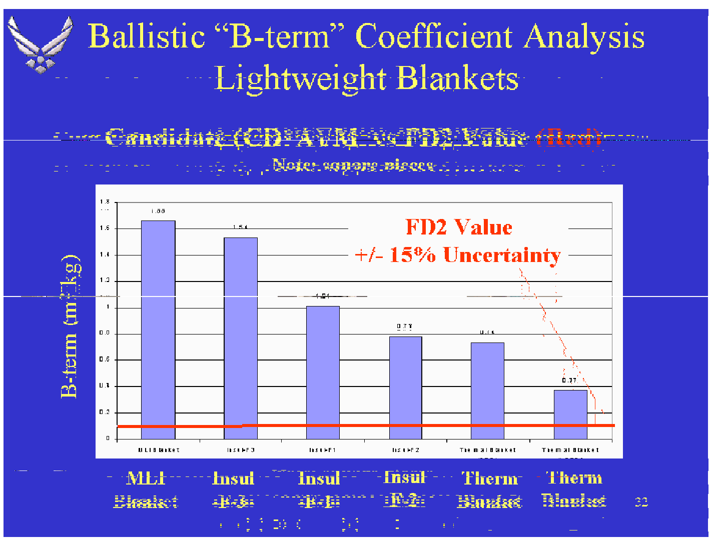


Figure 14 – B-term Calculation for 6 of the TCS Samples
Note that other TCS samples behaved similarly.

Table I - Summary of Ballistic and UFH RCS Results for FD2 Candidate assessments

Test Article	UHF RCS Results	Ballistic "B-term" Results	FD2 Candidate Conclusion	Comments
AFRSI	Excluded	Excluded	Excluded	12" x 12" sample
FRSI	Excluded	Excluded	Excluded	
HRSI LI900	Excluded	Excluded	Excluded	9 lb/ft^3 Shuttle tile
Dense HRSI LI900	Excluded	Excluded	Excluded	9 lb/ft^3 tile densified
HRSI LI2200	Excluded	Not Excluded	Excluded	22 lb/ft^3 Shuttle tile
Fib 001 TPS Blanket	Not Excluded	Excluded	Excluded	
Fib 002 TPS Hinge	Not Excluded	Excluded	Excluded	
Fib 003 TPS Radiator	Not Excluded	Excluded	Excluded	
Beta Cloth, no thread	Excluded	Excluded	Excluded	
Beta Cloth, metal thread	Excluded	Excluded	Excluded	
MLI004 Cargo liner	Not Excluded	Excluded	Excluded	
Freestar panel "A"	Not Excluded	Excluded	Excluded	
Freestar panel "B"	Not Excluded	Excluded	Excluded	
Freestar panel "C"	Not Excluded	Excluded	Excluded	
Freestar panel "Logo"	Excluded	Excluded	Excluded	
TPS Ins. Blanket 1	Not Excluded	Excluded	Excluded	
TPS Ins. Blanket 2	Not Excluded	Excluded	Excluded	
Lower Carrier Panel seg	Excluded	Not Excluded	Excluded	**Without** horse collar
Lower carrier panel seg	Excluded	Not Excluded	Excluded	**With** horse collar
Upper Carrier Panel	Excluded	Not Excluded	Excluded	
RCC Flight Edge Panel	Not Excluded	Excluded	Excluded	All bolts & tee seal
"Ear Muff" TPS Seal	Not Excluded	Not Excluded	Not Excluded	"Spanner beam insulator"
4-Tile lower carrier panel	Excluded	Not Excluded	Excluded	"Flight hardware"
3-Tile lower Carrier Panel	Excluded	Not Excluded	Excluded	"Flight hardware"
RCC Tee Seal (whole, #6-11)	Not Excluded	Excluded	Excluded	
TPS Crimping tool	(Not tested)	Excluded	Excluded	Similar for other tools
These Samples below are representative "Acreage" RCC fragments taken from recovered "right side" pieces				[1]**Note**: RCC acreage pieces must be on the order of 0.33" thick to meet B-term. These occur only in RCC panel areas 8,9,10. See text for complete description
RCC Fragment #51311	Not Excluded	Not excluded[1]	Not excluded[1]	RCC Fragment with lip
RCC Flat acreage #2018	Not Excluded	Not excluded[1]	Not excluded[1]	Locally flat
RCC Fragment #37736	Not Excluded	Not excluded[1]	Not excluded[1]	Large curvature, no lip
Tee Seal Fragment #51313	Excluded	Not excluded	Excluded	~34", no flange or apex

Used together, the RCS and B-Term exclusionary tests eliminated all but 4 items making up 2 different classes of materials. Let's examine each of the candidates that survived the exclusionary tests in detail.

We wish to begin with the "Ear Muff" spanner beam insulation piece. Made of "Inconel", a nickel alloy, with internal Cerachrome batting, the purpose of this piece is to protect the interior aluminum spar from the heat reradiated from the RCC edges into the *interior cavity* of the Shuttle edge. The principle threat is the reradiated IR from the RCC could damage the aluminum spar of the Shuttle if this piece were not present. However, for this piece to come out in orbit, several things would have to happen first. (1) A sufficiently large breech in the RCC would be required so as to allow this piece the opportunity to float out while on orbit. (2) The "ear muff" would have to break free of its four fasteners. This is where the third criteria discussed in Section IV comes into play. There is no forensic evidence to indicate the RCC edge and spanner piece were absent upon re-entry. In fact, forensic evidence indicates most of the RCC edge was originally in place, and chemical analysis performed on some of the recovered debris fragments in the vicinity of left wing RCC panel 8 and 9 show Inconel metal was deposited onto the recovered left wing RCC debris fragments. This reasonably excludes the possibility that the spanner beam insulator was absent, meaning it could not have been the FD2 object.

NASA engineers diligently brainstormed and thought of every lost tool or device that potentially could have been left in the Columbia's payload bay. After all, previous missions had released small, unexpected items from the payload bay into space. Scouring tool records and receipts, over a two year period, the NASA FD2 team assembled a list of about 10 tools/objects that "could have" been left in the payload bay at some time in the past. These included lost screwdrivers, sockets, and hex head Allen wrenches. Using our RCS expertise and the sizes of the tools, we quickly rejected them out of hand because their sizes were not consistent with the sizes necessary to produce the –1 dBsm circular polarization RCS peak observed on orbit. The AFRL team found no postulated tool or device other than those found in Table 1 that could have met the dual criteria for the FD2 object.

As of the CAIB public hearing of May 6, 2003, based on the measured UHF RCS data *available at that time*, AFRL/SN believed the Tee-seals could not be eliminated as a potential candidate for the flight day two object. However, we acknowledged at the hearing that there was a measurement inconsistency between the station 21 43" Tee-seal measured UHF RCS data results and the 35" measured Tee-seal fragment 51313. The former RCS results seemed to indicate the Tee-seal *was* a candidate for the FD2 object, while the latter UHF measurements seem to indicate it *was not* a candidate for the FD2 object because its UHF RCS values were too low. We testified that a more detailed study of the Tee-seal was warranted because we had only a approximate idea what length of tee seal fragment was needed to reach the requisite UHF RCS values for the FD2 object.

AFRL/SN rigorously followed up our 6 May 2003 testimony and the measurement discrepancy with a thorough study of the RCS characteristics of Tee-Seals #6 though #11 on the left side. Using the Boeing CARLOS moment method code, we systematically "cut up" a tee seal geometry in an incremental fashion and recomputed its RCS for tee-seal #9 starting with the region beyond the flange and adding one inch at a time until the entire tee seal was re-created. The results of this assessment were the following: (1) In no case, at 433 MHz, was the peak RCS of a partial Tee-seal as large as the RCS of a whole tee seal. (2) Although the Tee-seal 21 had a predicted CP RCS close to the –1 dBsm +/-1.3 dB peak value within the limit of the on-orbit measurement uncertainty, Tee seal 21 was only provided as a notional case, and is not of real interest in the current accident scenario. The Tee-seals #6 through #11 were of most interest. (3) No combinations of angles and Tee-seal piece sizes for Tee-seals #6 through #11 produced a Tee-seal candidate whose RCS met the –1 dBsm maximum within the +/- 1.3 dB on-orbit uncertainty.

The Tee-Seal #9 is shown in Figure 15 as it is incrementally "cut up" on the computer, and Figure 15 also shows the global maximum RCS calculated by Carlos for nearly 4π steradian coverage. This analysis, along with the correction of the original RCC Station 21 Tee-Seal RCS data from the 6 May 03 testimony now ***eliminates the Tee-Seal as a possible candidate for the FD2 object.***

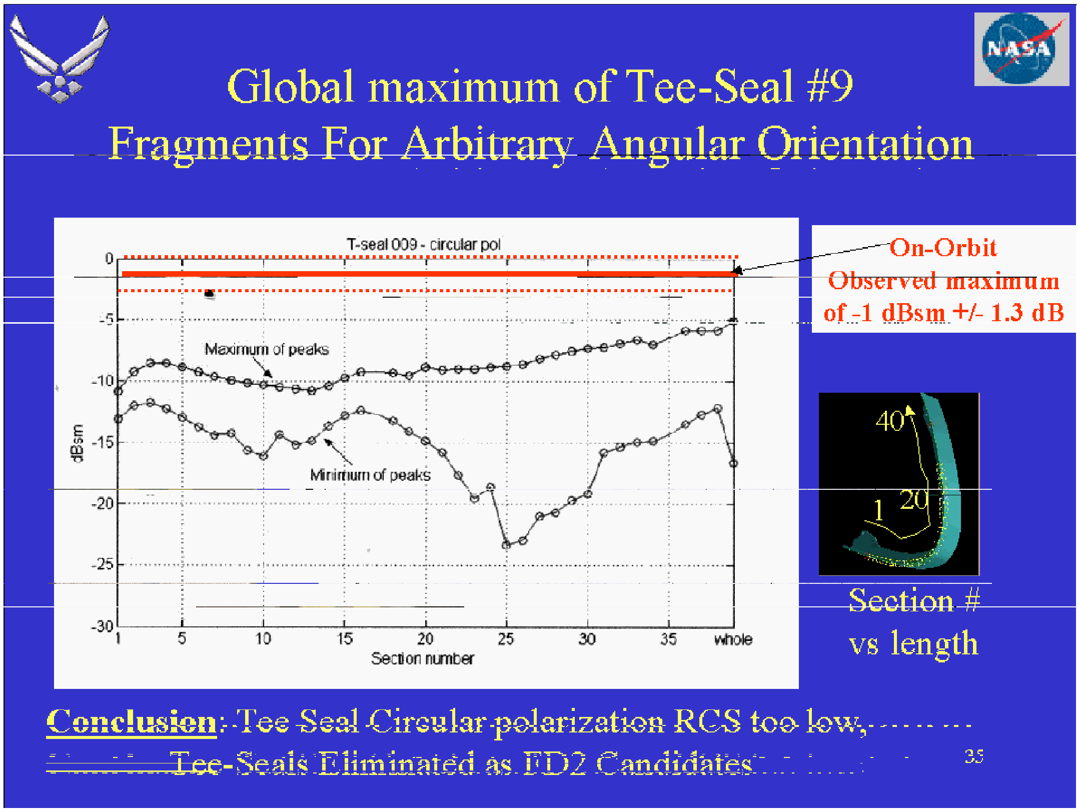


Figure 15 - Global RCS maximum and minimum of peaks of Tee-seal 009 versus incremental length. The highest possible RCS occurs for the whole Tee-seal.

To ascertain the validity of the RCS predictions, AFRL/SN laser scanned the tee-seal #21 provided by NASA-JSC and compared linear RCS measurements to CARLOS predictions. Initially, the prediction and measurement comparisons were off by 3-4 dB. We therefore re-examined all measured RCS data relative to the station 21 tee seal and tee-seal fragment 51313. We found that *for this set of files only* we had used the wrong theoretical calibration file in the creation of our original measured UHF RCS data for the Station 21 tee-seal. This produced RCS data that was about 3-4 dB higher than originally reported. Once we made the correction for the station 21 Tee-seal RCS results, we found that the resultant measurements and predictions were in outstanding agreement, giving our team confidence that the tool was working properly. A sample of the comparisons between theory and measurements of Tee-Seal #21 is shown in Figure 16 below. Note that Figure 16 shows the two linear polarization components. The circular polarization would lie somewhat between the two curves, clearly lower than the on-orbit circular polarized RCS maximum of –1 dBsm +/- 1.3 dB.

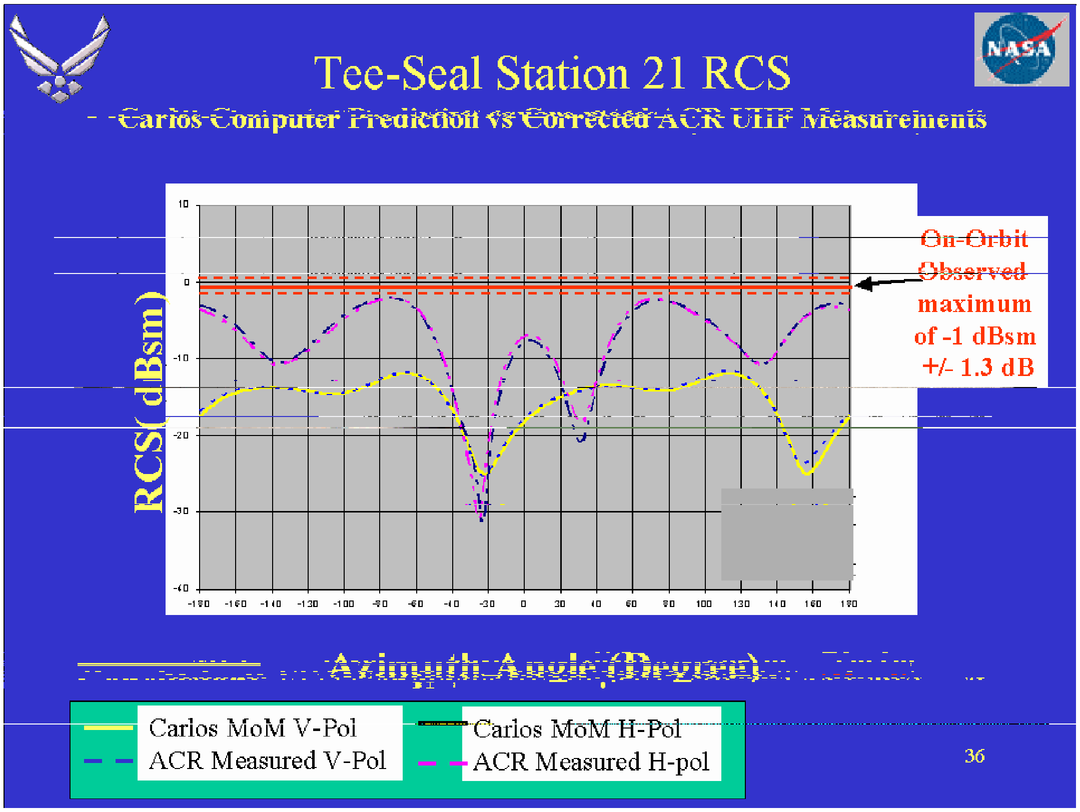


Figure 16 – Predicted CARLOS 3D RCS Vs AFRL/SN ACR UHF RCS Measurements at Linear VV and HH Polarizations. Note Tee Seal 21 is now below on-orbit observed maximum RCS for the FD2 Object. (From Appendix I)

We also thoroughly explored the resultant variations due to the unknown relative phase between HH and VV polarization in the prediction of the CP polarization. However, we also know we are interested in exploring the peak values of observed RCS, and that the peak observed RCS in CP could never exceed the highest linear polarization RCS data point, per the linear to CP polarization conversion equation in Appendix 1, equation 1. Once we understood that the CARLOS predictions and laboratory measurements assumed different phase reference points, the differences are easily explained.

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The overall conclusion of the detailed tee-seal RCS study is that, within on-orbit measurement uncertainties, AFRL/SN now believes the tee seal (#6,7,8,9, 10, or 11) are **no longer viable candidates for the FD2 object** based on our extensive evaluation of both whole tee-seals as well as fragmentary tee seal predictions.

Having provided background on what we could "eliminate" let's now shift towards FD2 candidates we ***cannot eliminate***. These include mainly fragments of leading edge RCC panels that might have been created in the event the RCC edge was struck in flight. Our team measured an entire RCC edge (although it was rejected as the FD2 object based on ballistic characteristics), and then measured 4 selected pieces of RCC debris recovered from Columbia's *right wing.* Several relatively small pieces of RCC were found to provide sufficient signature to meet the UHF RCS criteria However, forensic evidence rejects the idea that an entire leading edge wing segment departed the Shuttle on FD2, so we must consider more realistic cases. At this point, it became clear to us that if part of the RCC TPS system did separate from the Shuttle on FD2, it represented a serious issue regarding re-entry.

Since cutting up flight RCC hardware was prohibitively expensive, we requested permission to visit the Kennedy Space Center (KSC) Columbia debris recovery hangar to examine and select RCC fragments from the recovered *right wing* of the Orbiter that would be representative of RCC fragments that may have originated in flight on the *left wing*. We selected four RCC "fragments" from the Panel 8-9 area of the Orbiter's right side, and brought these samples back to WPAFB for additional compact range testing. Some of the RCC samples were relatively flat, others had lips or edges to them (sometimes called "webs"), while others had large curvature. However, the physical area of the RCC fragments chosen ran from ~90-140 square inches in physical size. In addition, we borrowed a recovered Station 9 Tee-Seal fragment approximately 35 inches in length, the largest recovered Tee-Seal piece found on the right side in the area of panels 8, 9, and 10. A picture of these debris fragments is shown in Figure 17 below.

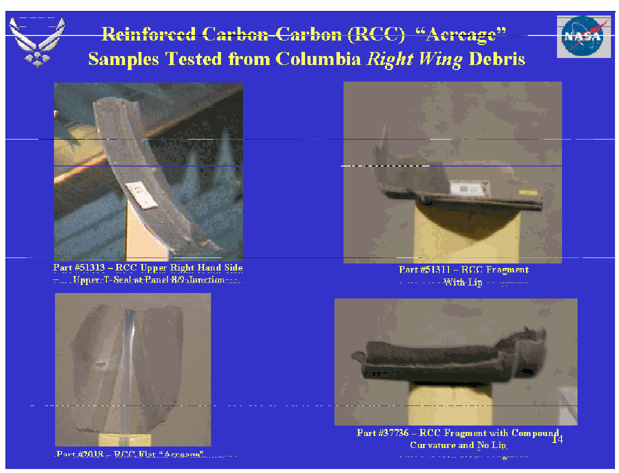

Figure 17 – RCC Fragments 51313 (Tee-Seal), 51311, 2018, and 37736
Recovered from Columbia's *right wing*

Fragment 51313 did not meet the on-orbit RCS values, which is consistent with the RCS computational analysis performed on a 35 inch piece of RCC tee-seal shown in Figures 15. Between the measured results (as corrected) for the station 21 Tee-seal and the fragment 51313, the Tee-seals were ultimately eliminated as candidates for the FD2 parts.

Subsequent RCS testing of the other RCC debris fragments showed their UHF RCS was consistent with on-orbit measurements, showing that fragments of RCC "acreage" could not be rejected as a class as the FD2 object. Figure 18 shows the RCS test results, while Figure 19 shows the B-term ballistic analysis.

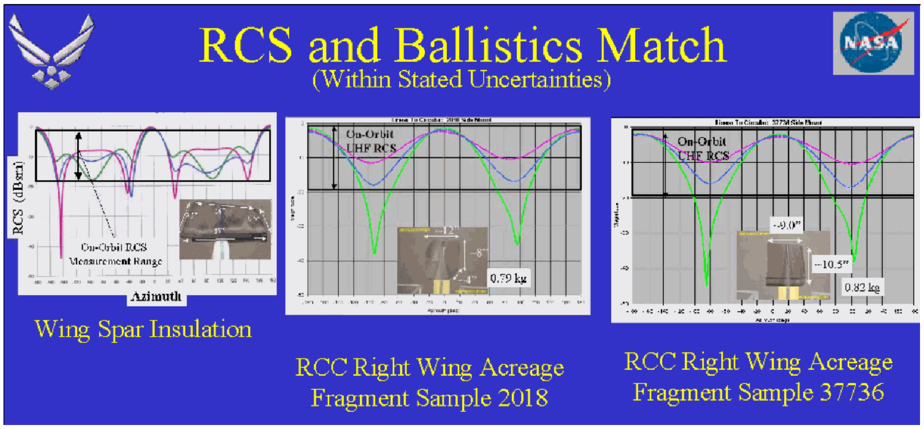

Figure 18- UHF RCS Test Results for RCC Acreage Pieces

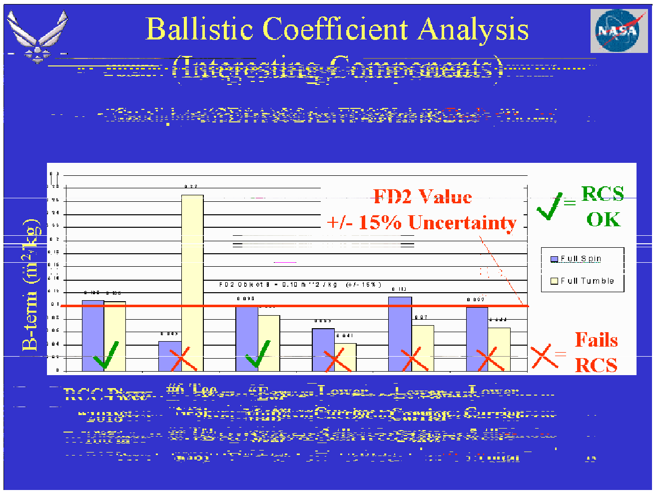

Figure 19- B-Term Analyses Results for RCC Tee seal and acreage pieces

Looking at the analysis of Figure 19, the RCC acreage piece "2018" fits very nicely with the observed on-orbit B-term data. Interestingly enough, the piece *only* fits the B-term if it is on the order of 0.33" thick. The RCC panels in the vicinity of the so-called "shock-shock" region of the wing are, in fact, 0.33" thick in the lower panel acreage regions. Most of the RCC on the Shuttle is only 0.25" thick, and this value is too low to meet the B-term. So the analysis indicates that RCC panels originating in the areas of panels 8,9, or 10 could meet these criteria. The other components shown in Figure 19 were rejected based on their RCS test data.

What can we conclude from the data and analysis performed to date? Clearly, RCC panel acreage satisfies both the B-term and UHF RCS criteria. Such a panel would have to be minimally 90-100 square inches in size, though larger sizes of 120-140 inches square clearly meet the criteria as well. Since the wavelength of the UHF radar is 27.28”, pieces with local curvature or a lip will still scatter similar to the values shown above. After a review of the corrected Tee-seal #21 data, as well as an extensive computational examination of RCC Tee-seal scattering described in Appendix I, no Tee-Seal from Seal #6 through seal #11, whether whole or in a fragment, met the UHF RCS maximum, and are hereby eliminated as a possibility for the FD2 object.

Section VI - Summary

In summary, the FD2 candidate list has been substantially reduced to the most probable candidate. This candidate is a class that includes a fragment of RCC panel acreage (0.33" thick) on the order of 90-140 square inches. All other candidates evaluated from the list of exterior Orbiter TPS or TCS materials failed to meet one or both of the RCS or B-term physically observed data. One candidate ("Ear muff seal") is not supported by the forensic debris evidence, and was rejected by that consideration.

Does this mean we can say with certainty the FD2 object was an RCC fragment? No, this cannot be said with absolute certainty, because the FD2 object burned up and was not recovered. Does this means that something else could have been the FD2 object? We concede this is a distinct possibility, although we as a team evaluated every candidate NASA has provided us, and to our knowledge the candidate list is exhausted at this time. Certainly if a new candidate emerges even after this report is written, AFRL and US STRATCOM could still evaluate that candidate and a potential FD2 object. But as of the date of this report, the only candidate we have to offer for the FD2 piece from a list of materials that are routinely present on the Orbiter is an RCC panel fragment originating in the region of #8, 9, or 10.

What can be said is that *if* the FD2 piece was a small acreage piece of RCC, that scenario is consistent with other aspects of the overall CAIB investigation. In addition, *if* the FD2 object was an RCC fragment of the size indicated (90-140 square inches) this missing piece would represent a serious breech in the RCC Thermal Protection System, and could well explain the remaining events that occurred on re-entry.

Section VII - References

[1] Hill, Paul s., Spencer, Ron, Edelen, Chris, Proud, Ryan W., Mrozinski, Richard B, Graybeal, Sarah R., Mendeck, Gavin F, Hartman, Scott, Herron, Mellisa, **Columbian Early Sighting and Assessment Team (ESAT) Final Report**, 13 June 2003, NASA-Johnson Space Center Mission Operations Directorate

[2] Cook, Chuck, Beauchamp, Karen, VonNiederhausern**, Bolt Catcher Debris Analysis for Shuttle STS-107**, Technical Note 25 June 2003

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