A Return to Innovative Engineering Design, Critical Thinking and Systems Engineering

For

The International Thermal Conductivity Conference (ITCC) and the
International Thermal Expansion Symposium (ITES)
Birmingham, Alabama
June 24-27, 2007

Charles J. Camarda
Deputy Director for Advanced Projects
NASA Engineering and Safety Center (NESC)

ABSTRACT

I believe we are facing a critical time where innovative engineering design is of paramount importance to the success of our aerospace industry. However, the very qualities and attributes necessary for enhancing, educating, and mentoring a creative spirit are in decline in important areas. The importance of creativity and innovation in this country was emphasized by a special edition of the Harvard Business Review OnPoint entitled: "The Creative Company" [1] which compiled a series of past and present articles on the subject of creativity and innovation and stressed its importance to our national economy.

There is also a recognition of a lack of engineering, critical thinking and problem-solving skills in our education systems and a trend toward trying to enhance those skills by developing K-12 educational programs such as "Project Lead the Way", "Science for All Americans", Benchmarks 2061", etc. [2, 3, 4]. In addition, with respect to spacecraft development, we have a growing need for young to mid-level engineers with appropriate experience and skills in spacecraft design, development, analysis, testing, and systems engineering.

As the Director of Engineering at NASA's Johnson Space Center, I realized that sustaining engineering support of an "operational" human spacecraft such as the Space Shuttle is decidedly different than engineering design and development skills necessary for designing a "new" spacecraft such as the Crew Exploration Vehicle of the Constellation Program. We learned a very important lesson post *Columbia* in that the Space Shuttle is truly an "experimental" and not an "operational" vehicle and the strict adherence to developed "rules and processes" and "chains of command" of an inherently bureaucratic organizational structure will not protect us from a host of "known unknowns" let alone "unknown unknowns" [5]. There are no strict rules, processes, or procedures for understanding anomalous results of an experiment, anomalies with an experimental spacecraft like Shuttle, or in the conceptual design of a spacecraft. Engineering design is as much an "art" as it is a science. The critical thinking skills necessary to uncover lurking problems in an experimental design and creatively develop solutions are some of the same skills necessary to design a new spacecraft. Thus, I believe engineers unfamiliar with or removed from design and development need time to transition and develop the required skill set to be effective spacecraft designers.

I believe the creative process necessary in design can be enhanced and even taught as early as grades K-12 and should continue to be nurtured and developed at the university level and beyond.

I am going to present a strategy for developing learning teams to address complex multidisciplinary problems and to creatively develop solutions to those problems rapidly at minimal cost. I will frame a real problem, the development of on-orbit thermal protection system repair of the Space Shuttle, and step through the series of skills necessary to enhance the creative process. The case study I will illustrate is based on a real project, the R&D Reinforced Carbon-Carbon (RCC) Repair Team's development of on-orbit repair concepts for damaged Space Shuttle RCC nose cap and/or leading edges.

IMPEDIMENTS TO CREATIVITY AND INNOVATION

It may seem strange that I should begin a paper on the importance of creativity and innovation by first discussing what I believe are some of the key impediments to innovative thought, however, what might seem as obvious to many will be highlighted over and over again throughout this paper by examples, as causes for numerous delays and failures.

I believe one of, if not the biggest, impediments to creativity is arrogance. When an individual who is highly competent crosses the line and becomes arrogant, that person stops listening, learning and growing and is not able to contribute 100 percent to the team. What can be said at the individual level is also true at the organizational level and can be much more damaging, especially if the organization breeds a culture which fosters arrogance. Many of the solutions to current problems have been addressed in the past. Researching what was done previously and viewing the problem through another's eyes or perspective often enhances ones insight to the problem and often allows alternative ideas to come forward. Fear of failure is another key impediment to innovation. Failure is an option, a necessary option for creative solutions to problems and the acceleration of knowledge and research.

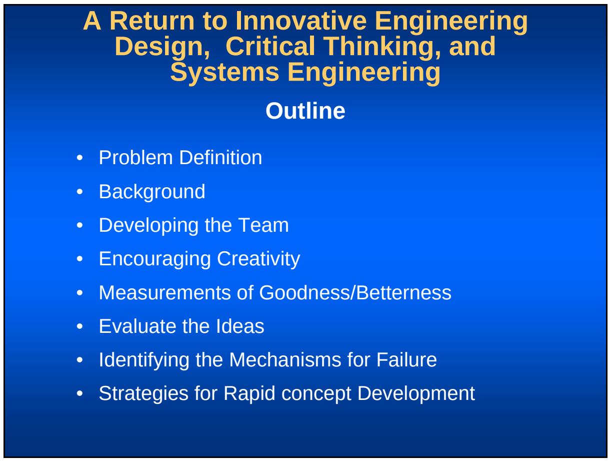
I believe a strict allegiance to process, procedures, chains of command and rigid, hierarchical, organizational structure are other artifacts of a system which stifles the creative flow of ideas. While this process and structure may be necessary in the final design stages of a project after final design and production; it will impede the conceptual design stage of a project to the point where it quickly exceeds both budget and schedule constraints and often results in the early demise of an otherwise promising project. Hence, flexibility and freedom are critical in the early stages of the design process when creativity and innovation are so important!

Time, schedule and resource constraints are often challenging to the creative process; however, a certain amount of pressure is also very helpful to encourage goal setting and to maintain a certain amount of focus for the team.

Other impediments to creativity are: an environment or culture which suppresses dissenting opinions and tries to encourage consensus; a lack of objective critical thinking skills; an ambiguous or ill-defined problem and/or constraint set; and a limited participation of all the relevant discipline skills early in the conceptual design phase.

OUTLINE

Figure 1 is an outline of the steps involved in the creative solution of problems. The process begins with a very broad multidisciplinary view of the problem and the constraints. Next is a very comprehensive review of all the necessary background information to obtain as complete an understanding of the problem and the critical discipline skills necessary to solve the problem. The next step is the development of as small a team as necessary having the required skills to solve the problem and as large a team as necessary to complete the job within the assigned schedule and budget constraints. Once a team is formed, it is important to develop an environment for collaboration, learning, efficient communication, teamwork, respect, reward, recognition and the necessary tools for encouraging creative thought and problem solving.



A Return to Innovative Engineering Design, Critical Thinking, and Systems Engineering

Outline

- Problem Definition
- Background
- Developing the Team
- Encouraging Creativity
- Measurements of Goodness/Betterness
- Evaluate the Ideas
- Identifying the Mechanisms for Failure
- Strategies for Rapid concept Development

Figure 1. Outline of steps to encourage/enhance innovative engineering design.

Techniques for problem-solving and concept development will result in a multitude of innovative ideas and concepts. These must be evaluated in a reasonable time to ensure success within the constraints and limitations of the problem. When we are in the process of developing solutions/concepts it is then necessary to establish what I call “measurements of goodness/betterness” with which to point us toward developing and improving the concepts we have identified. We proceed to identify the key unknowns and failure mechanisms of each concept and develop strategies for rapid development and technical maturation. Once we recognize the resources required to fully develop and mature each of the concepts we iterate again and re-prioritize/re-evaluate all the concepts. This iterative process is subject to change as our understanding and knowledge of the problem grows, and as even the requirements themselves may change over time. The key to designing as robust a solution as possible is to factor in as many of the relevant concerns as possible early in the design process. Then, develop strategies for minimizing risk based on our abilities to learn as we go and to conduct appropriate sensitivity studies to ensure we can remain well within our constraint boundaries.

PROBLEM DEFINITION: “EVERY PROBLEM IS A MULTIDISCIPLINARY PROBLEM”

I believe, to some degree, every problem is a multidisciplinary problem. Depending at what level you draw your dashed line around the problem or “system”, the number of disciplines involved can either be small or can become very large. In fact, one of the current problems with using terms like “systems engineering” is that the intended meaning can be quite different depending on where this dashed line is drawn — at the level of fidelity of analysis and testing and the exact point in the design process. For example, I contend that in the early stages of the design process, at the conceptual level, the roles and responsibilities of a “systems engineer” are different than what you would expect of a systems engineer at the later stages of the design development process where configuration management, process development, quality control etc., may be more important. For the purpose of this report, I am going to qualify my definition of a "systems engineer" as a person who understands how the entire system behaves, how perturbations to that system effect its performance, and how interfaces between disciplines which describe the system's behavior are coupled and can interact in totally unexpected ways to also result in non-traditional behaviors and failures. In essence, the systems engineer has to understand the big picture (e.g., pan out), yet be experienced enough to recognize when the level of understanding or analysis of a certain behavior of the system is insufficient to adequately describe the physics of the problem and/or predict key failure mechanisms. It may sometimes be necessary to increase fidelity of the analysis of the behavior of the system, e.g., zoom in. There is a need for the systems engineers and the discipline experts to move in and out as members of the design team as needed providing a "flexible critical mass", which changes as the scope of the project and/or focused problems occur and have to be addressed in a timely manner [6].

A good start at defining the problem is to describe the problem or design task as simply and completely as possible using "first principles" of science and engineering. If the design task is truly in response to a previous design deficiency, then it is often necessary to determine the "root cause" of the discrepant feature in order to solve the issue as expeditiously and completely as possible. If, on the other hand, the design task is truly the creation of a new concept or idea to satisfy a set of requirements and constraints, it becomes necessary to ensure there is a solid understanding of what the entire problem is and if there is any room for flexibility in either the requirements or constraints. This process identifies the variables and constraints of the problem as well as the "objective" or "cost" functions and, thus, determines the feasible design space within which the designers are to operate.

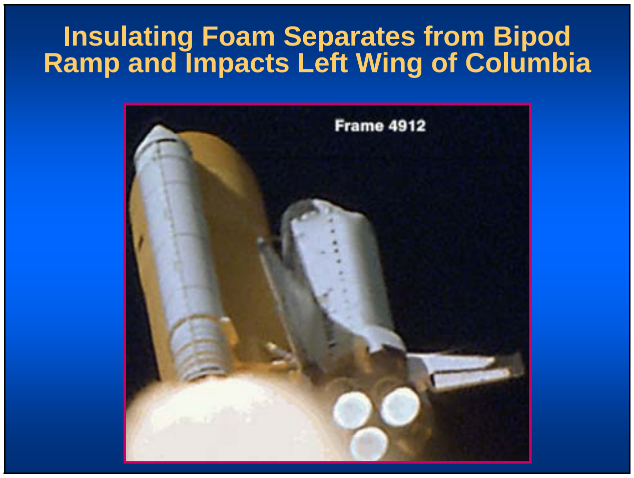
It is often helpful early in the process to have every member of the team write down what they believe is their perception of the problem statement and what they feel are the key drivers in the design. Having each member of the team share their perspective enables each team member to learn to view the problem through another "discipline's" eyes. This helps to keep the team grounded as a single unit and maintains the overarching need to "zoom in" to understand the intricacies of a particular discipline and/or to "pan out" when appropriate so as not to lose sight of the big picture.

When scoping what will be necessary to address the solution of a problem and/or a new design, the team needs to define the environment, including the human/operations side of the equation of applying the "right stuff" with the right approach. All constraints must be identified including technical, schedule, budget, political, etc. Identify all discipline skills necessary to solve the problem. More often than not the non-technical issues drive the solution of the problem or the selection of the design concept. Lastly, the team needs to identify the contradictions within the problem because it is often these very contradictions that will provide insight into the real innovative solutions which can offer significant design improvements.

STS-107 SPACE SHUTTLE *COLUMBIA* TRAGEDY

I will begin with the broadest definition of the problem and then zero in as quickly as possible to our piece of the problem and solution and show how it fits within the overall strategy of developing a successful strategy for return to flight (RTF).

The cause of the *Columbia* tragedy as described in the CAIB report [5] was twofold: a technical cause determined to be a piece of bi-pod foam which liberated during ascent and critically damaged a section of the Space Shuttle wing leading edge; and an equally important social/organizational cause which allowed several critical social issues to develop which caused wrong decisions to be made and impeded the flow of critical information. Figure 2 is the opening scene from the digitally-enhanced launch day video of STS-107 which shows a large piece of bi-pod foam liberating from the External Tank (ET) of the Space Shuttle and hitting the lower surface of the Orbiter and breaking up into tiny particles after impact.



Insulating Foam Separates from Bipod Ramp and Impacts Left Wing of Columbia

Figure 2. Launch video of STS-107 illustrating the impact of a large piece of external tank (ET) foam hitting the lower surface of the Orbiter.

The RTF was a very difficult problem to address for several reasons: 1) we had to identify the root cause of the problem (the proximate technical cause for the foam being liberated from the bi-pod region of the vehicle), 2) we had to understand what was the impact damage tolerance of RCC material, 3) we had to understand what the survivability of impact-damaged RCC would be during earth entry heating, 4) we had to develop inspection and detection methods which could detect the minimum critical damage to the RCC leading edges on orbit prior to undock from the International Space Station (ISS), and 5) we had to ensure a “safe-haven” capability where we could use the ISS to sustain the Shuttle and ISS crews long enough for launch of a rescue Shuttle.

While the development of an on-orbit repair capability was not necessary for RTF, in the view of many, including the members of the CAIB Commission [5], I considered it a high priority because it allowed us an opportunity to save the vehicle and/or the crew in the event of critical damage and a contingency with respect to our plans for a safe haven.

What we believe to be the proximate technical cause of the accident was that a piece of bi-pod foam (possibly as large as 2.2 lbs) was liberated from the ET at about 1:20 into the flight and struck the port wing leading edge of *Columbia* at approximately 800 fps (545 mph).

About 84,000 pieces of debris from *Columbia* were collected across Texas weighing about 85,000 lbs in total. Amazingly we recovered about 40 percent of the entire vehicle. These pieces of debris allowed investigators to build a 3-D reconstruction of the port wing leading edge of *Columbia* which was one of the pieces of data used to develop an understanding of how the wing came apart during earth entry (see Figure 3). In Figure 3, there are large sections of RCC panels 9 and 10 that were not recovered.

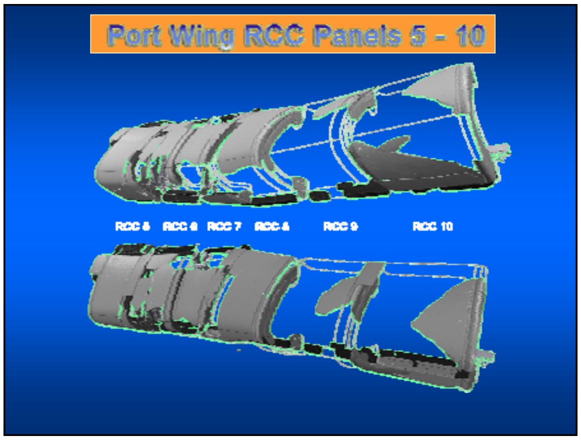


Figure 3. Debris reconstruction of a section of *Columbia*'s RCC port wing leading edge which was recovered after the tragedy.

A photograph of the inner surface of a port wing leading edge panel, shown in Figure 4, indicates there was a thin metallic film which was deposited on the inner RCC surface. This metallic coating probably resulted from a breach in the LE panel which vaporized the Inconel 617 metallic TPS protecting the front wing spar and was then deposited on the cooler inner surface of the panel. Hence, the leading theory was that the damage probably occurred on the lower surface of one of the port wing panels causing a hole to grow during entry, hot gas to ingress into the LE cavity, and eventually destroyed the vehicle.


Reconstructing the Left Leading Edges

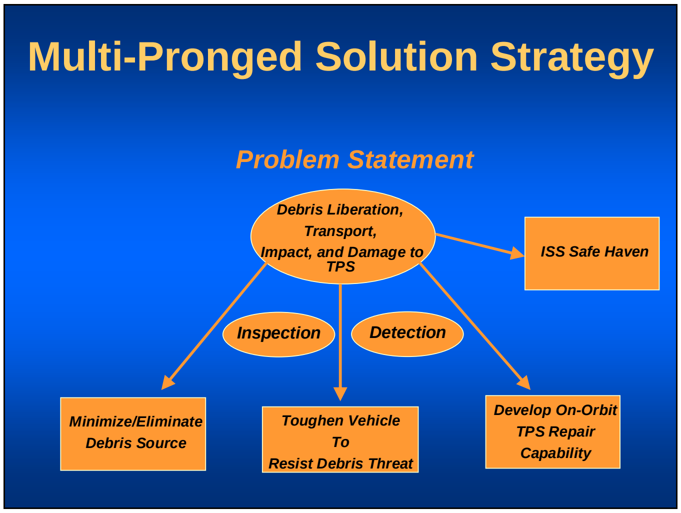
Figure 4. Inner surface of port wing RCC leading edge panel with thin metal coating believed to be deposited during hot gas ingress to the wing cavity.

As part of the Columbia Accident Investigation, a series of foam impact tests were conducted to understand the physics of the problem and to definitively ascertain if large foam impacts could cause critical damage to the wing leading edge. The result of a full-scale impact test of a rectangular piece of BX-250 foam (1150 cubic inches and 1.6 lbs) traveling at 777 fps (530 mph) is shown in Figure 5.

Figure 5. Large hole in panel 8 post test at Southwest Research Institute (SwRI).

SCOPING THE PROBLEM DOWN TO THE APPROPRIATE LEVEL

When you pan out and look at the entire problem from a RTF Team perspective, there was a multi-pronged solution strategy to mitigate risks to allow us to return to flight (Figure 6): 1) The Space Shuttle Program (SSP) would do everything possible to understand and mitigate the root causes of debris liberation, aerodynamic transport, impact and damage tolerance of the thermal protection systems (TPS); 2) The teams would develop both an inspection capability which could detect minimum size critical damage to the TPS and also detect impacts to the wing leading edges which could cause damage; 3) Minimize or eliminate debris sources; 4) Toughen the LE, if possible, to resist impact damage; and 5) Develop an on-orbit repair capability in the event of a contingency of the safe-haven or rescue-vehicle backup.



Multi-Pronged Solution Strategy

Problem Statement

Debris Liberation, Transport, Impact, and Damage to TPS

ISS Safe Haven

Inspection

Detection

Minimize/Eliminate Debris Source

Toughen Vehicle To Resist Debris Threat

Develop On-Orbit TPS Repair Capability

Figure 6. Multi-pronged solution strategy to ensure a safe return to flight (RTF).

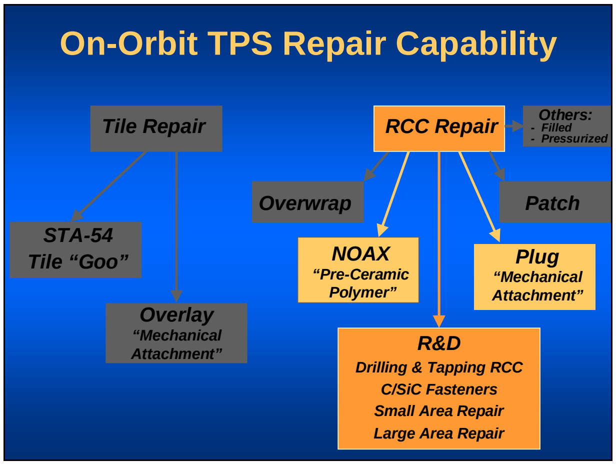
It became apparent as we proceeded in parallel paths with this multi-pronged approach that: 1) we would probably never be able to eliminate all sources of debris that could cause critical damage; 2) to toughen the leading edges sufficiently to resist critical damage would take too long and be too costly to design, analyze, fabricate and validate; and 3) a “safe-haven” and rescue vehicle strategy was possible, but relied on many parameters to be a completely reliable and robust concept.

Hence, a strategy to mitigate risk further was to develop an on-orbit TPS repair capability which could be used in a contingency situation.

ON-ORBIT TPS REPAIR

In the beginning of the RTF program, there were several categories of both tile and RCC repair. The tile repair categories were adhesive/ablative concepts that would fill a damaged tile cavity and mechanical “overlay” concepts that would include filling the cavity with fibrous insulation and securing a C-SiC cover plate, or “overlay”, and gasket which was secured with SiC fasteners to adjacent, undamaged tiles.

In the category of RCC repair, there were several options initially evaluated which included (Figure 7): 1) an “overwrap” concept which were complete C-SiC curved panels specially sized to fit securely over each individual RCC panel (44 total for port and starboard RCC leading edges); 2) “crack repair” pre-ceramic polymers such as NOAX (Non-Oxide Ablative Experimental) which were designed to be applied over small damaged regions (small areas of coating loss or small holes or cracks); 3) “Plug” concepts which were mechanical patches/plugs of C-SiC material which were secured through a hole in the wing leading edge (~1 inch diameter) by a high-temperature fastener; 4) a “patch” concept which was a flexible patch of high-temperature material which is cured in place and adhesively bonds over the damaged region of RCC; 5) filled leading edge cavity options; and 6) a separate set of solutions developed by an R&D team which provided an alternative set of mechanically- and adhesively-attached RCC repair concepts that spanned the solution space from small cracks and holes to holes as large as 16 x 16 inches.



On-Orbit TPS Repair Capability

Tile Repair

STA-54
Tile "Goo"

Overlay
"Mechanical Attachment"

RCC Repair

Others:
- Filled
- Pressurized

Overwrap

Patch

NOAX
"Pre-Ceramic Polymer"

Plug
"Mechanical Attachment"

R&D
Drilling & Tapping RCC
C/SiC Fasteners
Small Area Repair
Large Area Repair

Figure 7. Thermal protection system (TPS) concepts investigated.

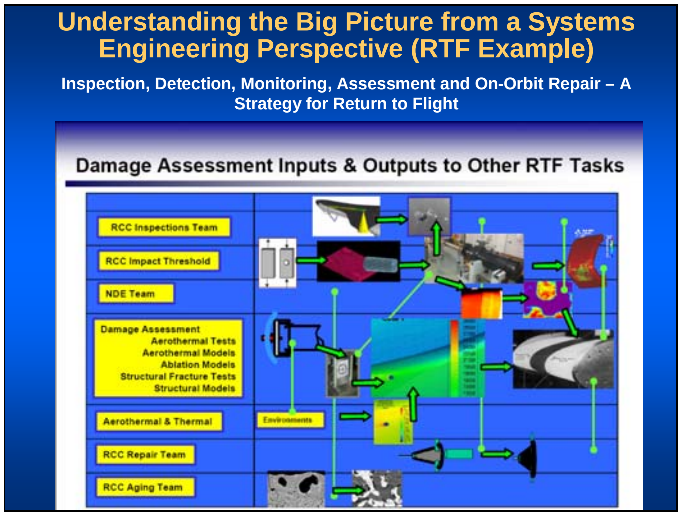
One of the purposes of this presentation is to demonstrate the utility of forming creative/innovative multidisciplinary teams to address complex problems in a timely fashion. The problem presented is the development of on-orbit techniques for repairing RCC leading edges.

ON-ORBIT RCC REPAIR

In scoping down the focus of the problem/design challenge, I will discuss 1) the two concepts which were chosen by the Program to develop; and 2) the state-of-the-art of these concepts prior to the first RTF mission, STS-114 (the NOAX crack repair material and the "Plug" concepts). I will then elaborate on the technologies developed by the R&D Repair Team.

Figure 8 pans us back out for a moment and allows us to view how the RCC Repair Project must fit within the overall strategy for RTF. It looks at the total picture for RCC repair and shows the interfaces and interconnections to other ongoing RTF projects is critical.

Figure 8 also attempts to illustrate the connectivity and integration of each of the various RTF activities associated with RCC inspection and repair (e.g., RCC inspection; impact threshold (damage criteria); non-destructive evaluation (NDE); damage assessment, aerothermal analysis and test; RCC repair; and effects of aging on RCC material properties).



Understanding the Big Picture from a Systems Engineering Perspective (RTF Example)

Inspection, Detection, Monitoring, Assessment and On-Orbit Repair – A Strategy for Return to Flight

Damage Assessment Inputs & Outputs to Other RTF Tasks

Figure 8. Demonstration of an integrated approach to solving the RCC inspection and repair problem.

What was sorely lacking during the RTF program was leadership which had the appropriate technical experience, development project experience and a true “systems” engineering understanding of this multidisciplinary problem. Not having this leadership resulted in a number of false starts and set backs and excessive expenditure of scant resources.

In the “Individual Observations” Section of the Return to Flight Task Group (RFTG) [7], Messrs. Joseph W. Cuzzupoli and Richard H. Kohrs make the following statement: “The utilization of operational-type management and engineers made the RTF of the Space Shuttle difficult. Nevertheless, the result was enormously positive for NASA. They got there!” Other RFTG authors [see Appendix A.2, ref. 7] were not as kind and noted “persistent cultural symptoms” which they observed throughout the assessment process: “We believe that the leadership and management climate that governed NASA’s return-to-flight effort, was weak in some important ways”…. “We believe these organizational and behavioral concerns are still pervasive throughout the human spaceflight program. “Yet while NASA leadership was focused on the 15 CAIB return-to-flight recommendations, they missed opportunities to address the enduring themes of dysfunctional organizational behavior that the CAIB and other external evaluators have repeatedly found”.

This is where a Project Manager with a strong systems engineering background would have been most beneficial.

BACKGROUND “ARROGANCE IS THE ENEMY OF CREATIVITY”

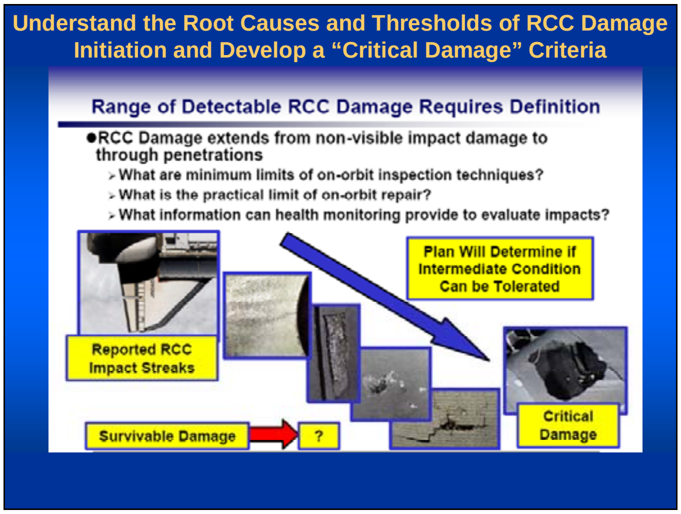
The next phase of the creative process is *background*. This is the collection of all the “background” information we can obtain related to the immediate problem and also to analogous or related problems. This is very similar to a thorough literature search for a Doctoral Dissertation and can include relevant patent searches, literature surveys, technical contacts, etc. We should seek analogous problems in related and unrelated fields. In fact, one of the solutions presented herein, the Plug repair concept, was an idea that came from a different repair problem for a different program. We should look to other sources for "field repairs" which say the military uses to repair aircraft, tanks, equipment in the field under extreme conditions. We could also look to commercial undersea repair activities as well as automated/robotic repair techniques.

Arrogance can be the primary obstacle to creativity and innovative ideas. For example, by limiting our search to only endeavors associated with "human spaceflight" and the misconception that only certain organizations that are familiar in developing hardware for "human" spaceflight are capable of designing such equipment. Another way that arrogance impedes creativity is that assuming we can approach the solution of the problem with a "clean sheet of paper" and solve all the necessary differential equations from scratch without the need for looking at how other researchers have solved the problem. By taking this myopic approach to problem solving, we miss the opportunity for viewing the problem from another person's perspective. Often when we do take the time to view the problem through someone else's eyes we gain so much more insight to the problem, a better understanding, and often times a creative or new technique for solving the problem.

When we collect all the relevant information about the problem and when our understanding of the problem and all its interfaces is complete, we can formulate a plan to attack the solution and make note of all the relevant variables/parameters and the necessary sensitivities of those variables which can help to guide the solution process toward improving the various concepts as they are proposed and developed.

ROOT CAUSES OF RCC DAMAGE, DAMAGE THRESHOLDS, AND DEVELOPMENT OF A "CRITICAL DAMAGE" CRITERIA

To understand how to repair RCC, we must first understand what is the impact threshold which initiates damage in RCC (both visible and non-visible (sub-surface damage, delaminations, backside coating loss, etc.)), see Figure 9. Next we need to understand what constitutes "critical damage". For example, what types of damage can grow to critical size which will result in the catastrophic breakup of the vehicle during earth entry. Once we understand what the critical damage size is for various locations on the wing leading edges, we must ensure that the inspection techniques we develop can detect the minimum amounts of damage as shown in Figure 8. Next we must identify what practical size damage we are willing to develop a repair strategy for and, thus, what size do we believe is a practical limit to shoot for in our development strategy. Lastly, are there any NDE techniques which we can use on orbit to assess the integrity of the repair once it is completed?



Understand the Root Causes and Thresholds of RCC Damage Initiation and Develop a "Critical Damage" Criteria

Range of Detectable RCC Damage Requires Definition

- RCC Damage extends from non-visible impact damage to through penetrations
  - What are minimum limits of on-orbit inspection techniques?
  - What is the practical limit of on-orbit repair?
  - What information can health monitoring provide to evaluate impacts?

Plan Will Determine if Intermediate Condition Can be Tolerated

Reported RCC Impact Streaks

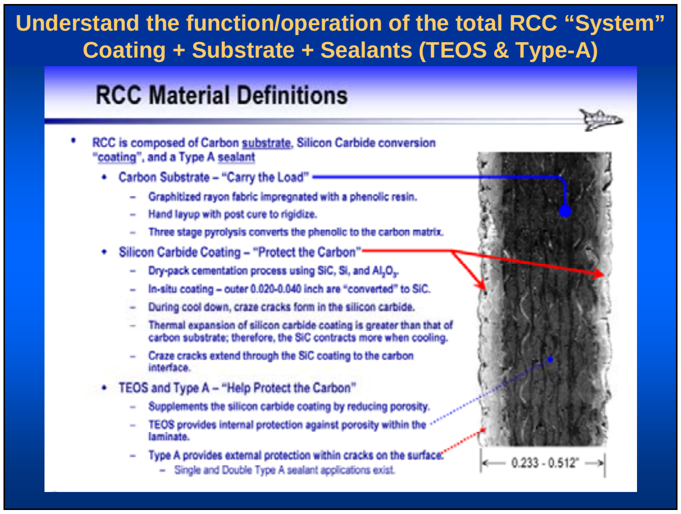
Survivable Damage → ?

Critical Damage

Figure 9. Understanding the root causes and thresholds of RCC damage initiation and the development of critical damage criteria.

Next, we must develop an understanding of how the RCC material system is manufactured and the functions of each of the constituents of the system. A comprehensive description of the design and manufacture of RCC and a detailed description of its constituents and functions is given in reference [8]. As shown in Figure 10, the RCC system is composed of a carbon-carbon (C-C) substrate whose primary function is to carry the load; thin SiC coating layers, inner and outer surfaces (approximately 0.030-inch thick each), to protect the C-C substrate from attack by oxidation; a Type A glassy sealant is used to fill the craze cracks, which are formed when the part cooled down after the SiC conversion firing (Type-A sealant is a mixture of Sermabond 487 sodium silicate solution, 1200 grit black silicon carbide powder, and ground WDF graphite felt); and the RCC is vacuum impregnated with activated tetraethyl orthosilicate (TEOS). The TEOS converts to a SiO_2 glass during cure and serves to fill the internal porosity of the laminate and provide additional protection from oxidation.

The RCC material is a very complex material system with various constituents which have various primary and secondary functions. To develop a repair solution for RCC requires and in-depth understanding of this system.



Understand the function/operation of the total RCC "System" Coating + Substrate + Sealants (TEOS & Type-A)

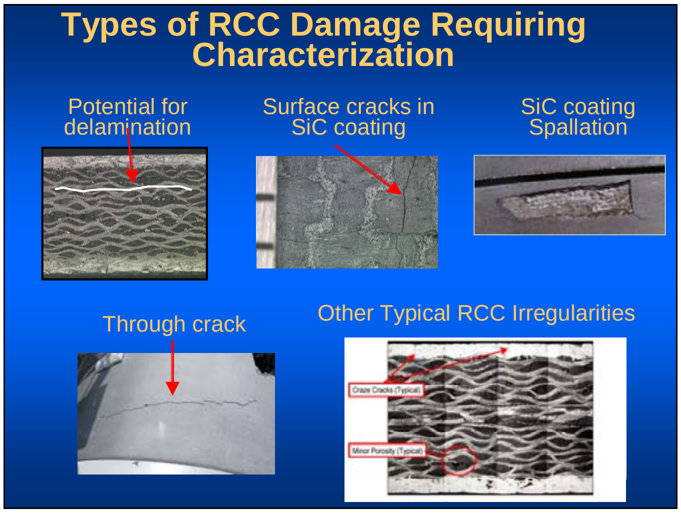
RCC Material Definitions

- RCC is composed of Carbon substrate, Silicon Carbide conversion "coating", and a Type A sealant
  - Carbon Substrate – "Carry the Load"
    - Graphitized rayon fabric impregnated with a phenolic resin.
    - Hand layup with post cure to rigidize.
    - Three stage pyrolysis converts the phenolic to the carbon matrix.
  - Silicon Carbide Coating – "Protect the Carbon"
    - Dry-pack cementation process using SiC, Si, and Al_2O_3.
    - In-situ coating – outer 0.020-0.040 inch are "converted" to SiC.
    - During cool down, craze cracks form in the silicon carbide.
    - Thermal expansion of silicon carbide coating is greater than that of carbon substrate; therefore, the SiC contracts more when cooling.
    - Craze cracks extend through the SiC coating to the carbon interface.
  - TEOS and Type A – "Help Protect the Carbon"
    - Supplements the silicon carbide coating by reducing porosity.
    - TEOS provides internal protection against porosity within the laminate.
    - Type A provides external protection within cracks on the surface.
      - Single and Double Type A sealant applications exist.

Figure 10. The RCC material system.

In addition to understanding how the pristine RCC material behaves under nominal conditions and use, it is also very important to understand the behavior of damaged RCC with respect to the environment of launch, on-orbit, and entry.

As shown in Figure 11, RCC can exhibit many different types of irregularities due to either processing and/or damage such as: SiC coating spallation, delamination of plys, surface craze cracks in the SiC coating, through cracks and internal voids due to processing.



Types of RCC Damage Requiring Characterization

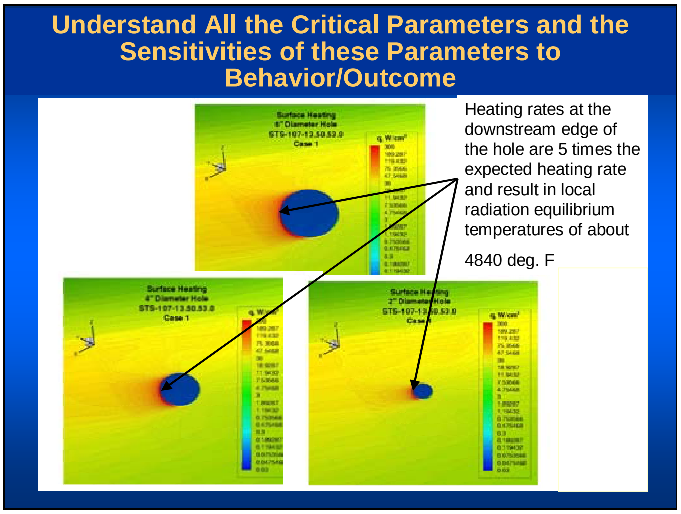
Figure 11. Types of RCC irregularities and damage requiring characterization.

UNDERSTANDING THE ENVIRONMENT

One of the first things we learned post *Columbia* was how little we really knew about the survivability of damaged RCC during entry. Our understanding of what was considered to be critical damaged had to be modified based on a new understanding of how RCC with SiC coating loss from both surfaces, through cracks, and subsurface delaminations.

During entry heating, local maximum temperatures can rise over 2,960 degrees F in the highly heated region and can cause damaged regions of RCC to grow into through cracks and holes which may become critical.

While conducting computational fluid dynamics (CFD) analyses of various size holes in RCC during entry to assess the possible causes of the accident, Dr. Peter Gnoffo of NASA's Langley Research Center (LaRC), discovered that when flow occurs at an angle to the damaged RCC leading edge, the downstream lip of the hole experiences heating up to five times that at the stagnation region of the leading edge as shown in Figure 12.



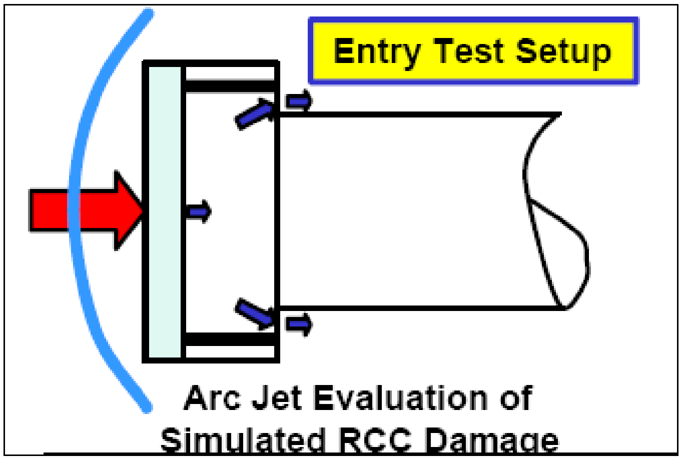
Understand All the Critical Parameters and the Sensitivities of these Parameters to Behavior/Outcome

Heating rates at the downstream edge of the hole are 5 times the expected heating rate and result in local radiation equilibrium temperatures of about

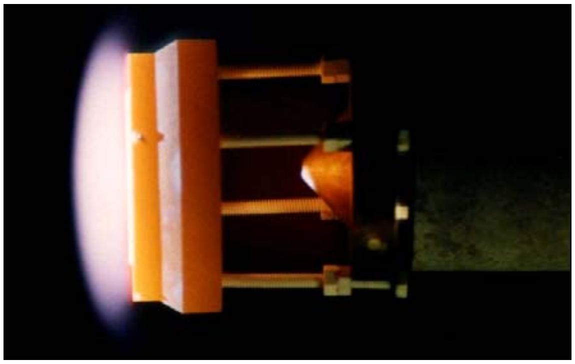
4840 deg. F

Figure 12. Computational fluid dynamic (CFD) analyses of flow at an angle to a hole in a wing leading edge and associated increases in heating and temperature of the downstream lip of the hole.

Results of CFD analyses of holes in leading edges by Peter Gnoffo showed that the stagnation testing currently in practice at JSC to define critical damage was non-conservative and that flow at an angle to a damaged leading edge could cause heating approximately 5 times higher than the levels expected during the 90-degree stagnation tests. This discovery by researchers at LaRC would cause the redesign of the testing approach used from the stagnation test samples (Figure 13) in favor of a newly developed "wedge" test technique which is shown in Figure 14.



a) Stagnation specimen configuration in the JSC arcjet facility.



b) RCC stagnation test in the JSC arcjet facility.

Figure 13. RCC stagnation testing configuration.

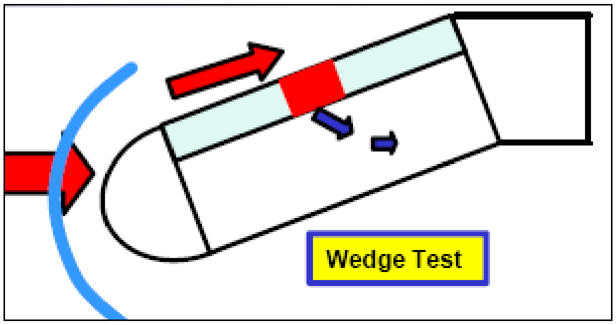


Figure 14. Newly designed "wedge" test to more accurately represent flow conditions of repairs on a leading edge.

Both the stagnation and the wedge tests would allow flow through a damaged specimen because, as reported in the next section, it was later discovered during early RCC damage assessment meetings [9] that coating loss from the front and back surfaces of RCC, together with delaminations within the substrate, severely limited the survivability of the damaged RCC during entry.

Prior to the *Columbia* accident, it was believed that the primary threat to the RCC leading edges and nose caps would come from micrometeoroid/orbital debris (MMOD) strikes while in orbit. Hence, the bulk of damage testing at that time was for simulated small regions of front surface coating loss and small through holes caused by hypervelocity impacts of simulated MMOD (Figure 15). Typical hypervelocity strikes did not result in significant delaminations in RCC material surrounding the impact site. The damage criteria prior to STS-107 called for a minimum hole of 0.25 inches. Small areas of coating loss on the front surface were not considered critical and, as evidenced by arcjet testing in the Atmospheric Reentry and Structures Evaluation Facility (ARMSEF) at JSC, were survivable. An example of a typical simulated MMOD impacted specimen to be tested in the arcjet is shown in Figure 16 [13]. Some tests were conducted with various levels of backside coating loss from 0 to about .426 inches x .44 inches. Results of those tests indicate that backside coating loss can cause flow through the specimen adding additional energy to the substrate, raising the peak temperatures and mass loss to critical levels [10].

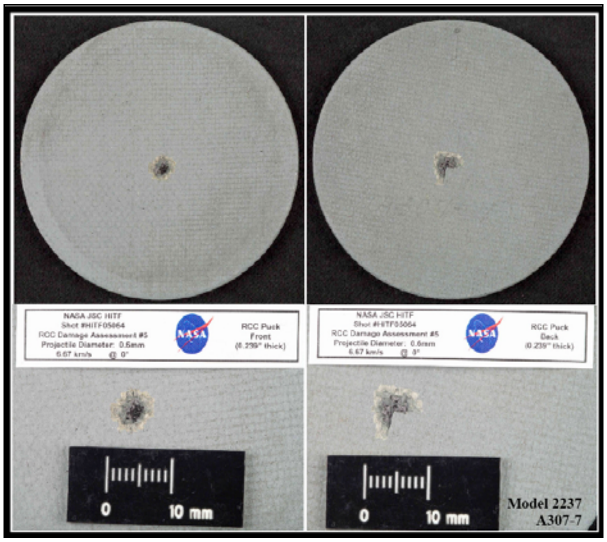


Figure 15. Simulated micrometeoroid-impacted RCC specimens prior to 90-degree stagnation testing in the JSC arcjet.

Further damage tolerance testing with simulated (in lieu of real impacted specimens) through cracks (saw cut through specimen) and with static indentations (used to simulate ballistic impact with debris) to simulate regions of coating damage/loss and subsurface delaminations was also conducted in the arcjet facility [14]. Results of those tests verified the downstream heating of a crack/hole lip as predicted by Gnoffo [9] and as evidenced by the wedge-like nature of the crack growth when tested at an angle to the flow in the wedge holder design (see Figures 14, 16 and 17). When the crack thickness increases from 0.013 inches to 0.039 inches the downstream heating of the crack lip is increased and a noticeable wedge shape hole readily forms. Crack widths smaller than 0.01 inches, typically did not grow to critical size and were considered to have survived the full re-entry trajectory. However, thin through cracks with coating and subsurface damage (simulated by static indentation) did grow to a wedge-like hole of critical dimensions. This was all new information which the Program needed in order to validate a robust criteria for critical damage.

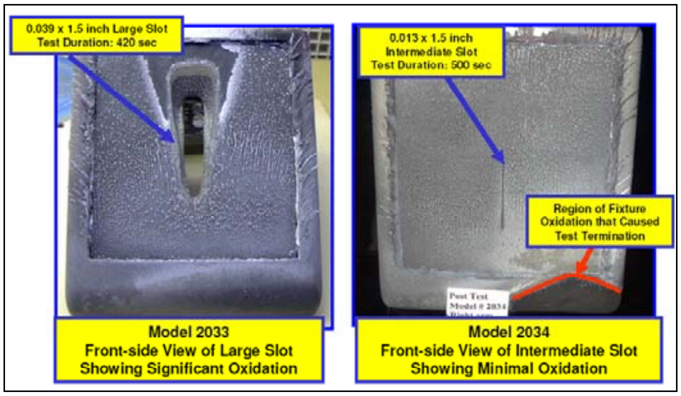


Figure 16. Effect of machined through slit thickness on arcjet performance of RCC specimen during a wedge test at JSC (flow is from bottom to top in the figure).

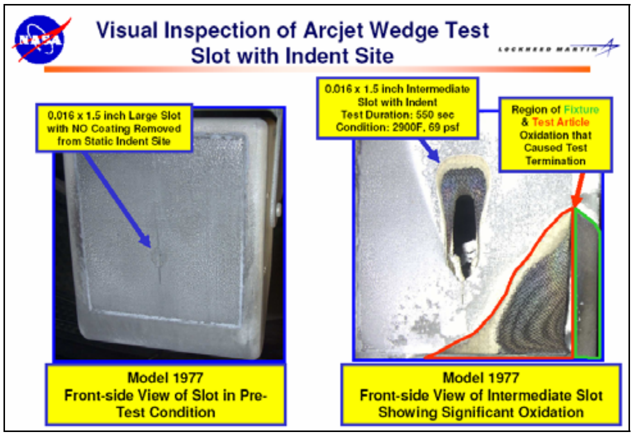


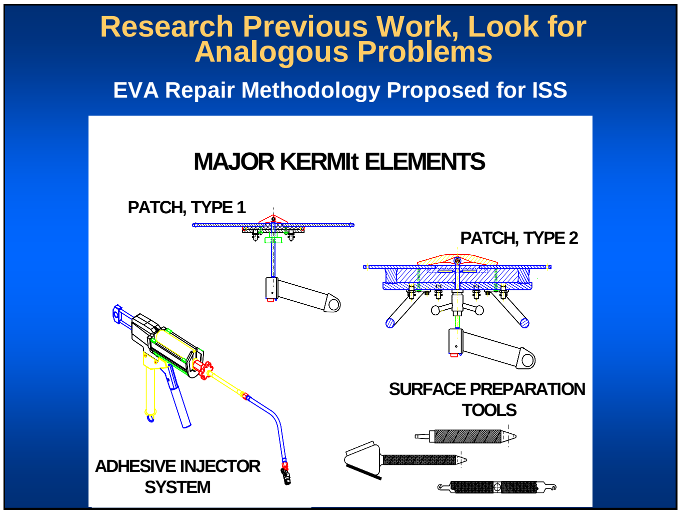
Figure 17. Effect of machined through slit thickness, damaged coating and subsurface damage on arcjet performance of RCC specimen during a wedge test at JSC (flow is from bottom to top in the figure).

STATUS OF RCC REPAIR CONCEPTS PRIOR TO R&D INNOVATIVE DESIGN WORKSHOP (JUNE 2004)

Plug Repair

One of the first recommended methods for repairing small holes in the wing leading edge was called the "plug" concept and it relied on a mechanical means to attach a rigid C-SiC patch or plug over the damaged region. As mentioned earlier, the background investigation should look at work in analogous fields.

One of these ideas for the plug concept was inspired by techniques developed by MSFC for repairing holes to the pressurized modules for the International Space Station using a Kit for External Repair of Module Impacts (KERMIt) [15] and shown in Figure 18. For the KERMIt application, a toggle-bolt-like mechanism would be passed through the hole and a two-part epoxy filler would be pumped into the hole and allowed to cure in place. Aside from the epoxy filler, this idea is also similar to a typical conventional home repair technique for a hole in drywall.



Research Previous Work, Look for Analogous Problems

EVA Repair Methodology Proposed for ISS

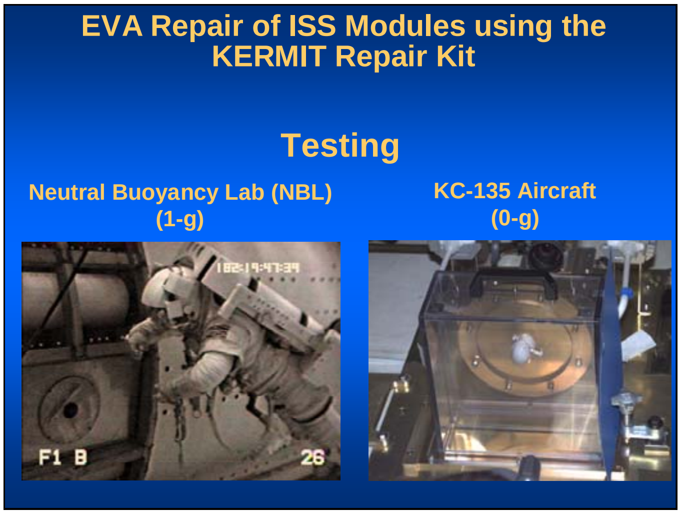
MAJOR KERMIt ELEMENTS

Figure 18. Analogous methods for repair such as the Kit for External Repair of Module Impacts (KERMIt) served as an initial idea or starting point for the “Plug” concept for RCC repair.

The KERMIt repair technique was developed to repair a hole in a previously pressurized ISS module which had to be isolated and, thus, completely depressurized. An EVA astronaut would have to effect a temporary repair of the module during a spacewalk to allow the module to be pressurized and then a permanent repair completed from inside the module. The EVA tools were developed and simulations were run in the Neutral Buoyancy Lab and in 0-g aboard the 0-g KC-135 aircraft at the Johnson Space Center as shown in Figure 19. In the lower right of Figure 19 the two part epoxy flows through the hole and into the cabin in 0-g and provides a leak-tight seal for re-pressurization. Tests were also conducted in glove box facilities at MSFC.

The first plug concept proposed by ATK Thiokol after the initial Technology Exchange Forum (TEF) held at JSC from June 3-4, 2003 is shown in Figure 20. The original idea uses a flexible molybdenum spider, a threaded high temperature fastener, and silica cloth umbrella, a front face rigid plug and a port for filling the umbrella with an ablative material.

Very early in the development stages, ATK Thiokol adopted a “torch” test technique to simulate the elevated temperature of entry heating at a very basic and material level. See Figure 21. It is important to use prototypes and sub-element tests to fail and learn fast and furious in what Jack Matson terms “Intelligent Fast Failure” [16].



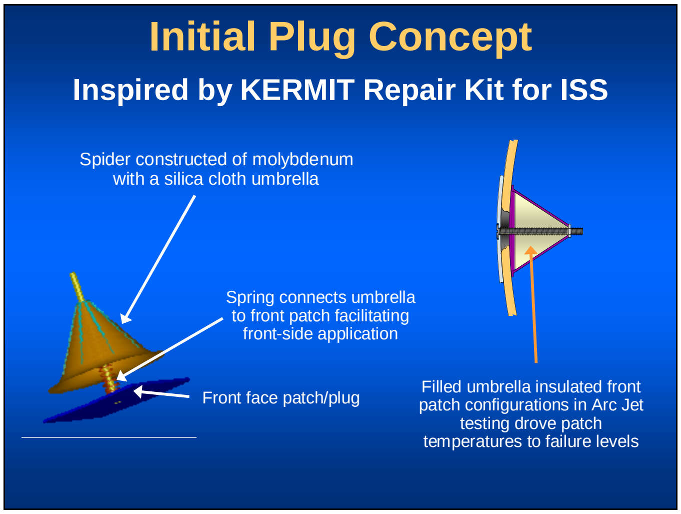
EVA Repair of ISS Modules using the KERMIT Repair Kit

Testing

Neutral Buoyancy Lab (NBL)
(1-g)

KC-135 Aircraft
(0-g)

Figure 19. Testing of the Kit for External Repair of Module Impacts (KERMIt) in the Neutral Buoyancy Lab (NBL) and in 0-g in the KC-135 aircraft.



Initial Plug Concept

Inspired by KERMIT Repair Kit for ISS

Spider constructed of molybdenum with a silica cloth umbrella

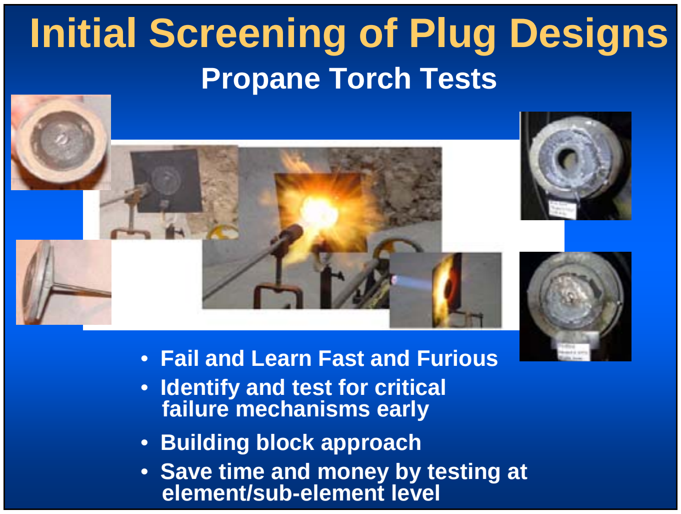
Spring connects umbrella to front patch facilitating front-side application

Front face patch/plug

Filled umbrella insulated front patch configurations in Arc Jet testing drove patch temperatures to failure levels

Figure 20. Analogous methods for repair such as the Kit for External Repair of Module Impacts (KERMIt) served as an initial idea or starting point for the "Plug" concept for RCC repair.

Failure is an option, often times a necessary option in design. However, failure to learn from our mistakes is not. The need to test and fail and learn and test etc. is crucial for the innovative design process. We learn so much more after a failure than a successful test and by doing so it often times stimulates the creative process. I equate "intelligent" in Dr. Matson's terminology to mean that we develop reasonable building block tests to address critical failure mechanisms early and have the foresight to recognize when and how our tests do not simulate the actual environment. Hence, do not discard concepts which may have failed due to non-realistic test conditions.



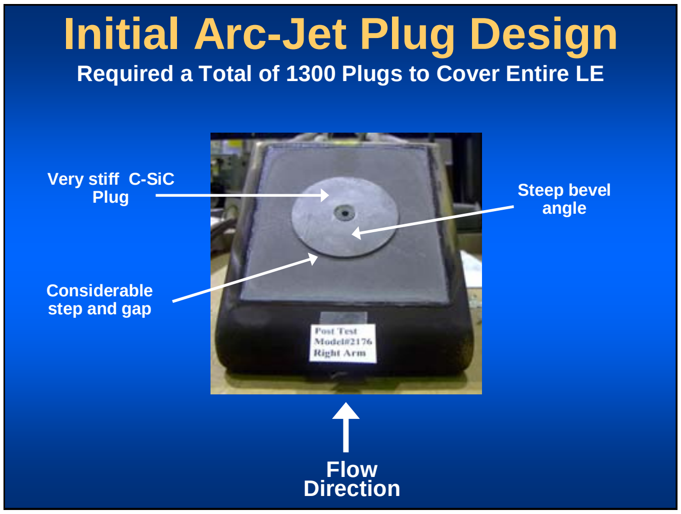
Initial Screening of Plug Designs

Propane Torch Tests

- Fail and Learn Fast and Furious
- Identify and test for critical failure mechanisms early
- Building block approach
- Save time and money by testing at element/sub-element level

Figure 21. Initial screening of plug RCC repair concepts using a torch test.

Prior to June 2004, the ATK Thiokol plug design evolved to the concept shown in Figure 22. Because it was thick and thus rigid, it required over 1300 different rigid C-SiC plugs (to accommodate the variations in curvature of the various critical regions of the RCC leading edge). In addition, it had a large step to the flow (> 0.1 inches) and had a steep bevel angle. The large step and steep bevel angle caused increased local heating and temperatures to rise above the active oxidation limit of SiC (3250 degrees F) and premature failure (Figure 22). The root cause of this problem, however, was not discovered and corrected until the R&D Repair Team suggested conducting parametric CFD analyses as documented in a later section. The requirement for 1300 plugs also made this design very unattractive from a cost, schedule, and operations standpoint. The Shuttle Orbiter would have to carry all plug concepts for the first mission and any stand-alone flights such as the Hubble repair mission.



Initial Arc-Jet Plug Design

Required a Total of 1300 Plugs to Cover Entire LE

Very stiff C-SiC Plug

Steep bevel angle

Considerable step and gap

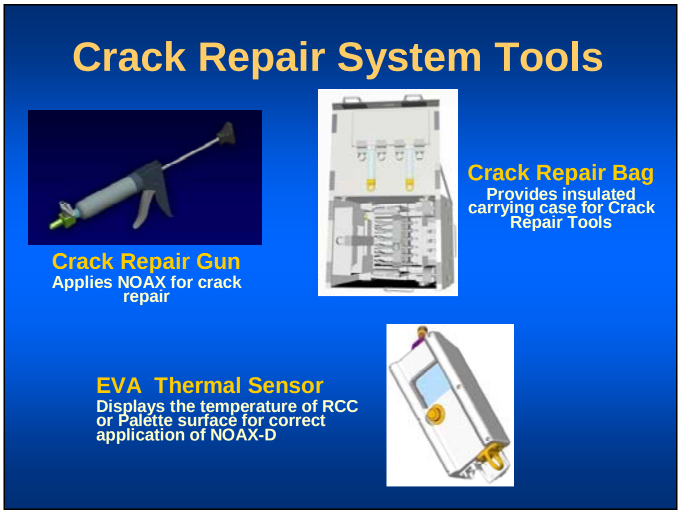
Flow Direction

Figure 22. Initial ATK Thiokol Plug design for RCC repair.

Hence, the status of the plug repair concept prior to the R&D Innovative Design Workshop was that none of the plug designs had survived the maximum design heating condition (peak temperature of 2960 degrees F) for more than a couple of minutes (the high heating portion of typical Shuttle entry lasts approximately 15 minutes).

CRACK REPAIR

A category of methods for repairing minor coating damage, small cracks and holes in RCC on orbit, called “crack repair”, included materials which would be applied to the damaged area by an EVA astronaut and cure and adhere to the surface of the RCC. The crack repair material which was downselected is a pre-ceramic polymer called NOAX (Non-Oxide Ablator Experimental). NOAX has a “putty-like” or “caulk-like” consistency at reasonable on-orbit temperatures and is applied manually using a caulk-gun-like applicator which has a vacuum-sealed container of the material as shown in Figure 23. This repair method requires the EVA astronaut to use tools to spread and outgass the material while EVA and to spread and apply the material smoothly over the damaged region.



Crack Repair System Tools

Crack Repair Gun
Applies NOAX for crack repair

Crack Repair Bag
Provides insulated carrying case for Crack Repair Tools

EVA Thermal Sensor
Displays the temperature of RCC or Palette surface for correct application of NOAX-D

Figure 23. EVA tools developed to apply the NOAX pre-ceramic polymer RCC crack repair material.

The application is very dependant on the temperature of the NOAX and the surface to which it is applied and, hence, requires the use of a thermal sensor to monitor application temperatures.

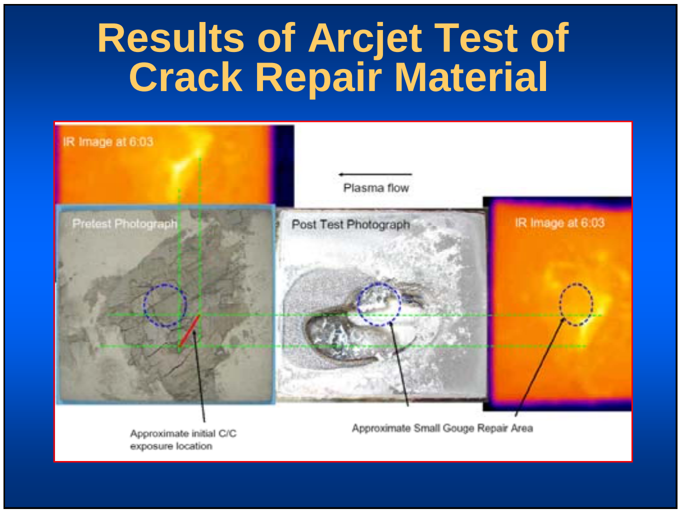
Once the material is applied to the surface, it cures during the normal day-night thermal cycles on orbit and then relies on the entry heating to convert the polymer to a ceramic material; thus, providing the high-temperature oxidation protection during entry.

Prior to the R&D Innovative Workshop at LaRC in June 2004, there were no successful tests of any crack repair materials in an arcjet. In addition, because it was extremely difficult to model this material behavior and predict performance, it would be necessary to conduct numerous tests for varying conditions with varying levels of damage to develop a comprehensive estimate of the probability of failure and/or risk of using this method in the event of a contingency and eventual return of the crew with a damaged wing leading edge.

One of the failure mechanisms observed during arcjet testing (Figure 24) was as the temperature rose to over 2800 degrees F, the material flowed and sheared off the surface. Another failure mechanism was if the material was applied at too low a temperature and was too thick, small chips or "flakes" of the NOAX came off and resulted in a large step to the local flow. The local temperatures at this step can become high enough (> 3250 degrees F) to burn through even a good section of the RCC with its SiC coating intact as shown in Figure 25.

Arcjet Test of Crack Repair Material

Figure 24. Arcjet test of NOAX RCC crack repair material.



Results of Arcjet Test of Crack Repair Material

Figure 25. Repair test of NOAX crack-repair material showing region where a chip of the material pops off and the resulting step causes local heating and temperatures to exceed the coating limit of SiC and subsequent burn through.

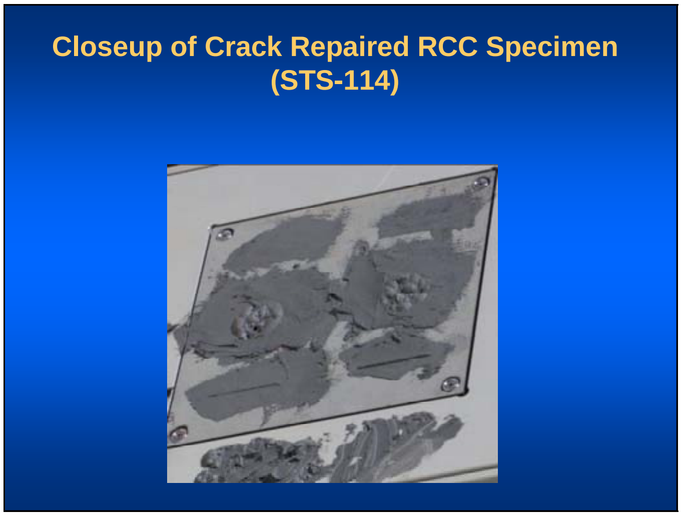
The dashed blue circle in Figure 25 depicts a region where the 0.030-inch SiC coating was machined off the front and rear surfaces of the RCC specimen. The solid red line depicts the region where a piece of the cracked NOAX coating flakes off during the test and causes the bright linear indications in the top left and lower right. These indications occur because the step in the NOAX material that remained was normal to the flow and produced excessive localized heating and eventual burn through of the specimen. This highlights the sensitivity of the damaged and repaired section of the leading edges to slight protuberances to the flow and the complexity of conducting a successful repair on orbit.

Figure 26 is a picture of astronaut Steve Robinson evaluating several of the newly developed tile and RCC TPS repair techniques in the payload bay of STS-114.


Tile and RCC Repair DTO

Figure 26. EVA astronaut Steve Robinson demonstrating several tile and RCC TPS repair techniques in the payload bay during STS-114.

Figure 27 is a closeup of the NOAX RCC crack repair Detailed Test Objective (DTO) after the NOAX material cured after several orbits. Notice that even though the material was outgassed and kept in a vacuum cartridge prior to flight, the material still can outgass and bubble up when applied on orbit if proper procedures are not developed. The potential problem with such outgassing is that the porosity formed can fracture during entry heating and form defects which can cause excessive local heating similar to that exhibited during the arcjet test shown in Figure 25.



Closeup of Crack Repaired RCC Specimen
(STS-114)

Figure 27. Closeup of RCC crack repaired specimen using NOAX pre-ceramic polymer on orbit during STS-114.

R&D RCC REPAIR TEAM INNOVATIVE DESIGN WORKSHOP (JUNE, 2004)

BACKGROUND

In early June it became obvious that the TPS repair teams were struggling to develop concepts for on-orbit tile or RCC repair. We approached the Orbiter Project Manager with a plan for developing a team to go off and brainstorm for new ideas for solving the repair problem. We hosted a small, 2.5 day innovative design workshop at NASA LaRC in June 2004. We selected a group of key researchers, engineers, etc., from around the country and developed a very short workshop at LaRC's Innovation Center. It provided several rooms with floor-to-ceiling white boards, A/V equipment, computer capabilities, supplies, IT support and a facilitator. We organized the meeting to first review the current status of the RCC Repair Project; summarize the design requirements (e.g., cost, schedule, technical requirements, constraints, etc.); present a technology status with respect to several key disciplines (e.g., aerothermodynamics, thermal, materials, and structures, etc.); review the status of several key concepts such as crack repair and plug repair; present a short review of effective techniques for enhancing innovative thinking such as brainstorming and TRIZ [17]; facilitate several brainstorming sessions; and develop a strategy for cataloging concepts and paring down the list to a manageable size. We arranged for keynote dinner speakers to help the team think outside the box and supplied each member with a copy of reference [17] to read prior to the meeting.

DEVELOPING THE TEAM

"Two heads are better than one, if at least one listens"

Selecting and developing the team is crucial. One of the most important aspects of a healthy team is good communication. I was very fortunate in being allowed much freedom in that I was allowed to hand pick each individual member of the original team. Only one or two of my original candidates could not attend the kickoff meeting or workshop. The list of attendees is shown in Figure 28.

Developing the Team

Aaron Matheson	ATK Thiokol	Material testing
Ali Yousefiani	Boeing HB	High temp materials & processes
Brian Sullivan	MR&D	Materials/Structures
Bruce Steinetz	NASA GRC	High Temp Seals/TPS and turbine engines
Charlie Camarda	NASA JSC	Thermal Structures, heat pipe, Crew
Clark Thompson	Boeing	EVA Systems
David Glass	NASA LARC	High temp structures and materials, heat pipes
Don Curry	NASA JSC	Thermal Protection Systems-RCC
Don Pettit	NASA JSC	Chemical Engineering, Crew, EVA
Francesco Iannett	Design Ideas, Inc.	Design concepts
James Reeder	NASA LARC	Material mechanics
Jim Nesbitt	NASA GRC	Oxidation, high T coatings
Joel Alexa	Lockheed Martin	Plasma Spray
John Koenig	SRI	Materials/Testing
Ken Cooper	NASA MSFC	Fabrication non-metallics
Mike Gubert	MSFC/Sverdrup	Thermal protection system
Pete Hogenson	Boeing HB	M&P TPS
Peter Gnoffo	NASA LARC	Aerothermo Environment
Steve Hales	NASA LARC	Metals and Plasma Spray
Steve Scotti	NASA LARC	Thermal Structures
Suraj Rawal	Lockheed Martin	C-C/C-SiC; TPS passive/active
Tom Horvath	NASA LARC	Aerothermo Environment
Wallace Vaughn	NASA LARC	C-C/C-SiC materials

Figure 28. Attendees of the R&D RCC Repair Team Innovative Design Workshop held at NASA LaRC, 15-17 June, 2004.

I believe it is important to have all the key disciplines and background experts available early on. I also believe it is important that every member of the team is given the "big picture" and is allowed to see where his/her piece fits in that big picture. I would also agree that it is important to keep the team as small as necessary and to have the required skills to solve the problem and, as a large team as necessary, to complete the job within the assigned schedule and budget constraints. The number of attendees was about 23 people with areas of expertise ranging from thermal structures, materials (both metallic and refractory composite), high temperature seals, coatings, RCC, ablation, manufacturing, aerothermodynamics, structures, fabrication, etc. In addition, I seeded the team with several out-of-the-box creative thinkers and two astronauts (myself and Dr. Donald Pettit).

It is important to instill ownership, responsibility and accountability in every member of the team, ensure everyone has access to the big picture and develop an atmosphere where rapid learning of multidisciplinary skills is easy and accessible to all.

What was amazing was that in 2.5 days we developed approximately 60 concepts which we distilled down to a manageable size (approximately 12) in several weeks and had developed and tested several prototype concepts successfully in only three months time. We applied for over 7 patents as a team of which NASA has chosen to pursue three. The number of concepts grew and shrank over the course of several weeks as did the "flexible critical mass" of people who made up the R&D Repair Team. I selected Dr. Steve Scotti from NASA LaRC to personally lead this team and the results and accomplishments of this team is the bulk of what I will present next.

ENCOURAGING CREATIVE THOUGHT

“Everyone is a da Vinci”

While it is very important to select a good team, it is also very important to do everything possible to enhance the creative output of that team. We selected a setting for our initial meeting and workshop which was removed from the normal work setting and designed a number of non-technical presentations to help accelerate the creative process. Conducting innovative workshops away from normal business or work settings and eliminating distractions is important. A relaxed setting with social activities and opportunities for informal discussion is also helpful. The atmosphere and environment you choose and the tone you set at the beginning or initiation of the project is very critical.

For creativity to flow there needs to be a universal recognition by every member of the team that “risk” taking is critical, there are no silly ideas and that “failure is not only an option but a requirement for success” is voiced. The “permission to try and try again” as described by NASA historian James Schultz [18], or what I would like to call “permission to fail” is necessary in research and is also vital during the learning phase of concept development. To quote Schultz: “Learning by repeated attempts may appear cumbersome, but failures indicated areas where further research was needed to improve the understanding of flight”. Jack Matson coins a term “Intelligent Fast Failure (IFF)”[17]. He describes this as a process by which you drive to experimentation early with rapidly developed, inexpensive prototypes early and fail and learn rapidly. In his words “the faster the experimental phase, the more likely a successful innovation will result”.

Fear of failure, I believe, is one of the biggest impediments to creativity and it is also one of the key impediments to each individual on the team from realizing his or her inner creative ability. Often times the people with the most knowledge/ expertise are the ones most reluctant to look foolish in front of a group and, hence, often times need to be coaxed to accepting public failure and potential ridicule. To draw the most from each individual team member early, the leader and/or facilitator must develop an environment where brainstorming “silly” ideas is encouraged. Often times by “flipping” the silly ideas around or blowing “conventional” ideas out of proportion we stumble on an insight to a novel solution of the problem at hand.

Another important ingredient for creativity is time. In particular, you must allow time for unconscious thought in trying to solve the particular problem at hand. Once you develop a set of ideas, it is often very helpful to let those ideas gel or incubate. After our first workshop, it took several months for ideas to morph and/or evolve before we were ready to focus in on a select set to pursue in the timeframe allotted.

During the workshop I brought several pieces of hardware to stimulate ideas. Other members of the team did likewise. The use of 3-D models and graphic tools are very helpful for stimulating creative thought. Other “tools” used were techniques of conventional and accelerated forms of “brainstorming and using other ideas such as TRIZ [17]. TRIZ is a Russian acronym for Theory of Inventive Problem Solving. It is a structured system or algorithm for inspiring creative solutions of problems which has been taught in Russia for over 40 years and can begin as early as the 5th or 6th grade of elementary education. I distributed copies of reference [17] to all members of our initial team to read prior to attending the workshop. In addition, I solicited the support of a facilitator from the LaRC Innovation Center, Ms. Donna Phillips, to help keep things moving and to offer suggestions and insights as to how the process was progressing.

R&D RCC REPAIR TEAM CONTRIBUTIONS TO RETURN TO FLIGHT OF STS-114

Prior to the initiation of the R&D RCC Repair Team, the SSP had expended considerable resources to develop on-orbit RCC repair techniques. After over a year of effort by industry (Boeing, Lockheed, ATK Thiokol, etc.) and NASA, in June 2004 we had not yet survived the full entry heating profile of the highest heating location on the leading edge. Both the NOAX crack repair and the plug repair concepts were failing wedge arcjet tests both at ARC and at JSC. After the initial innovative design workshop of the R&D RCC Repair Team, a plan for developing a series of new ideas and concepts was put in place with the intention of developing and maturing a collection of tools for repairing damaged RCC on orbit with sizes ranging from small coating damage to large holes (~16 x 16 inches). The various tools developed are shown in Figure 29.

Enhance Creativity and Innovation

(Return-to-Flight R&D RCC Repair Project)

Figure 29. Some of the tools developed for on-orbit RCC repair by the R&D RCC Repair Team.

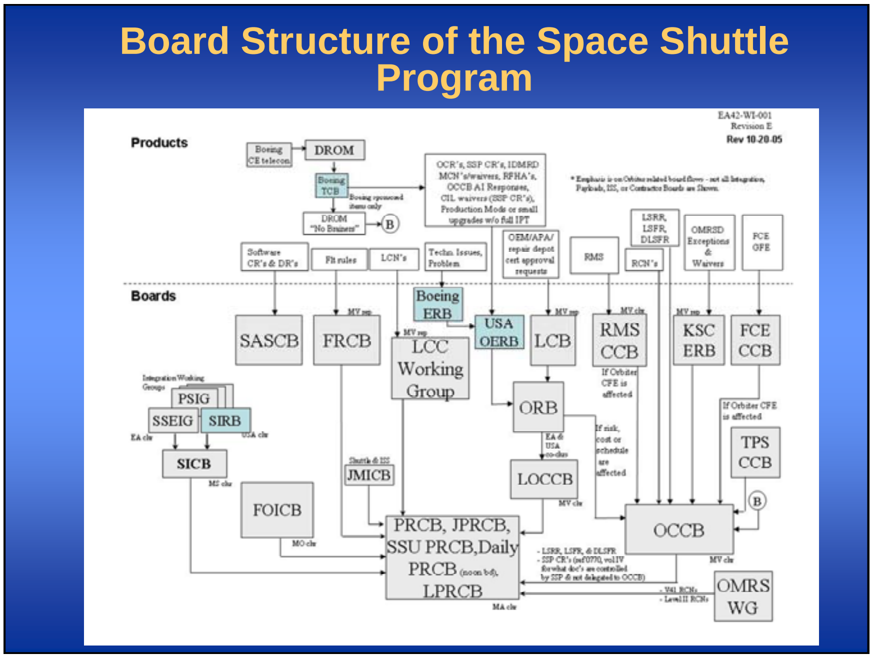
The relevant tools and repair concepts are summarized next. Then, I am going to illustrate the association of some of the TRIZ and brainstorming concepts that were used or that could be applied to understanding how and why these discoveries occurred. I will also discuss how these ideas were adopted by the SSP and used to enhance some of the existing concepts (such as the plug) to develop a workable solution which was eventually flown.

In less than three months the R&D team developed (Figure 29): 1) a series of drill bits that could drill and tap simultaneously through RCC material using the Power Grip Tool (PGT) used by the EVA astronauts; 2) C-SiC fasteners that would be used to either fill a small area of coating loss or a small hole and/or mechanically attach a SiC plug/patch; 3) a prototype torque limiter tool to be used by the astronauts to prevent over-torquing and damage to the C-SiC fasteners; 4) a thin, doubly-curved, flexible plug called a small area repair (SAR) and flexible gaskets to repair moderate size damage or holes; and 5) a large, flexible C-SiC repair patch which could cover a very large hole in a wing leading edge (~16 x 16 inches) and which used multiple SARs to secure it in place. The R&D team used a building block approach to simultaneously develop a set of tools or concepts that were matured sequentially and in parallel and which provided a capability to successfully repair larger and larger size damage. All the components of this repair system were matured to the point of successfully surviving arcjet tests up to the SAR. The LAR is still under development and the capability to test a full-scale mockup is impossible due to the limited size of current arcjets.

DEVELOPMENT OF A SELF-ADVANCING STEP-TAP DRILL

One of the ideas proposed at the initial Technology Exchange Forum in June 2003 by Francis Schwind of C-CAT Corporation was to drill and tap a hole in the damaged section of the leading edge and to fill that hole with either a RCC or a SiC fastener. Francis even carried a working model of his idea to the meeting. Unfortunately, the idea was never carried forward by the team. The SSP team attempted to drill a hole in RCC, however, they found it impossible to develop a drill bit which could penetrate the SiC coating of the RCC.

Some of the critical constraints to developing this tool were the fact that the PGT was limited to less than 25 in-lbs of torque and the normal force applied to the RCC surface had to be less than 5 lbs over a 10-sec application period. This last constraint was due to a dynamic motion limit of the EVA astronaut in foot restraints on the Space Station Robotic Manipulator System (SSRMS) and the Space Shuttle being suspended by the Shuttle Robotic Manipulator System (SRMS). Another constraint was that RCC material to use in the development and experimentation stages was in short supply and controlled by the Leading Edge Sub-System Problem Resolution Team (LESS PRT). Figure 30 is a schematic diagram of some of the SSP Boards and the paths that are necessary to have decisions made.



Board Structure of the Space Shuttle Program

Figure 30. Schematic representation illustrating the complexity of the Space Shuttle Board process for decision-making.

This is a very bureaucratic and structured process and all the power to decide the priority of RCC material resides in the LESS PRT which, immediately after the accident, had very little participation in RTF repair activities. The LESS PRT interfaces the Board process at the top through the "Technical Issues, Problem box and also at the right through the TPS CCB (configuration control board box). Hence, in order for the R&D team to quickly obtain small pieces of real RCC material to experiment with, the team relied on key individuals such as Dr. John Koenig of Southern Research Institute (SRI), Francis Schwind of C-CAT Corporation, and Suraj Rawal of Lockheed Missiles and Space Company (LMSC) who graciously provided specimens to test.

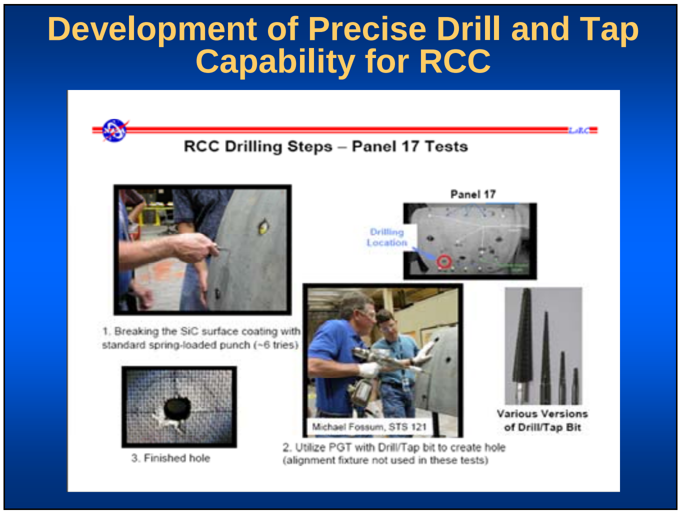
Much of the preliminary design and testing was done in the garage laboratory of Dr. Donald Pettit. Don flew on ISS as a crew member of the Expedition 6. Upon his return, he and I set out to conduct much of the preliminary testing in his garage/lab (Figure 31). I want to emphasize that a key to the success of the repair effort was the ability to prototype concepts quickly and to experiment/test, fail, and learn rapidly.

The Unofficial RCC Repair Lab

Figure 31. The unofficial RCC Repair Lab (Don Pettit's garage) (left to right Don, Dave Throckmorton, Charlie Camarda, and Woodrow Whitlow).

A key "aha" moment occurred in our preliminary design and testing of drill bits and that enabled us to develop a strategy to breach the very hard exterior SiC coating. Using a simple spring-loaded center punch, we were able to easily chip a very small hole in the SiC coating (after only 3-6 applications). Once the coating was breached and the C-C substrate was showing, it was then very easy to drill through the RCC specimen. Although most of the damage regions we would need to repair on orbit would already have substrate showing, it would also be necessary to drill through undamaged RCC to attach a LAR for example.

We then enlarged our small team to include a skilled toolmaker from LaRC (Ron Penner) and went to a small machine shop to fabricate several of our initial prototypes. The bits design was stepped to minimize the normal force necessary to below 5 lbs. We conducted tests using the PGT to verify that we could drill and tap up to a 1-inch hole in RCC with less than 5 lbs normal force (Figure 32). We were also able to design, fabricate, test and flight certify a set of such drill bits in only 7 months time from initial conception (Figure 33). See references [19] and [20] for further details concerning the development of the self-advancing step-tap drill.



Development of Precise Drill and Tap Capability for RCC

RCC Drilling Steps – Panel 17 Tests

1. Breaking the SiC surface coating with standard spring-loaded punch (~6 tries)

2. Utilize PGT with Drill/Tap bit to create hole (alignment fixture not used in these tests)

3. Finished hole

Figure 32. EVA astronaut on STS-121 Mike Fossom using a power grip tool (PGT) and testing the self advancing step-tap drill bit on a spare RCC leading edge segment.

RCC Drill Bits

Figure 33. STS-114 RTF astronaut Charlie Camarda with self advancing step-tap drill bits on orbit.

DEVELOPMENT OF C-SIC FASTENERS

Francis Schwind of C-CAT Corp. was responsible for the design of the C-C and C-SiC fasteners. We experimented with many materials, layups, and head designs that would enable a captive tool to use to interface with the EVA PGT. In addition, the design of the head had to have as low a profile as possible so as not to protrude into the flow and cause excessive local heating; yet it had to be robust enough to accommodate the torque required for securing the fasteners. One of the concepts developed is shown in the lower right hand corner of Figure 34. Fasteners were designed to be used alone, with SiC washers, or together with the SAR and LAR concepts.

Development of C-SiC Fasteners

Initial C-C Fastener and Washer For Demonstration

C-SiC Fasteners with Captive Head Design

Figure 34. R&D development of C-SiC fasteners to be used alone (to plug small hole damage and/or in conjunction tithe the small- and large-area repair concepts (SAR and LAR).

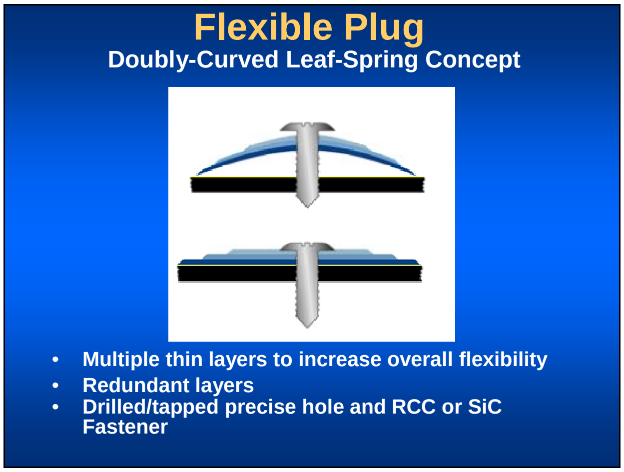
CHANGING THE PARADIGM

It was very difficult to convince the Program that is would be advantageous to actually drill a hole in RCC to repair it. However, when you think about it you are actually drilling out a region of damaged coating and/or substrate, which would have burned through during entry, and are replacing it with better material than what was there originally (in our case replacing the C-C substrate with a C-SiC fastener). Not that much different from what a surgeon does on a routine basis. Yet this was a very difficult concept for the LESS PRT and the SSP to accept even though the ATK Plug concept would require a 1-inch hole to enable the TZM T-bar to be placed into the leading edge cavity.

As you will see in the next section, the excellent fit of the fastener, the ability to evaluate the integrity after installation, and the ability to provide a redundant locking mechanism (e.g., coating the threads with a Type-A glass) makes this idea an attractive option to the crack repair or plug methods. Individual arcjet tests of small holes filled with C-SiC fasteners were conducted as a possible solution for small holes (e.g., those caused by micrometeoroids) which were too large for the NOAX crack repair material and much smaller that the 1-inch minimum hole size for the plug repair method. The logic was such that it would be preferable to only drill a small hole rather than have to enlarge a small hole to a 1-inch diameter to accommodate the T-bar section of the plug.

DEVELOPMENT OF FLEXIBLE C-SIC COVERS FOR PLUGS, SARS AND LARS

One of the key drawbacks of the original ATK Plug design was that it was too stiff and required over 1,300, 9-inch diameter unique plugs to cover all the critical areas of the leading edge. Several of the preliminary concepts the R&D Team developed were aimed at developing a highly flexible design which enabled large deformations and would flex and hug the curved RCC leading edge surface. One of the original embodiments, shown in Figure 35, was the use of multiple, very thin, curved C-C or C-SiC material which could be nested like “leaf-springs” to allow large deformations, and yet provide a large enough thickness to be robust and redundant and provide sufficient oxidation protection to the damaged RCC leading edge.



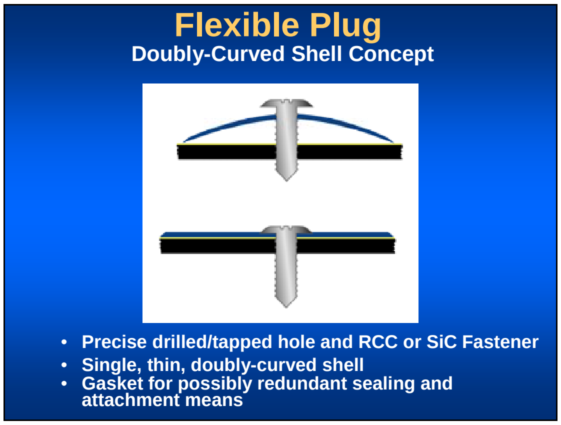
Flexible Plug

Doubly-Curved Leaf-Spring Concept

- Multiple thin layers to increase overall flexibility
- Redundant layers
- Drilled/tapped precise hole and RCC or SiC Fastener

Figure 35. R&D RCC Repair Team doubly-curved, thin shell, C-SiC leaf-spring idea for a flexible plug design.

Another variation of this idea was just a single doubly-curved, thin C-SiC shell, shown in Figure 36, which, together with a thin flexible gasket, could provide redundant attachment means and a further mechanism for preventing flow under the plug and oxidation of the substrate.



Flexible Plug

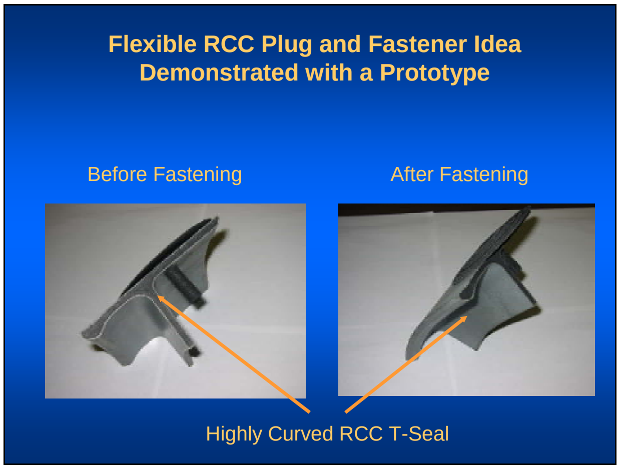
Doubly-Curved Shell Concept

- Precise drilled/tapped hole and RCC or SiC Fastener
- Single, thin, doubly-curved shell
- Gasket for possibly redundant sealing and attachment means

Figure 36. R&D RCC Repair Team doubly-curved, thin shell idea for a flexible plug design.

The R&D Repair Team also submitted a patent application for the curved shell flexible patch concept [21]. However, the application was not approved for submittal by JSC’s Patent Office.

To demonstrate the concept and to get buy-in from the SSP, I visited C-CAT and designed a curved shell concept out of C-C material. They were able to manufacture it together with a C-C bolt and a scrapped T-Seal (manufactured and delivered in only 1 week). This demonstrated that you could manufacture a “very brittle” C-C or C-SiC material to be doubly-curved and flexible enough to conform to a highly curved surface (see Figure 37).



Flexible RCC Plug and Fastener Idea Demonstrated with a Prototype

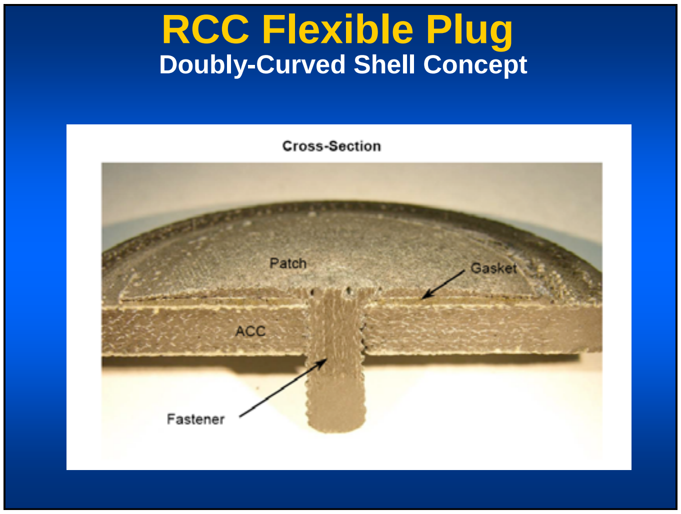
Before Fastening

After Fastening

Highly Curved RCC T-Seal

Figure 37. Rapid prototype of a doubly-curved, thin RCC plug fastened to a highly-curved RCC T-Seal and conforming nicely to the curved T-Seal shape. This concept was demonstrated to the Program on 9/17/04).

A cross section of the R&D SAR concept complete with C-SiC fastener and flexible gasket is shown in Figure 38. Notice the plug and gasket conform nicely to the RCC plate, and the threads of the C-SiC fastener and plate ensure a tight fit. Application of a Type-A glassy sealant on the threads of the fastener causes a secondary bond and fuses the fastener in place during entry heating. This can serve as a secondary locking feature for this design concept.

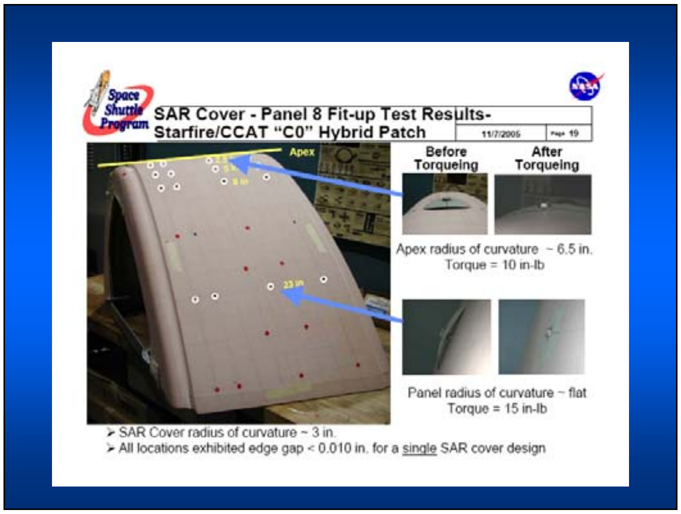


RCC Flexible Plug

Doubly-Curved Shell Concept

Figure 38. Cross section of the R&D 4-inch-diameter, doubly curved, C-SiC plug and flexible gasket (small area repair (SAR) secured to a RCC plate using a C-SiC fastener.

The R&D Repair Team's SAR design was a C-C or C-SiC 4-in.-diameter, doubly-curved thin shell which was fastened to the leading edge using a C-C or C-SiC fastener. A fit demonstration on the most highly curved Shuttle RCC leading edge was performed and is shown in Figure 39. As shown in the figure, the SAR covers a radius of curvature of ~3 inches and all locations exhibited a maximum edge gap of only 0.01 for a single SAR cover design.



SAR Cover - Panel 8 Fit-up Test Results-
Starfire/CCAT "C0" Hybrid Patch

11/7/2005 Page 19

Apex radius of curvature ~ 6.5 in.
Torque = 10 in-lb

Panel radius of curvature ~ flat
Torque = 15 in-lb

- SAR Cover radius of curvature ~ 3 in.
- All locations exhibited edge gap < 0.010 in. for a single SAR cover design

Figure 39. Fit check of the R&D RCC Repair Team's 4-inch diameter doubly curved, C-SiC small area repair (SAR) concept on the most highly curved Orbiter RCC leading edge.

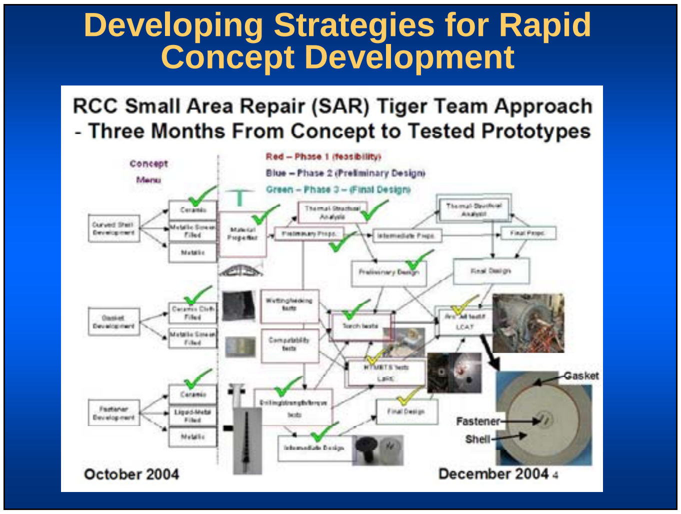
THE IMPORTANCE OF RAPID PROTOTYPING AND RAPID CONCEPT DEVELOPMENT

The term "rapid concept development" is a term I coined to describe the practical application of ideas such as intelligent fast failure [16]. This, combined with a building block approach for test and analysis, incorporates knowledge of both concept behavior in relevant environments and potential failure mechanisms of each concept.

The schematic diagram in Figure 40 illustrates the number of various concepts which were tested and analyzed to arrive at the selection of one of the final designs for the SAR concept. The R&D team evaluated: high temperature metallic, ceramic, and filled ceramic and metallic screens and cloths for doubly-curved cover materials; metallic and ceramic screens and cloths for flexible gaskets; high-temperature metallic and ceramic filled and unfilled fasteners; and various materials and designs for the self-advancing stepped-tap drill bit. We were able to rapidly develop and fabricate concepts and prototypes and conduct torch (Figure 41) and drill tests using Don Pettit's RCC Lab (Figure 31). In addition, we were able to make use of the Langley HYMETS (small arcjet facility) facility (Figure 42) to obtain representative heat, pressure and temperature tests of samples at the small coupon size. This was done quickly prior to having to be scheduled in the larger arcjet facilities, which at the time were heavily booked up evaluating other program concepts. This methodology for testing proved very efficient and effective and was crucial for us to be able to develop a SAR concept, complete with drill-and-tap tool;

fastener; gasket; and cover in only three months time (lower right-hand corner of Figure 40) which survived full-scale arcjet tests.

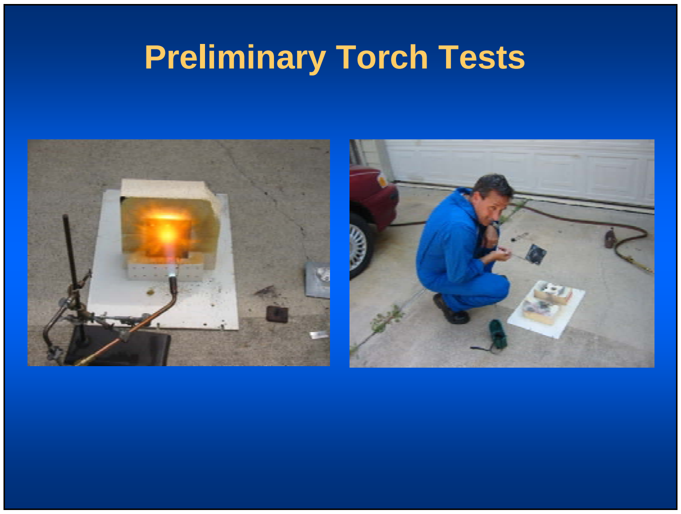
Using this strategy, we were able to evaluate many ideas/concepts rapidly and at very little cost to the Program.



Developing Strategies for Rapid Concept Development

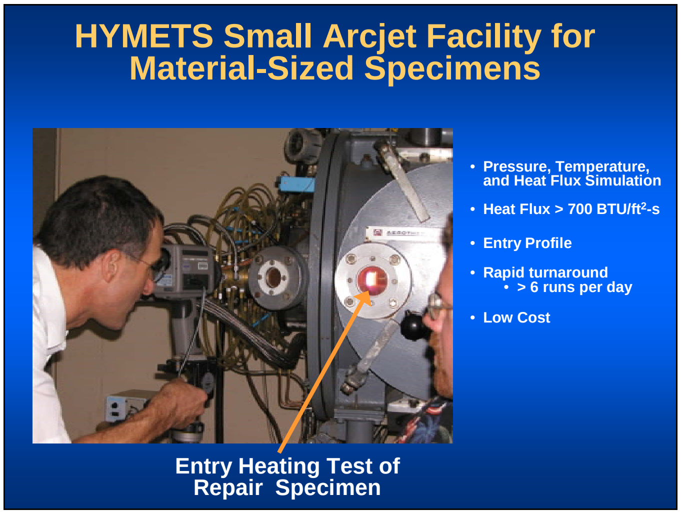
RCC Small Area Repair (SAR) Tiger Team Approach - Three Months From Concept to Tested Prototypes

Figure 40. Schematic diagram of rapid concept development strategy which led to a working small area repair (SAR) prototype which survived full-scale arcjet tests in only three months time.



Preliminary Torch Tests

Figure 41. Preliminary torch tests outside the Don Pettit Unofficial RCC Repair Lab.



HYMETS Small Arcjet Facility for Material-Sized Specimens

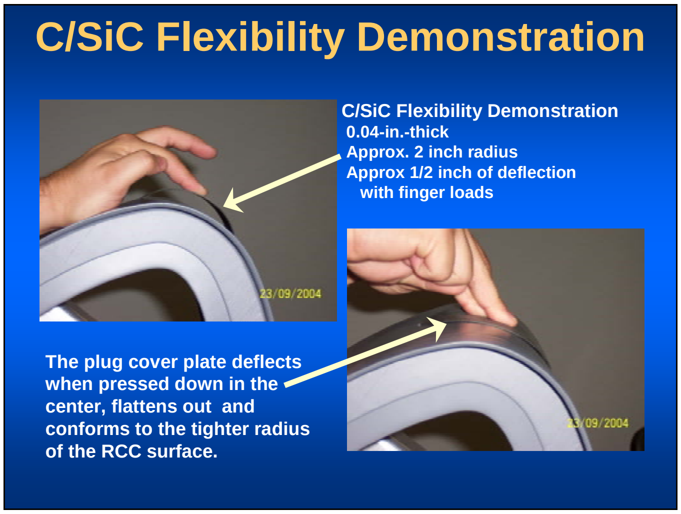
- Pressure, Temperature, and Heat Flux Simulation
- Heat Flux > 700 BTU/ft^2-s
- Entry Profile
- Rapid turnaround
  - > 6 runs per day
- Low Cost

Entry Heating Test of Repair Specimen

Figure 42. The RCC R&D Repair Team made much use of the small LaRC arcjet facility called HYMETS to rapidly evaluate many concepts for the small area repair (SAR) RCC repair concept.

Rapid Prototyping - The ability to rapidly prototype a working model to demonstrate the feasibility of a concept to program managers, who are not as knowledgeable technically or who may have incorrect pre-conceived ideas, is very important. It demonstrates the simplicity and feasibility of the concept and goes a long way in gaining support. After the flexibility demonstration of the C-CAT RCC doubly-curved shell concept (Figure 37) at an Orbiter Configuration Control Board (OCCB, see Figure 30) on 9/17/04, Kevin Rivers machined a “potato chip” C- SiC specimen shown in Figure 43. This was demonstrated to the SSP and to ATK Thiokol on 9/23/07 that they could also fabricate flexible, singly-curved, C-SiC Plugs and reduce the total number of plugs required from 1,300 to less than 20. A second patent was submitted for a flexible plug design [22]. This one was accepted by the JSC Patent Office for submittal as a patent to the US Patent Office.

At the time the R&D Team was presenting their demonstration of a flexible ceramic plug to the SSP, the Program was seriously considering cancelling ATK’s contract to produce 1,300 C-SiC plugs because it would take too long and cost too much. Hence, by incorporating ideas from the R&D Team, we were able to fix a problem with the ATK plug design and would be able to fly a set of 8 plugs on the first RTF mission, STS-114, in the event of moderate damage to the RCC leading edges during the mission.



C/SiC Flexibility Demonstration

C/SiC Flexibility Demonstration
0.04-in.-thick
Approx. 2 inch radius
Approx 1/2 inch of deflection
with finger loads

The plug cover plate deflects when pressed down in the center, flattens out and conforms to the tighter radius of the RCC surface.

Figure 43. Demonstration of a singly-curved, thin, machined C-SiC specimen to the program and ATK Thiokol on 9/23/07.

The final design of the ATK Thiokol 9-inch diameter plug is shown in Figure 44. The conceptual coverage of the “new” flexible plug design is shown in Figure 45 for coverage of RCC panels 8-10.

ATK Thin Plug Concept

Figure 44. Final design of the “new” ATK Thiokol thin, flexible C-SiC plug fro RCC repair.

Target Coverage for Panels 8-10

New Flexible Plug Design Results in ~13-18 Plugs for Total Leading Edge Coverage

Panel 8 plugs

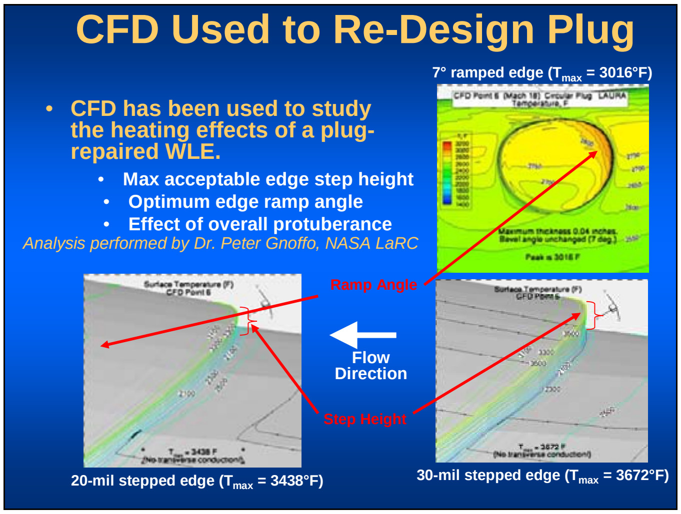
Panels 9 and 10 Left Wing

Figure 45. Demonstration of coverage of ATK Thiokol 9-inch diameter flexible plugs for RCC leading edge panels 8-10.

RE-DESIGN OF THE PLUG USING CFD ANALYSIS

In addition to helping to develop a flexible plug to reduce the number, the R&D Repair Team was also responsible for identifying key aerothermal failure mechanisms early and recommending an analysis/test program to help redesign the ATK plug concept because it had been experiencing premature failures due to local heating caused by the local step height and plug bevel angle.

At the very first R&D workshop in June 2004, Dr. Peter Gnoffo (LaRC) presented CFD aerothermal analyses of damaged RCC. It was at that meeting that we asked Peter if he could provide parametric analyses of the plug with varying step heights and bevel angles. Some of the results of Peter's analyses are shown in Figure 46.



CFD Used to Re-Design Plug

- CFD has been used to study the heating effects of a plug-repaired WLE.
  - Max acceptable edge step height
  - Optimum edge ramp angle
  - Effect of overall protuberance

Analysis performed by Dr. Peter Gnoffo, NASA LaRC

7° ramped edge (T_{max} = 3016°F)

20-mil stepped edge (T_{max} = 3438°F)

30-mil stepped edge (T_{max} = 3672°F)

Figure 46. CFD analyses used to redesign plug to avoid excessive local heating.

Hence, from Figure 46, you notice that if the step height of the plug is less than 0.1 inch and the bevel angle is below 6 degrees, the maximum temperatures remain below the active oxidation limit of SiC (3,250°F) and the plug will survive. When Thiokol designed their plugs to these tolerances and specifications the results in the arcjet tests were successful (Figure 47).

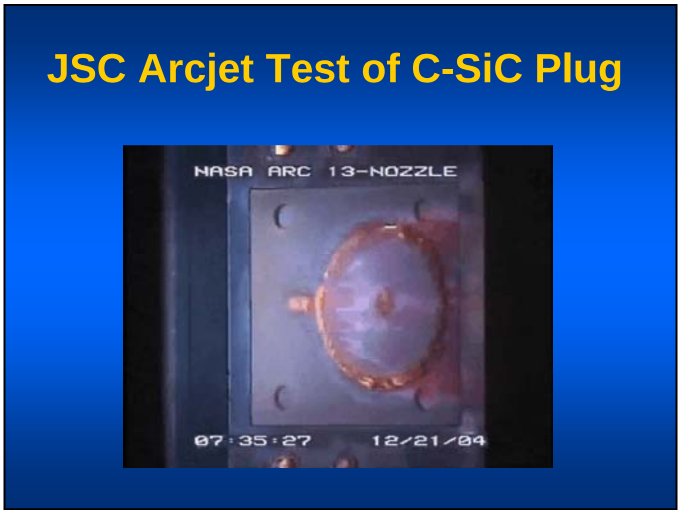

JSC Arcjet Test of C-SiC Plug

Figure 47. Successful arcjet test of a newly re-designed plug using the results of Pete Gnoffo’s CFD analyses.

Large Area Repair (LAR)

The last concept the R&D Repair Team examined and is still in the process of developing is the LAR. The R&D team is the only group that is developing a concept for repairing very large damage (~16 x 16 inches) or hole in the RCC leading edge. The idea is shown in Figure 48 and relies on the development of all preceding concepts described above related to the R&D development program (step and tap drill, C-SiC fasteners, gaskets, SAR, etc.). The only piece remaining to develop is the large, flexible C-SiC cover. The R&D team is currently in the process of developing this cover and, once complete, will have completed development of a full range of tools for repairing RCC on orbit from small coating or crack damage or holes to moderate size holes all the way up to very large size holes (16 x 16 inches). While many of these concepts will not be “certified”, they will be available to use in a last ditch or contingency situation to either save the vehicle and/or the crew.

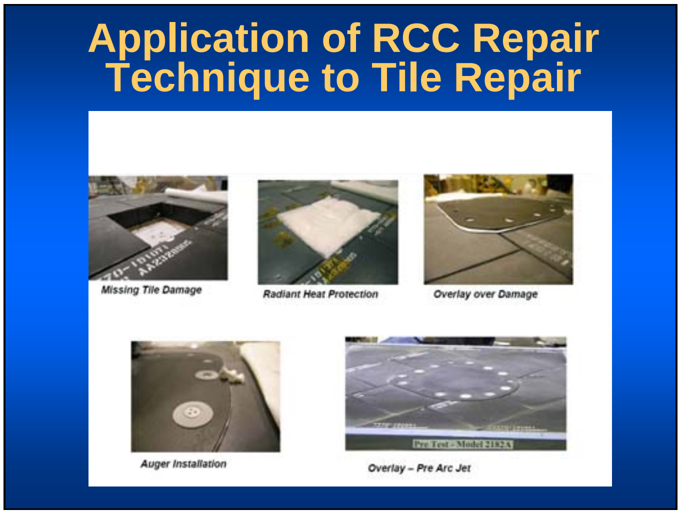
Large-Area RCC Repair

Flexible C-SiC Composite Installation on Panel 8 and 22 Mockups

- Starfire"normal fill", Three Ply Tailored, Flexible C-SiC sheet
  - 3.8:1 Tailored T-300 (1-K tow) weave cloth
  - 3 plies (0.030 in.) thick, densified with Starfire resin and
  - refractory powder fillers
  - C-SiC sheet held on using SAR patches and SAR bolts
- SAR spacing ~ 8in. gave windward gaps less than ~10 mils
- Gaps may be controlled using more SAR patches

Figure 48. Demonstration of large area repair (LAR) concept and attachment means to repair a RCC wing leading edge.

Ideas for mechanical attachment and repair of RCC which arose from the R&D Innovative Design Workshop in June 2004 were also helpful to inspire similar attachment and repair strategies such as the tile repair "overlay" concept shown in Figure 49. The tile "Overlay" concept is currently in the latter stages of testing and analysis and is also flown on-board the Shuttle Orbiter for every mission in case of a contingency.



Application of RCC Repair Technique to Tile Repair

Figure 49. Application of a RCC large area repair (LAR)-like concept for repairing large damage to the Shuttle ceramic tiles (concept called the "overlay" concept by the Tile Repair Team).

SUMMARY AND CONCLUDING REMARKS

This current paper addresses some thoughts on developing high-performing multidisciplinary teams to creatively solve complex engineering problems. The strategies for defining the problem; collecting relevant information and studies;

building the team; creating an environment which encourages learning and creativity; developing innovative concepts; evaluating those concepts; and rapidly prototyping, developing, and testing those concepts are discussed. The techniques presented, are reinforced by a case study from the return-to-flight experiences of the Space Shuttle which had tremendous schedule, budget, and political constraints. The example problem or case study was the development of on-orbit concepts and techniques for repairing damaged reinforced carbon-carbon (RCC) leading edges and/or nose cap. The paper contrasts the methods used by the Space Shuttle Program (SSP) and its contractors to a much smaller team of researchers, engineers and technicians which formed the R&D RCC Repair Team. By utilizing techniques presented herein, the R&D Team was able to develop working solutions for small to very large damage to RCC in a matter of months and for a very low cost. The R&D Team applied for over 7 patents for their ideas of which three were selected to be submitted to the US Patent Office. Some of the concepts which were developed include: a self-advancing step-tap drill for simultaneously drilling and tapping RCC; C-SiC fasteners to plug small holes and secure cover plates for larger damage; a flexible, C-SiC small area repair for repairing small holes (up to 3 inches); and a flexile C-SiC concept the only viable concept for repairing very large holes in RCC.

In addition to the concepts described above, the R&D team was successful in developing a flexible C-C and C-SiC doubly-curved shell which was adopted by ATK Thiokol and helped to reduce the total number of 9-inch plugs from 1,300 to less than 18. The team's use of key discipline experts to help re-design the plug also enabled it to survive worst case entry heating. The LAR concept also helped to inspire other mechanical repair concepts such as the "overlay" concept for tile repair.

I believe the success of the R&D Team in accomplishing so much in so little time can be attributed to the leadership of Dr. Stephen J. Scotti and the hard work and collaborative, creative spirit of the key individuals who were part of the team.

REFERENCES

1. *The Creative Company – How to Grow and Harvest Great Ideas,* The Harvard Business Review OnPoint, Executive Edition, Spring 2007.
2. *Project Lead the Way*, July 2005.
3. *Science for All Americans – Project 2061*, American Association for the Advancement of Science. Oxford University Press, 1990.
4. *Benchmarks for Science Literacy – Project 2061y*, American Association for the Advancement of Science. Oxford University Press, 1993.
5. *Report of the Columbia Accident Investigation Board,* Government Printing Office, Washington D.C., August 2003.
6. Graham, Margaret, B. W, and Shuldiner, Alec T., *Corning and the Craft of Innovation,* Oxford University Press, Inc. New York, 2001.
7. *Final Report of the Return to Flight Task Group*, July 2005.
8. Gordon, Michael P.: "Leading Edge Structural Subsystem and Reinforced Carbon-Carbon Reference Manual". Boeing Report XXXX , October 19, 1998.
9. Briefing to the Aerothermal Team supporting the CAIB entitled: "LaRC Computational Aerothermodynamics – supporting STS-107 Columbia Investigation". April 29, 2003.
10. Briefing to the Orbiter Project Office on Sept 12, 2003 by Charles Camarda, James Reeder, and Darwin Moon entitled: "Preliminary Damage Assessment Test and Analysis Plan" supporting PRCBD: S061954AR2.

11. Briefing to the RCC Repair Project IPT by Frank Ledbetter (MSFC) on September 15, 2004 entitled: "Crack Repair Material Status".
12. Briefing to the PRCB by Steve Poulos entitled: "RCC Repair Recommendation for Return-to-Flight". Space Shuttle Program Requirements Control Board (PRCB) SR2309, 27 May, 2004.
13. Rodriguez, Alvaro C.: "Micrometeoroid Orbital Debris (MMOD) Damage Tolerance Arc Jet Test for Reinforced Carbon-Carbon (RCC)". Thermal Design Branch Report, Engineering Directorate, Structural Engineering Division. JSC Report Number JSC-62998, May 2005.
14. Rodriguez, Alvaro C.: "Damage Tolerance Arc Jet Test for Reinforced Carbon-Carbon (RCC))". Thermal Design Branch Report, Engineering Directorate, Structural Engineering Division. JSC Report Number JSC-62928, March 2005.
15. Kit for External Repair of Module Impacts (KERMIt). Briefing presented by Charles Camarda to the Orbiter Flight Techniques panel on 2/27/03 at Johnson Space Center describing a repair system developed by MSFC for fixing a hole in a Space Station module (which was subsequently depressurized) to be fixed by EVA repair means.
16. Matson, Jack V.: "Innovate or Die – A Personal Perspective on the Art of Innovation". Paradigm Press Ltd., 1996.
17. Altshuller, Genrich: "And Suddenly the Inventor Appeared – TRIZ, the Theory of Inventive Problem Solving". Technical Innovation Center, Inc., Worcester Massachusetts, 2001.
18. Schultz, James: "Crafting Flight – Aircraft Pioneers and the Contributions of the Men and Women of NASA Langley Research Center". NASA SP-2003-4361, 2003.
19. Pettit, Donald R.; Penner, Ronald K.; Franklin, Larry D.; and Camarda, Charles J.: "Self-Advancing Step-Tap Drill", Patent Application MSC-23954-1, Feb. 2007.
20. Richter, Alan: "Tools in Space", Cutting Tool Engineering, April 2007.
21. Camarda, Charles J.; Scotti, Stephen J.; Schwind, Francis; et. al.: "Curved-Shell Flexible Patch Concept, Patent Application MSC 23909, Aug. 2006.
22. Rivers, H. K.; Lester, Dean; Scotti, Stephen J.; Camarda, Charles J.; et. al.: "Flexible Plug Repair for Shuttle Wing Leading Edge", Patent Application MSC-24347-1, March 2007.