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for the period June 1, 1988 to December 1, 1988

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

MARS MISSION RESEARCH CENTER

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Submitted by

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SUMMARY

The Mars Mission Research Center is one of nine University Space Engineering Research Centers established by NASA to broaden the nation's engineering capability to meet the critical needs of the civilian space program. It has the goal of focusing on research and training technologies for planetary exploration with particular emphasis on Mars. The research combines (1) composite materials and fabrication, (2) light-weight structures and controls, and (3) hypersonic aerodynamics and propulsions in a cross-disciplined program directed towards the development of the space transportation system for planetary travel.

Hypersonic aerodynamics will determine the exterior flowfield and surface conditions for aerodynamic braking during entry into the atmosphere of Mars and Earth. This information is used by the structures and materials investigators in the design and fabrication of an aeroshell. Light-weight structures and controls are involved in the interface between the aeroshell and payload. Composite materials and fabrication have three major thrusts: (1) analysis and modeling of braided and woven composites, (2) micro-and macro-mechanics and testing of the composites, and (3) processing and fabrication from pre-forms developed by the faculty in Textiles. During this initial six months of the program, efforts have been directed towards developing the computational facilities, laboratories, and equipment necessary to conduct this research. In addition to the research, students are being trained in space related topics which will give them the background to pursue careers in the space program at universities, industries, or NASA Centers and other governmental laboratories.

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Researchers - W. J. Craft (A&T), A. El-Shiekh (NCSU), E. C. Klang (NCSU), L. Silverberg (NCSU)

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INTRODUCTION

The Mars Mission Research Center (M^2RC) is one of nine University Space Engineering Research Centers established by NASA's Office of Aeronautics and Space Technology (OAST) in June 1988. They support NASA's goal to broaden the nation's engineering capability to meet the critical needs of the civilian space program. The goal of the M^2RC is to focus on research and training technologies for planetary exploration with particular emphasis on Mars. The research combines (1) composite materials and fabrication, (2) light-weight structures and controls, and (3) hypersonic aerodynamics and propulsion in a cross-disciplined program directed towards the development of the space transportation system for planetary travel. It is a cooperative effort involving North Carolina State University and North Carolina A&T State University. Faculty, undergraduate, and graduate students from the College of Engineering at NCSU and A&T and Textiles at NCSU participate in the program. Interactions with other universities, industry, and NASA Centers are being pursued. This report describes the progress of the M^2RC from June 1, 1988 to December 1, 1988.

HYPERSONIC AERODYNAMICS AND PROPULSION

The thrust of the hypersonic aerodynamics research in the Mars Mission Research Center is directed towards problems associated with reentry physics with special emphasis on aerobraking technology. The flow fields under consideration are characterized by vibrational, chemical, and radiation nonequilibrium. Our analytical and experimental efforts are directed towards the understanding and prediction of these flow fields.

For experimental simulation of these flowfields, Dr. Wayland Griffith and two of his students will be working with Drs. Gary Chapman and Anthony Strawa of the Aerothermodynamics Branch, NASA Ames Research Center. They will be developing test techniques and carrying out relevant experiments in the high speed gas dynamics facilities there. Dr. John Perkins is in the process of redesigning CF_4, He and N_2 nozzles for hypersonic research. This work is being conducted in conjunction with Charles Miller, Experimental Aerodynamics Branch, NASA Langley Research Center. Because of the high Mach numbers being contemplated, old design methods which are based on the method of characteristics and boundary layer calculations are not valid. The effort will require developing new computational capabilities based on the Navier-Stokes equations.

The ultimate objective of the experimental work is to develop experimental facilities and diagnostic techniques to the point where reliable data can be obtained at hypersonic Mach numbers for code validation. Another planned use of the test facilities is the projected test of aeroshells needed for aerobraking.

The analytical work in progress is designed to build our computational capabilities using both the continuum gas dynamics equations and direct simulation Monte Carlo methods. Dr. Scott McRae is pursuing further development of a code developed initially under his direction and is developing a new code. The first code is an explicit PNS Code developed by Gielda and McRae using a McCormack method. The code was later modified to include a hydrogen-oxygen combustion model and was used to produce successful computations for three dimensional scramjet flow fields. The second code is based on the work of Korte and McRae in which a rotated upwind scheme is used to solve the PNS equations. The rotated upwind scheme models the Riemann problem more accurately than projection schemes. The new code will solve the Full Navier Stokes equation for 3-D time dependent flows. Both of the above codes will be modified to compute thermo-chemical nonequilibrium including radiation.

The Monte Carlo work is being undertaken for two major reasons. The first is that it is the only reliable and viable procedure for calculating flows in the transition regime. Second, when dealing with nonequilibrium flows, it is not clear which temperature (translational, vibrational, or electronic) to use in rate expressions. The issue does not arise in Monte Carlo simulations because cross sections and not rates are required. The work is performed under the direction of Dr. H. A. Hassan in cooperation with Drs. Kenneth Sutton and James Moss, Aerothermodynamics Branch, NASA Langley Research Center. Current emphasis is being placed on the interaction between vibrational relaxation and dissociation. Because of the anharmonicity of diatonic molecules, there is the tendency for each diatomic species to exist as two subspecies: one is characterized by low vibrational modes while the other is characterized by high vibrational modes. As a result, most of the dissociation involves only molecules in the higher vibrational modes. This model results in reduced dissociation and increased convective heating for noncatalytic surfaces.

Approximate numerical methods are being developed to calculate three dimensional inviscid/boundary layer and fully viscous shock layer methods. Both methods use Maslen's second-order pressure equation in a shock-oriented coordinate system. The inviscid/boundary layer technique is appropriate for higher Reynolds numbers whereas the fully viscous shock layer is applicable to the lower Reynolds numbers. The three dimensional inviscid method has been applied to blunted cones and an interacting boundary layer technique is under development. Axisymmetric fully viscous shock layer solutions have been obtained for a variety of blunt-nosed reentry bodies and this technique is being extended to three dimensional flow fields. A third effort involves development of an approximate nonequilibrium gas model to increase the computational efficiency of calculating nonequilibrium hypersonic flows. The research involving the approximate numerical methods is under the direction of Dr. F. R. DeJarnette with the assistance of four graduate students and in cooperation with Mr. Vince Zoby, Dr. Peter A. Gnoffo, and Dr. Kenneth Sutton of the Aerothermodynamics Branch at NASA Langley Research Center.

All of the above activities involve graduate students. There is a parallel activity involving undergraduate students. Dr. Griffith is supervising two undergraduates who are investigating aerobraking in the Earth's atmosphere upon return from a geostationary orbit. Single and multiple pass encounters are considered with the ballistic coefficient as a parameter. Another effort is carried by a prospective undergraduate student who is currently studying at the NC School of Science and Mathematics. He is working out Earth-Mars-Earth transfer times and the relative velocities involved for rendezvous with Mars, its moons and orbiting satellites and return to Earth orbit. These investigations will provide the atmospheric flight conditions for the computational codes.

The numerical methods and experimental results will be used to determine the flow fields and surface properties which are needed by the composite materials and light-weight structures investigators in the design of an aeroshell.

LIGHTWEIGHT STRUCTURES AND CONTROLS

The Mars entry aeroshell used on the Viking lander in 1975 was composed of a minimum gage aluminum structure using aluminum stiffeners. The primary concern of this design was buckling of the shell under uniform pressure anticipated for the Mach 5 entry velocity. The geometry was a blunt 120° conical shell about 12 feet in diameter. Expected maximum temperature for the structure was approximately 300°F with the higher external temperature being handled by an ablative covering.

The proposed NASA Aeroassisted Flight Experiment is intended to prove design concepts for controlled entry into the Earth's atmosphere at much higher Mach numbers and therefore higher temperatures. The current design incorporates an all metal support structure insulated with a nonablative cover. The shell geometry is much larger than the Viking aeroshell and uses a blunted elliptical cone with a raked base. Such a shape precludes an axisymmetric analysis model.

It is anticipated that the requirement for lighter weight and higher loading conditions of the proposed Mars Mission will necessitate the use of composite materials in the new design. Additionally, the structure will be required to operate at greater temperatures to limit the use of insulating materials.

An efficient light weight design may mean that the structure is quite flexible and will require active control to ensure that the shell retains the correct shape for aerodynamic purposes. The control algorithms for accomplishing this are being developed by Dr. Silverberg at NCSU. Initial work has centered on discrete decentralized control of flexible structures. An experiment used to demonstrate some of the analytical models is being developed using a flexible H-beam structure. Five degrees of freedom can be included in the current experiment. Data acquisition and control electronics are currently being purchased.

The structural model for the anisotropic non-axisymmetric shell is being developed by Dr. Klang at NCSU. Combinations of gasdynamics, thermodynamics, structures, and materials will be required in the new shell design. High temperature gradients and possible nonlinear deformations will require newly developed numerical techniques. Additionally, there is a need for greater interaction with aerodynamic models than were required on previous designs. Initial steps in this area have been taken in the accurate modeling of composite box beams loaded with aerodynamic pressures.

Accurate constitutive properties are required by both the control model and the shell model. These properties include damping (to be studied by Dr. Silverberg) and stiffnesses and strengths (to be studied by Drs. Klang, Craft, and Filatovs). Due to the abundance of composite preform geometries generated by this center's composite materials group, it is necessary to produce accurate models to predict the constitutive behavior. Dr. Craft at A&T and Dr. Klang at NCSU have the lead in this area. Discussions with Drs. Whitcomb, Starnes, and Dexter at NASA Langley indicate that stiffness properties have already been modeled with some success; however, strength and damping remain elusive. Apparently the complex geometries of the composite preforms will require numerical methods of analysis. A model based on the finite element method has begun at NCSU by Genevieve Dellinger, a master's degree student.

Experimental verification of these models will require fabrication of the new materials as discussed above. Impact testing of these materials is well underway. Dr. El-Shiekh has constructed a test fixture for low energy impact and Drs. Klang and Mohamed are developing techniques for high energy impact utilizing the MAE department's gas guns. Strength, stiffness, and damping properties will be tested at both A&T and NCSU using servohydraulic test equipment.

It is anticipated that the testing of large scale subcomponents will require higher capacity test machines slated for purchase in subsequent years. Additionally, high temperature environmental chambers in place at A&T and proposed for NCSU will be needed to determine properties of the materials operating at elevated temperatures.

Carbon-carbon composite materials have been targeted by this center for higher temperature applications. Professor Sadler at A&T will lead in the fabrication of these materials. Nonlinear material properties of carbon-carbon coupled with nonlinear deformations present a formidable challenge in the development of analytical models for the aeroshell design.

Finally, the support structure which forms the interface between the aeroshell and the payload is being investigated. The envisioned truss structure may be manufactured using the weaving and braiding techniques being developed by Drs. Mohamed and El-Shiekh at NCSU. The methods for the damping and maneuver of the support truss will be verified using the H-beam experiment being developed by Dr. Silverberg. Due to the low temperature environment experienced by this structure, thermoset matrix composites appear to be viable. This is the area of current research being investigated by several researchers at both universities. The low temperature and 1-D geometry of this structure pose no new problems in the area of static structural analysis.

COMPOSITE MATERIALS AND FABRICATION

Analysis and Modeling

Beginning September 1, 1988, Dr. William J. Craft began formal participation in the M^2RC. Eric Goforth was appointed as an undergraduate research assistant in

October and Mr. Peter Fay, an MSME graduate, began participating through his three-hour project course.

Mr. Goforth is assisting in the review of a literature search directed to the analysis of the elastic properties of woven and braided composites. Items of interest are the effective modulus, stiffness, coefficient of expansion, and strength. (1) The preliminary search has included 340 abstract citations and 24 papers are on hand. (2) Several papers were found concerning 3-D composite materials and the design of the aeroshell for the Viking lander. (3) Eric Klang and Bill Craft have agreed to exchange literature material and they will meet to compare ideas and coordinate complementing analytical studies in woven and braided composites. The search will be refined and extended during 1989.

Dr. Craft visited NASA Langley Research Center on November 17th and discussed M^2RC activities with several people including John Whitcomb who is actively working in the analysis of composites. He presented some model "cells" that may form the basis of unique finite elements in the future, and he expressed interest in M^2RC work. A significant contact will have to be established with summer faculty and student involvement.

Mr. Peter Fay is completing a computer program to model resistive networks for a brittle conductive coating as a strain and crack sensor. There are ongoing contacts at Langley about an M^2RC related project in this area.

Micro-and Macro-Mechanics and Testing

Micromechanics

Learning specimens have been fabricated and are being tested. The results will guide the development and design of test methods and fixtures, and analytical techniques. Dr. Filatovs is conducting a search, using optical and Scanning Electron Microscopy techniques, for quantifying features and structural descriptors, and for an appropriate "unit cell" of the structure; these are for eventual use in analysis and modeling.

There is little published work on braided and woven composites. Therefore, the initial work will address the study of compressive and buckling behaviors, as this area does have some useful literature. The intent is to correlate buckling failure, some models for which are cast in terms of sinusoidal structures, with the braided/woven structure. This will guide the development of a more applicable and realistic modeling system which will incorporate more structural and materials parameters. For example, in the braided/woven composites the presence of much more shear will make the interface exert a large influence, and this will have to be incorporated into analytic expressions. The projected work is to develop a qualitative feel for the materials and tests, to develop approaches, and to conduct exploratory fractography of the failure modes.

Damping Properties and Control Algorithms

Dr. Silverberg's activities fit into two overall goals: (1) Test, evaluate, and improve damping properties of woven and braided composite members; and (2) Develop advanced control algorithms for aerobraking maneuvers.

The first goal requires investigating the individual effects of the design parameters on the damping characteristics in the axial and transverse directions. These design parameters are (a) the 3-D geometry, (b) the fiber, and (c) the matrix. This work will focus on developing testing methods for evaluation of the damping properties, on comparisons with layered composite beams with similar geometries based on frequency of oscillation and mass property, and on identifying design parameters to improve particular damping characteristics. The first bundle of braided test specimens is currently being fabricated in the form of rectangular beams with dimensions 1/2" x 1/4" x 12" by other Center investigators. An experimental damping test for these specimens has been developed. Tests will be carried out on the basis of frequency of oscillation and mass property.

The second goal will focus on the development and experimental verification of control algorithms to satisfy two primary concerns: The first is to develop decentralized actuation and sensing algorithms to improve system level reliability. The second is to develop control algorithms exhibiting near-optimal dynamic and control performances while being well suited for in-space implementation. Jim Redmond (graduate student) and Lance Mangum (technician) are gaining experience with the use of strain gauges to measure distributed displacements over the length of beams. Jim attended a hands-on 3-day workshop on the use of strain gauges and has instrumented a cantilever beam from which inertial displacements over the length of the beam will be sensed in real-time. Lance will also gain experience with two newly purchased angular rate sensors including calibration, testing of cross-axis coupling, etc. Lance has also designed a 30-channel special purpose strain gauge amplifier which will be completed by December, 1988. These devices will be used as part of a series of aeroshell maneuver experiments to be carried out in the Aerospace Structures Laboratory.

Woven Preforms and Composites

Professor Mohamed and colleagues have modified the manually operated model for weaving 3-D preforms and improved to produce higher density long samples. Slabs of dimensions 2" x 1/4" x 20" have been produced from 6K, T300 carbon fibers with x, y, and z fiber orientation and volume fraction of 42-45%. Impregnation with epoxy resin has been tried by Dr. Fahmy and additional trials will be made by Larry Dickinson using the molds designed by Dr. Klang. Microscopical examination of the structure indicated that the fibers remain straight in all three directions, which is desirable to maximize their contribution to strength and stiffness. Although infiltration of the lightly woven sample was not easily achieved, the cross-sections showed good distribution of the matrix between the individual fibers. Samples of dimensions 3/4" x 1/4" cross-section are being woven for use by Professor Sadler at A&T.

In parallel with the hand weaving of structure, good progress has been made in the design of an automated 3-D weaving machine. Parts of the machine have already been produced and are being assembled. However, the decision concerning the shedding mechanism has not been finalized. Ideally, an electronic Jacquard head should be used for this. The cost of such a head is approximately $50,000 which cannot be purchased during the first year. Plans are being made to secure a quotation from one of the manufacturers, who are all European companies.

Braided Preforms and Composites

Professor El-Shiekh and his students have been working in the following areas:

A sample, computerized, fully automated 2-Step 3-D braiding machine has been developed and running in a slow but reasonable speed. Faster speed can be achieved by modifying the control software programmed by ourselves.

The main bed of a 4-Step 3-D braiding machine with 2,000 carriers has been constructed and semi-automated. Various preforms have been produced on that including panels up to 4' wide made of fibers such as Carbon, Silicon Carbide.

Consolidation of the 3-D braided preforms with epoxy resin (thermo-set) and Peek (thermo-plastic) has been started. Experience has been gradually achieved and some nice specimens have been obtained.

A simple device for low velocity impact test has been built. The impact test of the 3-D braided Carbon/Epoxy composites are being conducted to investigate the effect of the processes and parameters on the damage tolerance of the composite material.

Theoretical and experimental analysis of 3-D braided preforms are being conducted. In addition, molds for the manufacture of 3-D composites were developed in cooperation with Klang. Equipment for resin transfer molding was purchased and has been used successfully by our students. Finally, a 22 kip servohydraulic test machine has been ordered by Klang. This machine will be used by several M^2RC researchers to study the mechanical behavior of composite materials.

Composite Processing and Fabrication

Professor Sadler and some of his colleagues at A&T have been busy (a) in getting the Composite Processing and Fabrication Laboratory ready, and (b) in preparing the composites out of preform architectures as some of the facilities became functional during this initial reporting period. The accomplishments, briefly stated, are as follows:

Composite Fabrication Laboratory

The laboratory location was selected in late October and the site preparation began almost immediately. The Composite Fabrication Laboratory will contain an area of about 1500 square feet. A 100 square foot humidity controlled room has been provided where humidity sensitive prepregs and other materials can be prepared and loaded into curing fixtures.

The major equipment items to fabricate organic composites were moved into place and the installation is nearing completion. The major equipment items include a compression press (150 ton, 18" x 18" platens), an autoclave (13" x 13" x 36", 750 degrees F, 330 psi), a low temperature plasma (12" D x 24", 1500 watt, 13.56 MHz RF), and a filament winding machine (maximum mandrel envelope - 14" diameter by 18" long). Various supporting equipment such as vacuum pumps, vacuum chamber, vacuum oven, ovens, refrigerator and electronic scales are already in service.

The laboratory will also have the capability to fabricate carbon/carbon composites in the near future. A study is being made to identify and prepare engineering specifications for the equipment required to support this endeavor. One piece of equipment will be a furnace for carbonization. This furnace will require temperatures up to 1100 degrees C in an inert atmosphere. At this time, a working interior of 12" x 12" x 12" is thought to be suitable.

Composite Fabrication

Dr. Aly El-Shiekh, NCSU College of Textiles, has supplied four samples of graphite braid to A&T. Two of these braid samples have been fabricated into four six-inch bars. Another sample has been fabricated at A&T by two graduate students from NCSU. Two of these samples have been used as technique demonstration items. The third and fourth samples have been turned over to Dr. Juri Filatovs for mechanical evaluation.

Thus far, only one process and two materials have been used to fabricate the samples. All samples have been molded in a stainless steel mold. The initial evaluations of composites fabricated with this process indicate a nearly void free product.

Composite Work Plan

The initial composite work plan includes fabricating test coupons from various fiber braids, supplied by NCSU, and epoxy resin. Coupons fabricated from more conventional forms of fiber will also be made available for comparative studies. The evaluation of these samples will enable the investigators interested in mechanical properties and computer modeling to determine the viability of braided composite as a structural material.

Another section of the work plan includes the fabrication of carbon/carbon composite test coupons. This will start when the required equipment is installed in the Composite Fabrication Laboratory. As in the case of the epoxy matrix materials, coupons will be fabricated from preforms supplied by NCSU. In this case, it is expected that the fibers will be in both the braided and 3-D structures. These materials will be impregnated and carbonized in our laboratory. Again the coupons will be provided to the project investigators for property determination and modeling. Results from each set of evaluations should lead to improvements in the next generation of experiments.

The final section of work involves composites fabricated from resin matrix materials in powder form. Techniques for introducing resin powders into tow and retaining it there will be investigated. The resins reserved for the process cannot be used in the normal liquid impregnation processes. The use of fluid bed and electrostatic processes would be included in this study.

RENOVATED AND NEW FACILITIES

An essential part of the program at A&T requires renovation of several existing facilities. The most urgent need is the development of a composite processing and fabrication facility. Renovation of this facilities is in progress and has an estimated completion date of December 31, 1988. Other existing facilities which require renovation are the Composite Materials Testing Laboratory, Light and Scanning Electron Microscope Laboratory plus several facilities for smaller scientific equipment. The renovation of these facilities will begin when authorization is received from the A&T administration.

Architects are designing an NCSU Research and Technology Development Building for the new Centennial Campus and the M^2RC will occupy about one-third of it. The plans call for offices for faculty and students, rooms for computers and work stations, a composite materials laboratory with a high bay area, an instrument room, and a processing room. The net square footage allocated for M^2RC is 6,700 and the scheduled completion date is September 1990. At that time, all of the activities of the M^2RC at NCSU would be moved to this new facility which is about one mile south of the main campus. The entire College of Textiles will also move into new facilities adjacent to the Research and Technology Development Building in 1990. Transportation will be provided for students and faculty between the main campus and the new facility.

INTERACTION WITH NASA CENTERS, INDUSTRIES, AND OTHER UNIVERSITIES

Preliminary discussions have been held with personnel at the following organizations:

NASA Ames Research Center

Aerothermodynamics Branch
Drs. Gary Chapman, Steve Diewert, and Toni Strawa

NASA Langley Research Center

Aerothermodynamics Branch
Drs. Peter Gnoffo and Kenneth Sutton

Applied Materials Branch
Drs. Benson Dexter, Gary Farley, and Howard Maahs

Fatigue and Fracture Branch
Drs. John Crews, Howard Maahs, and John Whitcomb

Polymeric Materials Branch - Dr. Terry St. Clair

Guidance and Control Division Chief - Dr. Willard Anderson

Spacecraft Controls Branch
Drs. Claude Keckler, Doug Price, and Bill Suit

Structural Mechanics Branch - Dr. James Starnes

Lawrence Livermore National Laboratory - Mr. Jay Lepper

Oak Ridge National Laboratory - Mr. David Post

McDonnel Douglas, Huntington Beach, CA
Mr. John Garvey and Dr. Robert Wood

Pratt & Whitney, West Palm Beach, FL - Mr. Wayne Pecic

Institute for Space and Terrestrial Studies and University of Toronto Space Institute
Drs. Phillip Lapp, Ian Howard and Rod Tennyson. Also Mr. Doug Ditto, Canadian Deputy Consul General

Corning Glass Works - Dr. Roger A. Allaire

RECRUITMENT OF STUDENTS, FACULTY, AND STAFF

North Carolina A&T State University added a new Adjunct Research Assistant Professor, Dr. Wadida Oraby on November 7, 1988. They are presently recruiting to fill the following positions:

1. Three Faculty Positions in Analysis and Modeling, Testing and Characterization, Processing and Fabrication.

2. Administrative Assistant

3. Two Research Technicians in Polymer Processing and Fabrication and in Mechanical Testing of Composite Materials.

Professor Raphael Tsu, Research Professor, resigned from A&T last summer.

North Carolina State University hired Mrs. Emily Tate as an Administrative Assistant starting October 1, 1988. Recruitment of two Research Faculty positions is in progress for two of the following four areas: hypersonic aerodynamics, composite materials and fabrication, light-weight structures, and spacecraft controls.

CONCLUDING REMARKS

The Mars Mission Research Center has started developing the computational facilities, laboratories, and equipment necessary to pursue cross-disciplined research in the areas of (1) composite materials and fabrication, (2) light-weight structures and controls, and (3) hypersonic aerodynamics and propulsion. Students and faculty are involved in developing the technology which is needed for the design of an aeroshell for space transportation systems. In addition, students are being trained in space related topics which will give them the background necessary to pursue careers in the space program at universities, industries, or governmental laboratories. Interactions with other organizations and NASA Centers are being pursued to enhance the academic and research programs at both North Carolina State University and A&T State University.