

Review

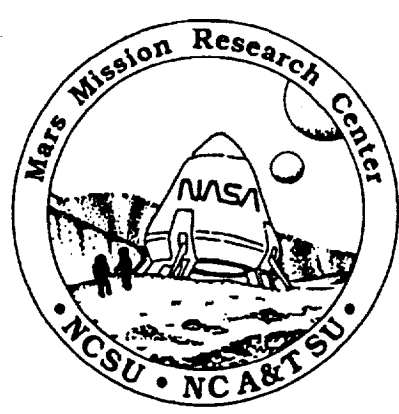
**Third Annual Report
for the period July 1, 1990 to June 30, 1991**

**North Carolina State University
and
North Carolina A&T State University**

*GRANT
IN-91-CR*

MARS MISSION RESEARCH CENTER

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**a University Space Engineering Research Center
supported by NASA Grant NAGW-1331**

N94-13088

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**National Aeronautics and Space Administration
Office of Aeronautics, Exploration and Technology
Code RS
Washington, DC 20546**

G3/91

Submitted by

**Fred R. DeJarnette, Director
Mars Mission Research Center
North Carolina State University
Raleigh, NC 27695-7910**

(NASA-CR-194034) MARS MISSION
RESEARCH CENTER Annual Report No.
3, 1 Jul. 1990 - 30 Jun. 1991
(North Carolina State Univ.) 75 p

July 1991



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MARS MISSION RESEARCH CENTER



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**Fred R. DeJarnette, Director
Mars Mission Research Center
North Carolina State University
Raleigh, NC 27695-7910**

July 1991

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EXECUTIVE SUMMARY

The Mars Mission Research Center (M²RC) is one of nine University Space Engineering Research Centers established by NASA in June 1988. It is a cooperative effort between NCSU and A&T in Greensboro. The goal of the Center is to focus on research and educational technologies for planetary exploration with particular emphasis on Mars. The research combines (1) Mission Analysis and Design, (2) Hypersonic Aerodynamics and Propulsion, (3) Structures and Controls, (4) Composite Materials, and (5) Fabrication Methods in a cross-disciplined program directed towards the development of space transportation systems for lunar and planetary travel.

The Center supports 25 faculty, 29 graduate students, 34 undergraduates, plus an additional 50 students on the aerobrake, HL-20 Personnel Launch System (PLS), and Orbiter Ejector projects. Minority participation in the Center includes two faculty, four graduate, and eleven undergraduate students. Numerous faculty and students supported by other sources work with the Center.

Funding from NASA was \$1,978,505 for the third year with an additional cost sharing of \$444,697 from NCSU and A&T. Interactions with NASA Ames, NASA Langley, NASA Johnson, McDonnell Douglas Space Systems Company and Astronautics Corporation, and Lawrence Livermore National Laboratory have led to summer programs and additional support. The faculty have been active in obtaining additional funding to supplement the grant from NASA Headquarters. During the past year, they participated in 35 grants with a funding of \$4.9 million in addition to funding for the Center.

On September 14, 1990 students and researchers from the the Center and NASA Langley Research Center unveiled a full-scale research model and cradle of the HL-20 Personnel Launch System, a project begun on January 15, 1990. The PLS is currently being studied by NASA researchers as a possible supplement to the Space Shuttle Program. It would be used to carry personnel and small cargo to and from an Earth-orbiting space station, where a Mars spacecraft may be built and launched. Other possible uses for the PLS vehicle include satellite maintenance and astronaut rescue. The model will be used at Langley and Johnson Space Center to study crew seating arrangements, habitability, equipment layout, crew ingress and egress, and maintenance and handling operations.

The dedication of the Center for Composite Materials Research was held on September 28, 1990 at A&T State University in Greensboro. This Center was established in September 1988 with Dr. V. Sarma Avva as the director. This Center has established a national reputation and complements the research of the Mars Mission Research Center.

A full-scale set of tests with an astronaut, divers, and a telerobotic arm was conducted in mid-October on the mock-up of the aerobrake, a mechanism for slowing the Mars mission spacecraft down as it approaches Mars and returns to Earth. Basic assembly concepts were again assessed, and timelines on alignment, soft docking, latching and thermal protection system closeout were generated. Tests were performed in the Underwater Facility at McDonnell Douglas in Huntington Beach, California. Evaluation of the data is still continuing.

The Center sponsored a workshop on "Technology for Lunar/Mars Aerobrakes" October 30-31, 1990 at the Mission Valley Inn in Raleigh. It had 95 attendees from NASA, industry, and universities, and featured talks and panel discussions involving 11 students, 14 faculty, and 7 invited speakers. The topics discussed reflected the basic research areas of the Center.

In January 1991, the Center also sponsored a seminar on hypersonic flight experience by Dr. Gerald Walberg of George Washington University's and NASA Langley's Joint Institute for Advancement of Flight Sciences. Dr. Walberg will join the faculty of Mechanical and Aerospace

Engineering at NCSU effective July 1, 1991. In addition, he has been appointed Deputy Director of the Mars Center.

The third annual review by the NASA Team of Monitors was held on April 3 and 4, 1991 at the McKimmon Center, NCSU, Raleigh, NC. As a result of the review, all technical groups will participate in the design of an aerobrake for a lunar return vehicle under the direction of Dr. Gerald Walberg.

This year (Fall 1990-Spring 1991) students at NCSU designed two lunar transfer vehicle (LTV) aerobrakes-- an erectable rigid structure and a deployable structure. The deployable structure was selected as the candidate design for fabrication and a 1/10 scale model was constructed for demonstration purposes. This design, along with LTV configuration, mission scenario, and EVA for a lunar mission, were assembled for presentation at the Southeastern AIAA Student Design Conference in April.

The Mars Mission Research Center was awarded a contract to construct an Orbiter Ejector for NASA Johnson Space Center. The Orbiter Ejector will fly on the Space Shuttle Orbiter and eject six calibration spheres into precise orbits. These spheres will be used to calibrate ground based radar to enable us to see smaller objects, like debris, in space. The Ejector is currently scheduled to fly on flight STS-47 in September 1992. Ten undergraduate students from Electrical, Mechanical, and Aerospace engineering are working on the project and expect to complete the construction by fall 1991.

August is the scheduled completion date of the Research and Technology II building on NCSU's new Centennial Campus, about one mile south of the main campus. The building is the newest addition to the Centennial Campus, which already has Research and Technology Building I and a four-building complex housing the College of Textiles. The new building also houses the Business Innovation and Technology Center, biotechnology laboratories, and 7000 sq. ft. of office and laboratory space for faculty and students working with the Center.

Faculty and students have been active in presenting 51 papers at national and international meetings as well as publishing results in reports and in 18 archival journals. Additional publicity on the M²RC and the research being performed has been provided by numerous newspaper and magazine articles, press releases, and radio and television programs. The activities of the M²RC are expected to have a significant influence on the space program, and to help gain the support of the nation for a dedicated space program. In addition, it will provide new research and academic programs and promote cooperative programs for students and faculty at the two Universities.

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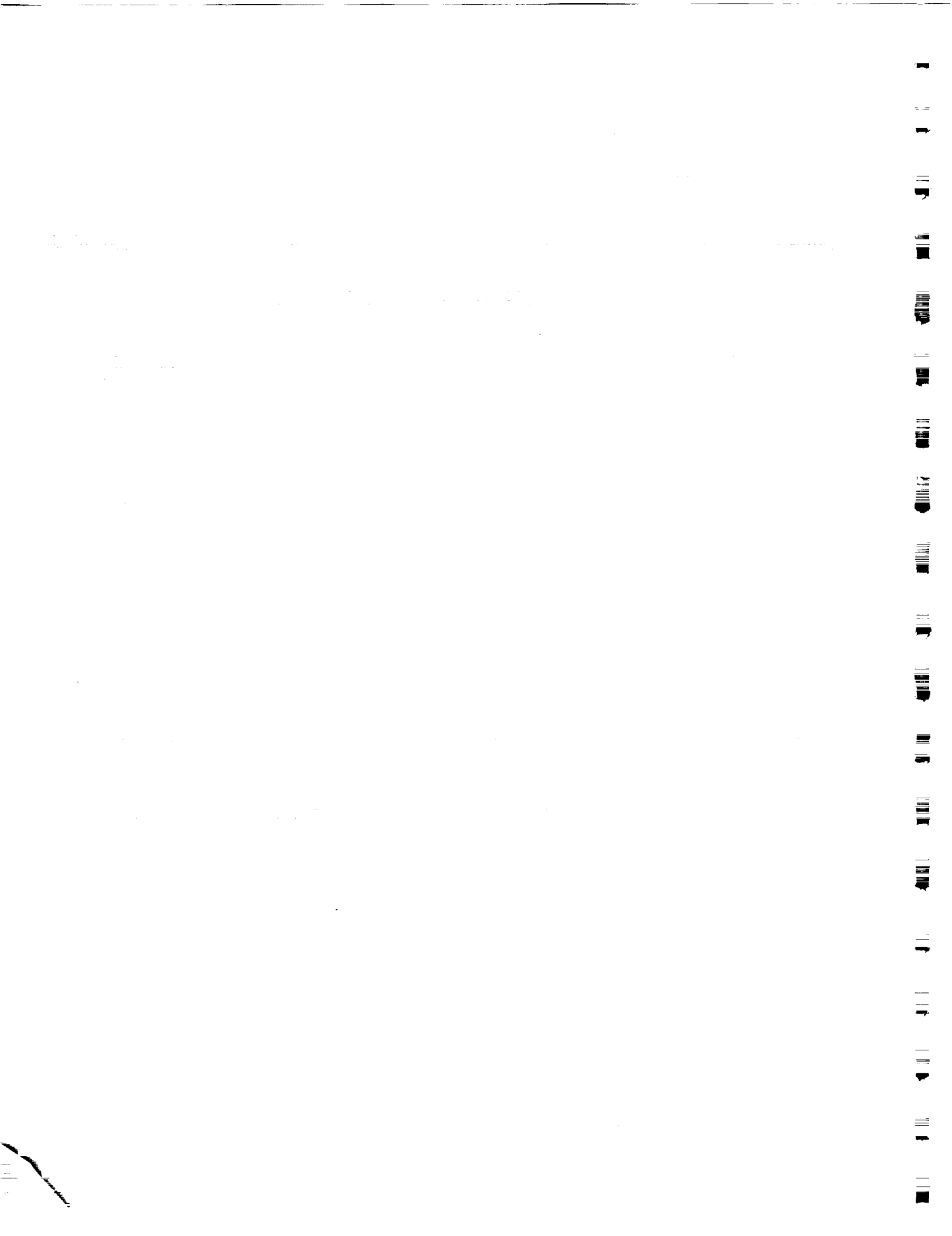
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**ORGANIZATION OF FACULTY
IN
MARS MISSION RESEARCH CENTER**

Director, Fred DeJarnette, NCSU
Associate Directors: Sarma Avva, A&T and John Perkins, NCSU

Mission Analysis and Design (3)

Gerald Walberg, GWU, Coordinator
Fred DeJarnette, NCSU
William Rasdorf, NCSU

Hypersonic Aerodynamics (6)

Hassan Hassan, NCSU, Coordinator
Graham Candler, NCSU
Suresh Chandra, A&T
Wayland Griffith, NCSU
Scott McRae, NCSU
John Perkins, NCSU
Fuh-Gwo Yuan, NCSU

Structures and Controls (6)

Gordon Lee, NCSU, Interim Coordinator
Ivatury Raju, A&T
Bill Craft, A&T
Eric Klang, NCSU
Larry Silverberg, NCSU
Fuh-Gwo Yuan, NCSU

Materials (5)

Sarma Avva, A&T, Coordinator
Abdul Fahmy, NCSU
Juri Filatovs, A&T
Ray Foye, A&T
Sal Torquato, NCSU

Fabrication (5)

Aly El-Shiekh, NCSU, Coordinator
Mansour Mohamed, NCSU
Bob Sadler, A&T
Leon Skeen, A&T
Gary Tatterson, A&T

PLS Project

Robert Vess, NCSU, Director
Thurman Exum, A&T

Aerobrake Project

Gordon Lee, NCSU, Director
Juri Filatovs, A&T

Calibration Spheres Project

Larry Silverberg, NCSU,
Director

**Other faculty participating in
but not supported by M²RC**

Mission Analysis and Design

Tony Danby, NCSU

Hypersonic Aerodynamics

ND Chokani, NCSU
Lonnie Sharp, A&T

Structures and Controls

Bert Chukwu, NCSU
Wes Doggett, NCSU
Tom Miller, NCSU

Faculty Participants: 33

**Faculty Supported
M²RC: 25**

STUDENTS SUPPORTED BY MARS MISSION RESEARCH CENTER

BS Degree Program

Armstrong, Tonya (A&T)
Barefoot, Andy (NCSU)
Bass, Joseph (A&T)
Becker, Fredrika (NCSU)
Blunk, Thomas (A&T)
Brady, Sandra (NCSU)
Brasier, Terry (NCSU)
Bruce, Lloyd (NCSU)
Crawford, Jack (A&T)
Engelbert, Charles (A&T)
Ellison, Jovanna (A&T)
Garner, Gaylynn (A&T)
Gibbs, Carlton (A&T)
Guthrie, Douglas (NCSU)
Hall, Alphonso (A&T)
Hall, Arthur (NCSU)
Hardy, Angela (A&T)

Hipps, Chris (NCSU)
Hockaday, Rodney (NCSU)
Jones, Raphael (A&T)
Kriegsman, Franklin (NCSU)
Locklear, Mary (NCSU)
Lucky Jerome (NCSU)
Martin, Thomas (NCSU)
McCormick, Ray (NCSU)
Morgan, Todd (NCSU)
Park, Joseph (NCSU)
Parkinson, Carmon (NCSU)
Perick, Claudia (NCSU)
Robinson, David (NCSU)
Santiago, Pedro (A&T)
Smith, Nanette (A&T)
Smith, Erica (A&T)
Tran, My Hao (NCSU)

Total Undergraduates = 34

MS Degree Program

Brauns, Frank (NCSU)
Cates, Joel (NCSU)
Clark, Eric (NCSU)
Drew-Lyon, Desiree (A&T)
Fruth, Gregory (GWU)
Goforth, Eric (A&T)
Hairr, John (NCSU)
Jones, Kevin (NCSU)
Kieffer, Douglas (NCSU)
Lyon, Malcolm (A&T)
Muir, Randi (NCSU)
Nicholson, Joel (NCSU)
Reid, Rona (NCSU)

Rogers, Davis, Jr. (A&T)
Salem, Elsaid (NCSU)
Shimshi, Jason (GWU)
Smeltzer, Stan (NCSU)
Stabler, Wilson (A&T)
Stanley, Robert (NCSU)
Thaxton, Cirrelia (NCSU)
Walton, Michael (A&T)
Ward, Prentise (A&T)
Washington, Greg (NCSU)

PhD Degree Program

Gabel, Robert (NCSU)
Kontinos, Dean (NCSU)
Meyer, John (NCSU)

Lyne, Evans (NCSU)
Olds, John (NCSU)
Redmond, James (NCSU)

Total Graduates = 29

OTHER STUDENT PARTICIPATION

AEROBRAKE PROJECT

Undergraduates (20):

Batten, Jonas M.
Beasley, Kenneth
Beaty, Kenneth
Bendl, Robert
Bouchelle, Steven
Brauns, Frank
Carpenter, Paul W.
Choi, Inho
Cook, Price
Deal, Blake

Goller, Scott
Hoffler, Alan D.
Moses, Samuel
Neel, Ray
Nguyen, P. D.
Ruta, Scott
Smith, D. C.
Smith, Russell
Stanley, Robert (II)
Tao, Gary

Graduates (2):

Clark, Eric
Hamilton, Jonathan

PERSONNEL LAUNCH SYSTEM

Undergraduates (20):

Alexopoulos, Greg
Brewer, Robert
Burchell, Mike
Burton, Kevin
Cate, Joel
Cockran, Keith
Duncan, Mike
Edge, Chris
Gibbons, Bill
Kelly, Adam

Lewis, Michael
Long, Robert
McLeod, Stephen
Pauley, Heather
Plate, Brian
Robinson, D.
Shepard, Alan
Steffen, Joe
Tetterton, Scott
Young, Matt

PLS SPECIALISTS (3):

Driver, Dean
Hickam, Jeffrey
Wilson, Don

ORBITER EJECTOR PROJECT

Undergraduates (10):

Ayberk Abayhan
Mark Cassada
Joseph Cody
Robert Long
Andrew Mueller

Michael Norton
Paul Schumacher
Alan Shepard
Peter Sramka
Robert Trask

STUDENTS GRADUATED BY MARS MISSION RESEARCH CENTER

Student	Degree Received	Present Status
Bennett, Jinan (NCSU)	BS	Aston Press Fabrics
Boring, Melissa (NCSU)	BS	State Conservation Centre of South Australia
Brauns, Frank (NCSU)	BS	MS/M ² RC
Chandra, Vikas (NCSU)	BS	IBM, RTP, North Carolina
Cozart, Aaron (NCSU)	BS	MS/NASA Graduate Student Researchers Program
Drew-Lyon, Desiree (A&T)	BS	MS/M ² RC
Evans, Nancy (NCSU)	BS	Hoechst Celanese
Gallimore, Ian (NCSU)	BS	Naval Air & Test Center Patuxent River, Maryland
Cate, Joel (NCSU)	BS	MS/M ² RC
Goforth, Eric (A&T)	BS	MS/M ² RC
Hash, David (NCSU)	BS	MS/M ² RC
Hickman, Charles (A&T)	BS	MS/ME Department
Lyon, Malcolm (A&T)	BS	MS/M ² RC
Polo, Jay (NCSU)	BS	
Reid, Rona (NCSU)	BS	MS/M ² RC
Riddick, Jennifer (A&T)	BS	Industry
Ringer, Melissa (NCSU)	BS	Hoechst Celanese
Rogers, Davis, Jr.	BS	MS/M ² RC
Stanley, Robert (NCSU)	BS	MS/M ² RC
Stone, Theresa	BS	MS/NASA Graduate Student Researchers Program
Thaxton, Cirrelia (NCSU)	BS	MS/M ² RC
Uzzell, Janeen (A&T)	BS	Industry
Walton, Michael (A&T)	BS	MS/M ² RC
White, Yvette	BS	
Young, Terry (NCSU)	BS	MS/M ² RC
Dellinger, Genevieve (NCSU)	MS	NASA Langley
Dickinson, Larry (NCSU)	MS	Lockheed, NASA Langley
Hamilton, Jonathan (NCSU)	MS	Boeing Aerospace, Alabama
Kontinos, Dean (NCSU)	MS	PhD/M ² RC
Owen, Vicki (NCSU)	MS	NASA Langley
Packard, Jim (NCSU)	MS	PhD/M ² RC
Redmond, James (NCSU)	MS	PhD/M ² RC
Senibi, Simon (A&T)	MS	PhD/M ² RC
Smeltzer, Stanley (NCSU)	MS	NASA Marshall
Vaidyanathan, Nirmala (A&T)	MS	PhD/Penn State
Voss, Stefan (NCSU)	MS	Teaching Chemistry Lab UNC-Charlotte
Washington, Greg (NCSU)	MS	PhD/M ² RC
Miller, Charles Andy (NCSU)	PhD	EPA, RTP, North Carolina

NASA MONITORING TEAM

Steve Wander, Chairperson
NASA Headquarters
Code RP
600 Independence Avenue
Washington, DC 20456
(202) 453-2857

Dr. Kenneth Sutton
NASA Langley Research Center
MS 366
Hampton, Virginia 23665-5225
(804) 864-4406

Dr. Steve Deiwert
NASA Ames Research Center
Code RTA
Moffett Field, CA 94035
(415) 604-6198

Dr. Herbert J. Gladden
NASA Lewis Research Center
MS 5-11
Cleveland, OH 44135
(216) 433-5871

Dr. Howard Goldstein
NASA Ames Research Center
Code RTM
Moffett Field, CA 94035
(415) 604-6103

Dr. Winston Goodrich
NASA Johnson Space Center
on assignment in Paris, France

Dr. James H. Starnes, Jr.
NASA Langley Research Center
MS 190
Hampton, VA 23665-5225
(804) 864-3168

Gordon Johnston, Program Manager
for the Space Technology
University Programs
NASA Headquarters
Code RF
600 Independence Avenue
Washington, DC 20456
(202) 453-2755

Ex-Officio Member
Dr. Samuel Massenberg
NASA Langley Research Center
MS 105A
Hampton, VA 23665-5225
(804) 864-4000

ACADEMIC BOARD

PURPOSE:

1. Work with Center Director to insure that the research and academic programs are consistent
2. Coordinate personnel, space, and equipment requirements of the Center.

MEMBERSHIP:

Deans and Department Heads of Participating Faculty

CHAIRPERSON:

Rotating Chairperson, Elected by Membership (except for initial period), for Three-Year Period

MEETINGS: Twice a Year

CURRENT MEMBERSHIP:

Dean R. A. Barnhardt, Dean of Textiles, NCSU, Chairperson

Dean James Ferrell, Interim Dean of Engineering, NCSU

Dean H. L. Martin, Dean of Engineering, A&T

Dr. J. A. Bailey, Head of Mechanical and Aerospace Engineering, NCSU

Dr. E. D. Brill, Head of Civil Engineering, NCSU

Dr. W. J. Craft, Head of Mechanical Engineering, A&T

Dr. J. J. Hren, Head of Materials Science and Engineering, NCSU

Dr. Frank King, Head of Chemical Engineering, A&T

Dr. C. D. Livengood, Head of Textile Engineering, Chemistry, and Science, NCSU

INTRODUCTION

The Mars Mission Research Center is one of nine University Space Engineering Research Centers established in 1988 by NASA's Office of Aeronautics and Exploration Technology (OAET) to broaden the nation's engineering capability to meet the critical needs of the civilian space program. It is a cooperative program between North Carolina State University at Raleigh (NCSU) and North Carolina A&T State University at Greensboro (A&T). The goal of this center is to develop educational and research programs that focus on the technologies for space exploration with particular emphasis on Mars. The research combines (1) mission analysis and design, (2) hypersonic aerodynamics and propulsion, (3) composite materials, (4) spacecraft structures and controls, and (5) fabrication techniques.

After nearly twenty years with very little exploration of space by the U.S., a renewed interest in the exploration of our Moon and Mars began in 1987 by NASA's Office of Exploration. On July 20, 1989, President Bush made an address to the nation to commemorate the 20th Anniversary of the first landing of humans on our Moon. He said, "I am proposing a long-range, continuing commitment. First, for the coming decade for the 1990's ... Space Station Freedom ... Our critical next step in space endeavors. And next ... for the new century ... back to the Moon. Back to the Future. And this time, back to stay. And then ... a journey into tomorrow ... a journey to another planet ... *a manned mission to Mars.*"

After President Bush's address, NASA appointed a committee, chaired by Aaron Cohen, to study lunar/Mars missions and a report on that 90-day study was developed. Most scenarios for human missions to Mars require a heavy-lift launch vehicle to transport components of the spacecraft to Space Station Freedom where spacecraft would be assembled and then launched for Mars. A typical round-trip mission to Mars would take about two years. The return trip to Earth would have the spacecraft dock with the space station and the crew returned to Earth by a space shuttle or a new personnel launch system (PLS).

The 90-day study was followed by the Report of the Advisory Committee on the Future of the U.S. Space Program, chaired by Norm Augustine and released in December 1990. The Synthesis Group, chaired by General Thomas Stafford, released a report on lunar and Mars exploration on June 11, 1991. It illustrated four mission scenarios which would land the first humans on Mars in 2014 and 2016.

One of the key technologies for the design of both lunar and Mars spacecraft is the mechanism used to reduce the speed of the vehicle at Mars and for the return trips to Earth. One technique uses propulsive braking, but the additional propellant required increases the size and weight of the vehicle significantly. An alternate technique, called aerobraking, uses aerodynamic drag in the atmospheres of Mars and Earth to slow the spacecraft, and it could prove to require less volume and mass than propulsive braking.

The Mars Missions Research Center is investigating aerobraking for lunar/Mars spacecraft. Aerobrakes somewhat like the shape of the Viking Aeroshell and the Aero-Assisted Flight Experiment (AFE) are being considered. However, the size of the spacecraft would be much larger than the 14 foot base-diameter of the AFE. The lunar return aerobrake would be nearly 45 feet while a Mars aerobrake would be over 100 feet in diameter.

This report describes the activities of the students and faculty in the Mars Mission Research Center for the third year (July 1, 1990 to June 30, 1991). Last October, in addition to the continuation of previous research, the Center initiated the calibration spheres project at the request of NASA Johnson Space Center. As with other special projects, this project has expanded and enriched the research and educational opportunities of the Center.

MISSION ANALYSIS AND DESIGN

Aerospace Vehicle Design Integration Composite Material Database and Computer-Aided Analysis System Computational Structural Analysis

William Rasdorf

Past Research

A prototype computer-aided analysis (CAA) system, integrating several components of engineering software using a relational database, has been developed. The objectives of the system are to enhance data transfer between, and interaction among, the programs with minimum user interaction and to effectively capture the broad scope of data necessary to effectively represent composite material properties.

The focus of the CAA system is on the assembly, manipulation, and use of composite materials data, resulting in the transfer of two- and three-dimensional composite materials property data into several finite element analysis programs. Despite the fact that such integrated systems are not new in many domains, their introduction to the realm of composite materials analysis and design has not successfully occurred. This outcome is due in large part to the nature of the materials themselves and the overhead they bring to the development of a successful life-cycle model. The benefits of the system include the ability to generate a laminate in an ad hoc manner and have its material properties both immediately available for formatted FEA input and archived in a materials database. Particular attention is given to material properties for analysis and design of components and structures using thick composite materials.

Proposed Research

The proposed research falls into three broad categories: design, parallel processing, and composites.

DESIGN

Design can be viewed as a process of transformation from requirements, specifications, and goals to a manifestation of a physical object. The transformation itself, called the design process, requires the use of past design experience in a uniform and systematic way for obtaining future designs.

A far reaching goal of the Mars Mission Research Center is to design an interplanetary vehicle or its components. (More near term objectives are to solve research problems to enable this to happen). The objective of the activity proposed here is to develop the database concepts to support design knowledge capture of the spacecraft and its components as they evolve.

Two investigations are needed: TMIS and PDES. First, the Technical Management Information System of the Space Station Freedom Office must be explored thoroughly. The database and design knowledge capture development taking place there must be understood. Second, the Product Definition and Exchange Standard that is evolving as an international standard for describing engineering objects must be thoroughly explored. The applicability of this mechanical/civil/ship data exchange standard to aerospace applications must be understood. Furthermore, the commonalities and differences between TMIS and PDES must be identified and enumerated. The result will be a contribution to the definition and exchange of aerospace engineering components in CAD environments.

PARALLEL PROCESSING

Research in engineering has long been concerned with solving systems of equations. Because of the tedious and time consuming nature of the large-scale problems of this type, computer solutions are mandated. However, the size of computational structural mechanics and computational fluid dynamics problems is becoming so large that conventional computers cannot solve them. Therefore, researchers are looking toward parallel and vector computers as a potential solution to the problem. These computers are opening the door to solutions for previously unsolvable problems. However, this requires developing new procedures and modifying old ones in order to exploit the parallel and vector capabilities of these computers. Furthermore, it requires a new type of engineering researcher who possesses deep, fundamental knowledge in parallel computing as well as their specific discipline.

The work proposed here is the static and transient analysis of a geostationary platform using model superposition and Newmark-Beta methods. The objective is to solve a realistic structural analysis problem whose applicability could be extrapolated to the Mars aerobrake. NASA LaRC PVSOLVE and PVDR codes will be used. These analysis codes, for static and dynamic displacement determination, are two of the first structural analysis codes that exploit the parallel and vector capabilities available today. An exploration will then be made of the applicability of the codes and the results for analysis of the Mars aerobrake.

COMPOSITES

This research has two thrusts. One is to develop the structure of a database for fiber-reinforced composite material characterization. The second is to define the scope and organization of an overall computational environment for life-cycle composite component definition, analysis, and design.

With respect to aerospace applications, some use of thick composites is expected to occur. Unfortunately, not much research has been directed at thick composites. As a result, the development of models to accurately predict 3D properties has been limited. One of the key limitations has been the lack of an organized repository of detailed, well presented, and broad ranging ply property data as well as historical laminate data. The key to designing with composite materials is obtaining complete and accurate data to predict the performance of the composite in a design scenario. One thrust of this research is to explore the design and development of such a material property database so that results from material science research are made available.

Despite the fact that integrated systems are not new in many domains, they have not successfully been introduced into the realm of composite materials analysis and design. The goal sought is to be able to design and assemble laminates in an ad hoc manner, immediately generate appropriate 3D material properties, and generate input files for finite element analysis. A prototype computer aided analysis system to do so has been developed. The objective of this research is to expand the capability of the CAAS to incorporate 3D braided and woven composites.

Mars/Lunar Mission Analysis and Design

Gerald D. Walberg

Past Research

The primary objectives of the Research Program on the Assessment of Aerobraking Vehicles for Manned Mars Missions are to carry out studies of Mars mission scenarios and vehicles, to correlate NASA and industry studies with those being carried out in the Joint Institute for Advancement of Flight Sciences and the Mars Mission Research Center, and to identify preferred mission and vehicle concepts.

Since the inception of the program in September, 1989, the Principal Investigator has carried out numerous analyses and assessments of mission scenarios and vehicle concepts. The results of these investigations have been presented in a number of references. The major findings are as follows:

As a result of design studies for Manned Mars Missions carried out over the past four years, a tentative consensus regarding mission and vehicle characteristics has emerged. The mission scenario receiving the most attention at present uses chemical rocket propulsion and aerobraking and involves early opposition-class (500 day) sortie missions followed by conjunction class (1000 day) resupply missions. The 500 day missions, with their higher entry velocities provide the primary design drivers for aerobraking vehicles. The preferred aerobrake configuration is a blunt shape with a maximum hypersonic L/D of approximately 0.5 for Mars aerobraking. For Earth return aerobraking an L/D of 0.2 appears acceptable. For the early mission, Earth return aerobraking is usually accomplished with a small, Apollo-like, crew return capsule rather than attempting to reuse the Mars aerobraker. For the later (1000 day) missions, reuse of the Mars aerobrake at Earth is highly desirable but appears to be prohibited by the present state-of-the-art for TPS materials. If entry velocities and ballistic coefficients are minimized, reuse at Mars appears achievable. Packaging and sizing studies show the Mars aerobrakers to be large, with major diameters of 30-37m and masses on Mars arrival of 150,000 - 200,000 kg. Launch vehicle size limitations result in a requirement for some type of on-orbit assembly or deployment of the Mars aerobrake. Several approaches have been proposed, but no consensus has yet developed regarding the preferred technique. This is one of the most important outstanding issues in the design of aerobraking vehicles for manned Mars missions.

Since a near consensus has been reached regarding overall mission characteristics, attention is being focused on detailed definition of the Mars parking orbit, and descent to and ascent from the Martian surface. The oblateness of Mars has been shown to cause significant precession of the parking orbit. Hence, parking orbits must be chosen that provide access to scientifically interesting regions of Mars and also have an end-of-stay-time orientation favorable for rendezvous of the Mars ascent vehicle and departure to Earth. Results obtained in our studies show that indiscriminate parking orbit selection can result in significant mission (weight) penalties. On the other hand, parking orbits have been identified that minimize weight penalties and provide access to large portions of the Martian surface. Studies of the descent-ascent phase of the missions, as well as complementary studies of Lunar parking orbits are also being carried out.

Long duration mission scenarios are also being addressed. The characteristics of several mission architectures presented at the Case for Mars IV Conference have been reviewed. For these missions, artificial gravity is used on the transfer vehicles, and near-Hohmann transfers are utilized with resulting low entry velocities. These low entry velocities are shown to have a major impact on aerobrake technology requirements. Most importantly, radiative heating becomes much less important at Mars, and Earth return velocities are reduced to the point that the combination of Apollo and AFE flight data may constitute an adequate basis for vehicle design. For these long

duration missions, Earth-return entry velocities are reduced to near Lunar-return levels, hence allowing much more commonality between Mars-return and Lunar-return aerobrakers.

Proposed Research

- a) Investigation of techniques for optimizing Mars mission scenarios. A review of optimization approaches will be carried out and numerical experiments will be performed using the IPOST (Interplanetary Program to Optimize Simulated Trajectories) algorithm which is currently being brought into operation at NASA LaRC.

Primary Investigator: Gregory Fruth (under direction of Dr. Walberg)

Products: •Assessment of optimization techniques for planetary missions
•Evaluation of IPOST
•Refinement of currently accepted Mars mission scenarios
•M.S. Thesis

- b) Experimental investigation of convective heating for blunted wide-angle cones at angle of attack in various test gases.

Primary Investigator: Jason Shimshi (under direction of Dr. Walberg)

Products: •Measured distributions of heating rates and pressures, and comparison with various analysis techniques
•Improved predictions of heating rate distributions over Mars aerobrakes
•Assessment of impacts on aerobrake design
•M.S. Thesis

- c) Carry out analyses of overall Mars/Lunar mission scenarios

Principal Investigator: G. D. Walberg

Products: Identification of preferred mission and vehicle concepts
Overall focus for MMRC research program

- d) Investigation of mission penalties associated with using propulsive braking to reduce Earth-return entry velocities to Lunar-return (Apollo) levels

Lead Researcher: Graduate Research Assistant to be chosen in September

Products: Assessment of feasibility of constraining Earth entry velocities to levels that would require no flight tests beyond Apollo and AFE; assessment of impact on Earth-return vehicle design; MS Thesis or Ph.D. Dissertation.

HYPersonic AERODYNAMICS

Computation of Hypervelocity Flows

G. V. Candler

Past Research

The third year research activities have centered on the development of techniques for the prediction of hypersonic flows in the Martian atmosphere. A numerical method has been developed that solves the governing equations for an eight species reacting gas that models the carbon-dioxide and nitrogen atmosphere of Mars. This technique was used to predict the convective heating rate and surface pressure distribution on an ellipsoid-cone geometry entering the Martian atmosphere. The primary conclusions of this work are that the flow, for the conditions tested, is nearly thermally equilibrated and, at low speeds, chemically equilibrated. The convective heating rates are similar to those obtained in air. This numerical technique is currently being used to predict the aerothermal loads on the aeroshell for NASA's proposed MEASUR probe. This work is being performed in conjunction with the NASA Ames and Langley Research Centers.

Additional research that has stemmed from the above study, is the development and implementation of a more detailed thermo-chemical nonequilibrium model for the Martian atmosphere. This model, which is applicable at higher speeds than the eight species model discussed above, uses eighteen chemical species to model the Martian atmosphere. It is capable of being coupled to a nonequilibrium thermal radiation prediction algorithm to determine the radiative heating rate during entry. This has been done and was reported in a recent AIAA paper.

On a more fundamental level, work is under way to study the relationship between the vibrational state of a gas and its dissociation and recombination rate. This study is funded by NASA Ames Research Center and will have results which are applicable to the Mars Mission Research Center. This work will lead to an increased understanding of the dissociation process and how to model it. Results obtained from this study will be implemented in the above-mentioned aerothermodynamics algorithms.

Further analysis has been initiated to study the flow over an aerobrake with surface irregularities. Such a situation may arise during atmospheric entry if the aeroshell deforms under loading. So far, a parametric study has been performed to determine the increase in heating rate due to a surface deformation. It has been found that for irregularities of moderate height to width ratio, the local heating rate can approach the stagnation point heating. This work is being done in conjunction with the structural designers to establish a minimum stiffness of the aerobrake structure.

Proposed Research

The proposed research program has three basic elements, all of which are related to the prediction of hypervelocity flows. This work builds on the previously developed techniques for the computation of thermo-chemical nonequilibrium flows. These three topics will be discussed below and their inter-relationship will be highlighted.

The first objective of the proposed research is to continue the development and testing of a numerical algorithm for the simulation of hypersonic flows in the Martian atmosphere. This work has resulted in two publications and is one of the few (if the only) technique currently available for the prediction of nonequilibrium Martian atmospheric entry flows. The key problem with this algorithm is that the vibrational relaxation rate of high temperature carbon-dioxide is not well

known. Because of this uncertainty, the vibrational state and degree of chemical reaction in the simulated flowfields is uncertain. Thus, a key aspect of the proposed research is to extensively compare the computational results to experimental evidence to determine the uncertainty in the thermophysical model of carbon dioxide. This has been done to a minor extent, but more experimental data are now available for the flow of hypervelocity carbon-dioxide over ellipses. These data show highly resolved flow structures, and it is felt that a fair degree of confidence may be obtained in the chemical kinetics if these flows can be accurately reproduced. Additional work is ongoing on this topic by researchers at both NASA Ames and Langley Research Centers. This collaboration will result in a data base useful for the design of aeroshells for Martian atmospheric entry. As an example of this work, computations are being carried out to aid in the design of NASA's MEASUR probe.

The second area of proposed research has the ultimate goal of the development of a three-dimensional computational fluid dynamics algorithm for the simulation of thermo-chemical nonequilibrium flows. This numerical technique would then be used to study the flight data obtained during the development of the Apollo re-entry vehicle. This extensive data base shows an interesting and puzzling trend in that the predicted pitching moment of the vehicle was significantly different than that obtained in flight. It has been postulated that this difference was a result of chemical reactions in the flowfield which did not occur in the wind tunnel experiments that were used to design the vehicle. Also, others have suggested that the protrusions and cavities on the Apollo vehicle caused the pitching moment shift. The proposed research would address this problem and should answer it. The results obtained from this study would be useful in the design of future entry vehicles such as the Mars Mission aerobrake.

The algorithm that would be used in the proposed study was developed by Yoon and Jameson and has been used by other researchers with promising results. In particular, Eberhardt *et al* have shown that a very efficient scheme may be developed to simulate thermo-chemical nonequilibrium flows using this method. They report computational times that are small enough that a very good analysis of the Apollo entry vehicle may be performed on current supercomputers. During the current proposal period, it is anticipated that a three-dimensional, perfect gas version of the algorithm would be developed and debugged. Initial computations of the Apollo re-entry vehicle would be completed. Further extensions of the method would follow. This computational technique would be available to other researchers in the Mars Mission Research Center for the prediction of aerothermal loads on aerobrakes.

The third aspect of the proposed research is the development of techniques for the simulation of flows with surface ablation. The high heating rates that are likely to be encountered during Martian atmospheric entry, and upon return from Mars dictate that an ablative heat shield must be used. However, the state-of-the-art in the prediction of ablating flows leaves much to be desired because the ablation rate is determined using an empirical formula, and not from the intrinsic properties of the material¹⁰. Also, the high temperature shock layer air mixes with the ablation products forming a layer in which thermo-chemical nonequilibrium processes occur. Currently, it is assumed that this interaction process is in equilibrium. Thirdly, the effects of radiative energy transport are neglected in current analyses. These effects must be included if an accurate prediction of the ablation process is to be made. The proposed research would make the first steps toward improving our predictive capacity and would lead to further development of techniques to study flows with ablation.

The proposed research is directly applicable to the charter of the Center and would be used by other researchers. This work would lead to the ability to accurately predict the aerothermodynamic environment of aerobrakes entering the Martian atmosphere and returning to earth. The heating rates and surface pressure distributions will be made available to the other researchers in the Center so that they may better design the aerobrake structure and thermal protection system.

Experimental Hypersonic Aerodynamics

Wayland C. Griffith

Past Research

Title: Quantification of Vapor Screen Analysis
Project Director: Wayland C. Griffith, (919) 737-2365
Sponsoring Agency: USAF-USN-NASA Contract NAGW-1072
Point of Contact: Dr. William J. Yanta, (301) 394-1928
Dates: May 1990 - January 1991

Description: This work was accomplished at the Naval Surface Warfare Center, White Oak, Maryland under a cooperative agreement between N.C. State University and NSWC. It constituted the M.S. thesis of Mr. Lance Benedict. The study explores the feasibility of making quantitative measurements of laser light scattering from condensed water particles in the supersonic flow of moist air in order to determine gas flow density fields. For the cases tested, a 2-D biconvex model at three different angles of attack, good agreement between measurements and a CFD computer solution was found.

Title: Analysis of a Fine-Wire Thermocouple Stagnation Temperature Probe for Use in Hypersonic Nitrogen Flows
Project Director: Wayland C. Griffith, (919) 737-2365
Sponsoring Agency: USAF-USN-NASA Contract NAGW-1072
Point of Contact: Dr. William J. Yanta, (301) 394-1928
Dates: May 1990 - May 1991

Description: This work was accomplished at the Naval Surface Warfare Center, White Oak, Maryland under a cooperative agreement between N.C. State University and NSWC. It constitutes the M.S. thesis of Mr. Brian Hollis, who expects to finish in May 1991. A two-element thermocouple developed initially for supersonic flows is being modified for use in hypersonic streams and boundary layers. Appropriate extensions of the heat transfer analysis are being made to yield total temperature data.

Title: Mach 18 Tunnel
Project Director: Wayland C. Griffith, (919) 737-2365
Sponsoring Agency: USAF-USN-NASA Contract NAGW-1072
Point of Contact: Dr. William J. Yanta, (301) 394-1928
Dates: May 1990 - December 1990

Description: This work was accomplished at the Naval Surface Warfare Center, White Oak, Maryland under a cooperative agreement between N.C. State University and NSWC. It constitutes the PhD thesis of Mr. Ken Jones. Prior operating data from hypersonic nitrogen tunnels at NSWC and elsewhere shows that substantial supercooling occurs prior to the onset of equilibrium partial condensation of the working fluid. This effort is directed toward the design of an experimental Mach 18 nozzle, using the same tunnel supply and test cell section as are in place for the Tunnel 9 Mach 14 nozzle. New sections are currently in fabrication. Tunnel calibration and Mach 18 boundary layer surveys will be made later this year.

Title: A Ballistic Investigation of the Aerodynamic Characteristics of a Blunt Vehicle at Hypersonic Speeds in Carbon Dioxide and Air
Project Director: Wayland C. Griffith, (919) 737-2365
Sponsoring Agency: NASA Mars Mission Research Center, NAGW-1331
Point of Contact: Dr. A. J. Strawa, (415) 604-3437
Dates: May 1989 - October 1990

Description: This work was done at NASA Ames as a part of the research for the M.S. degree by Mr. James Packard. Computer-aided model design methods were programmed and, in collaboration with the Ames staff, more automated methods were developed and checked out for analyzing the ballistic range shadowgraphs for the aerodynamic coefficients. The Pioneer Venus shapes were shot in carbon dioxide and air at Mach numbers from 7 to 20 and Reynolds numbers from 0.01 to 4 million. Data on C_l , C_d and C_m were obtained. Capitalize the two data reduction techniques tested, a five degree-of-freedom routine employing weighted least squares with differential corrections was found to give the greater accuracy.

Proposed Research

The Mars Mission involves atmospheric maneuvering at speeds and densities outside the ranges for which adequate aerodynamic data are available for vehicle design purposes. Substantial advances in measurement methods are being explored, particularly with non-intrusive electro-optic techniques coupled to digital computer data processing. The hope is to provide adequate information for validating CFD codes that can then be applied to the actual flight conditions expected. Some gains can also be made in the performance of ground test facilities in filling the gap between existing test conditions and those to be encountered in flight tests. The research proposed here relates to facilities at NASA Ames (ballistic range and shock tunnel) and at NSWC - White Oak (hypersonic nitrogen tunnels).

A recent paper describes the introduction of holographic interferometry into the NASA Ames ballistic range. In the future it may be possible to employ similar methods in the shock tunnel. In both cases this will be the first opportunity to obtain quantitative flowfield data beyond the traditional spark shadowgraphs from ballistic ranges. The introduction of digital processing of holograms offers major gains in flow data retrieval as illustrated in the paper. A major problem remains however, in finding the integer fringe shift across shock waves generated by bluff bodies since the digital method can only identify relative phase and optical refraction effects mask the actual fringe locations in the immediate neighborhood of the strong shocks produced at hypersonic flight speeds. Two further complications arise: gas chemistry alters the constant gamma condition previously assumed in analyzing interferograms, and the wake flow is made non-symmetric by bodies flying at angle-of-attack or by asymmetric models such as the AFE in general. Techniques for overcoming these problems have been devised and are being tested as part of the thesis research of a student. The continuing research proposed here includes extending these preliminary analytical techniques to a larger range of conditions and putting the theory in a form suitable for computer processing. The ultimate goal is to provide experimental data sets on the wake density fields to the CFD group for code validation. Thus, data on candidate Mars entry and Earth return vehicles can be obtained. This work relates directly to that of Dr. Chokani, an experimentalist, and the CFD work of Drs. Candler and McRae, both of whom also spend some time at NASA Ames.

With NSWC, White Oak, we have had six students participate in a cooperative research program. A common theme underlying the research of the four most recent students is vapor condensation in wind tunnels or the lack of it: supercooling. When condensation to particles did occur, we used the scattering of laser beams or light screens to quantify some interesting aspect of the flow. The limits of non-equilibrium supercooling have also been explored, and were found to be both consistent and large in the three NSWC hypersonic nitrogen tunnels. This finding in turn has led to the design of an experimental Mach 18 nozzle for Tunnel 9, in which the same Mach 14 supply

pressure and heating system will be used with a further expansion of the flow to $M = 18$. The proposed research centers on quantifying real gas effects appearing at the test cell states to be achieved: departure from the Perfect Gas equation of state due to intermolecular forces, non-constant specific heat due to freezing out of rotational internal energy states, limits to supercooling based on the spinodal, and identification of the fringes for rarefied gas effects. Also, a Ph.D. candidate will be working at NCSU on other funding to complete a thesis using NSWC tunnel data on Mach 18 boundary layers. For Mars, the extension of wind tunnel testing capability from $M = 14$ to 18 is significant. The use of CFD methods in tunnel design is being studied by Drs. Perkins and Candler.

Study of Equilibrium and Nonequilibrium Radiation for Reentry Vehicles

H. A. Hassan

Past Research

The work that I have conducted pertains to modeling of flows past reentry vehicles using Monte Carlo methods. Because Monte Carlo methods are direct physical simulations, the results of the simulation are a direct result of the physical assumptions employed. The physics in the Direct Simulation Monte Carlo method require a great deal of improvement. The issues that have received and continue to receive attention are:

- (i) Role of grid resolution
- (ii) Species and temperature dependent vibrational probabilities
- (iii) Direct simulation of vibration-dissociation coupling
- (iv) Consistent calculation of ionization and ambipolar diffusion
- (v) Consistent calculation of radiation

Monte Carlo simulations are needed to define the heating environment of reentry vehicles. Such calculations are important for the design of the aerobrake and the spacecraft.

Other work which is still in the early stages of development involves study of nonequilibrium and equilibrium radiation.

Proposed Research

The proposed research involves the development of a code based on the Navier-Stokes equations to do equilibrium calculations. Current calculations of equilibrium flows are obtained as a limiting form of nonequilibrium. This is both inefficient and probably inaccurate. The latter statement is a result of the fact that the speed of sound in a nonequilibrium flow is the frozen speed of sound, while in an equilibrium calculation, it is the equilibrium speed of sound. Because the two speeds are different, any property that is sensitive to the Mach number will be different.

The first phase of this work will concentrate on an axi-symmetric two-dimensional flow solver. The equilibrium radiation model developed by Nicolet and used in the Hyvis code will be used. Future plans call for incorporating a nonequilibrium radiation model and extension to 3-D geometries.

The above research complements the work of other faculty who are working in hypersonic aerodynamics.

Rotated Upwind Solver

D. S. McRae

Past Research

ROTATED UPWIND SOLVER FOR HIGH SPEED FLOWS

A significant percentage of the numerical PDE integration techniques in use today are based on treating the discrete differences in pressure between mesh points as a local Riemann problem. The solution proceeds by using an approximate Riemann solution in two directions aligned with the local coordinate direction, regardless of the orientation of any local pressure discontinuities. This procedure has been observed to result in excess dissipation and inaccurate solutions.

In order to correct this problem, a rotated upwind solver has been developed. This technique uses a local coordinate system rotated to align with the local orientation of the chosen Riemann discontinuity. An approximate Riemann solver is then applied in the rotated direction normal to the local orientation of the Riemann discontinuity with central differencing parallel to the discontinuity. Solving the flowfield in this manner results in more accurate and physically correct results.

First order rotated results using quadratic interpolation have been found to be nearly as accurate as second order grid-aligned solutions. Second order rotated solutions have also been obtained, with improvement over grid-aligned solutions noted but not as dramatic as is the case with first order solutions. Improved interpolation techniques are being sought to further improve the second order results.

This is a fundamental effort directed toward improving the accuracy of our high speed flow solvers for spacecraft flowfields. It will also be used in the solution of spacecraft aft body flows.

Virtually all flow solvers today use upwind methods. The results of this research will be available for incorporation in other flow codes used to computer spacecraft flowfields.

SPACECRAFT AFT BODY FLOWS

Two 3-D time dependent codes have been developed which include the dynamic flow adaptive mesh algorithm of Benson and McRae. These codes have been used to solve supersonic flows about spherical segments and axial corners as a code development case. The codes use central differencing with Kwak Yoon damping in the first and a Roes Upwind Solver in the second. The mesh algorithm has been shown to operate properly in 3-D and to provide enhanced accuracy by adapting simultaneously in all three coordinate directions.

Figure (1) shows the 3-D adapted mesh for supersonic flow over a spherical segment. Velocity directions in a portion of the out flow plane and a sample mesh surface from the interior of the mesh are also shown.

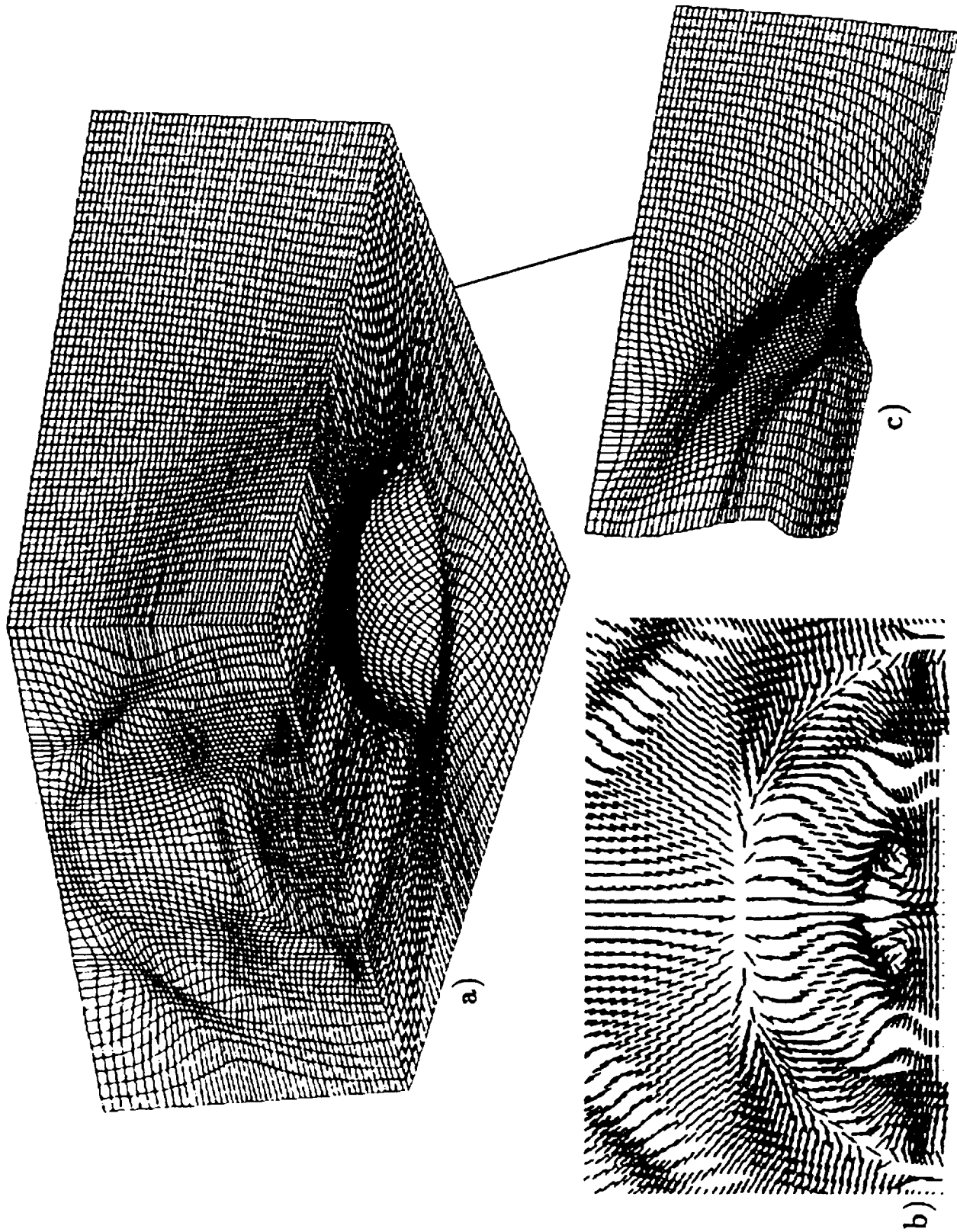


Fig. 1 Domain grid, velocity direction plot, and constant k -plane grid for the spherical segment flow

Proposed Research

Upwind methods have become standard for computation of high speed flowfields. However, the methods, when aligned with the coordinate grid, are not properly modeling the physical behavior of the flowfield. This project will build on the successful, explicit upwind solver for the parabolized Navier-Stokes solver developed by Korte (Mars Mission Annual Report, 1989; AIAA papers 88-0716, 89-1829). An idea proposed by Korte is being used to apply a Riemann type solver (specifically Roe's method) in a coordinate system exactly transformed to align with the local direction of pressure discontinuity in the finite difference stencil. This will allow the Riemann solver to be applied only across the discontinuity with central difference techniques applied to the discontinuity. The results are then transformed back into the computational coordinate system.

Results have been obtained in 2-D that indicate more accurate solutions result from the rotated upwind technique.

The work for the coming period will involve extending the method to three-dimensions and improving the accuracy of the formulation. We expect that the addition of chemistry and an adaptive mesh solver will then follow. Riemann type solvers have been demonstrated to alleviate problems with dispersive oscillations, encountered in central difference solvers, that cause large errors in chemistry in the vicinity of shock waves and strong expansions. The code proposed will be a prime candidate for use in design verification for earth entry, spacecraft and gas Mars entry (with CO₂ chemistry). This work will provide continuum flow analysis capability to complement the DSMC work of H.A. Hassan.

COMPOSITE MATERIALS AND FABRICATION (NCSU)

Full-Scale Automation and Characterization of 2-D and 3-D Braided Preforms for Composites

Aly El-Shiekh

Past Research

Last year's research activities focused on the development of machines for the production of 3-D composite preforms. Continuing the automation of 3-D braiding machines, a 2-step circular 3-D braider was designed and assembled, with work to automate it currently underway. In addition, a fully automated filament winder was built and is currently operational. This machine is being used to produce preforms for research on filament wound tubes.

The 3-D braiding group continued to develop techniques to fabricate complex shapes, with truss, J-stiffeners, rocket nozzles, and splinter panels being successfully produced.

Proposed Research

A spacecraft for travel to Mars will require complex structures. The components will need the stiffness and the strength to meet the load requirements for such a mission. Our goal is to find the optimum structure for spacecraft components through the characterization of composite materials. An important step in reaching this goal is the automation of the braiding process, to ensure the repeatability of the material and the reliability of the characterization properties. Once the components are fabricated, they will need to be assembled to make the spacecraft. Thus, there will be an investigation of joint systems, specifically bolted joints.

Joining the results of these activities with the work of other Mars Mission Research Center faculty, such as Drs. Fahmy, Klang, Silverberg, Avva, and Mohamed and Professor Sadler, we envision, in the near future, the building of a model spacecraft that could be tested for performance on earth.

Thermal and Elastic Properties of Advanced Three-Dimensional Fibrous Composites

Abdel Aziz Fahmy

Past Research

In this period, we concentrated on the thermal conductivity of fiber reinforced composites, both experimentally and analytically. The analytical approach included vigorous calculation of the transverse conductivity based on two over-simplified models as well as a computer aided finite element analysis. The finite element analysis was conducted on more realistic models in which the volume fraction of fibers, as well as their distribution, was controlled. We utilized a computer code, COSMOS, which is primarily a structural analysis program and adapted it to our use. It was thus possible to obtain detailed temperature distribution within the composite when a thermal gradient is imposed, on it and the heat flows through each point on the boundaries were added to enable the calculation of conductivity.

It became clear through the above analysis that the matrix, or continuous phase played a dominant role in determining the thermal conductivity. On the experimental side, we devised a method for the determination of the transverse thermal conductivity of fibers. The method consists of selecting a suitable matrix and a fixed fiber volume fraction; then preparing a number of unidirectional composites of the same matrix, each containing a fiber of a known thermal conductivity. These are fibers known through their structure and morphology to be isotropic such as glass, FP3, Se'C...etc. The transverse conductivity of these composites is then plotted against the transverse conductivity of the fiber to produce a "master curve" which is then used to yield the transverse conductivity of the unknown fiber once the conductivity of its composite is measured.

This approach is still valid, but both experiment and analysis show that the conductivity of the unknown fiber has to be within an order of magnitude of known ones.

Proposed Research

The research will consist of an experimental phase and an analytical phase. The experimental phase includes the evaluation of a large number of fibers, both for their reinforcement potential as well as thermal performance. Thermal expansion behavior and thermal conductivity are still aspects that have not been adequately addressed, and yet they are critical aspects that are closely related to the mechanical performance of fibrous composites. The fibers considered range all the way from high thermal insulators such as silica fibers to high thermal conductors such as the pitch based fibers with conductivities in excess of double or triple that of copper. The first group - the insulators - are of potential use in the thermal shield of a space vehicle - with or without binder. The second may provide the key to the manufacture of substrates for the electronic modules on the spacecraft that passively dissipate the produced heat and yet are dimensionally compatible with the electronic components. The experimental phase also includes the actual preparation of the "composites" and their testing.

The analytical phase is a continuation of an effort we started in the study of heat flow through heterogeneous media. It has become clear from work performed so far that, in a particular matrix, the presence of a discontinuous phase - such as fiber - can only change the conductivity within a surprisingly narrow range - maybe one order of magnitude group for infinitely insulating to infinitely conductive fibers. Fiber - fiber contact at the provision of a conducting path through the matrix from one fiber to the other is evidently needed if one is to obtain the flexibility in tailoring the properties. This will be an aspect we shall focus on in our studies. The relevance of this is that insulating foams such as used in insulating blankets in the thermal shield of spacecraft are made up of fibers with random - or near random - orientations which are simply interlocked. The insulating

properties of such insulators must be related to the properties of the fibers, their volume fraction, their orientation, and obviously, the quality and quantity of fiber - fiber contacts. This work will thus be helpful in:

Providing a better appreciation of the variables involved in determining the thermal conductivity in heat shields - hopefully making it possible to design them and produce them better.

As a side line: developing a light weight, highly conductive, dimensionally compatible substrate for the electrane modules of the spacecraft.

3-D Weaving of Structural Components for Space Applications

Mansour Mohamed

Past Research

Development of the automated 3-D weaving machine continued. A patent application was submitted to the U.S. Patent Office on August 28, 1990,. There are four companies who expressed interest in obtaining a machine. Two are U.S. companies, one German and one Japanese. These companies are:

1. Textile Technologies, Inc.
2. Southern Weaving
3. MBB (German Aerospace)
4. Nikon Oil Company (Japan)

Three-D carbon fiber woven panels (6" wide x 1/4 thick) were infiltrated with two types of epoxy resins. One set was produced at NCSU in Dr. Klang's laboratory and the second was produced at NASA Langley by arrangement with Mr. Benson Dexter. Tensile, compression, and compression after impact testing was also conducted at NASA Langley. Comparison of the two resins and the two infiltration techniques were made for three different preform structures. The results were presented at the 4th European Composites Conference in Stuttgart, Germany, September 25-28, 1990 and published in the proceedings of the Conference which were published by Elsevier Applied Science. The results showed the presence of voids in the samples produced at NCSU and microcracks in the samples produced at NASA Langley. The properties of both sets of samples were found to be fairly similar.

Presently work is underway, conducted by Randi Muir at A&T under the supervision of Professor Bob Sadler, to incorporate microballoons with the epoxy resin. Samples have been produced using the same preform and matrix with two levels of microballoon content, 5% and 10%. Microscopical examinations will be made and the results will be discussed at the Annual Review.

Another area of research related to overcoming the problem of infiltrating 3-D woven preforms involves the use of carbon/PEEK intermingled fibers. This work will be carried by Machfud. After weaving 3-D panels, the preforms were subjected to heat and pressure. This consolidation was done in Dr. Klang's laboratory using a heated press. The PEEK fibers melt and flow to form the matrix between the carbon fibers. Microscopical examination of composite samples indicated the presence of voids, but they do not seem to pose any problem. Some of the results of this work will also be discussed during the Annual Review.

A third area of research involves combination of 2-D braiding and 3-D weaving to yield preforms with fiber orientation in five directions. Three-D woven panels and beams were infiltrated with and without the braiding, and the results of testing the bending behavior of these will also be discussed during the Annual Review. This work has been carried out by Elsaid Salem, and the infiltration is done at A&T. A patent disclosure was submitted to the NCSU Patent Committee.

The move to the new building delayed the development of the second 3-D weaving machine with electronic jacquard. However, the gantry has been built and efforts are underway to try to show the machine operating during the Annual Review.

We continued to weave different shapes for structural elements and the next shape which we hope to show during the Annual Review will be a box channel.

Proposed Research

- (a) Continue the development of the 3-JD weaving machine. The second machine is almost completed and the gantry for electronic jacquard head has been built. The next step will be to select a suitable drive for the electronic jacquard head. With this addition we will be able to weave different 3-D structures. We will also be able to weave holes and slots. This will lead to the study of the effect of drilling holes and cutting slots in the composited as compared to weaving them. We continue to improve the capability of the machine in terms of shape and size of the components.

This work is relevant to one of the major objectives of the Mars Mission Research Center, developing light weight composite structures. The work relates to the research of other faculty in the fabrication group, the composite group and the light weight structures group.

We have woven samples for A&T and woven samples for Dr. Fahmy's work.

- (b) Study of the weavability of various high modulus fibers and the influence of weaving on the degree of damage to these fibers. This is very important in determining the best processing conditions to achieve the highest translation of advanced fibers properties to needed performance of the final composites.
- (c) Work will continue on exploring the use of different matrix material and consolidation techniques and study their influence on the final products. This work includes the use of thermoplastic polymers in the form of fiber or powder. We have already started preliminary experiments with intermingled Carbon/PEEK yarns. A proposal was submitted to NASA Langley to obtain additional funding to work on the processing of carbon fiber with thermoplastic powder sprayed or adhered to the fibers.

These materials are still in the early development stages, and we might be able to make a breakthrough in composite manufacture. BASF works on the powder technology under a contract from NASA.

This work is relevant to the construction of a spacecraft and to several of the faculty involved in fabrication, composites and structures groups.

- (d) Combination of 3-D weaving and 2-D braiding is also under investigation. The advantage of this will be to provide fiber orientation in five directions. A patent disclosure on this idea has been submitted to the NCSU patent committee.

Microstructure and Thermoelastic Properties of Composites

Sal Torquato

Past Research

In the last year, I studied the problem of predicting the thermal conductivities, thermal expansion coefficients, heat capacities, and elastic moduli of composites by incorporating nontrivial microstructural information on the materials of interest. As it turns out, thermoelastic properties (such as thermal expansion coefficients) are intimately related to elastic moduli in the absence of temperature gradients.

This work has resulted in 5 technical papers: 3 published, 1 in press and 1 submitted. These papers are briefly described below:

- (1) Bounds on the thermal expansion coefficients and heat capacities have been computed for the first time for particulate media in which the particles have a size distribution.
- (2) The thermal conductivity of particulate composites have been computed with heretofore unattained accuracy.
- (3) Elastic properties of fiber-reinforced materials have been determined for equal-sized fibers.
- (4) Elastic properties of fiber-reinforced materials have been obtained for fibers of different sizes.
- (5) A novel algorithm was developed to simulate sterically hindered fragmentation in reactive solids.

Proposed Research

It is well known that the macroscopic properties of heterogeneous materials depend upon the details of the microstructure (i.e., volume fraction and interfacial surface area, inclusions, shape, size and orientation, spatial arrangement of the inclusions, etc.). Nonetheless, much of the previous work does not incorporate nontrivial microstructural information, and hence, the resulting formula can never be predictive. The general goal of the proposed research is to rigorously relate the thermal conductivities, thermal expansion coefficients, and elastic moduli of any composite material to nontrivial information about the microstructure. If such a program is successful, it will lead to a highly cost-effective means of optimally designing composite materials (e.g., chopped fiber and particulate composites, ceramic and metal-matrix composites, etc.).

The specific problems we intend to examine are the following:

- 1) Development of methodologies to quantitatively statistically characterize the microstructure of composites.
- 2) Predict the thermoelastic properties of models of fiber-reinforced and chopped fiber composites.
- 3) Predict the elastic moduli of models of fiber-reinforced and chopped-fiber composites.

Composite materials used in a spacecraft for a Mars Mission may require certain desirable properties, such as possessing light weight, optimal damping properties, resistance to high temperatures, high stiffness, etc. In other words, they must be specially designed. The proposed research attempts to address this problem.

The proposed research overlaps with the research of several faculty in the Mars Mission Research Center, including Professors Fahmy, Klang, and Filatovs.

COMPOSITE MATERIALS AND FABRICATION (A&T)

Overview - Composite Materials

V. Sarma Avva

Introduction

The overall objectives are (a) to assess the suitability of textile composites as structural materials in the design of aerobrake elements, and (b) to provide appropriate inputs to the materials processing and fabrication, and the aerospace structural design groups with quantitative mechanical and thermal property data. Consequently, the faculty and the students working in the materials group are engaged in testing the textile composites with a goal of comparing their properties with the "traditional" laminated composites.

Past Research

Since our Second Annual Review of the Mars Mission Research Center activities in May 1990, the following is a summary of research work performed by our staff:

Avva and Lyon: The mechanical (tensile) properties of some of the braided coupons, with and without microballoons, were evaluated. Preliminary and limited data indicated that braids with microballoons may offer a slight advantage by way of weight reduction. It was also observed that stabilization of braid angle in a given batch of "compression-molded" test coupons is important in determining the mechanical properties. As a result, a few test coupons were fabricated by introducing about 20% fibers in the *axial* direction of the braids to "stabilize" the drift in the braid angle. A limited number of results obtained using the axials will be presented. Some additional results on braided coupons fabricated by using "resin transfer molding" technique will also be presented. Further, some of the mechanical properties of plain weaves needed to verify the analytical models will also be presented.

Fahmy, Gabel, and Voss: The determination of thermal and thermomechanical properties of fibers and fibrous composites is being conducted. The study includes both experimental and analytical techniques. Some of the results that were presented included the experimental determination and modeling of thermal conductivity of selected fibers and composites. Some additional results enlarging this area of research will be presented.

Filatovs and Drew-Lyon: Some of the earlier studies were concerned with the fracture behavior braided composites in compression mode. It is envisioned that near-net-shaped composites, in particular, can be used to enhance the energy absorption of aerobrake structural elements. As a result, the presentation covers both the development of test methods and the characterization of 3-D braided materials with the goal of correlating the effects of loading mode, microstructure, and failure mode on the properties of braided composite materials. Further, it discusses the approach to modeling and will highlight results from micro-compression testing and fracture mechanics tests with supporting fractography.

Foye: The presentation includes the preliminary design/analysis of aeroshell elements. The elements of this work are: (a) Assembled aeroshell truss members, and (b) Self deploying aeroshell TPS support structure. An analysis of 3-D coefficient of thermal expansion for fabric reinforced composites will also be presented.

Proposed Research

The main objective of the Materials Group is to investigate the potential that the textile composites have in the design of structural components leading to the development of viable aerobrake concepts. To that end, the Materials Group proposes to continue its research and development activities in determining and assessing the mechanical and thermal properties of the textile composites. This activity will assist the Fabrication and the Structures Groups in developing the new thrusts and technologies needed in the preliminary design of aerobrake components.

Prof. Ayva and his students propose to continue the testing and evaluation of textile composites processed and fabricated by the Mars Mission Research Center staff. Specifically, the test coupons will be fabricated using the textile technologies (braids, weaves, etc.). During the next eight months of the Mars Mission Research Center program, they plan to evaluate the mechanical properties of textile composites subjected to tensile, impact, and fatigue loads. Further, they also plan to evaluate the *integrally* stiffened panels subjected to axial and normal loads.

Prof. Fahmy and his students propose to continue to evaluate the thermal and thermomechanical properties of the fibrous composites, experimentally and analytically. The effect of various fabrication processes (hot press, autoclave, etc.) on the thermomechanical properties in 2-D and 3-D textile composites will be studied. The experimentally determined properties will be compared with those that can be predicted analytically.

Prof. Filatovs and his students' proposed work centers on the continuation of the investigation of 3-D braid properties. Ongoing work suggests some strategies for overcoming some of the previously discussed shortcomings. A method currently being investigated is the incorporation of microballoons into the resin to act as stress dispersants. Provisional indications are that the crack growth can be stabilized. Another potential method is the use of low-temperature plasma to strengthen the interface, which would prevent runaway interfacial crack growth. These approaches would be explored, along with continuing development of SEM/optical fractography methods to determine more exactly the conditions for crack initiation and growth.

Work would also continue, albeit less aerobrake specific, on the issues of space structures. The goal is to bring together and synthesize scattered efforts in areas crucial to a Mars Mission vehicle, such as self-assembly, materials systems such as the TPS, and the hardware for these.

Prof. Foye proposes to characterize the effects of voids on the properties of fabric reinforced composite materials. When composites are cured in the absence a positive pressure (in-space), the tendency to form voids is much greater. Instead of only emphasizing their removal, space structures that are fabricated on site, will have to be designed to live with a significant void content. The mechanics of voided composites is not well developed. This work will initially focus on interstitial voids, i.e., voids within the bulk resin pockets that form between neighboring tows of the fabric reinforcement. Methods for predicting the variation in all of the 3-D elastic moduli of the composite as a function of the interstitial void content will be developed. This work also provides some guidance for concurrent experimental work under Prof. Robert Sadler for controlling interstitial void content with microballoon fillers. Trends in moduli and thermal expansion coefficients will be developed for the common weaves and braids of graphite/epoxy and fiberglass/epoxy. Experimental verification will be provided.

Materials and Structures for Space Vehicles

G. J. Filatovs

Past Research

There have been two main areas of work:

- Structural factors in strength and toughness of 3-D composites
- Design and fabrication of a Mars-mission aerobrace mock-up.

The composites have been primarily 3-D braided graphite fibers in epoxy matrix. Materials were epoxy matrix with graphite fibers. Work has comprised several interrelated tasks centering on quantifying the strength - structure relationship. Testing has been based on two previously developed methods, a micro compression test and a modified ASTM E 399 notched flat tension test. Braided materials offer many obstacles such as interpretative ambiguities of the crack path and the large statistical variability due to fabrication. These have led to auxiliary tasks such as development of suitable fractography methods and tests for processing variability.

Some of the failure mode observations arising from fractography are given as typical examples. The braided bundles of fibers behave as single units, in effect making them into giant fibers. Failure is initiated most frequently by sliding of bundles, with the matrix/bundle interface the failure initiator. The resin-rich areas lower the fracture toughness.

Work on adapting the E 399 test has shown that it is useful only as worst-case indicator. It will produce Mode I failure only when the notch is parallel to the principal braid direction. For this case, the composite usually fails at a value of one-half of that of the matrix alone. The failure is usually by cleavage of the matrix/bundle interface.

A second effort has been participation in the design and construction of a partial, but full-scale, mock-up of a Mars-mission aerobrace. Work was at NCSU, under contract from McDonnell Douglas Aerospace. Gordon Lee was the project director, and actual construction was by senior and graduate students. The mock-up was for the purpose of addressing the issues of in-space assembly and transport, and was for testing in the M-D neutral buoyancy facility in Huntington Beach, California. This introduced other constraints such as neutral buoyancy, diver safety, corrosion resistance, and transportability. The mock-up was successfully tested in August 90.

Proposed Research

Investigation of 3-D braid properties continued. Ongoing work suggests some strategies for overcoming some of the previously discussed shortcomings. A method currently investigated is the incorporation of microballoons into the resin to act as stress dispersants. Provisional indications are that crack growth can be stabilized. Another potential method is the use of low-temperature plasma to strengthen the interface, which would prevent runaway interfacial crack growth. These would be explored, along with continuing development of SEM/optical fractography methods to determine more exactly the conditions for crack initiation and growth.

Work would also continue, albeit less aerobrace specific, on the issues of space structures. The goal is to bring together and synthesize scattered efforts in areas crucial to a Mars mission vehicle, such as self-assembly, materials systems such as the TPS, and hardware for these. Gordon Lee and I would develop the industrial and NASA contacts established during the aerobrace project, and visit some of them this summer.

Materials for Self Deployable Space Structures

Ray Foye

Past Research

THERMAL EXPANSION OF FABRIC REINFORCED COMPOSITES

This work is concerned with estimating coefficients of thermal expansion for fabric reinforced composites. Anticipating these properties is basic to composite use in all space applications and essential to predicting thermal stresses, curing stresses and creep response. The method, based on 3-D finite element analysis of the fabric unit cell, is general enough to apply to almost all reinforcing microgeometries, simple or complex. Experimental correlation is obtained for various different graphite/epoxy weave geometries. This complements the analytical work of Dr. Raju and the experimental work under Dr. William J. Craft.

A GRAPHICAL DESIGN METHOD FOR AEROBRAKE TRUSS MEMBERS

Most composite element optimization consist of the selection of fiber orientation angles so as to minimize laminate thickness and satisfy strength, stiffness and stability requirements. Complex constraints such as lack of an adequate data base and cost considerations are usually ignored. Present workstation capacities and speeds have improved to the point where all possible design parameter values can be investigated and their safety margins presented graphically. This permits the design selection process to proceed with all constraints considered. Examples of the design of tubular composite truss elements of the aerobrake structure are given. This work complements the prior truss sizing and loads analysis of Raju.

MATERIALS FOR SELF DEPLOYABLE SPACE STRUCTURES

Any aeroshell concept that uses either an inflatable or mechanically deployable skirt is suspect for two reasons. One is flutter of the flexible panels. The other is static strength of the flexible TPS. A rigidizable TPS backing could resolve both issues. some consideration has already been given to composites that can be cured in the space environment, and interest is increasing from such unrelated applications as on-site space station construction (and repair) and moon habitats. The initial work on this task has been the consideration of several materials/structural concepts for downselection.

Proposed Research

When composites are cured in the absence of positive pressure (in-space) the tendency to form voids is much greater. Instead of only emphasizing their removal, space structures, that are fabricated on site, will have to be designed to live with a significant void content. The mechanics of voided composites is not well developed. This work will initially focus on interstitial voids, i.e., voids within the bulk resin pockets that form between neighboring tows of the fabric reinforcement. Methods for predicting the variation in all of the 3-D elastic moduli of the composite as a function of the interstitial void content will be developed. This work also provides some guidance for concurrent experimental work under Robert Sadler for controlling interstitial void content with microballoon fillers. Trends in moduli and thermal expansion coefficients will be developed for the common weaves and braids of graphite/epoxy and fiberglass/epoxy. Experimental verification will be provided.

Composite Fabrication Laboratory

Robert L. Sadler

Past Research

As reported last year, most of my research activities were centered around the Composite Fabrication Laboratory. As for new equipment, a prepreg system was purchased and installed. It has been checked out and an undergraduate student has been assigned to learn to operate it. It will be used initially to attempt to develop a carbon fiber/epoxy prepreg that would be suitable for textile preform fabrication. This is a challenging task but the payoff could be an important achievement.

Several new processes have been started during this year. Liquid transfer molding operations have become an every day process although much development work remains to be done. Randy Stabler, a graduate student, has studied the pressure filling process in a transparent mold and has decided to concentrate on the use of a vibrating mold to improve the mold filling process and minimize bubbles in the molded composite specimens. He is still in the early stages of development. The introduction of an epoxy resin especially for liquid transfer molding (Tactic 123) has made his job somewhat easier. He has also made significant improvements in the resin transfer system. In addition to Randy's work on liquid transfer molding, we have an undergraduate student assigned to another aspect of the effort. He is utilizing a new 36" mold with multi injection ports. Work with this mold is also progressing well although minor surface bubbles are present. Both of these efforts to develop a liquid transfer molding process will continue until a reliable process is in use.

This semester we have assigned an undergraduate research assistant to work on the filament winding machine. This effort is designed to develop the process for filament wind carbon composite tubes. These tubes will be used to compare with tubes fabricated from braided textile preforms.

The Mars Mission Research Center Structure Group requested that a model of the Mars aerobrake be fabricated in the Composite Fabrication Laboratory. The model was to be a 1/30th scale of a candidate aerobrake shell. The model was needed to give them a platform to build models of various candidate truss designs. A plaster pattern was fabricated from tooling plaster with the aid of a template. A fiberglass/polyester resin mold was formed over the sealed plaster pattern. Four fiberglass shells were molded in the mold. A polyurethane foam layer was added to the inside of the shells to add stiffness. Another layer of fiberglass was added to cover the urethane foam and to form a sandwich structure. The shells were then painted.

Proposed Research

This year an effort will be extended to further develop liquid resin transfer molding as a method for fabricating composites from textile preforms. Transfer molding appears to be the process of choice if the major processing problems can be overcome. A major problem being addressed is entrained bubbles. Some progress in this effort has been achieved this year.

This year we are going to start a composite tube study. A graduate student, Prentiss Ward, made a decision to determine the relative properties of tubes fabricated by three manufacturing processes as her thesis project. Tubes will be fabricated by typical commercial fabrication processes such as filament winding and prepreg wrapping. These tubes will be compared with composite tubes fabricated from braided textile preforms by liquid transfer molding. The effort to filament wind tubes has already met with some success as +/- 45 degree tubes are ready for testing. The next set of tubes will be fabricated with +/- 17 degree windings. These tubes will be more directly comparable with braided tubes as that is a typical braid angle. Prepreg wrapped tubes will also be

fabricated with a +/- 17 degree wrap angle. Beside fabricating these tubes, Prentiss will develop testing fixtures and measure their mechanical properties. This work should allow us to put braided tubes into proper perspective with tubes fabricated from other methods.

Another effort for this year will be to determine the fatigue properties of composites fabricated from braided textile composites. For fatigue measurements to be effective, test coupons of high uniformity must be used. A special effort is being made to produce a series of coupons of extreme uniformity. Arrangements have been made for our graduate student, Yashpal Hanspal, to braid his own textile preforms at N. C. State using only one lot of fiber. Further, he will use these textile preforms to fabricate his own composites test pieces and of course he will do his own mechanical testing. All these actions by the same student should pay dividends in the quality of the fatigue data.

Design of Mechanical Jigs and Fixtures

Leon Skeen

Past Research

Primary mission is supporting role to design and have fabricated the tooling, fixtures and other miscellaneous hardware needed in the fabrication of advanced composite components. The above has primarily included areas such as compression molding, transfer molding, tube transfer molding, and filament winding.

Proposed Research

The proposed research will be primarily assisting the faculty and students in their research work on a continuing basis. Various structural configurations envisioned by the staff for the aerobrake will be fabricated, assembled, and finished. Some of the special jigs, fixtures, and other accessory components will be designed and tested with my assistance. The research includes responsibility for writing specifications, maintaining, trouble shooting, and for other related tasks pertaining to the major equipment.

An Investigation into the Causes and Prevention of Pinholes in Trusses Manufactured by Resin Transfer Molding

Gary B. Tatterson

Past Research

The research of the past year has been experimental studies in the manufacture of test trusses by resin transfer molding to understand the importance of various operating parameters. Various tests were made in which temperature of the mold, temperature of the resin, pressure drop, braid density, volume, resin type, braid angle and mold fill time were studied. These were exploratory studies using crude equipment. Unfortunately, no conclusive results were obtained.

Proposed Research

The experimental equipment consists of a rectangular mold, a pressurized feed system, and a vibration unit. Carbon braid, resin and wax are supplies used in the experimentation. The experimental procedure is straightforward. The mold is waxed. The braid is placed in the mold and the mold is filled with epoxy from one end at a specific pressure. After filling, the braid/epoxy system cures and the solid truss is then examined for pinholes by a simple counting technique. The data are primarily qualitative for these studies. The number of pinholes will be determined as a function of waxing conditions, vibration and initial bubble concentration in the feed.

The operating variables, which will be held constant, include the mold geometry, the mold and resin temperatures and the type of resin used. The braid density is determined from the quantity of braid in the mold and will be measured. The fill pressure, vibration of the mold and surface waxing of the mold will be varied in an attempt to either generate or eliminate pinholes in the surface. The time to fill the mold will also be recorded.

The ultimate objective of the work is to develop a process to make high quality composite materials by resin transfer molding devoid of entrained bubbles. Another more specific objective is to use the information in actual lab scale production runs in the manufacture of the trusses.

The application of this work to the Mars Mission Project and to the Mars Mission Research Center is in the manufacture of trusses out of composite materials. One specific application is the truss manufacture for support structures, e.g., the Aerobrake.

STRUCTURES AND CONTROLS

Modeling and Analysis of Aerobrake Structures

Ivatury S. Raju

Past Research

The aerobrake is a light weight large shell with supporting substructure designed to withstand the deceleration loads the spacecraft experiences in the re-entry phase near Mars. The specific objectives of the structures group are as follows:

- (a) To develop candidate aerobrake load bearing structural configurations.
- (b) To develop models for these configurations.
- (c) To develop generic analytical programs to calculate deformations and stresses.
- (d) To develop sizing algorithms that yield minimum mass structural configurations.
- (e) To study the performance characteristics of the structural configurations.

During the past year the structures group has developed four types of structural configurations for the aerobrake. They are space frame, space truss, aeroshell (semi-monocoque), and semi-rigid structures. A 1/30th model of the aerobrake, a 1/50th scale model of the space-frame structures, and a model of the semi-rigid type (collapsible) structure were built. A finite element program to analyze space frame structures was developed. A sizing algorithm was also built inside the FE program. To be able to visualize the aerobrake and the structure at various view orientations, graphics routines that use PHIGS graphics software were written. A mesh generator that models the aerobrake structure as space frame elements was developed. With this mesh generator cone-sphere symmetric and asymmetric aerobrakes can be very easily modeled.

The space-truss aerobrake structures were analyzed using the EAL finite element program. For this structural configuration also sizing algorithms were developed. Various designs of the aerobrake were studied with this program. The third concept of modeling the aerobrake is assuming that the structure is an aeroshell. The aerobrake is assumed to be part-spherical semi-monocoque shell. This shell was, first, analyzed assuming that the shell carries only membrane loads. Next, the shell was also analyzed assuming the shell is capable of carrying bending loads. In these analyses, closed-form analytical solutions were aimed at because these solutions are more convenient to study the effect a variety of parameters than the numerical solutions such as those due to finite element methods. In addition, the predictions of the analysis will be used to provide guidance for evaluating the accuracy of finite elements for modeling aerobrake sandwich shell panels.

The above analyses aim at analyzing the aerobrake structure globally. Detailed analyses near joints, regions of stress concentrations and local stresses in individual plies of the composite tubular members of the space frame and the truss are also needed. Therefore, closed form analytical results were obtained for thick composite tubes subjected to bending loads.

Proposed Research

During the current year the structures group will aim at studying various designs for the aerobrake. Both symmetric and asymmetric configurations will be studied. Constant and variable pressure loadings on the aerobrake will be considered. Vibration frequencies and buckling loads of the candidate configurations will be obtained. The effect of inherent material nonlinearity on buckling loads will also be studied.

Analysis of Aerospace Structures

William J. Craft

Past Research

Earlier research activities carried over from the previous year to last year have been directed in support of completing thermal expansion studies and tests and in applying the results to finite element analysis to determine the bulk thermal expansion properties of braids and weaves. In addition research has been initiated in determining the geometries of possible aerobrake configurations. This work has resulted in the development of coordinate generators and FEM codes to determine the minimum weight configurations for these configurations. These efforts have been joint efforts of I.S. Raju and W. J. Craft. Structural analysis of the Aerobrake to determine minimum weight configurations is of primary importance in determining the relevance and safety of the Mars mission.

Proposed Research

My proposed research for the next year will center on the development of candidate aerobrake structural configurations subjected to critical loading configurations. In addition, I want to remain active in assisting and coordinating the 1992 ASME Winter Annual Meeting special program on the Space Science and Engineering Center Sessions.

For the first several months of the upcoming year, Dr. Raju and I will continue our modeling and conclude our work on thermal expansion modeling of braids and laminated and fully three-dimensional weaves. We will also complete a paper on the preliminary work that we presented in the fall on minimum weight algorithms for the aerobrake frame. We will continue to work with two A&T graduate students, Messrs. Dave Rogers and Michael Walton through the completion of their theses both of which relate to the aerobrake structure. A new research professor would be joining us during the coming fall and work will continue to be directed to aerobrake design. The emphasis and direction will be dependent upon the new structures leadership.

Generally, a great deal of refinement needs to be done on the sizing of composite truss and frame members regarding stress distributions and buckling and on the impact on minimum weight. A more refined structural analysis that relies heavily on precise boundary and trajectory conditions. A great deal of valuable information still needs to be generated on symmetric and asymmetric aerobrake configurations. This includes the effect on weight of load magnitude and distribution and of payload attachment. In addition, global buckling and possible flutter need to be incorporated in the aerobrake design.

Aerobrake Construction Concepts and Related Structural Considerations

Eric Klang

Past Research

This past year has seen significant progress in the area of structural design of the aerobrake. Both Greg Washington and John Hairr have been working on the design. Greg's work has focused on the design of an aerobrake using a truss structure. This work has been closely coordinated with the research being performed at the Spacecraft Structures branch at NASA Langley Research Center. Greg spent last summer at Langley working closely with Harold Bush and John Dorsey. A result of this research has been the close coordination of Greg's work and the on-going work of Dorsey. Greg is concentrating on the truss support structure while Dorsey is working on the external panel design. To date, the code which sizes the truss members according to internal loading has been completed. We are in the process of comparing structural weights for various aeroshell shapes and loading conditions. Greg is nearly finished with his work and should write his thesis within three months. I anticipate that significant papers will be forthcoming this summer.

One of the problems associated with the design of a semi-monocoque structure is the infinite variations available for the geometry of the structural stiffeners. I felt it was important to narrow the configurations to a few promising candidates early so that time would not be wasted constructing several finite element models of the structure. It was also desirable to become familiar with the major factors which influence the structural efficiency of shell structures. For these reasons I had John Hairr begin work by investigating shell theory and as many closed form solutions as possible. This proved to be extremely helpful in isolating which parameters were important and which were not. With this information in hand, John has now moved on to a finite element analysis of the structure. John has been using the EAL code which is used extensively by the Spacecraft Structures branch at Langley. This code allows fully asymmetric geometry and loading, but John currently has limited the analysis to a configuration with six-fold symmetry. The baseline structure is all Aluminum and will be used to compare with composite material constructions. Deformations, stresses and buckling modes have been checked for the baseline structure and some optimization has been performed. I anticipate that John's work will be completed in three to four months.

A new effort in the area of Boundary Element development was initiated this year. The work was suggested by researchers at McDonnell Aircraft Company. The long term goal is to develop a fully capable code for handling the structural analysis of composite plates which is more efficient and easier to use than the finite element method. Stan Smeltzer had the opportunity to work with one of the experts in this field - Dr. Raju by temporarily transferring to A&T. Stan's work went extremely well and we now have one of the best boundary element codes available anywhere. Stan's code handles fully anisotropic composite plates loaded in-plane. Stan has completed his work and his thesis has undergone two revisions. I anticipate Stan will graduate in the next few weeks. Future work will concentrate on extending the method to include transverse loading and eventually stability analysis.

The final area of research has centered on the study of particle impact of composite materials. Tests have been performed on laminates and the woven material produced in the College of textiles. Genevieve Dellinger has worked on preliminary numerical analysis of the impact in addition to the development of instrumentation for the experimental tests. This work was presented at the 1990 ASME Winter Annual Meeting in Dallas. Genevieve has finished a rough draft of her thesis and should graduate within a month. I anticipate that Joel Cate will continue this work when he enters graduate school this summer.

Proposed Research

The first area of research will focus on extending the current aerobrake designs to include more refined descriptions of the geometry and loadings. One new MS student will be needed for this work, I plan on putting Carl Kirby on this project. The second area will extend the work begun on medium/high velocity impact of composites. I plan on using Joel Cate for this work. Finally the work on Boundary Element code development seems very important to many at NASA and I would like to put Greg Washington on this project if he is willing.

The first two projects are directly related to work being performed by researchers at NCSU. The third project would involve Dr. Raju and others at NASA.

Thermoviscoelastic Characterization High Temperature Composites Spacecraft Structures

Fuh-Gwo Yuan

Past Research

The research during the past year has concentrated on developing analytical methods for determining the response of aerobrake composite truss structures under various loading conditions. Since composite materials can be tailored to provide high stiffness /weight and strength/weight ratios, they have been used extensively as load carrying structural components in the aerospace industry. An aerobrake, characterized by large, complex geometry and heavy aerodynamic load, is one such structure. In order to design lightweight, better performance and more reliable composite aerobrake structures, the fundamental understanding of structural response under various loading conditions is indispensable. The structure's state of stress is essential to establish a rigorous analytic solution in the area of composite laminate aeroshell structures. A closed form solution has been developed that predicts the response of a composite aerobrake space frame subjected to various loadings. Based on the theory of cylindrical anisotropic elasticity, coupled partial differential governing equations have been developed using Lekhnitskii's stress function approach. The general expressions for the stresses and displacements in the laminated aerobrake composite truss have been established. Results have shown the structural response strongly depends on the radius-to-thickness ratio, coupling structural stiffness, and stacking sequence.

Proposed Research

Subsequent research will concentrate on the development of a light weight thermal protection system for spacecraft structures. A critical technology for the design of spacecraft involves the development of more structurally efficient materials which are protected from the high temperatures encountered in space or during launch from or return to earth. The development of new, high-temperature materials that ensure long-term structural integrity under severe environments and applied loads during aerodynamic and in-orbit heating is necessary. Advanced composite hardware exposed to temperature environments above 127°C (260°F) must be fabricated from materials with resin matrices whose thermal resistance is superior to that of conventional epoxy-matrix systems. A class of polyimide based resins such as Bismaleimide (BMI), PMR-15 and LaRC-RP40 has evolved during the past few years that exhibits excellent thermo-oxidative stability and improved toughness for high-temperature technology applications. Since polyimide composite materials reveal a significant amount of time and temperature mechanical behavior, the efficient design and utilization of such composites in load bearing members and in other structurally related applications demands a good understanding of their time and temperature dependent behavior.

At present, there is a lack of fundamental understanding of composite materials behavior and the temperature dependant properties are not well understood yet. This proposal will develop an analytical method to characterize the time and temperature behavior of advanced high-temperature composite LaRC-RP40. Extensive experimental research will be focused on characterizing the properties for the constitutive relations at elevated temperatures, and observing the deformation and fracture behavior necessary for the development of a valid analytical model. All the experimental studies involve laboratory tests of composite specimens under controlled conditions. The testing will be accomplished using high temperature extensometers and environmental chambers which can be numerically controlled to provide the required temperature and gaseous environment. Combined with the analytical modeling, the experimental measurements will provide better insight into the long-term properties and structural reliability of spacecraft structures.

Real-Time Control of Multi-Body Flexible Structure Gordon Lee

Past Research

This past year's research activities have focused on three areas: (1) development of a distributed digital filtering architecture for a controls/structures testbed (10-bay flexible structure); (2) fabrication and testing of a Mars aerobrake mock-up and design of a lunar transfer vehicle mock-up; and (3) development of several real-time control algorithms and design/fabrication of two experimental testbeds: a dual-arm three axis flexible structure and a mobile telerobotic coordinated servicer.

- 1) This research effort focused on the design and development of a distributed digital signal processor. Large space structures are distributed parameter system containing, in practice, a large number of flexible modes. Furthermore a large number of sensors (potentiometers, encoders, rate sensors, accelerometers) produce system information while a large number of actuators (motors, thrusters, reaction devices) produce the necessary command signals for desired system performance. In order to efficiently process sensor information and send appropriate actuator commands, a distributed architecture has been designed, based upon single loop control. Several low pass filters have been designed including Butterworth, Bessel-Thompson and Chebyshev filters and several approaches including bilinear-z and impulse invariance have been used. A virtual passive controller, based upon research work done at NASA Langley, has been selected as the prototype compensator.

Currently, the algorithms have been developed and evaluated using a model of the 10-Bay Flexible Structure, a NASA Langley experimental testbed. Future activities include building the hardware for the distributed distributed architecture, based upon a micro-controller configuration, implementing the algorithm on the architecture and evaluating the tests based upon time delays, stability characteristics, robustness and hardware constraints.

This research effort is consistent with the Controls/Structures Interaction (CSI) missions whereby one objective is to develop and verify candidate control/filter algorithms through actual hardware implementation in ground testing. The results may be used as a reference for other CSI projects, including the Evolution phase 1/2 model.

- 2) One option for delivering large aerobrakes to space entails shipping the structure in pieces, followed by on-orbit assembly. The research effort for this past year focused upon the fabrication of a Mars aerobrake mock-up and testing the structure in a series of underwater neutral buoyancy tests that address this on-orbit assembly issue. The effort was sponsored by McDonnell Douglas Space Systems Company (MDSSC) in Huntington Beach, California. The aerobrake mock-up design (done in the Fall of 1989 and Spring of 1990) was based upon a baseline shape of 32m by 27m to provide an L/D of at least 0.5. Three pieces (petals) and part of the central core were selected for fabrication; these pieces provide candidate assembly tasks under the constraint that the mock-up must fit into the 21.3m diameter, 10m deep underwater test facility (UWTF) tank at MDSSC.

The mock-up contains several features which may be used in on-orbit assembly: hard docking latches to connect the petals, soft docking alignment pins, truss assembly with joint fasteners, close-out panels for the thermal protection system (TPS), hand and foot restraints for extra vehicular activity (EVA) and visual cues for assembly ease. The entire work was made neutrally buoyant to simulate in-space operation.

Swim through tests were performed in June using scuba-equipment to verify both the structural soundness of the mock-up and viability of the proposed assembly procedures while a second series of test were done in October with an EVA-suited subject and telerobotic arm.

The results demonstrated that astronauts can align large dimensional components and activate hard docking latches with reasonable time and effort. The candidate TPS close-out concept proved to be less effective than anticipated and further development will be necessary.

This semester students at NCSU are performing a design of an LTV (lunar transfer vehicle) aerobrake and fabrication of a 1/10 model, for demonstration purposes. The design will include components attached to the shell, including payload, crew module and propellant tanks. The design will be presented at the Southeastern Regional AIAA Student Design Conference this April.

- 3) In order to validate some of the control algorithms currently being developed at the Mars Mission Research Center, two experimental testbeds are being designed and fabricated. The first test article is a dual flexible beam, three-axis structure which will be used to evaluate some collocated and non-collocated digital filters and self-tuning non-collocated control methods. The dual-beam testbed can simulate satellite re-orientation maneuvers where large solar panels may vibrate during the slewing. Two servo motors are used to independently control each panel while a stepper motor is used to re-orient the entire structure. Control actuation is performed through a data acquisition system and an IBM computer while optical encoders and strain gages provide hub and beam information, respectively.

The second testbed is a mobile coordinated telerobotic servicer. In many mission scenarios, on-orbit assembly requires a coordinated effort between astronautics and a robotic system. In order to enhance robot capabilities, a teleoperator actuates desired robot trajectories, within the limits of the robot's workspace. Many of the current robotic designs use a movable assembly node to position the robotic arm in an appropriate location for the required task. Due to this inherent base motion and the vibration of the manipulator links and joints during its positioning, the controller must compensate for these movements as well as track the desired trajectory, initiated by the teleoperator's command signal.

This research project addresses some of the controls issues associated with a mobile coordinated telerobotic system. Further, a telerobotic dual-manipulator system has been designed and fabrication has started on one of the arms. Future activities will focus on completing fabrication of the two arm system, design and fabrication of the telerobotic device, development and implementation of the robust controllers for vibration suppression and trajectory tracking and completion of the mobile platform. An evaluation of the control methods in terms of robustness and limits within the workspace for on-orbit assembly missions will be conducted.

This work will supplement work currently going on at NASA Langley in the area of space robotics and on-orbit assembly issues.

Proposed Research

Many of the proposed design for space structures consists of one or more components coupled together at flexible joints. One such structure is the space crane, made up of multiple bays of variable lengths, with adjustable bars at the joints and an end-effector for object retrieval. The advantages of flexible structures such as the space crane are many including speed of response and the relatively smaller actuators required to move the link around the field of operation. However, due to the flexibility of the links and joints, the system exhibits many low resonant frequency modes that usually appear closely spaced. This low damping characteristic make control, particular non-collocated control, a challenge for the design.

In order to evaluate such structures, particularly from a controls point of view, several research issues may be addressed. These include: Three-dimensional dynamic analysis; payload variation and its effects on system performance; real-time inverse dynamics computation and trajectory planning; robust control for accurate trajectory or end-point following with vibration suppression, and ground test for algorithm/dynamic modelling verification.

This effort focuses on robust control design of these structures with ground testing validation as future research activities. The specific research objectives of this effort are as follows:

- (1) Design and model a two-link flexible structure which provides flexibility in all directions: the horizontal, torsion and vertical axes. The bays will be made up of flexible rods such that the dominant flexible modes have a frequency of oscillation below 10Hz. Although the structure will have flexibility in all directions, coupling between directions must be such that controllability is maintained. NASTRAN generated models will be used in these research activities.
- (2) Design actuators which provide control action for each link independently. The actuation at the base is straightforward; a single servo mechanism can provide enough torque to move the complete system. The challenge lies in the second actuator for the upper link. In order not to constrain flexibility and to uphold light weight requirements, the actuator can not be directly mounted at the joint between links. A suspension system need also be designed to simulate a zero gravity environment.
- (3) Develop and simulate the control schemes with the two-link model in order to address the feasibility of real-time control of a two-link manipulator. Initially, simple control algorithms will be employed to see if the processing time requirements as well as desired system objectives can be met, without any disturbances or varying payloads. Then more complex control algorithms will be investigated later to see if these schemes are feasible for real-time implementation.

In this research effort, two classes of control algorithms will be investigated. In the first class, non-collocated PD control with zero-placement and decoupled pole assignment will be studied.

In PD control, a phase compensator is designed based upon position and velocity information (collocated or non-collocated) while in zero-placement, a digital filter provides additional degrees of freedom to reduce oscillations.

For the second class of controllers, an initial feasibility study will be performed to see if model reference adaptive control is implementable in real-time. A new algorithm will be studied, based upon a global linearization and inner loop PID structure.

Both classes of controllers will be simulated with the two-link model and an evaluation of their performance will be conducted, based upon processing time constants and robustness. These results will be used in future activities involving actual hardware implementation.

Spacecraft Controls for Mars Mission Vehicles

Larry Silverberg

Past Research

My Center activities focus on the motion control of future Mars mission vehicles. The following describes some of the projects.

Title: Impulse Control

Students: Jim Redmond, Lester Foster, Kenneth Coulter

Other Center Researchers: Dr. Burt Chukwu

Description: Impulse control algorithms are used on rigid spacecraft for rigid-body maneuvers. This research extends impulse control to include damping and roll modulation of aerobrake structures. The algorithms under development are minimum-fuel. They also apply to space station reboost, and in general to large flexible spacecraft, such as others anticipated in Mars mission scenarios. The research concentrates on varying the formulations to accommodate a wide range of control problems, and on the development and implementation of simplified approximate algorithms of the otherwise complex solutions. This work is also coordinated with the CSI office at NASA Langley Research Center.

Title: Experimental Testbeds for Spacecraft Control

Students: John Meyer, Jay Polo, H. Don Gage

Other Center Researchers: Dr. Tom Miller

Description: A series of testbeds has been developed for the verification of proposed control algorithms. The first experiment is a horizontal slender cantilevered beam instrumented with strain gages for sensing and with thrusters for actuation. This system admits two significant flexible-body modes. The second experiment is the same beam now hinged to allow for in-plane slewing maneuvers. The third experiment is a long slender beam hanging vertically in the Aerospace Structures Lab. This beam admits four or more significant flexible-body modes. The fourth experiment is an H-beam back frame to an aerobrake structure (three slender beams fixed together in the shape of the letter H) hanging from its center by a long slender rod. This system admits five rigid-body modes and six or more flexible-body modes. This configuration allows for in-plane slewing (roll-modulation) and out-of-plane vibration suppression (wobbling control).

Title: Self-Tuning Control

Students: Rob Irvine, Leslie Weaver

Other Center Researchers: Dr. Gordon Lee

Description: This research develops self-tuning algorithms for control. The need for tuning arises from sensor/actuator calibration errors, from structural modelling errors, and from component failures. This activity was coordinated with AFOSR at Edward Air Force Base. The self-tuning algorithms were physically verified on the grid testbed at Edwards Air Force Base. This effort was concluded during this period.

Title: Electrodynamically Charged Membranes
Students: K. Park, J. Nicholson
Other Center Researchers: Dr. W. O. Doggett

Description: This activity focuses on the development of self-tuning control algorithms and on the design of electrodynamically charged membrane surfaces for the shape control of large antennas. This research concentrates on the development of analytical models of the multibody dynamics of large antennas for the purposes of design and optimization. Furthermore, the effort concentrates on the verification of electrodynamically controlled membrane charges in physical experiments.

Title: Multibody Control
Students: J. Richard Gardiner
Other Center Researchers: Dr. Tom Miller

Description: This research focuses on the development of control algorithms for multibody systems. A serial five-link mechanism with base excitation and subject to a nonlinear load serves as a candidate multibody system. The candidate system is then controlled using a variety of state-of-the-art strategies and hybrids. This effort was also coordinated with NASA Langley Research Center and with the Robotics Laboratory at Case Western Reserve University. This effort was concluded during this period.

Proposed Research

Title: Impulse Control
Students: Jim Redmond, Lester Foster, Kenneth Coulter
Other Center Researchers: Dr. Burt Chukwu

Description: Impulse control algorithms are used on rigid spacecraft for rigid-body maneuvers. This research extends impulse control to include damping and roll modulation of aerobrake structures. The algorithms under development are minimum-fuel. They also apply to space station reboost, and in general to large flexible spacecraft, such as others anticipated in Mars mission scenarios. The research concentrates on varying the formulations to accommodate a wide range of control problems, and on the development and implementation of simplified approximate algorithms of the otherwise complex solutions. This work is also coordinated with the CSI office at NASA Langley Research Center.

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SPECIAL PROJECTS

Design and Fabrication of a Full Scale Research Model of the NASA HL-20 Personnel Launch System

Robert Vess, Dean Driver, Thurman Exum, and Dennis Hugley

One of the concepts that is under study at NASA Langley Research Center to place people and small payloads into low earth orbit is referred to as the HL-20 Personnel Launch System (PLS). Its primary mission is to provide a ten man crew rotation link between earth and Space Station Freedom within a three day total mission duration window. The vehicle is characteristically small in size due to a requirement that it fit entirely within the payload bay of the existing Shuttle orbiter. Consequently, a significant packaging problem exists which could possibly compromise the ergonomic issues. The Mars Mission Research Center at NCSU and A&T State University was funded to construct a full scale research model of the HL-20 PLS.

In order to meet the proposed research objectives, individual fabrication efforts were undertaken at the two universities. The composite PLS model was designed and constructed by NCSU faculty and students while the required articulating steel support structure was built by A&T personnel. A complementary mixture of experienced staff members, motivated students, and innovative fabrication methods resulted in the productivity necessary to complete these two sub-assemblies and join them within approximately six months. The vehicle was then delivered to NASA Langley Research Center in Hampton, Virginia where A&T faculty and students have since installed mockups of interior components and structure. An extensive test program involving analysis in both the horizontal and vertical vehicle attitudes has begun and is expected to last several months.

Aerobrake Mock-up Project

Gordon Lee, Juri Filatovs, and Eric Clark

One option for delivering large aerobrakes to space entails shipping the structure in pieces, followed by on-orbit assembly. The research effort for this past year (Spring 1990) focused upon the fabrication of a Mars aerobrake mock-up and testing the structure in a series of underwater neutral buoyancy tests that address this on-orbit assembly issue. The effort was sponsored by McDonnell Douglas Space Systems Company in Huntington Beach, California.

The mock-up contains several features which may be used in on-orbit assembly: hard docking latches, soft docking alignment pins, truss assembly with joint fasteners, close-out panels for the thermal protection system, and hand/foot restraints. The entire structure is neutrally buoyant.

Swim through tests were performed in June using scuba equipment to verify both the structural soundness of the mock-up and viability of the proposed assembly procedures and a second series of tests were done in October with an EVA-suited subject and a telerobotic manipulator. A type will be shown illustrating the results of the test.

This year (Fall 1990 - Spring 1991) students at NCSU have designed two lunar transfer vehicle (LTV) aerobrakes -- an erectable rigid structure and a deployable structure. The deployable structure was selected as the candidate design for fabrication and a 1/10 scale model is currently being constructed for demonstration purposes. This design, along with LTV configuration, mission scenario, and EVA for a lunar mission, have been assembled for presentation at the upcoming Southeastern AIAA Student Design Conference in April.

Orbiter Ejector Project

Larry Silverberg, Project Director

The Mars Mission Research Center was awarded the contract to construct an Orbiter Ejector for NASA Johnson Space Center. The Orbiter Ejector will fly on the Space Shuttle Orbiter in September 1992 and eject six calibration spheres into precise orbits. These spheres will be used to calibrate ground based radar to enable us to see smaller objects in space. Perhaps the most unique aspect of the project is that the orbiter ejector has been designed and fabricated entirely by North Carolina State Undergraduate engineering students.

The purpose of the orbiter ejector is to eject three pairs of spheres 5, 10, and 15 cm in diameter and to place them in precise orbits where ground based radar will track them. By tracking the spheres and by carrying out calibration tests, the radar will be able to detect smaller objects in space. As it turns out, there is a large undetermined amount of debris orbiting the Earth left over from satellites and rockets. We currently can't see most of the debris. This test will help us see objects less than 10 cm in size through ground based radar and other optical instruments.

The Mars Mission Research Center was awarded the contract to build the Orbiter Ejector flight hardware after students at N. C. State completed a related conceptual design study in the spring. The study was part of a specially arranged engineering design course. Eighty-four undergraduate students from Aerospace, Mechanical and Electrical engineering applied and 40 were accepted. These 40 students were divided into 4 competing design teams of 8 students each, and 12 orbital safety team. The design teams each developed their own design and built a prototype to demonstrate their concept. The orbital safety team was responsible for digesting the maze of safety regulations and must be satisfied before the orbiter ejector could be certified for flight. On April 14, the students traveled to NASA Johnson Space Center in Houston, Texas for the Critical Design Review for Payload Selection. Team III was announced as the winning design and NCSU was then awarded the contract to build two of the designs - the Team I and Team III designs, now called the OEM-6 and OE-6 Orbiter Ejectors, respectively.

One of these Orbiter Ejectors will be placed in a special cannister (called the Get Away Special cannister or GAS Can for short) which is located in the Cargo Bay of the Space Shuttle Orbiter. The shuttle will first open its doors, and orient itself so that the spheres will eject in the direction of the shuttle's velocity vector. The lid on the GAS can will open (the lid is called the Motorized Door Assembly or MDA for short) and then a mission specialist will give the command to eject the 6 spheres into precise orbits.

The orbiter ejector is being built by 10 students. Seven of them are involved in fabrication here at NCSU and 1 student is working under the direction of Dr. Tony Danby, a mathematics professor and specialist in orbital mechanics here at NCSU. The 2 other students are now summer co-ops at NASA Johnson Space Center and they're helping out with the flow of information between NASA and NCSU and with certification. The seven fabrication students are Andy Mueller, Peter Sramka, Ayberk Abayhan, Mark Cassada, Paul Schumacher, Robert Long, and Joseph Cody. The orbital mechanics student is Alan Shepard. The 2 co-op students now at NASA Johnson Space Center are Mike Norton and Robert Trask.

This engineering project was originally the brainchild of an NCSU undergraduate student, Andy Mueller. While a co-op student at NASA Johnson Space Center, Andy convinced the NASA scientists that NCSU undergraduates were up to the challenge. He then introduced Dr. Larry Silverberg to the idea. "Andy's demonstrated leadership qualities are quite impressive. It shows how one person can really make a difference-even while you're in school," said Dr. Silverberg.

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- Redmond, J., and Silverberg, L., "Fuel Consumption in Optimal Control," *Journal of Guidance, Control and Dynamics*, in press.
- Ro, P. I., Choi, H. S. and Lee, G. K. F., "Effects of Dynamic Decoupling on Two-Arm Motion Coordination", Int'l Symp. on Robotics and Manufacturing, Vancouver (1990).
- Shults, J. R., Brubaker, T. A., and Lee, G. K. F., "A Fast Algorithm for Control and Estimation Using a Polynomial State-Space Structure," Fourth Workshop on Computational Control of Flexible Aerospace Systems, Williamsburg (1990).
- Silverberg, L. "Motion Control of Space Structures," presented at SPACE 90 Conference, Albuquerque, NM, April 23-26, 1990, also *Journal of Aerospace Engineering*, Vol. 3, No. 2, p. 223-234 (October 1990).
- Silverberg, L., "Impulsive Damping of Spacecraft Exhibiting Normal Mode Behavior," *Journal of Guidance, Control and Dynamics*, in press.
- Silverberg, L., and Foster, L., "Decentralized Feedback Maneuver of Flexible Spacecraft," *Journal of Guidance, Control and Dynamics*, Vol. 13, No. 2, p. 258-264 (March-April 1990).
- Silverberg, L., and Norris, M.A., "Self-Tuning Algorithms for Uniform Damping Control of Spacecraft," presented at the 31st Structures, Structural Dynamics, and Materials Conference, Long Beach, CA, (April 2-4, 1990).

- Silverberg, L., and Yunis, I., "The Compromise Inherent in Structural Feedback Control," presented at the AIAA/AAS Astrodynamics Conference, Aug. 1988; also *Journal of Applied Mathematical Modelling*, Vol. 14, p. 362-369 (July 1990).
- Wang, S.S. and Yuan, F.G., "Analysis of Delamination in Fiber Composite Laminates Out-of-Plane Under Bending," Final Report, NASA-Langley Research Center, Hampton, Virginia (1990).
- Yuan, F.G., and Miller, R.E., "A Higher Order Finite Element for Thick Laminated Beams," *Composite Structures*, Vol. 14, pp. 125-150 (1990).
- Yuan, F.G., "Analysis of Composite Shells Under Internal Pressure," to be presented at the 32nd AIAA/ASME/ASCE/AHS/ASC SDM Conference, Baltimore, Maryland (April 1991).
- Yuan, F.G., "A Triangle Finite Element for Flat Plates with Shear," to be presented at 1st U.S. National Congress on Computational Mechanics, Chicago (July 1991).
- Yuan, F.G., "Exact Solutions for Laminated Composite Cylindrical Shells in Cylindrical Bending," to appear in *International Journal of Solids and Structures*, (1991).
- Yuan, F.G., Miller, R.E., "A High Order Finite Element for Thick Plates," to appear in *Journal of Engineering Mechanics*, ASCE (1991).

RECRUITMENT OF STUDENTS AND FACULTY

Both undergraduate and graduate students work with M²RC. Undergraduate students typically work half to full-time during the summer and quarter-time during the academic year. Outstanding undergraduates are encouraged to continue into a graduate program. Due to the success of recruiting undergraduates into the graduate program the number of undergraduate students was increased from 25 to the current 29.

A flyer was distributed nationally to recruit graduate students for both NCSU and A&T. The research areas in the M²RC helped us increase the number of graduate students from 22 to 26 in the second year. One significant feature of the program is that some students and faculty spend part of their time at one of the participating NASA Centers or industries. This interaction gives the students an opportunity to work with world-class personnel and facilities in addition to their on-campus education. All students supported by M²RC must be U. S. Citizens or permanent residents.

Dr. Ivatury Raju, Coordinator for the Structures and Controls Group, resigned his position at A&T to return to NASA Langley Research Center. However, he still works with the Center as an Adjunct Professor at A&T. Dr. Suddin Ilias, Faculty member in Chemical Engineering, A&T, will be a new member of the Materials Group at A&T effective July 1, 1991.

Dr. Gerald D. Walberg, Research Professor at GWU/JIAFS, has been appointed Professor of Mechanical and Aerospace Engineering at NCSU effective July 1, 1991. He has also been appointed Deputy Director of the Mars Mission Research Center to direct technical activities of the Center and direct the Aerobrake Design Methodology Project. Dr. Walberg worked at NASA Langley Research Center from 1957 until he retired in 1989 as Deputy Director for Space. Since 1989, he has been a Research Professor at the Joint Institute for Advancement of Flight Sciences, George Washington University at NASA Langley Research Center. In addition, he worked with the Mars Center as an Adjunct Professor at NCSU during that time. We are delighted to have Dr. Walberg serve as Deputy Director of the Center.

RENOVATED AND NEW FACILITIES

August 1991 is the scheduled completion date of the Research and Technology II building on NCSU's new Centennial Campus, about one mile south of the main campus. The building is the newest addition to the Centennial Campus, which already has Research and Technology Building I and a four-building complex housing the College of Textiles. The new building also houses the Business Innovation and Technology Center, biotechnology laboratories, and 7000 sq. ft. of office and laboratory space for faculty and students working with the Center. The Center facilities include offices for the director, administrative assistant, and secretary/receptionist; offices for 11 faculty; cubicles for 20 graduate students; conference and board rooms; a computer room, two work station rooms, and a printer/plotter room; an instrument room and processing room; and an 1800-square feet, high-bay laboratory facility with a structural testing wall.

The dedication of the Center for Composite Materials Research was held on September 28, 1990 at A&T State University in Greensboro. This Center was established in September 1988 with Dr. V. Sarma Avva as the director. This Center has established a national reputation and complements the research of the Mars Mission Research Center.

ACCOMPLISHMENTS AND PLANS

- Recruitment of new faculty (7), graduate students (7), undergraduates (8), and staff (3).
- Minority Participation: faculty (2), graduate students (4), and undergraduates (11).
- Interactions with NASA Langley, NASA Ames, NASA Johnson, McDonnell Douglas Space Systems Co., and Lawrence Livermore National Laboratory.
- Supplementary Funding: \$4.9 million
- Publications (51) and Presentations at National and International Conferences (21)
- Laboratories Developed (4): Composites Weaving & Braiding, Structures, and Material Testing
- Students Graduated: (25) BS, (8) MS, and (1) PhD.
- Sponsored workshop on "Technology for Lunar/Mars Aerobrakes," October 30 - 31, 1990, Raleigh, NC
- Distributed Proceedings of Workshop
- Annual Report Distributed
- October and April Newsletters Distributed
- Completed Two Design and Construction Projects
 - Mars Aerobrake
 - Full Scale Research Model of HL-20 Personnel Launch System
- Initiated Two New Projects
 - Lunar Transfer Vehicle
 - Calibration Spheres
- Outreach Program Implemented

PLANS FOR 1991

I. MISSION ANALYSIS AND DESIGN

- A. Assessment of Mars Aerobrake Parameters
 - 1. Pressure and heating distributions
 - 2. Relative importance of equilibrium and non-equilibrium radiative heating
 - 3. Thermal protection systems
 - 4. Real-gas effects on lift-to-drag ratios
- B. Establish a Baseline Mars Aerobrake shape for all groups
- C. Refinement of Mars Mission Scenarios

II. HYPERSONIC AERODYNAMICS

- A. Extend CFD to include thermochemical nonequilibrium and radiation for continuum and low-density flows
- B. Incorporate Mars atmosphere as well as air in CFD codes
- C. Perform ballistic range tests in Co₂ at NASA Ames
- D. Determine physiological effects of long-term weightlessness on tolerance to deceleration forces of atmospheric braking (by Evans Lyne, MD)

III. SPACECRAFT CONTROLS

- A. Develop Real-time algorithms for self-tuning control of flexible spacecraft
- B. Experiment on impulse control of large flexible spacecraft

IV. FABRICATION

- A. Continue development of 3-D, automated weaving and braiding machines
- B. Measure mechanical and thermal properties of woven and braided composite structures. Compare results with conventional spacecraft structures.
- C. Measure mechanical and thermal properties of laminated and 3-D fibre reinforced composites.

V. COMPOSITE MATERIALS

- A. Analysis of microstructures of their relation to thermal, thermoelastic, and mechanical properties
- B. Tests to evaluate material properties and failure modes of composite materials subjected to applied thermal and mechanical loads
- C. Develop methods to trace failure fronts through a structure
- D. Identify areas in a spacecraft where composites are superior to conventional materials
- E. Study strength behavior of materials in tension, compression, and under impact loads
- F. Study effects of gas composition of bubble coalescence in epoxy resins.
(Information needed for manufacture of composite materials.)

VI. LIGHT-WEIGHT STRUCTURES

- A. Evaluate structural design concepts for large aerobrakes
- B. Investigate impact resistance of laminated, woven, and braided composites
- C. Develop elasticity solutions for laminated composite shells under thermal loading

VII. EXPAND INTERACTIONS WITH NASA CENTERS AND INDUSTRIES

- A. Boeing/Huntsville
- B. Martin Marietta/Colorado
- C. Rockwell International
- D. NASA Johnson Space Center
- E. NASA Marshall Flight Center

VIII. AEROBRAKE DESIGN METHODOLOGY

IX. ORGANIZE SESSIONS FOR PROFESSIONAL SOCIETY CONFERENCES

- A. Space 92 (April 1992)
- B. ISY 92 (AIAA, Reno, Nevada, January 1992)
- C. ASME Aerospace Division, Winter Annual Meeting, Atlanta, GA, Dec. 1-6, 1991

X. INTERNATIONAL COOPERATION FOR EXPLORATION OF MARS

- A. Life sciences (USSR)
- B. Student exchanges (USSR)

APPENDIX A: WORKSHOP
TECHNOLOGY FOR LUNAR/MARS AEROBRAKES

Sponsored by

North Carolina State University and North Carolina A&T State University
MARS MISSION RESEARCH CENTER (M²RC)
a NASA University Space Engineering Research Center

Mission Valley Inn, Raleigh, NC
October 30 - 31, 1990

PROGRAM

Tuesday, October 30, 1990

- | | | |
|---------------|----|--|
| 7:45 - 8:30 | am | Registration, Mission Valley Inn |
| 8:30 - 8:45 | | Welcoming Remarks, James Ferrell, Dean of Engineering, NCSU
Overview of M ² RC, Fred DeJarnette, Director |
| 8:45 - 9:15 | | "An Overview of the Space Exploration Initiative (SEI) and Exploration
Technology Programs"
Invited Speaker - Steve Wander, NASA Headquarters |
| 9:15 - 9:45 | | "The Space Exploration Initiative Aerobraking Technology Project"
Invited Speaker - Chuck Eldred, NASA Aerobraking Technology
Project Manager |
| 9:45 - 10:15 | | "Recent Developments in Mars/Lunar Mission Studies"
Gerald Walberg, JIAFS/George Washington University |
| 10:15 - 10:30 | | Break |
| 10:30 - 11:00 | | "Integration of Aerobrake Technologies into Mars Mission Systems"
Invited Speakers - Irwin E. Vas and Gordon R. Woodcock,
Boeing Aerospace and Electronics |

MCDONNELL DOUGLAS-M²RC AEROBRAKE PROJECT

- | | | |
|---------------|----|--|
| 11:00 - 11:05 | | Introductory Remarks
Gordon Lee, NCSU |
| 11:05 - 11:20 | | "Mars Aerobrake Assembly Demonstration"
Invited Speaker - John Garvey, McDonnell Douglas Space
Systems Company |
| 11:20 - 11:35 | | "Design, Fabrication, and Testing of an Aerobrake Mock-up"
Robert Stanley, NCSU |
| 11:35 - 11:45 | | Concluding Remarks and Future Activities
Gordon Lee, NCSU |
| 11:45 - 1:00 | pm | Lunch - Mordecai Room, Mission Valley Inn |

HYPERSONIC AERODYNAMICS

- 1:00 - 1:30 "Overview of Hypersonic Aerodynamics Research at the Mars Mission Research Center"
Experimental Research - N. Chokani, NCSU
Computational Research - H. Hassan, NCSU
- 1:30 - 1:45 "Surface Pressure Distribution on a 60° Blunt Cone"
Graham Candler, NCSU
- 1:45 - 2:00 "Direct Simulation Monte Carlo with Ionization and Radiation"
Invited Speaker - Ann Carlson, NASA Langley Research Center
- 2:00 - 2:10 "Equilibrium Radiation Calculations for Mars and Earth Entry"
Brian Platz, NCSU
- 2:10 - 2:20 "Effect of Surface Deformation on Heating Rates"
Stacey Rock, NCSU
- 2:20 - 2:30 "Ballistic Range Measurements of Lift, Drag, and Pitching Moment for a Blunt Cone at Mach Numbers 6 to 21 in Carbon Dioxide and Air"
Jim Packard, NCSU
- 2:30 - 2:45 Discussion of Hypersonic Aerodynamics
- 2:45 - 3:00 Break

STRUCTURES

- 3:00 - 3:20 "Overview of Aerobrake Structures - Structural Configurations, Modeling and Analyses"
Ivatury Raju, A&T
- 3:20 - 3:40 "Modeling and Analysis of Aerobrake Space Frame Structures"
William Craft, A&T
- 3:40 - 3:55 "Modeling and Analysis of Aerobrake (Space Frame) Structures Under Bending"
Fuh-Gwo Yuan, NCSU
- 3:55 - 4:00 "Modeling and Analyses of Aerobrake (Truss and Semi Monocoque Structures)"
(Introduction to Student Presentations) - Eric Klang, NCSU
- 4:00 - 4:15 "Modeling and Analyses of Aerobrake Truss Structures"
Greg Washington, NCSU
- 4:15 - 4:30 "Modeling and Analyses of Semi Monocoque Structures"
John Hairr, NCSU
- 4:30 - 4:45 Discussion of Structural Issues
- 6:30 Social Hour (with cash bar) - Expo Center, Mission Valley Inn
- 7:30 Pig Pickin' - Expo Center, Mission Valley Inn (informal dress)
Speaker: John A. Bailey, Head of Mechanical and Aerospace Engineering, NCSU

Wednesday, October 31, 1990

MATERIALS

- 8:15 - 8:30 "Assessment of Materials for Aerobrake Components"
Sarma Avva, A&T
- 8:30 - 8:45 "On the Thermal Conductivity of Fibers and Fibrous Composites"
Abdul Fahmy, NCSU
- 8:45 - 9:00 "Fracture Mechanics Studies of Braided Composites"
Juri Filatovs, A&T
- 9:00 - 9:15 "Composite Material Concepts for Semi-rigid Aerobrakes"
Ray Foye, A&T
- 9:15 - 9:30 "Evaluation of Mechanical Properties of Braided Composites with and
without Embedded Microballoons"
Malcolm Lyon, A&T
- 9:30 - 9:45 Discussion of Materials for Aerobrake
- 9:45 - 10:00 Break

FABRICATION

- 10:00 - 10:05 Introductions of Student Presentations
Aly El-Shiekh, NCSU
- 10:05 - 10:15 "An Overview of the Fabrications"
Rona Reid, NCSU
- 10:15 - 10:30 "Liquid Transfer Molding of Structures and the Manufacture of a 1/30
Scale Fiberglass Aerobrake"
Randy Stabler, A&T

SPACECRAFT CONTROLS

- 10:30 - 11:00 "A *Priori* Evaluations of the Terminal Descent Phase of the Viking
Lander"
Invited Speaker - Ray Montgomery, NASA Langley Research Center
- 11:00 - 11:15 "Introduction to Minimum Fuel/Time Control of Large Flexible
Spacecraft"
James Redmond, NCSU
- 11:15 - 11:30 "Development of Experimental Structure for Verification of Aerobrake
Minimum Fuel/Time Control Techniques"
John Meyer, NCSU
- 11:30 - 11:45 Discussion of Fabrication and Controls
- 11:45 - 12:30 pm Visit to Centennial Campus
- 1:30 - 3:00 Informal Visit to Laboratories
2110A Broughton (Dr. Silverberg)
202C Nelson (Dr. Mohamed)
306B Nelson (Dr. El-Shiekh)
239A Riddick (Dr. Fahmy)

Summary Information on Workshop
TECHNOLOGY FOR LUNAR/MARS AEROBRAKES

Sponsored by

North Carolina State University and North Carolina A&T State University
MARS MISSION RESEARCH CENTER
a NASA University Space Engineering Research Center

Mission Valley Inn, Raleigh, NC
October 30 - 31, 1990

ATTENDANCE

NASA		12
Industry		7
Students		50
Faculty		26
	TOTAL	95

PAPERS PRESENTED

Invited Speakers		7
NASA	4	
Industry	2	
George Washington University	1	
Students		11
Faculty		14
	TOTAL	32

RESEARCH AREAS OF PAPERS

Overviews and Mission Analysis		5
McDonnell Douglas-M ² RC Aerobrake Project		3
Hypersonic Aerodynamics		7
Structures		6
Composite Materials		5
Fabrication Methods		3
Spacecraft Controls		3
	TOTAL	32

APPENDIX B: AGENDA FOR THIRD ANNUAL REVIEW

MARS MISSION RESEARCH CENTER

McKimmon Center
North Carolina State University
Raleigh, North Carolina
April 3 - 4, 1991

Wednesday, April 3, 1991

- 7:30 - 8:30 a.m. Refreshments
- 8:00 - 8:30 Posters on display
- 8:30 - 9:00 Welcoming Address, Chancellor Monteith, NCSU
Status Report, Fred DeJarnette, NCSU
- 9:00 - 9:30 **MISSION ANALYSIS AND DESIGN**
"Technology Issues as Defined by Mars/Lunar Mission Analyses,"
Gerald Walberg, GWU
- 9:30 - 10:00 p.m. **HL-20 PROJECT**
"Design and Fabricaton of a Full Scale Research Model of the
NASA HL-20 Personnel Launch System," Robert Vess and Dean
Driver, NCSU; Thurman Exum and Dennis Hugley, A&T
- 10:00 - 10:15 Break
- 10:15 - 11:45 **HYPERSONIC AERODYNAMICS**
"Overview of Hypersonic Aerodynamics Research at the Mars
Mission Research Center - Computational Research," Graham V.
Candler, NCSU
"Overview of Hypersonic Aerodynamics Research at the Mars
Mission Research Center - Experimental Research," Wayland C.
Griffith, NCSU
"Nonequilibrium Radiative Heating Prediction Method for
Aeroassist Flowfields with Coupling to Flowfield Solvers," Lin C.
Hartung, NCSU
"Vibration-Dissociation Coupling in Nonequilibrium Flows," D.
Brian Landrum and Graham V. Candler, NCSU
"Monte Carlo Simulation of Nonequilibrium Shock Fronts," David
P. Olynick, NCSU

"The Use of the Direct Simulation Monte Carlo Method for Martian Entry," David Hash, NCSU

"A Dynamic Flow Adaptive Mesh Algorithm Applied to 3-D Flow Fields," Rusty Benson, NCSU

"A Fine-Wire Thermocouple Probe for Measurement of Stagnation Temperatures in Real Gas Hypersonic Flows of Nitrogen," Brian R. Hollis, NCSU

12:00 - 1:00 p.m.

Lunch, McKimmon Center

1:00 - 1:30

AEROBRAKE PROJECT

"Aerobrake Mock-up Project," Gordon Lee, NCSU; Juri Filatovs, A&T; and Eric Clark, NCSU

1:30 - 2:45

MATERIALS

"Overview - Composite Materials," V. Sarma Avva, A&T

"An Automated Thermal Strain Data Acquisition and Recording System," Eric W. Goforth, A&T

"Thermal Properties of 3-D Composites," Robert Gabel and Abdul Fahmy, NCSU

"Strength and Fracture of Braided Composites," G. J. Filatovs, A&T

"Mechanical Properties of Textile Composites," Malcolm Lyon and V. Sarma Avva, A&T

2:45 - 3:00

Break

3:00 - 4:15

FABRICATION

"An Overview of the Fabrications Group," Aly El-Shiekh, NCSU

"Developments in 3-D Braiding," Rona Reid, NCSU

"Automation in Laminate Formation," Cirrelia Thaxton, NCSU

"3-D Weaving Machine Development," Pu Gu, Elsaid Salem, and Mansour Mohamed, NCSU

"Woven/Braided Preforms," Elsaid Salem, A. Fahmy, and Mansour Mohamed, NCSU

"Microballoon Infiltration," Randi Muir, Bob Sadler, and Mansour Mohamed, NCSU

"Intermingled Carbon/PEEK Composites," NFN Machfud, H. Hamada, and Mansour Mohamed, NCSU

"Fabrication Laboratory Research Activities," R. L. Sadler, A&T

4:15 - 5:00 Visit Centennial Campus - Textiles and Research Building II

6:00 - Informal Social and Dinner - McKimmon Center, casual dress

Thursday, April 4, 1991

7:30 - 8:30 a.m. Refreshments

8:30 - 10:00 **STRUCTURES AND CONTROLS**

"An Overview of Structures and Controls," Ivatury S. Raju, A&T

"Effects of Support Location on the Aerobrake Mass," Davis Rogers, A&T

"Modeling and Analysis of Aerobrake Truss Structures," Gregory Washington, NCSU

"Analysis of a Stiffened Spherical Shell with Uniform Axisymmetric Loading," John Hairr, NCSU

"Finite Element Development for Buckling for Composite Aeroshell Panels," Fuh-Gwo Yuan, NCSU

"Design of Aeroshell Elements," Ray Foye, A&T

10:00 - 10:30 **CALIBRATION SPHERES PROJECT**

"An Overview of the NASA/NCSU Calibration Spheres Project," Andrew T. Mueller, NCSU

"Orbital Safety in the Calibration Spheres Project," J.M.A. Danby, NCSU

10:30 - 10:45 Break

10:45 Closed meeting - Team of Monitors

APPENDIX C: BUDGET

Budget for Fourth Year
(March 1, 1991 to September 30, 1991)

Combined NCSU, A&T, and GWU Budgets

	<u>NASA</u>	<u>M²R C</u>
I. Salaries		
1) Faculty (24)	\$295,502	\$158,002
2) Staff (6)	80,804	
3) Graduate students (25)	201,632	38,292
4) Undergraduates (20)	61,480	
II. Fringe Benefits	74,507	32,552
III. Travel	74,125	
IV. Materials, Supplies, and Maintenance	34,218	
V. Publications and Communications	18,500	
VI. Overhead	331,392	108,217
VII. Equipment and Computer Terminal Support	290,840	10,000
TOTAL	<u>\$1,463,000</u>	<u>\$347,063</u>

Graduate Programs in Space Engineering

MARS MISSION RESEARCH CENTER



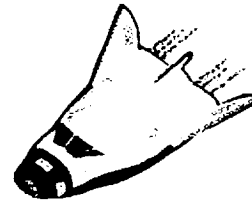
**North Carolina State University
and
North Carolina Agricultural and Technical
State University**

The Mars Mission Research Center is one of nine University Space Engineering Research Centers established by NASA in 1988 to broaden the nation's engineering capability to meet the critical needs of the civilian space program. It is a cooperative effort between North Carolina State University (NCSU) at Raleigh, NC and North Carolina Agricultural and Technical State University (A&T) at Greensboro, NC. Graduate programs are established for Master of Science and Doctor of Philosophy Degrees. Areas of specialization are:



Aerobrake

- Mission Analysis and Design
- Hypersonic Aerodynamics
- Spacecraft Structures and Controls
- Composite Materials
- Fabrication



HL-20 Personnel Launch System

Research projects focus on new technology to design space transportation systems for planetary travel with particular emphasis on the exploration of Mars. A significant feature of the program is that students and faculty spend part of their time at one of the NASA Centers or participating industries. While there, students work on their thesis or dissertation project and coordinate the research with outstanding researchers off campus as well as on campus. Some students participate in projects such as the design and construction of full-scale mockups of the Mars aerobrake and Personnel Launch System shown above.

The M.S. degree requires 24 semester credits of course work and a thesis. Typical programs of study require one to two years. Typical Ph.D. programs have two or three semesters of course work beyond the M.S. degree and dissertation project which generally requires about two years of full-time effort. The Ph.D. degree is granted by NCSU and offered by A&T through a cooperative program with NCSU.

Graduate Research Assistantship stipends range from \$900 to \$1,050 per month for half-time work on campus with rates increased to almost double for research periods at one of the NASA Centers or participating industries. Highly qualified applicants are considered for supplemental fellowships available in the College of Engineering at NCSU. These fellowships are for one year only and provide stipends from \$3,000 to \$6,000 plus all tuition and fees to supplement the Graduate Research Assistantship. This program is limited to U.S. citizens, and participants are exempt from out-of-state tuition.

Highly qualified applicants should contact one of the following:

Dr. Fred R. DeJarnette
Director
MARS MISSION RESEARCH CENTER
North Carolina State University
Box 7910
Raleigh, NC 27695-7910
(919) 737-2365

Dr. V. S. Avva
Associate Director
MARS MISSION RESEARCH CENTER
NC A&T State University
ME Department
Greensboro, NC 27411
(919) 334-7620

NCSU and A&T are committed to equality of educational opportunity and do not discriminate against applicants, students, or employees based on race, color, national origin, sex, age, or handicap.

