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Task 4 Supporting Technology
Detailed Test Plan for Leading Edge Tile Development

Payment Milestone No. LE01 Part 1 of 2
WBS 1840

Cooperative Agreement NCC8-79

May 30, 1995

P. A. Hogenson
Principal Investigator

D. P. Weeks
Technology Team Leader

Rockwell Aerospace
Space Systems Division

(NASA-CR-198633) TASK 4 SUPPORTING TECHNOLOGY. PART 1: DETAILED TEST PLAN FOR LEADING EDGE TILE DEVELOPMENT. LEADING EDGE MATERIAL DEVELOPMENT AND TESTING (Rockwell International Corp.) 39 p

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Detailed Test Plan - DTP 6667-801
Leading Edge Material Development and Testing

X-33 Cooperative Agreement NCC8-79
WBS 1840 Leading Edge Material Development and Testing

Prepared by: Paul Staszak and Karrie Hinkle
Task Leader: Paul Staszak

May 24, 1995

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1.0 OBJECTIVE

This task develops two alternative candidate tile materials for leading edge applications: coated AETB tile and SIRCA tile. The following subtasks will be performed in this development effort. The first two subtasks, which involve the materials development, take place this fiscal year, 1995. The third through the fifth begin this fiscal year and continue into the next fiscal year if funded. The last two subtasks, which involve the design and assembly of a leading edge, occur during the first half of fiscal year 1996 if funded.

Subtask 1: Tile Coating Development.

TUFI coating for AETB tiles was developed by NASA-ARC and consists of densifying the outer tile surface with a ceramic-based slurry for durability and emittance control. Modifications of the current TUFI coating process will be developed to enhance durability and increase temperature resistance. Leading edge use of TUFI-coated tiles will require this additional development because of the substantial impacts that will result from rain and debris and due to the desire to increase the performance temperature. Modifications will include changing the slurry composition, changing the application process, and overcoating with a top coat. The coating that is developed will then be characterized and tested. The products of this subtask will be a process specification and durability/thermal test data.

Subtask 2: SIRCA Tile Development.

SIRCA is produced by preparing a low-density (8 to 22 lbs/ft^3) tile material and filling it with a silicone resin. The first task will be to transfer the tile preparation and impregnation technology from NASA-ARC to Rockwell. The second task will be to produce SIRCA at Rockwell. (In addition, a process may be needed to produce a durable, high-emittance outer surface.) The third task will be to characterize Rockwell-produced SIRCA using physical, thermal, and mechanical testing.

Subtask 3: Robustness Testing of Tiles.

Testing of the tile materials for resistance to natural and induced environments will then be performed. The tests will include rain impact, hypervelocity impact, and tool impact. These tests will be used to evaluated the robustness of the tile materials.

Subtask 4: Tile Repair Development.

Limits of acceptable tile coating damage (acceptable for flight without repair) will be determined by creating controlled defects that simulate rain and debris damage and by exposing the tiles to an arc jet environment. The tiles will then be repaired and subjected once again to arc jet testing. An evaluation of tile repair techniques will then be performed.

Subtask 5: Tile Operations/Processing.

The requirement to waterproof leading edge tiles will be evaluated and established for the developed materials. The type and durability of the exterior coating of the tiles will be the determining factor for waterproofing. Water drop exposure and wind and rain tests will be used in the evaluation. In addition, rewaterproofing techniques will be investigated if necessary.

Methods for attaching tiles to the leading edge substructure will also be investigated as well as assemble/disassemble procedures. Additionally, the need for gap fillers will be determined and developed if necessary.

Subtask 6: Tile Leading Edge Configuration.

A test article consisting of a graphite/polyimide leading edge substructure with durable tiles bonded to the exterior surface will be designed. The article shall consist of several tiles and will be instrumented to evaluate step and gap effects. Arc jet tests will be used to demonstrate the concept of a leading edge configuration with tile insulation. Test parameters shall be based on X-33/RLV thermal analysis.

Subtask 7: Life Cycle Testing.

A limited sequence of environmental (life cycle) testing will be performed. One cycle will include pad wind/rain conditions, ascent conditions, on-orbit conditions, descent thermal/pressure conditions, and an impact requiring repair (first cycle only). Three complete cycles will be performed.

2.0 BACKGROUND

Upon reentry of the X-33/RLV space vehicle, the leading edges experience the highest heating rates and temperatures. The wing leading edge and nose cap experience peak temperatures in the range 2000°F to 2700°F. Reinforced carbon-carbon (RCC) is presently used on the space shuttle orbiter for these particular applications. Replacing RCC with tile-based TPS materials is the primary objective of this task. Weight, complexity, coating impact damage, and repairability are among the problems that this tile technology development will address.

Presently, tile substrate materials are comprised of silica, alumina, and aluminoborosilicate fibers. The substrate can be produced with various densities depending on the insulation requirements. Densities typically used on reusable launch vehicles range from 6.0 to 22.0 lbs/ft^3. The insulating materials have the following designations and compositions:

LI (Lockheed Insulation)	- 100% silica fibers
AIM (Advanced Insulation Material)	- 100% silica fibers
FRCI (Fibrous Refractory Composite Insulation)	- 78% silica fibers
	- 22% aluminoborosilicate fibers
HTP (High Thermal Performance)	- 65 to 78% silica fibers

	- 22 to 35% alumina fibers
AETB (Alumina Enhanced Thermal Barrier)	- 68% silica fibers
	- 20% alumina fibers
	- 12% aluminoborosilicate fibers

These tile materials are typically coated with silica-based glass materials as shown below:

RCG (Reaction Cured Glass)	- silica frit
	- silicon tetraboride
TUFI (Toughened Unipiece Fibrous Insulation)	- silica frit
	- silicon hexaboride
	- molybdenum disilicide

The overall performance of coated tiles is limited by temperature. Presently, TUFI coated AETB has the highest temperature capability of the insulation materials. The highest temperature AETB can achieve without deformation is approximately 2700°F. The coatings typically can endure temperatures to about 2500°F. These thermal limitations are the driving force behind investigating coating materials. Additionally, mechanical limitations exist which need to be addressed.

SIRCA is a ceramic tile insulation material that was developed by NASA-ARC. It was originally intended for one time use on planetary probes, however, tests have shown that it can survive repeated thermal cycles. Because of its demonstrated ability to withstand repeated thermal cycles, it is being considered as a candidate material for the RLV wing leading edge. SIRCA consists of a low density (8-22 lbs/ft^3) silica fiber tile material that is impregnated with silicone resin. The tile is capable of withstanding temperatures up to 3000°F for short periods of time.

The leading edge tiles will require quantitative characterization with respect to performance in the various adverse environments which impact the X-33 vehicle. Testing will be used to demonstrate the robustness of the tiles under realistic, simulated flight conditions. Environmental concerns include:

Launchpad and Handling Environment:

- Launch pad wind-driven rain
- Ice/frost formation between/within tiles
- Corrosive effects of salt spray
- Effects of lightning strike
- Tool (low speed) impact
- Substance exposure

Flight Environment:

- In-flight rain impact
- Flight impacts from ice crystals and/or hail
- Atmosphere re-entry heating performance
- Aerodynamic surface loads
- Lightning strike

Orbit Environment:

- Orbital impacts from micrometeoriods and space debris
- UV exposure
- Atomic oxygen exposure

Analysis will be performed to define the natural and induced environments that will best demonstrate the robustness of the tile materials. Establishment of damage limits and subsequently, techniques for repair of damages, will also be necessary.

The ultimate goal of the this material technology investigation will be to design and produce a tile-based leading edge. The resultant article will be tested under life cycle conditions in order to evaluate its performance.

3.0 GENERAL REQUIREMENTS

3.1 Documentation

3.1.1 Detailed Test Procedure (DTP)

All testing will be conducted in accordance with this test procedure.

3.1.2 Laboratory Notebook

A Laboratory Notebook will be maintained by the Rockwell Responsible Test Engineer (RTE) depicting a complete test history. Test article configuration, instrumentation, test anomalies and all other pertinent data and information will be recorded.

3.1.3 Test Report

The test agency will issue a Laboratory Test Report (LTR). The test report will depict the complete test program, instrumentation, test procedures and results, test setup, photographs, test data, and any other pertinent information.

3.2 Test Facility

Test equipment and facilities will be utilized at both government and industry sites. Appropriate facilities will be selected to simulate the interaction of identified adverse environments with specific TPS components fabricated in this task. Test facilities which have been identified are listed below.

- NASA-ARC arc jet facility (60 and 20 MW facilities)
- NASA-ARC light gas gun (hypervelocity facility)
- AFWL rain impact facility
- Rockwell tile production unit fabrication facility
- Rockwell tile coating facility

- Rockwell mechanical testing facility
- Rockwell rain/wind facility
- Rockwell vibroacoustic facility
- Rockwell radiant heat facility
- Rockwell atomic oxygen facility

Schedules and test requirements are defined in the detailed test description section of this document.

3.3 Instrumentation

All measurement instrumentation shall be calibrated and have a decal showing a valid calibration date. A list of all test instrumentation will be maintained in a Laboratory Notebook.

3.4 Test conduct

The test program will be conducted under the direction of the task leader or a designated representative.

4.0 SUBTASK DESCRIPTION

The leading edge material technology task shall be broken down into seven subtasks.

Subtask 1: Tile Coating Development
Subtask 2: SIRCA Tile Development
Subtask 3: Robustness of Tiles
Subtask 4: Tile Repair Development
Subtask 5: Tile Operations/Processing
Subtask 6: Tile Leading Edge Configuration
Subtask 7: Life Cycle Testing

4.1 TILE COATING DEVELOPMENT

Modifications to the current TUFI coating process shall be developed to enhance durability and increase temperature resistance. The coating that is developed will then be characterized and tested.

Tile coating development shall involve the completion of the following subtasks:

Subtask 1.1: Modify Tile Coating
Subtask 1.2: Characterize Tile Coating

4.1.1 Modify Tile Coating

An examination of high temperature materials shall be made in an effort to acquire information on the processing of improved coatings for TPS. From this examination, a reformulation of the tile coating will be made. The reformulation will include modifying the slurry composition, changing the application process, and/or overcoating with a top coat. The overall objective will be to obtain a high temperature coating. Issues that will also be addressed include high temperature performance, mechanical performance, material compatibility, and emissivity.

4.1.1.1 Introduction/Background

TUFI (toughened unipiece fibrous insulation) was developed by NASA-ARC as a high temperature porous tile coating for use on the space shuttle orbiter. TUFI is sprayed on the surface as a slurry and penetrates into the fibrous tile approximately two millimeters. The coating is then fired. The coating contains high temperature emittance agents (silicon hexaboride and molybdenum disilicide) which make the coating black. The coating was designed to replace RCG (reaction cured glass) which is a thin non-porous glass. TUFI was intentionally made porous to eliminate venting problems, increase durability, and to provide added resistance to thermal cracking. Both TUFI and RCG begin to melt at temperatures above 2500°F.

For leading edge applications, it is necessary to increase the temperature capability of TUFI and reduce its porosity. A decrease in the porosity can be achieved by placing an RCG layer over the

TUFI layer. This, however, does not increase the temperature resistance. In addition, the emittance agent that is in RCG is not as stable as the agents in TUFI. Further modifications may be required.

Alternative coating materials for high temperature applications include alumina and silicon carbide. Additions of agents such as molybdenum disilicide, silicon hexaboride, or silicon carbide are necessary for high temperature emittance.

4.1.1.2 Applicable Documents

Proposal CAN8-1 - Reusable Launch Vehicle (RLV) Advanced Technology Demonstrator: X-33.
Cooperative Agreement - NCC8-79 Leading Edge and Seals Thermal Protection System Technology Demonstration.
Rockwell Specification MPP609M301M02 rev. L - Coat and Fire RSI Tile Type I, Type IV, and Type V, Class 2 and Type III, Class 2 Ceramic Plugs.
Rockwell Specification MPP606M326M01 rev. B - Coat and Fire Toughened Unipiece Fibrous Insulation (TUFI).
NASA Specification TUFI-F - Specification for Toughened Unipiece Fibrous Insulation.
NASA Specification AETB-12-20-68 - Specification for Alumina Enhanced Thermal Barrier.
Rockwell IR&D 25002 Report - Advanced TPS Development of AETB Tile Material.

4.1.1.3 Requirements

An evaluation of potential coating materials is required prior to the onset of fabrication. The optimal properties will be established and then materials that meet the requirements will be selected for fabrication.

4.1.1.4 Detailed Test Article/Test Specimen Description

Ninety 2"x2"x2" AETB coupon will be made from three tile production units for the preliminary screening of the various developed coatings.

4.1.1.5 Test Procedures

Various coating compositions will be formulated at the Rockwell-Downey site or procured. Additionally, AETB tile production units will be produced at Rockwell-Downey from which coupons will be made. The tile coupons will then be coated at the Rockwell-Palmdale or Rockwell-Downey sites.

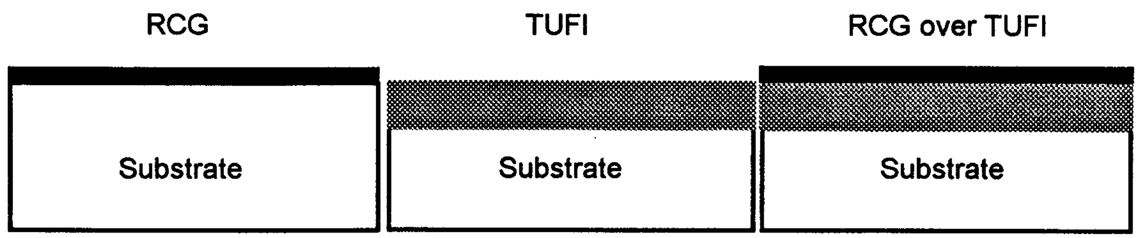
4.1.1.6 Sample Data Sheets

Data sheets will include information regarding coating compositions, fabrication, application methods, firing procedures, and evaluations.

4.1.1.7 Test Equipment

Equipment located at the Rockwell-Downey coating facility and the Rockwell-Palmdale coating laboratory shall be used. This equipment includes: ball mills for slurry fabrication, Binks spray guns for slurry application, and a kiln for firing the coated specimens.

4.1.1.8 Sketches and Schematics



Cross-Sectional Representation of the Coating Concepts Used in this Task

4.1.1.9 Schedule

Initiate contact of coating vendors for optimal materials	June 1, 1995
Initiate purchase of coating and AETB materials	June 1, 1995
Begin fabrication of AETB tile production units for coating	June 15, 1995
Begin formulating coatings	June 15, 1995
Apply modified coatings to AETB tile coupons for evaluation	July 1, 1995

4.1.2 Characterize Tile Coating

The tile coating shall then be characterized using thermal, physical, optical, and mechanical testing. Thermal testing will include DTA (differential thermal analysis), thermal expansion, radiant heat, and arc jet tests. Physical testing will include examining the coating using optical and scanning electron microscopy. Optical testing will include emissivity tests. Mechanical tests will include impact, compression, and tensile testing.

4.1.2.1 Introduction/Background

A series of tests will be conducted in order to characterize the coated tile. The information obtained from the characterization will be used to optimize the coating. The key properties for optimization will be identified. Among the properties presently identified as critical are emissivity, high temperature stability, and compatibility with the substrate material.

4.1.2.2 Applicable Documents

Appendix A (DTP 6451-810) - Standard Test Procedure - Arc Jet Testing.
Appendix J (DTP 6451-819) - Standard Test Procedure - Radiant Heat Testing.
ASTM E 408, Method A - Emittance Measurement Procedure.
ASTM E 490-73a - Absorptivity Measurement Procedure.

4.1.2.3 Requirements

Samples for thermal expansion, radiant heat, tensile strength, compressive strength, impact testing, DTA, emissivity, absorptivity, and arc jet testing will need to be made. A procedure for testing the tensile and compressive strengths of the coatings needs to be determined.

4.1.2.4 Detailed Test Article/Test Specimen Description

Five 6"x6"x2" AETB tiles will be coated for arc jet testing. Several coated AETB tiles will be used to obtain physical, mechanical, and thermal properties.

4.1.2.5 Test Procedures

Thermal characteristics will be measured on the coated tiles using the radiant heat facility at Rockwell-Downey. Test articles will be run at temperatures greater than 2500°F simulating typical temperature and pressure profiles. Additionally, differential thermal analysis (DTA) will be performed on the coating materials to determine the melting temperature and the thermal characteristics of the coatings.

Mechanical testing will include measuring the tensile and compressive strength of the coating. Testing shall be performed according to M&P procedures. All testing will be done at room temperature.

Optical property testing will consist of measuring solar absorptance and total normal emittance. Four measurements will be taken on each block, 1.5 inches from each edge at the corners. These tests will be performed using a Beckman DK2A Spectroreflectometer, and a Gier Dunkle Model DB100 reflectometer. Physical properties will be characterized at Rockwell-Downey.

Five test articles will be arc jet tested at NASA-ARC using the 20 megawatt facility. Eight tests will be made on four of the test articles to determine the upper temperature limit of the coated tiles. Five tests will be performed on one test article to demonstrate the performance of the optimized coating.

4.1.2.6 Sample Data Sheets

Thermal, mechanical, and physical testing will be presented in a report. Optical properties will be reported as follows:

Test Sample - Test Location	Solar Absorptance	Total Normal Emittance	Solar Absorptance/ Total Normal Emittance
1-1			
1-2			

Results of arc jet testing will be in the form of a report including all profiles run, all thermocouple readings taken during the runs, and a summary of the test setup.

4.1.2.7 Test Equipment

The mechanical testing will be conducted using MTS and Instron testing equipment. Optical property measurements will be conducted using a Reflectometer Gier-Dunkle, DB100 infrared and a Spectrophotometer Beckman, DK-2A UV-VIS-NIR. The Rockwell radiant heat facility and DTA apparatus will be used to obtain thermal properties data. Arc jet testing will be performed at NASA-ARC in the 20 megawatt facility.

4.1.2.8 Sketches and Schematics

N/A

4.1.2.9 Schedule

Prepare samples for characterization	July 1, 1995
Initiate physical properties testing	July 15, 1995
Initiate optical properties testing	July 15, 1995
Initiate mechanical properties testing	July 15, 1995
Initiate thermal properties testing	July 15, 1995
Prepare samples for arc jet testing	July 15, 1995
Perform arc jet tests	August 1, 1995*

4.2 SIRCA Tile Development

Silicone impregnated reusable ceramic ablator (SIRCA) is a ceramic tile insulation material that was developed by NASA-ARC. The tile is capable of withstanding temperatures up to 3000°F. The objectives of this task are to obtain from NASA-ARC the technology needed to produce SIRCA, to fabricate several representative tiles, and then to characterize the thermal and mechanical performance of SIRCA.

SIRCA development will involve the completion of the following subtasks:

Subtask 2.1: Technology Transfer
Subtask 2.2: Tile Processing
Subtask 2.3: Tile Characterization

4.2.1 Technology Transfer

Arrangements with NASA-ARC shall be made to coordinate the transfer of the technology needed to fabricate SIRCA.

4.2.1.1 Introduction/Background

SIRCA was developed by NASA-ARC as an ablator material. The intent of this subtask is to transfer the technology in its current level of development to Rockwell. All SIRCA to be used in this test program for characterization and testing will be fabricated at Rockwell-Downey in the existing tile PU fabrication facility.

4.2.1.2 Applicable Documents

A process specification outlining, in detail, all steps necessary to arrive at the final SIRCA product will be obtained from NASA-ARC. Additionally, any raw material specifications and/or callouts that are needed to support fabrication of the SIRCA will be obtained from NASA-ARC.

4.2.1.3 Requirements

The technology transfer must be complete in order to proceed with tile processing and characterization.

4.2.1.4 Detailed Test Article/Test Specimen Description

Samples of SIRCA fabricated by NASA-ARC will be visually examined by Rockwell personnel to enhance familiarization with the material.

4.2.1.5 Test Procedures

Results of all testing performed to date on SIRCA at NASA-ARC will be reviewed. This includes all mechanical, physical, and thermal data. Test methods and procedures will also be obtained and reviewed.

4.2.1.6 Sample Data Sheets

N/A

4.2.1.7 Test Equipment

N/A

4.2.1.8 Sketches and Schematics

N/A

4.2.1.9 Schedule

Initiate contact with NASA-ARC for technology transfer	May 1, 1995
Obtain information regarding SIRCA fabrication	June 1, 1995

4.2.2 Tile Processing

The processing of SIRCA tiles involves the fabrication of a silica fiber substrate followed by the impregnation of the tile with silicone resin. Additionally, it may be necessary to develop a coating for SIRCA depending on thermal and optical performance.

4.2.2.1 Introduction/Background

The goal of this subtask is to produce repeatable and acceptable SIRCA material based on the technology transferred to Rockwell by NASA-ARC. Minor changes and/or optimizations to the NASA-ARC procedure may be necessary in order to accommodate differences in equipment, or inconsistencies in the produced material. Technologies already established at Rockwell-Downey for the production of AETB materials will aid in the completion of this task.

4.2.2.2 Applicable Documents

NASA Specification AETB-12-20-68 - Specification for Alumina Enhanced Thermal Barrier.
NASA Specification SIRCA - Specification for Silicone Impregnated Reusable Ceramic Ablator.
Rockwell Processing Sheet - Production Unit Processing Record for AETB.
Rockwell Specification MBO115-042 - Silica Fiber.
Rockwell Specification MBO130-119 type II - RTV 560 Material Specification.
Rockwell Specification MAO106-319 - RTV Silicone Adhesive-Bonded Silica Reusable Surface Insulation (RSI) System.
Rockwell M&P Procedure 3320-026 - Flatwise Tensile Testing.

4.2.2.3 Requirements

All material produced shall be made according to NASA-ARC specification provided in the technology transfer. Any deviations from the supplied procedure will be noted.

4.2.2.4 Detailed Test Article/Test Specimen Description

Ten blocks of the silica fiber substrate, AIM (advanced insulation material), will be fabricated in order to become familiar with the fabrication process. Each block will have an as-fired, trimmed size of approximately 7"x7"x4". The AIM blocks will be evaluated for consistency by measuring overall density, density gradients, and flatwise tensile strength. Additionally, ten blocks of silica substrate will be fabricated and impregnated with silicone resin and processed according to the NASA-ARC specification. Each block will have an as-fired, trimmed size of approximately 7"x5.5"x4". This will enable a 1" slab to be taken from the side of the AIM block prior to impregnation for evaluation of density gradients and strength (process control). The impregnated blocks (SIRCA) shall also be evaluated for consistency by measuring overall density, density gradients, and flatwise tensile strength.

4.2.2.5 Test Procedures

Overall Density: Each block shall be weighed (to the nearest 0.01 gram) and measured (to the nearest 0.1 inches). The overall density will then be calculated. The value will be ±0.5 lbs/cu ft of the nominal density specified by the NASA-ARC specification.

Density Gradient: A slab of material will be cut from the edge and from the center of the block. 1"x1"x1" cubes will then be cut from the slabs, weighed (to the nearest 0.01 gram), and measured (to the nearest 0.1 inches). See diagram below. These measurements will be used to calculate the density of each cube and the density gradients both through the thickness and from the edge to the center of the block.

Flatwise Tensile Strength: Five of the blocks that meet the requirements for overall density and density gradients will be evaluated for tensile strength. Tensile strength samples will be taken from the same slabs as the density gradient samples. See diagram below. The samples will be tested according to M&P Procedure 3320-026 at room temperature.

4.2.2.6 Sample Data Sheets

A data sheet similar to that for Rockwell's AETB will be used during the fabrication of the AIM. The data sheet will be modified based on the information provided in the technology transfer. A data sheet for the impregnation and subsequent processing will also be laid out.

Tests for density will be reported in the following format:

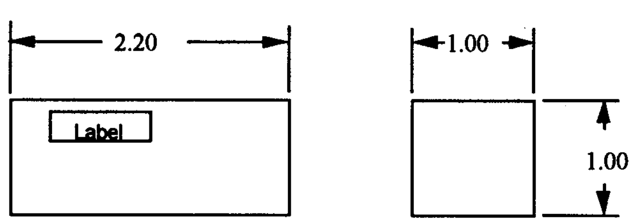
Sample	Length (in)	Width (in)	Height (in)	Weight (gm)	Density (lbs/cu ft)
Overall					
S1					

Flatwise tensile test results will be reported on a Mechanical Property Data Sheet, Form 3940-X.

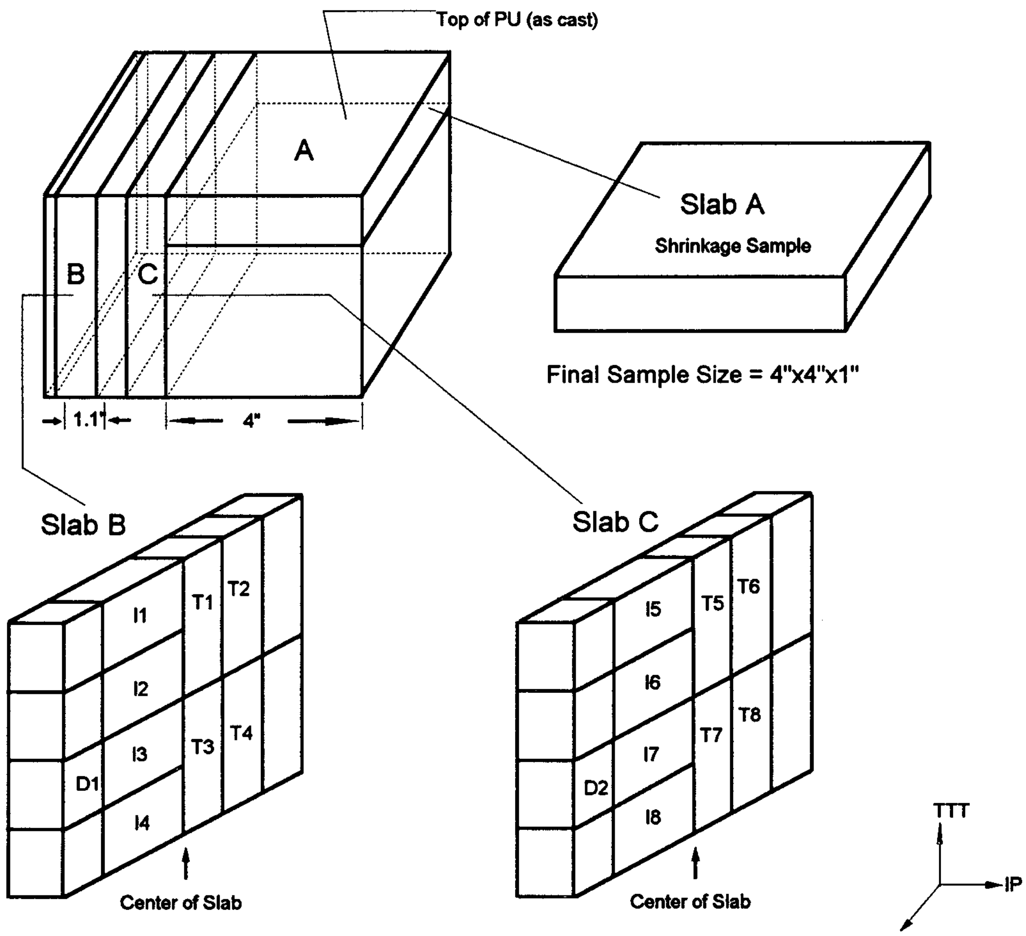
4.2.2.7 Test Equipment

The mechanical testing will be conducted using MTS and Instron testing apparatus.

4.2.2.8 Sketches and Schematics



Flatwise Tensile Test Coupon



I1-8 Are In-plane Flatwise Tensile Coupons And Density Gradient Samples

T1-8 Are Thru The Thickness Flatwise Tensile Coupons

D1-2 Are Devitrification Samples

Final Sample Size = 1"x1"x2.2"

4.2.2.9 Schedule

Order materials necessary to fabricate SIRCA tiles	June 2, 1995
Initiate fabrication of tile substrate	July 5, 1995
Initiate impregnation of tiles	June 12, 1995
Rockwell produce SIRCA tile	July 11, 1995*

4.2.3 Tile Characterization

The SIRCA tiles which are produced by Rockwell shall then be characterized.

4.2.3.1 Introduction/Background

A series of tests will be conducted in order to characterize the SIRCA tile. The information obtained from the characterization will be used to optimize the SIRCA fabrication process and establish the properties of Rockwell-produced SIRCA. Among the properties presently identified as critical are emissivity and high temperature stability.

4.2.3.2 Applicable Documents

Rockwell M&P Procedure 3320-026 - Flatwise Tensile Testing.
Rockwell M&P Procedure 3320-027 - Compression Testing.
Shrinkage Testing per procedure noted in lab notebook No. 0649.
ASTM E 408, Method A - Emittance Measurement Procedure.
ASTM E 490-73a - Absorptivity Measurement Procedure.

4.2.3.3 Requirements

SIRCA tiles will be characterized for mechanical, optical, and thermal properties to sufficiently enable the release of a Rockwell process specification with established limits. Optical property testing will be done in order to determine the performance of SIRCA tile without a coating. Based on emissivity and absorptivity data, the decision will be made on whether or not a subsequent coating is necessary. The optical requirements are for a Total Normal Emittance of 0.80 minimum, and a Solar Absorptance/Total Normal Emittance ratio of 0.7-1.1. Furthermore, SIRCA will undergo arc jet testing to establish the thermal performance in a simulated reentry environment. Data will be gathered on life cycles and on thermal stability with repeated exposure.

4.2.3.4 Detailed Test Article/Test Specimen Description

Mechanical testing will be done on six blocks of SIRCA material representing two fabricated lots. A total of 30 flatwise tensile samples and 30 compression samples from the six blocks will be tested. Flatwise tensile and compression samples will have configurations as shown below.

Optical testing will be done on 5 blocks of SIRCA tile. Each block will consist of a 6"x6"x2" tile.

Three samples will be subjected to arc jet testing simulating typical reentry conditions. The sample configuration will be determined based on design needs.

4.2.3.5 Test Procedures

Mechanical testing will be performed according to the M&P procedures outlined above. All testing will be done at room temperature.

Optical property testing will consist of measuring solar absorptance and total normal emittance. Four measurements will be taken on each block, 1.5 inches from each edge at the corners. These tests will be performed using a Beckman DK2A Spectroreflectometer, and a Gier Dunkle Model DB100 reflectometer.

Arc jet testing will be performed on three samples. One test will be run on each of two samples to compare thermal performance of Rockwell fabricated SIRCA to that of NASA-ARC fabricated SIRCA. A third sample will be tested for multi-cycle capability. Ten cycles will be run.

4.2.3.6 Sample Data Sheets

Flatwise tensile and compression test results will be reported on a Mechanical Property Data Sheet, Form 3940-X. See Attachment.

Optical properties will be reported as follows:

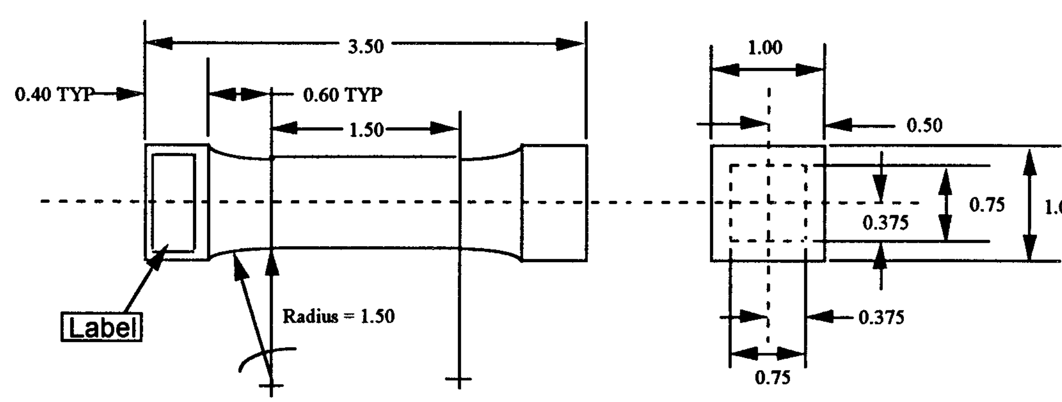
Test Sample - Test Location	Solar Absorptance	Total Normal Emittance	Solar Absorptance/ Total Normal Emittance
1-1			
1-2			

Results of arc jet testing will be in the form of a report including all profiles run, all thermocouple readings taken during the runs, and a summary of the test setup.

4.2.3.7 Test Equipment

The mechanical testing will be conducted using MTS and Instron testing equipment. Arc jet testing will be performed at NASA-ARC in the 20 megawatt facility. Optical property measurements will be conducted using a Reflectometer Gier-Dunkle, DB100 infrared and a Spectrophotometer Beckman, DK-2A UV-VIS-NIR.

4.2.3.8 Sketches and Schematics



Compression Test Coupon

4.2.3.9 Schedule

SIRCA arc jet tests	August 10, 1995*
SIRCA process specification and rain impact	November 17, 1995*

4.3 Robustness of Tiles

Testing for resistance to natural and induced environments shall be performed to evaluate the robustness of coated AETB tiles and SIRCA tiles.

The robustness study will involve the completion of the following subtasks:

Subtask 3.1: Rain Impact Tests
Subtask 3.2: Hypervelocity Tests
Subtask 3.3: Tool Impact Tests

4.3.1 Rain Impact Tests

Rain impact tests will be used to evaluate the natural environmental performance of tiles. The leading edge tiles will be exposed to simulated launch and landing rain conditions. The potential for flight through rain will also be addressed.

4.3.1.1 Introduction/Background

Thermal protection system (TPS) materials are exposed to a number of natural environments. One such environment is rain. A reusable launch vehicle can encounter rain at several times throughout its mission (on the launch pad, during take off, after reentry, and upon landing). The most severe rain impact condition occurs after reentry. The effects of rain impacts can severely damage TPS materials. Exposure of tile coupons to simulated rain environments will help define the robustness of the leading edge materials. One aspect of this subtask will involve determining the sample test configuration necessary to simulate the effects of rain on the leading edge.

4.3.1.2 Applicable Documents

Wright Laboratory Rain Erosion Test Apparatus, Utilization Policies, Operating Procedures, and Configurations, Revision 4, University of Dayton Research Institute, Dayton, OH, June 1992.
Appendix D (DTP 6451-813) - Standard Test Procedure - Rain Impact (Rotating Arm Facility).
Appendix E (DTP 6451-814) - Standard Test Procedure - Rain Impact (Single Drop Impact Facility).
Appendix F (DTP 6451-815) - Standard Test Procedure - Rain and Wind Impingement.

4.3.1.3 Requirements

Samples shall need to be made that fit into the rain erosion facility sample holders at Wright Laboratory. A number of test configurations can be used to simulate the rain environment. The proper conditions must be determined. Surface erosion and coating damage will need to be noted for each sample after rain exposure is completed.

4.3.1.4 Detailed Test Article/Test Specimen Description

Ten coated AETB coupons and ten SIRCA coupons will be fabricated for rain impact tests. The coupon size will be determined based on the test design. Typically rain impact coupons are 0.25 inches thick and smaller than 2"x2".

4.3.1.5 Test Procedures

The test coupons produced from tile materials will be subjected to various rain environments at the Wright Laboratories. Samples which are mounted in a rotating arm apparatus will be exposed to rain environments for predetermined times. The time at which the specimens fail will be recorded.

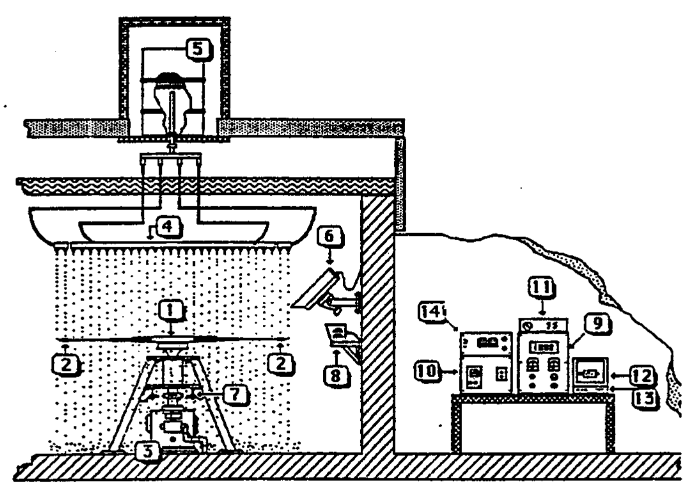
4.3.1.6 Sample Data Sheets

Data sheets are provided for each sample by Wright Laboratory. The data reported includes the sample number, all of the test parameters, and the time-to-failure.

4.3.1.7 Test Equipment

Testing will be performed at the Wright Patterson Air Force Base rain erosion test facility. The facility uses a rotating arm to accelerate test specimens to velocities up to 650 mph. Rain drops approximately 2.0 mm in diameter and falling at a rate of one inch per hour are produced from 96 hypodermic needles. Various angles of impact can be achieved by changing the angle of the sample holder.

4.3.1.8 Sketches and Schematics



1. DOUBLE ARM BLADE
2. MATED TEST SPECIMENS
3. VERTICAL DRIVE GEAR BOX AND SHAFT
4. CURVED MANIFOLD QUADRANT
5. WATER STORAGE TANK FOR RAIN SIMULATION
6. REMOTE CONTROLLED CAMERA
7. MAGNETIC PICK-UPS FOR FIRING THE STROBE
8. HIGH INTENSITY STROBE LIGHT FOR STOP MOTION VIEWING
9. VARIABLE SPEED READOUT AND CONTROL
10. STROBE CONTROL FOR SPECIMEN SELECTION
11. REMOTE COLOR CAMERA CONTROL
12. COLOR MONITOR FOR SPECIMEN VIEWING
13. VCR FOR VIDEO TAPING TESTS
14. RAIN SIMULATION CONTROL

4.3.1.9 Schedule

Fabricate rain impact test tile coupons	August 15, 1995
Perform rain impact tests on coated tiles	September 11, 1995*
Fabricate rain impact test SIRCA coupons	November 15, 1995
Perform rain impact tests on SIRCA	December 15, 1995

4.3.2 Hypervelocity Tests

Hypervelocity impact tests will also be used to evaluate the environmental performance of tiles. The testing shall be used to quantify the damage from solid particles with sizes, densities, and velocities characteristic of low earth orbit (LEO).

4.3.2.1 Introduction/Background

The leading edge tiles will encounter many particles (e.g., meteoroids and space debris) in low earth orbit. Hypervelocity impact testing shall be used to simulate the high velocities characteristic of these particles. Debris particle sizes will be critical in determining the threshold damage levels of the tiles. Exposure of tiles to simulated impacts will further define the robustness of the leading edge materials.

4.3.2.2 Applicable Documents

Appendix C (DTP 6451-812) - Standard Testing Procedure - Debris Impact Testing (Hypervelocity).

4.3.2.3 Requirements

Standard characterization of hypervelocity impact damage shall be performed. This includes physical measurements of specimen damage as well as relevant measurements to witness plates. A photographic record of impact damage shall also be made. Projectile mass, diameter, density, and impact angle will be recorded. All tests shall be performed using witness plates behind the test specimens in order to characterize the impacts that cause through-damage.

4.3.2.4 Detailed Test Article/Test Specimen Description

Three 6"x6"x2" coated AETB tiles and three 6"x6"x2" SIRCA tiles shall be fabricated for hypervelocity impact tests.

4.3.2.5 Test Procedures

NASA-ARC standard test procedures will be followed throughout this effort. Each impact test shall be defined by specimen type, impact velocity, impact angle, projectile density, and projectile diameter.

Hypervelocity impact testing at NASA utilizes a standard light gas gun apparatus which accelerates various sized particles at the specimens. The gun operates as follows. A powder charge accelerates a piston thereby compressing H_2 gas in the first stage of the light gas gun. At a predetermined pressure, a restraining disk bursts and the compressed H_2 gas expands into the evacuated second stage which contains a sabot which holds the projectile. The sabot and projectile are accelerated down the second stage barrel where they enter the impact chamber. The sabot is stripped away from the projectile and stopped by an aperture and finally the projectile impacts the target. Projectile velocity is typically calculated from a photographic record immediately before impact.

4.3.2.6 Sample Data Sheets

A photographic record of impact damage shall be made. Projectile mass, diameter, density, and impact angle shall be recorded. The data will include the sample number and all of the test parameters.

4.3.2.7 Test Equipment

Testing will be performed at the NASA-ARC hypervelocity impact facility. NASA utilizes a standard light gun apparatus to accelerate particles to velocities up to nearly 8 km/sec. The facility can accommodate specimens up to 18"x18".

4.3.2.8 Sketches and Schematics

N/A

4.3.2.9 Schedule

Fabricate hypervelocity impact test tile coupons	August 15, 1995
Perform hypervelocity impact tests on coated tiles	September 15, 1995
Fabricate hypervelocity impact test SIRCA coupons	November 15, 1995
Perform hypervelocity impact tests on SIRCA	December 15, 1995

4.3.3 Tool Impact Tests

Low velocity impact tests shall be used to evaluate the induced environmental performance of tiles. The testing will be used to quantify the damage characteristic of handling related impacts (tool impacts) during vehicle operations.

4.3.3.1 Introduction/Background

Induced environments that leading edge tile materials experience will be simulated in tool impact tests or low velocity impact tests. Exposure of tiles to simulated low velocity impacts will further define the robustness of the leading edge materials.

4.3.3.2 Applicable Documents

McDonnell Douglas Aerospace Document MDC-93B0068 rev. B - Low Velocity Impact Testing.

4.3.3.3 Requirements

The proper low velocity testing parameters must be determined.

4.3.3.4 Detailed Test Article/Test Specimen Description

Three 6"x6"x2" coated AETB tiles and three 6"x6"x2" SIRCA tiles shall be fabricated for tool impact tests.

4.3.3.5 Test Procedures

Each impact test shall be defined by specimen type, impact velocity, impact angle, projectile density, and projectile diameter. Impacts will simulate typical handling practices.

4.3.3.6 Sample Data Sheets

A photographic record of impact damage shall be made. Projectile mass, diameter, density, and impact angle shall be recorded. The data will include the sample number and all of the test parameters.

4.3.3.7 Test Equipment

Test equipment shall be determined based on testing parameters.

4.3.3.8 Sketches and Schematics

N/A

4.3.3.9 Schedule

Fabricate tool impact test tile coupons	August 15, 1995
Perform tool impact tests on coated tiles	September 15, 1995
Fabricate tool impact test SIRCA coupons	November 15, 1995
Perform tool impact tests on SIRCA	December 15, 1995

4.4 Tile Repair Development

Techniques for repairing damaged tiles shall be investigated. Limits of acceptable damage will first be established using arc jet testing. Repair techniques will then be implemented and verified again using arc jet testing.

4.4.1 Introduction/Background

Tiles can be damaged through natural environments (micrometeorite or rain impacts) or from incidental contact (tool impacts). Tile damage may occur in the outercoating, be a crack in the tile, or be a damage zone that extends down into the tile substrate. The limits to which a tile can be damaged and still perform its function is the lower limit of the repair threshold. A tile that is so badly damaged that it is more practical to replace it than repair it defines the upper limit of the repair threshold.

Once the threshold limits are established, repair techniques similar to those established in the space shuttle orbiter program will be developed. These repair techniques typically involve replacing portions of the damaged tile.

Testing shall be done to evaluate the performance of both repaired and unrepaired leading edge tile materials. Evaluation of the tiles will involve subjecting them to arc jet testing. This testing shall serve to verify the utility of the repair methods.

4.4.2 Applicable Documents

Appendix A (DTP 6451-810) - Standard Test Procedure - Arc Jet Testing.

4.4.3 Requirements

Repair techniques/materials will need to be established for each of the tile materials.

4.4.4 Detailed Test Article/Test Specimen Description

A total of six 6"x6"x2" coated AETB and SIRCA tiles shall be fabricated for the arc jet tests. Several additional tiles shall be used to develop the repair techniques.

4.4.5 Test Procedures

Three samples shall be evaluated using arc jet testing in order to determine the acceptable damage limits. Three additional samples with repairs shall be arc jet tested to verify damage repair techniques.

Damages will be inflicted onto tile materials in the form of chips, cracks, and gouges. These damages shall be done using simulated impacts. Repair techniques will involve mending damaged coating and substrate materials.

4.4.6 Sample Data Sheets

Results of arc jet testing will be in the form of a report including all profiles run, all thermocouple readings taken during the runs, and a summary of the test setup.

4.4.7 Test Equipment

Arc jet testing will be performed at NASA-ARC in the 20 megawatt facility.

4.4.8 Sketches and Schematics

N/A

4.4.9 Schedule

Tile damage limits arc jet tests	November 15, 1995
Repair damaged tiles	December 15, 1995
Repaired tile arc jet tests	January 15, 1996

4.5 Tile Operations/Processing

This task shall attempt to address the following issues concerning the tile leading edge operations and processing procedures:

- procedure for attaching tiles to vehicle.
- need for gap filler.
- need for waterproofing and rewaterproofing of tiles.
- procedures for assembly/disassembly of tiles to the vehicle.

4.5.1 Introduction/Background

Methods for attaching tiles to the leading edge substructure shall be determined as well as assemble/disassemble procedures. Additionally, the need for gap fillers will be determined and developed if necessary. The tiles on the space shuttle orbiter are typically attached to a strain isolator pad (SIP) using an RTV adhesive. Gap fillers are placed in the gaps created between the tiles. The SIP and filler bars are used to eleviate thermal expansion mismatch between the tiles and the substructure. The gap fillers are used for thermal protection in the gaps and also to reduce chatter effects between tiles.

The requirement to waterproof leading edge tiles shall be evaluated and established. For coated AETB tiles, the type and durability of the exterior coating will be the determining factors. Water drop exposure and wind/rain tests will be used for the evaluation. In addition, rewaterproofing techniques will be investigated if necessary. Typically, the tiles on the space shuttle orbiter are waterproofed prior to installation and, subsequently, after every landing.

4.5.2 Applicable Documents

Rockwell Specification MBO130-119 type II - RTV 560 Material Specification.
Rockwell Specification MAO106-319 - RTV Silicone Adhesive-Bonded Silica Reusable Surface Insulation (RSI) System.
Rockwell Specification MBO135-077 - Base Stock, Fabric Gap Filler.
Rockwell Specification MAO605-308 - Fabrication of Fabric Gap Fillers - Space Shuttle Orbiter.
Rockwell Specification MPP6009M301M04 - Waterproofing of RSI Tile, Vapor Deposition.
Rockwell Specification MLO601-9024 - Process 113-RSI Tile Rewaterproofing.

4.5.3 Requirements

Methods for attaching coated AETB tiles and SIRCA tiles to the substructure need to be established. The necessity of strain isolator pads and gap fillers must be examined. The necessity of waterproofing and rewaterproofing needs to be determined. Assemble/disassemble operations need to be addressed.

4.5.4 Detailed Test Article/Test Specimen Description

Several 6"x6"x2" coated AETB and SIRCA tiles shall be fabricated for attachment to a graphite/polyimide composite substructure. Several coated AETB and SIRCA coupons shall be fabricated for use in the waterproofing/rewaterproofing study.

4.5.5 Test Procedures

In-plane strain and substrate deflection tests shall be used to evaluated the strength of the tile bonding. The in-plane strain test will involve attaching a tile to one side of a tapered composite and applying a load. Strain gauges shall be mounted to the tile and composite to monitor the strain. The substrate deflection test will involve placing a tile attached to a composite into a four-point bend load fixture. Bending beam deflection gauges shall be used to monitor the deflection at the center point.

A test article with gaps will be exposed to radiant heat. The gap temperature will be monitored. Radiant heat test shall be used to determine the need for gap fillers.

SIRCA and coated AETB tiles will be submerged in water and tested for water pick-up. If waterproofing is required, various waterproofing materials shall be applied to the tiles.

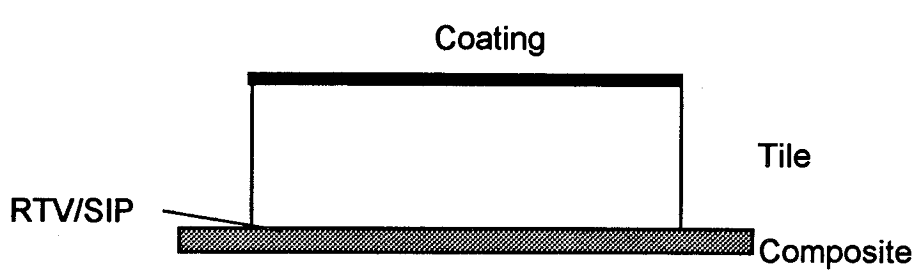
4.5.6 Sample Data Sheets

N/A

4.5.7 Test Equipment

The radiant heat facility, the waterproofing oven, and the mechanical testing equipment located at Rockwell-Downey will be used in the investigation.

4.5.8 Sketches and Schematics



4.5.9 Schedule

Initiate attachment investigation	August 1, 1995
Initiate waterproofing investigation	August 15, 1995
Initiate gap filler investigation	August 15, 1995
Initiate assemble/disassemble investigation	September 1, 1995
Initiate rewaterproofing investigation	October 1, 1995

4.6 Tile Leading Edge Configuration

Tile Leading Edge Test Article Design. A test article consisting of a graphite/polyimide leading edge substructure with durable tiles attached to the exterior surface will be designed. A typical structure is shown below. The test article will include at least six tiles or tile segments in order to evaluate step and gap effects. Both coated AETB and SIRCA tiles will be included. Joints (gaps) will be provided between AETB tiles, between SIRCA tiles, and at AETB/SIRCA tile interfaces.

Test Article Fabrication/Assembly. Advanced tiles will be fabricated and coated to meet the test article design requirements. The graphite/polyimide substructure will be fabricated and tiles installed in accordance with the test article design. The method of attaching tiles to the substructure will be based on the results of RLV technologies (NCC2-9003). Instrumentation will be installed to measure tile, substrate, and gap area temperatures.

Arc Jet Testing. Arc jet testing will demonstrate the concept of a leading edge configuration with tile insulation. Test parameters will be based on X-33/RLV thermal analysis.

4.6.1 Introduction/Background

In order to improve the durability of tile and increase its temperature capability, NASA-ARC and Rockwell have been working together to develop TUFI coating and AETB tiles. TUFI-coated FRCI tiles have been flown on the space shuttle orbiter in a high-impact area and have demonstrated improved durability. This project attempts to further develop these concepts and demonstrate the validity of using tiles in a leading edge application.

Presently, the shuttle uses reinforced carbon-carbon (RCC) for leading edge applications. Coated AETB tiles and SIRCA tiles are being developed as a low-cost, durable, maintainable leading edge alternative to RCC.

4.6.2 Applicable Documents

Appendix A (DTP 6451-810) - Arc Jet Testing Procedure.

4.6.3 Requirements

The design for the leading edge must meet the necessary thermal and mechanical testing criteria. The fabrication of the leading edge will involve placing tiles on a composite substructure.

4.6.4 Detailed Test Article/Test Specimen Description

The leading edge configuration will be approximately 46"x28"x21". The substructure will be a composite material. Either SIRCA or coated AETB tiles shall be used on the test article. A possible leading edge configuration is shown below

4.6.5 Test Procedures

Tiles and the substructure will be fabricated and assembled to the specifications outlined in the leading edge design generated by the Rockwell design group. Arc jet tests will be performed to demonstrate the leading edge design and to evaluate the step and gap requirements.

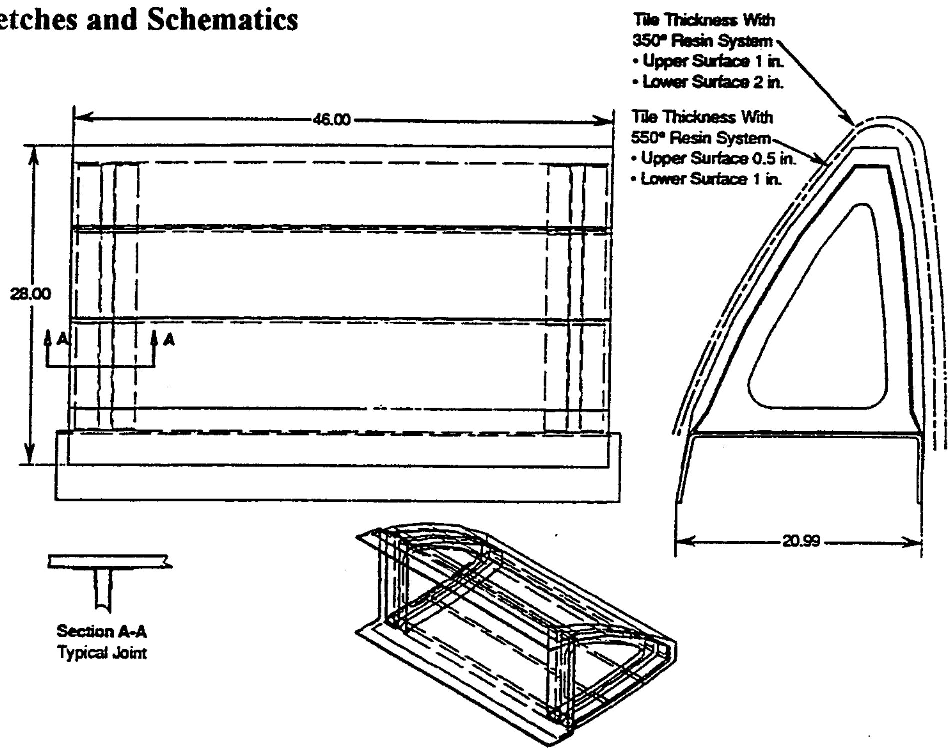
4.6.6 Sample Data Sheets

N/A

4.6.7 Test Equipment

Arc jet testing will be performed on the test panel using the 60 megawatt facility at NASA-ARC.

4.6.8 Sketches and Schematics



Preliminary Design for Leading Edge Test Article

4.6.9 Schedule

Tile leading edge arc jet test article design	January 19, 1996*
Fabricate tiles	April 1, 1996
Fabricate composite substructure	April 1, 1996
Assemble leading edge	March 1, 1996
Tile leading edge arc jet specimen fabricated	March 15, 1996
Tile leading edge arc jet tests	March 15, 1996
Initiate rewaterproofing investigation	October 1, 1995

4.7 Life Cycle Testing

A limited sequence of environmental (life cycle) testing will be done to demonstrate the performance of the leading edge configuration. One cycle will include pad wind/rain conditions, ascent conditions, on-orbit, descent thermal and pressure conditions, and an impact requiring repair (first cycle only). At least three cycles will be performed. The life cycle testing will include vibroacoustic, arc jet, wind tunnel, and rain impact tests.

4.7.1.1 Introduction/Background

Life cycle tests will be used to evaluate the performance of the tile leading edge configuration.

4.7.1.2 Applicable Documents

Appendix H (DTP 6451-817) - Vibroacoustic Testing Procedure.
Appendix A (DTP 6451-810) - Arc Jet Testing Procedure.
Appendix B (DTP 6451-811) - Wind Tunnel Testing Procedure.
Wright Laboratory Rain Erosion Test Apparatus, Utilization Policies, Operating Procedures, and Configurations, Revision 4, University of Dayton Research Institute, Dayton, OH, June 1992.
Appendix D (DTP 6451-813) - Standard Test Procedure - Rain Impact (Rotating Arm Facility).
Appendix E (DTP 6451-814) - Standard Test Procedure - Rain Impact (Single Drop Impact Facility).
Appendix F (DTP 6451-815) - Standard Test Procedure - Rain and Wind Impingement.

4.7.1.3 Requirements

Ascent and entry thermal and dynamic conditions will support X-33/RLV design. Pad/wind exposure will be in accordance with the robustness test definition from RLV technologies (NCC 2-9003).

4.7.1.4 Detailed Test Article/Test Specimen Description

The test article will be approximately 20 inches by 20 inches. It will consist of tiles attached to a composite substructure. Both SIRCA tiles and coated AETB tiles shall be on the panel. In addition, tiles in various damaged conditions will be included on the panel.

4.7.1.5 Test Procedures

Accelerometers will be applied to the leading edge test panel and it will be subjected to a vibration and acoustic loading progressive wave of 160 dB. Arc jet testing will be performed on the test panel using the 60 megawatt facility at NASA-ARC. Rain/wind conditions will be simulated using the rain erosion and wind tunnel facility. Three cycles will be run.

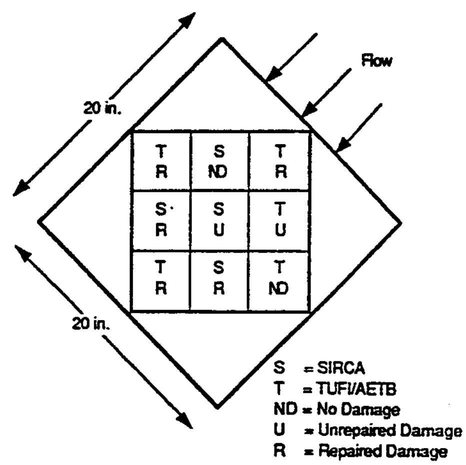
4.7.1.6 Sample Data Sheets

N/A

4.7.1.7 Test Equipment

Testing shall involve using the vibroacoustic, arc jet, wind tunnel, and rain impact facilities.

4.7.1.8 Sketches and Schematics



Test Panel for Life Cycle Tests

4.7.1.9 Schedule

Initiate specimen fabrication	April 1, 1996
Initiate testing	May 1, 1996
Arc jet testing of life cycle test article	July 1, 1996

5.0 APPENDICES

5.1 Milestones

Payment Milestones	Date	Description
LE-01	5-25-95	Detailed test plans complete
LE-02	7-11-95	Rockwell produce SIRCA tile
LE-03	8-10-95	TUFI and SIRCA arc jet specimen fabrication
LE-04	9-11-95	TUFI rain impact testing
LE-05	10-13-95	Tile damage limits arc jet samples
LE-06*	11-17-95	SIRCA process specification and rain impact
LE-07*	12-15-95	New seal materials selected
LE-08*	1-19-96	Tile leading edge test article design
LE-09*	2-16-96	New seal concept fabrication complete
LE-10*	3-15-96	Tile leading edge arc jet specimen fabricated
LE-11*	5-26-96	New seal test article arc jet tests
LE-12*	7-26-96	Test reports and data analysis