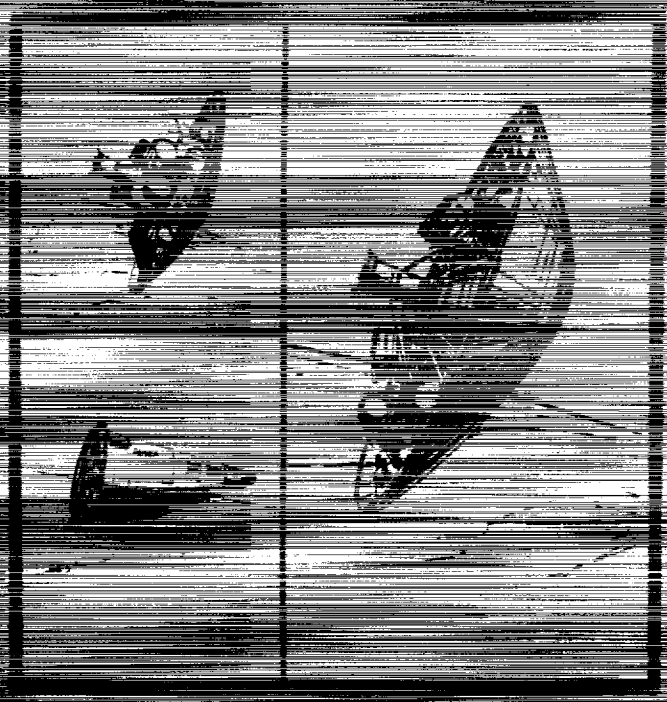
NASA

Pathfinder

High Energy Aerobraking Workshop

Ames Research Center
Moffet Field, CA



Workshop Proceedings

Technology

(NASA-TM-101118) PATHFINDER: HIGH ENERGY AEROBRAKING WORKSHOP (NASA) 375 p

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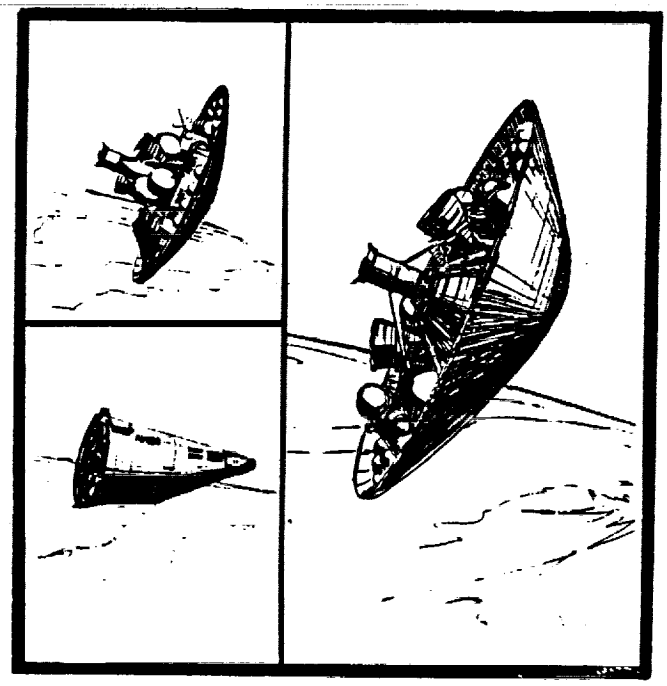
OAST

PATHFINDER

High Energy Aerobraking Workshop



Ames Research Center
Moffet Field, CA
January 31 - February 2, 1989

Workshop Proceedings

Office of Aeronautics and Space Technology
National Aeronautics and
Space Administration
Washington, D.C. 20546

OAST

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

NASA

Reply to Attn of: RT:229-3

February 24, 1989

TO: Distribution

FROM: James O. Arnold, Chief, Thermosciences Division
David M. Cooper, Chief, Computational Chemistry Branch

SUBJECT: ARC Sponsored High Energy Aerobrake HEAB Workshop, January 31-February 2, 1989.

Ames Research Center hosted a workshop to discuss High Energy AeroBraking (HEAB) activities of Project Pathfinder on January 31-February 2, 1989. The workshop was attended by 69 participants with representatives from NASA Headquarters (Codes R, Z, and M), Ames, Langley, and Lewis Research Centers, Jet Propulsion Lab, Johnson Space Center, Boeing, Martin-Marietta, Lockheed, Stanford, San Jose State, and North Carolina State Universities.

The workshop served as a forum to communicate the status of current HEAB activities, to discuss interests, and to describe capabilities and prior work which could impact/assist and future HEAB research. The first day and a half was used to describe HEAB related activities and studies. (copies of all of the material presented are enclosed.) The afternoon of the second day was spent in an open discussion to identify key challenges, issues, and technology requirements as they relate to the HEAB program. A complete tabulation of these issues is also attached. The participants then divided into the following subgroups:

1. System Studies
2. Aerothermodynamics
3. Thermal Protection Materials and Structures
4. Guidance, Navigation, and Control
5. Flight Experiments
6. Experimental and Computational Facility Requirements

to analyze the issues and make recommendations for future action items. The sub groups spent the morning of the third day working the issues and the last afternoon was used to present and discuss the conclusions and recommendations of the subgroups. Copies of the summary charts used by the subgroups to report to the entire workshop are enclosed.

In addition agreement to conduct in-house system studies to the identification of important issues and directions for technology maturation, other significant accomplishments included:

1. Agreement to conduct system studies on minimum (using AFE-type technology) and ambitious (vis-a-vis HEAB) piloted Mars missions to focus/span/scope HEAB technology maturation.
2. A tentative definition of human G-tolerance in terms of both G loads and time subjected to loading.
3. A clarification of the uncertainties in the structure of Mars' atmosphere and that modeling activities could reduce this uncertainty.

The participants recommended that similar workshops should be held semi-annually. The date and location of the next workshop will be identified later.

James O. Arnold

David M. Cooper

Enclosures

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CHAPMAN

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PURPOSE AND EXPECTED PRODUCT OF PATHFINDER HIGH ENERGY AEROBRAKING WORKSHOP

JANUARY 31 - FEBRUARY 2, 1989

BY

JAMES O. ARNOLD

BACKGROUND FOR PATHFINDER HEAB WORKSHOP

- JAN. 1987 - PRESENT: CODE Z, M SYSTEM STUDIES INCLUDING MRSR
- JAN. 1988 - PRESENT: FORMATION OF OAST HEAB TEAM, LIST OF QUESTIONS FOR CODE Z, TECHNICAL PLAN AN INITIATION OF CODE R FUNDED RESEARCH AT ARC, LaRC JPL & JSC.

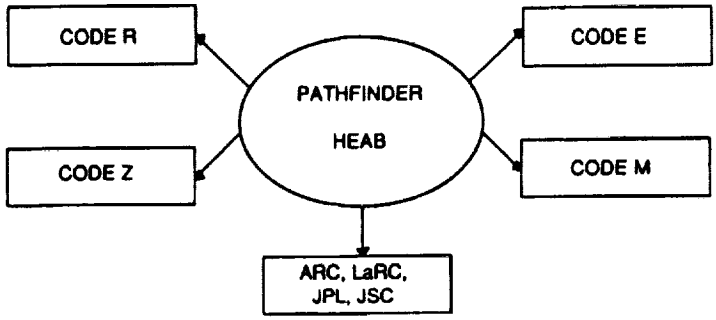
  - ESTABLISHED NEED FOR JOINT WORKSHOP WITH CODE Z.
- NOV. 17-19, 1988: CODE R/Z GLOBAL WORKSHOP

  - TRANSPORTATION SAA
  - MARTIN-MARIETTA (CLARK VIS-A-VIS AEROBRAKES)
  - BOEING (WOODCOCK VIS-A-VIS AEROBRAKES)
  - AFE
  - OAST HEAB REPORT
  - NEED FOR FUTURE, FOCUSED WORKSHOPS
- DECEMBER 1988

  - WOODCOCK VISIT
  - DEVELOPMENT OF CONSENSUS FOR WORKSHOP

PURPOSE OF WORKSHOP

- COMMUNICATION OF INTERESTS, OBJECTIVES, STATUS OF STUDIES AND CAPABILITY VIS-A-VIS PATHFINDER HEAB.



- DEFINE KEY AEROBRAKING ISSUES, "DISCONNECTS", REQUIRED RESEARCH & COMPUTATIONAL & EXPERIMENTAL (GROUND & FLIGHT TEST) FACILITY REQUIREMENTS.

- DEVELOP IMPROVED COMMUNICATIONS, RECOMMENDATIONS FOR FUTURE ACTIVITY & POTENTIAL NEED FOR SEMI-ANNUAL WORKSHOP.

WORKSHOP PRODUCT

- WORKSHOP PROCEEDINGS
  - PRESENTATION VU-GRAPHS
  - LISTING OF "ISSUES"
  - RECOMMENDATIONS FROM WORKING GROUPS

- BETTER UNDERSTANDING OF MISSION REQUIREMENTS VIS-A-VIS HEAB & DRIVERS FOR TECHNOLOGY MATURATION

ADMIN. DETAILS

- ATTENDANCE LIST

- SIGN-UP FOR DINNER ON FEBRUARY 1, 1989 AT RESTAURANT

LIST OF QUESTIONS TO CODE Z FROM THE PATHFINDER HIGH ENERGY AEROBRAKING TEAM

(QUESTIONS GENERALLY APPLY TO BOTH THE MRSR AND MMM MISSIONS)

0.0 IN-SPACE ASSEMBLY OF AEROBRAKES

- FEASIBILITY/PRACTICALLY OF PRODUCING AEROBRAKE TPS FROM LUNAR MATERIAL
  - CAPABILITY OF ASTRONAUTS/ROBOTS IN ASSEMBLY OF AEROBRAKE

1.0 TRANSIT

- ALLOWABLE TRANSIT TIME - BOTH WAYS
- EFFECT ON SPACECRAFT THERMAL CONTROL BY ENTRY THERMAL PROTECTION SYSTEM
- EFFECT OF IN-SPACE EXPOSURE ON TPS

2.0 MARS ENTRY AND LANDING

- RESULTS OF RECENT CODE Z SPONSORED STUDIES
- ACCURATE INFORMATION ON HEIGHT OF FOUR VOLCANOES AT + 20 AND -10 DEGREES LATITUDE - CURRENTLY LISTED AS HIGH AS ABOUT 27 KM AND SHOWN IN VARIOUS PUBLICATIONS AND MAPS WITH FACTORS OF TWO DIFFERENCES
- AMOUNT OF DUST INCLUDING SIZE DISTRIBUTION IN MARTIAN ATMOSPHERE AS FUNCTION OF ALTITUDE AND MARTIAN YEAR-MAY EFFECT TPS DUE TO IMPACT
- DESIRED PARKING ORBIT(S), LANDING SITES AND TIME TO BE SPENT ON SURFACE
- PRACTICAL LIMITS ON MISSION SCENARIOS/DESIRED MASSES TO BE PLACED ON MARTIAN SURFACE
- ACCEPTABLE G-LOADS ON CREW DURING MARS ENTRY FOLLOWING LONG PERIOD OF SPACE FLIGHT

13.0 EARTH RETURN

- PRACTICAL LIMITS ON MISSIONS SCENARIOS/DESIRED MASSES BE RETURNED TO EARTHY/CORRIDOR WIDTH - INCLUDE DIRECT ENTRY AND SPACE STATION RENDEZVOUS
- ACCEPTABLE G-LOADS BY CREW DURING EARTH RE-ENTRY FOLLOWING LONG PERIOD OF SPACE FLIGHT
- IMPACT OF AI/ROBOTICS ON EARTH ENTRY MANEUVER/SPACE STATION RENDEZVOUS
- WOULD THE HEAT OF RE-ENTRY SUFFICE TO STERILIZE THE RETURN ENTRY CAPSULE OF MARS "BUGS"

PERSPECTIVE FROM OFFICE OF EXPLORATION SPACE TRANSPORTRATION INTEGRATION AGENT

R. Durrett
MSFC
1/31/89

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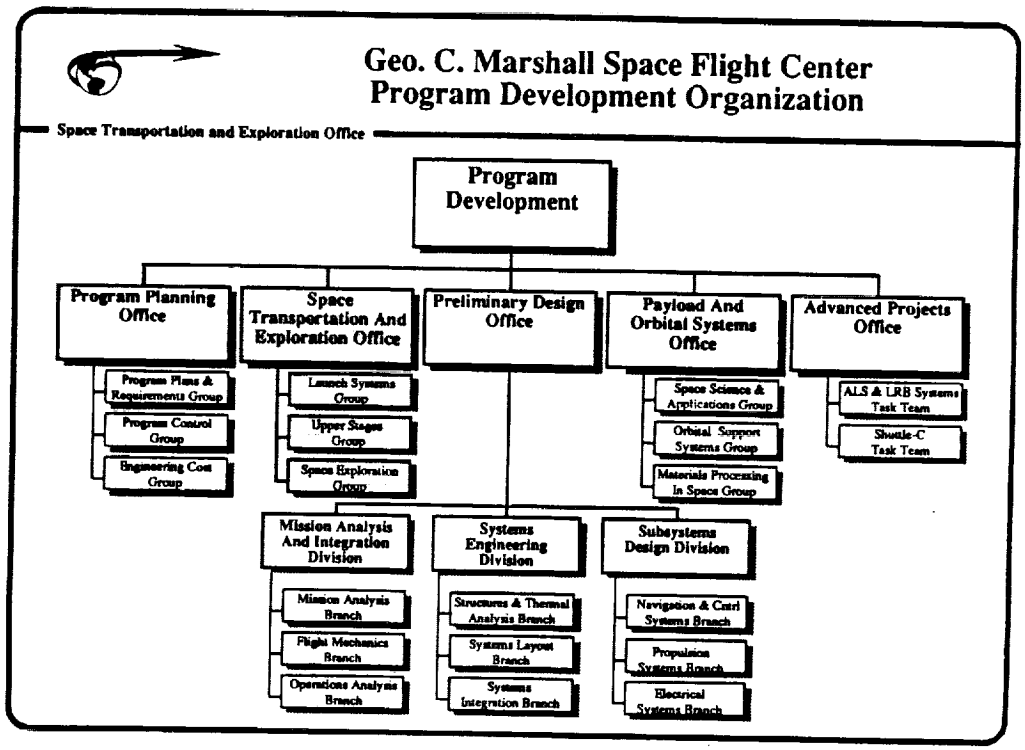
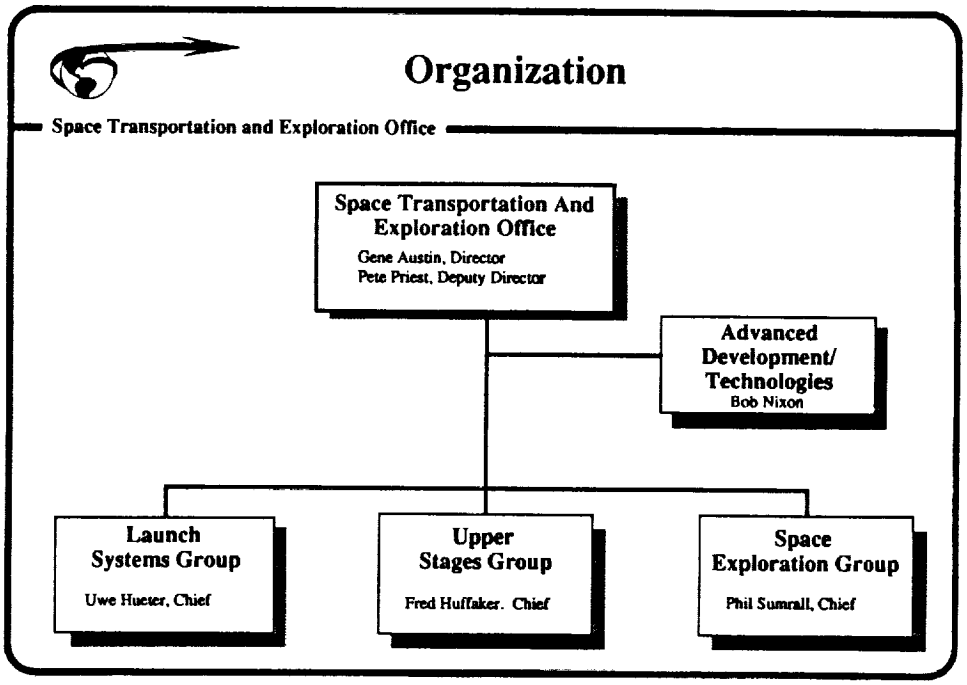

Geo. C. Marshall Space Flight Center
Program Development Organization
Space Transportation and Exploration Office
Program Development
Program Planning Office
Space Transportation And Exploration Office
Preliminary Design Office
Payload And Orbital Systems Office
Advanced Projects Office
Program Plans & Requirements Group
Program Control Group
Engineering Cost Group
Launch Systems Group
Upper Stages Group
Space Exploration Group
Space Science & Applications Group
Orbital Support Systems Group
Materials Processing In Space Group
ALS & LRB Systems Task Team
Shuttle-C Task Team
Mission Analysis And Integration Division
Systems Engineering Division
Subsystems Design Division
Mission Analysis Branch
Flight Mechanics Branch
Operations Analysis Branch
Structures & Thermal Analysis Branch
Systems Layout Branch
Systems Integration Branch
Navigation & Cntrl Systems Branch
Propulsion Systems Branch
Electrical Systems Branch


Organization
Space Transportation and Exploration Office
Space Transportation And Exploration Office
Gene Austin, Director
Pete Priest, Deputy Director
Advanced Development/ Technologies
Bob Nixon
Launch Systems Group
Uwe Hueter, Chief
Upper Stages Group
Fred Huffaker. Chief
Space Exploration Group
Phil Sumrall, Chief

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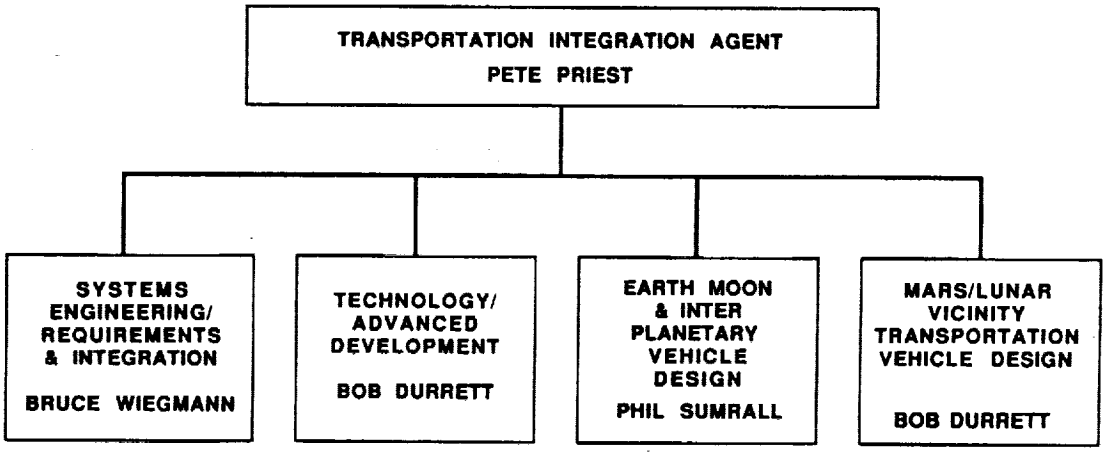
OFFICE OF EXPLORATION TRANSPORTATION IA MANAGEMENT PLAN



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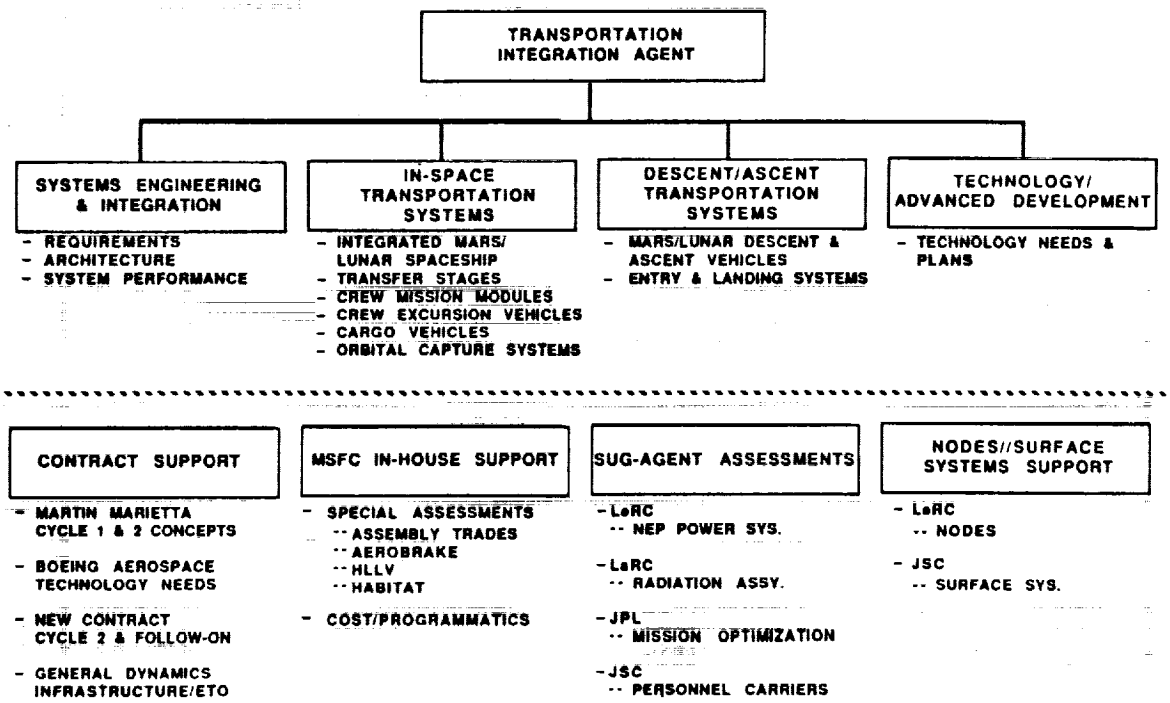
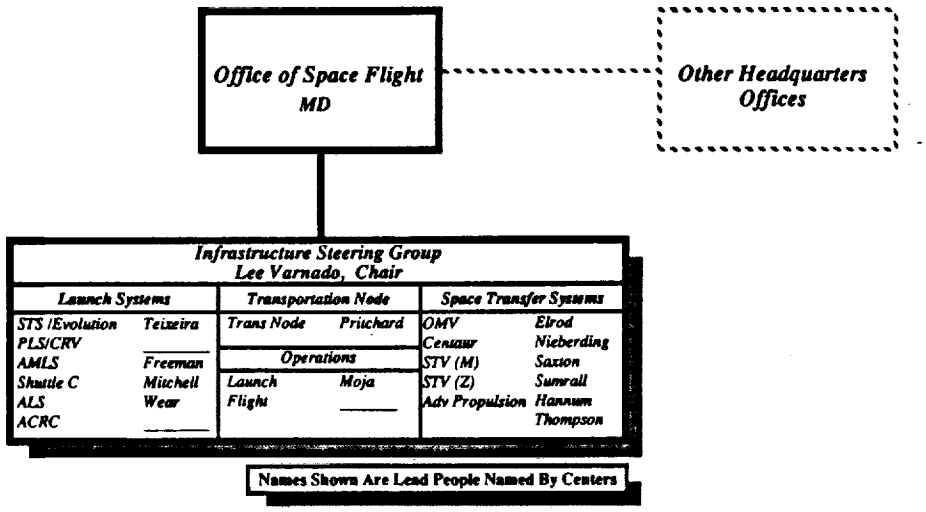
TRANSPORTATION INTEGRATION AGENT (TIA) FUNCTIONAL ORGANIZATION



Space Transportation and Exploration Office

INFRASTRUCTURE STUDY
STEERING GROUP COORDINATION

NAME : L. VARNADO
DATE : FEB. 1989



Space Transportation and Exploration Office

SPACE TRANSPORTATION INFRASTRUCTURE STUDY
OVERVIEW

NAME : L. VARNADO
DATE : DEC. 1988

- ONE CONTRACT AWARDED (GENERAL DYNAMICS SP. SYS. DIV)
- FIRST 18 MONTHS--TASKS AS SPECIFIED IN S.O.W. OR BY TECHNICAL DIRECTIVES
- FINAL 18 MONTHS - TASKS AS SPECIFIED BY TECHNICAL DIRECTIVES
- ALLOWS FOR ADDITION OF SPECIAL STUDY TASKS .
- MAXIMUM (3 YEAR) TOTAL UP TO $5.5 M
- NASA-WIDE INVOLVEMENT

- CODES M, S, R , Z	- MSFC
- JSC	- LaRC
- KSC	- LeRC

INFRASTRUCTURE STUDY

TASK SUMMARY

TASKS

A COLLECT/COMPILE BASIC (CORE) MISSIONS AND REQUIREMENTS

B COMPILE/ANALYZE DATA ON CURRENT AND PLANNED TRANSPORTATION SYSTEM ELEMENTS

C DEVELOP DATA FORMATS AND ANALYSIS PROCEDURES TO DETERMINE TRANSPORTATION REQUIREMENTS AND INFRASTRUCTURE FOR SPECIFIC MISSION COMBINATIONS

D COMPILE/ANALYZE CSLI DATA

- DETERMINE VARIANTS/IMPACTS TO BASIC TRANSPORTATION INFRASTRUCTURE
- ASSESS RESULTS OF COMBINING WITH BASIC SET OF MISSIONS

E ANALYZE TRANSPORTATION / INFRASTRUCTURE REQUIREMENTSFOR UPPER STAGES, INTER-ORBIT TRANSFER AND LAUNCH VEHICLES

F EXAMINE THE ROLE OF CURRENT AND PLANNED LAUNCH VEHICLE SYSTEMS (AND THEIR DERIVATIVES) IN FUTURE SPACE TRANSPORTATION INFRASTRUCTURES. WHERE INDICATED, PROPOSE AND EXAMINE OTHER VEHICLE CONCEPTS / SIZES WHICH MIGHT BE BETTER SUITED TO THE SET OF MISSIONS UNDER STUDY.

G PERFORM STUDIES WHICH SHALL INCLUDE EXAMINATION OF POTENTIAL CONCEPTS SUCH AS:

- LOCATION OF SPACE-BASED TRANSPORTATION NODES
- CONCEPTS FOR HUMAN TRANSPORTATION UP/DOWN AND TRADES AS TO EXTENT OF ASSOCIATED CARGO TRANSPORT
- MEANS FOR RETURN OF SELECTED CARGO/PAYLOADS FROM LEO

H ASSESS TECHNOLOGY OPTIONS/BENEFITS THROUGH TRADE STUDIES

I CONDUCT COST ANALYSES AND TRADE STUDIES

J PERFORM PROGRAM PLANNING TASKS

K PERFORM SPECIAL STUDIES AS SPECIFIED IN TECHNICAL DIRECTIVES

1-600-9-7T

OEXP TECHNOLOGY WORKING GROUP CHARTER

GOAL

- ENSURE THE TIMELY AND ACCURATE IDENTIFICATION OF THE TECHNOLOGY NEEDS FOR HUMAN EXPLORATION OF THE SOLAR SYSTEM

OBJECTIVES:

- REVIEW THE APPROPRIATE TECHNOLOGY PROGRAMS TO UNDERSTAND THE PROJECTED AVAILABILITY OF TECHNOLOGY TO SUPPORT HUMAN EXPLORATION
- FACILITATE THE KNOWLEDGE AND USE OF VALIDATED TECHNOLOGY FORECASTS IN THE DESIGN OF ADVANCED MISSION CONCEPTS
- COORDINATE AND INTEGRATE THE IDENTIFICATION OF TECHNOLOGY NEEDS ACROSS ALL OEXP ORGANIZATIONAL ELEMENTS (i.e., MASE, IAs, SAAs)
- DEVELOP AND INTEGRATE A RECOMMENDED SET OF TECHNOLOGY NEEDS FOR THE TIMELY TRANSMITTAL TO THE TECHNOLOGY DEVELOPMENT COMMUNITY
- DEVELOP AND INTEGRATE EXPLORATION NEEDS FOR ADVANCED DEVELOPMENT AND MAJOR TECHNOLOGY DEMONSTRATION NEEDS

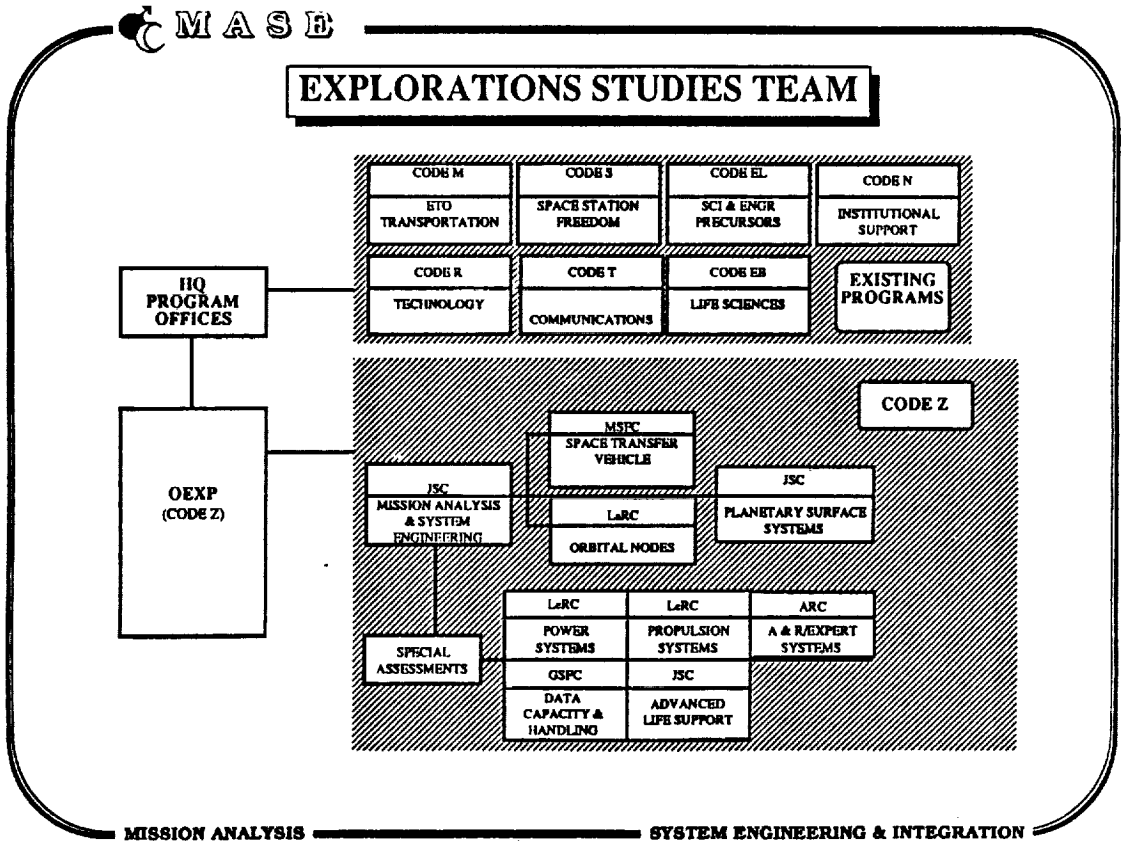


FIGURE 1.2-1

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EXPLORATION STUDY APPROACH

- CASE STUDY PROCESS
  - ANNUAL STUDY ACTIVITY (1988-1991)
  - ANALYZE ALTERNATIVE EXPLORATION STRATEGIES (NOT DEFINING "PROPOSED" MISSIONS)
  - BUILD A TECHNICAL & PROGRAMMATIC DATA BASE
  - POSTURE AGENCY FOR FUTURE RECOMMENDATION ON SPECIFIC EXPLORATION MISSION(S)

1988

- HUMAN EXPEDITION TO PHOBOS
- HUMAN EXPEDITIONS TO MARS
- LUNAR OBSERVATORY
- LUNAR OUTPOST TO EARLY MARS EVOLUTION

→ 1988 ANNUAL REPORT

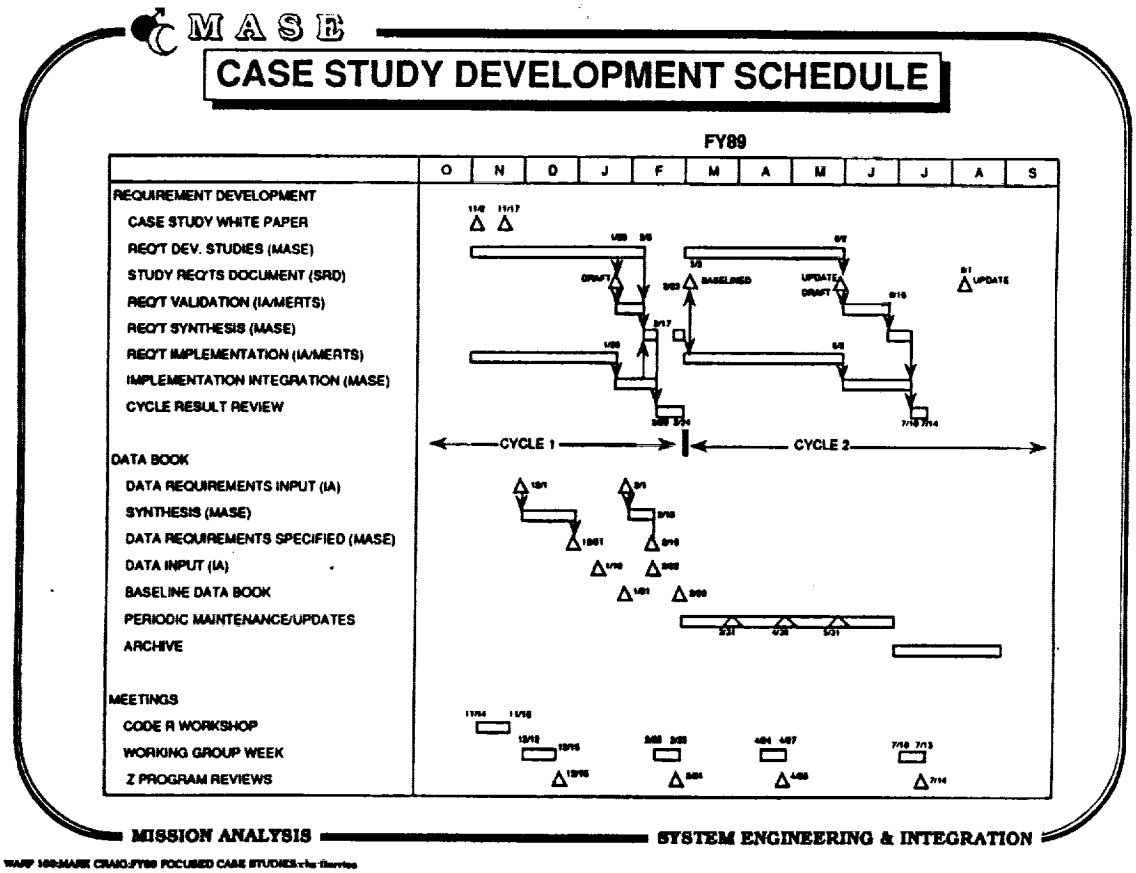
1989

- LUNAR EVOLUTION
- MARS EVOLUTION
- MARS EXPEDITION

→ 1989 ANNUAL REPORT

- GATEWAY STUDY
  - -- MARS/LUNAR OPTIONS
  - -- REDUCE SCALE OF ACTIVITIES

→ SPECIAL REPORT TO THE ADMINISTRATOR



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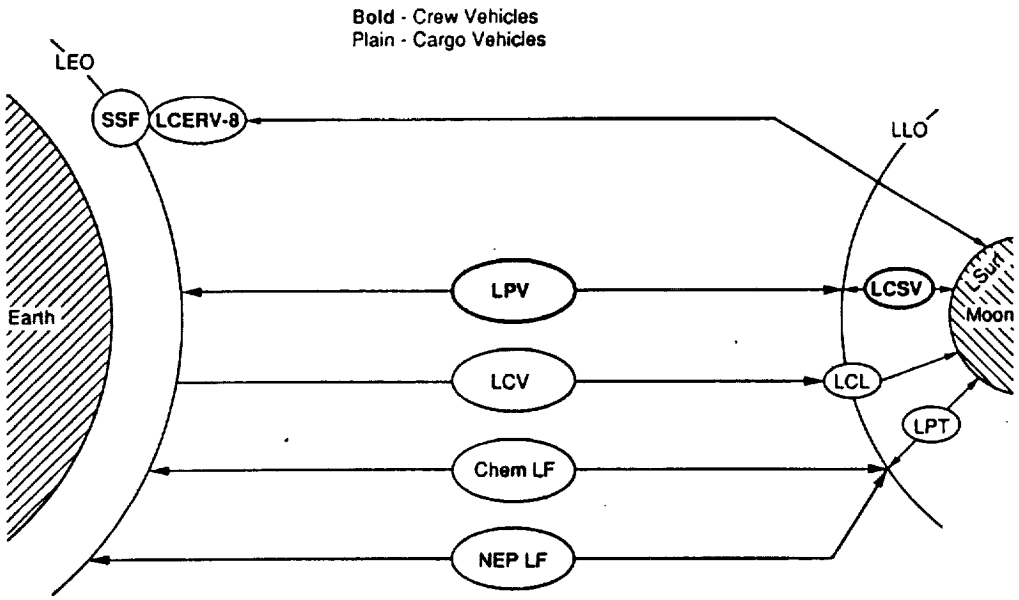
1989 EXPLORATION CASE STUDIES

LUNAR EVOLUTION CASE STUDY

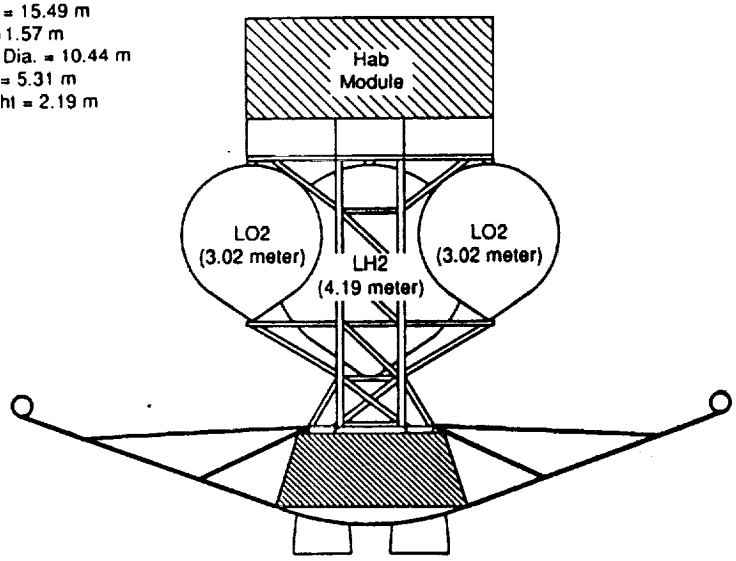
- ESTABLISH A HUMAN-TENDED OUTPOST WHICH GROWS TO A SMALL PERMANENT BASE AND THEN TO AN EXPANDED SELF-SUFFICIENT FACILITY
- FIRST LUNAR MISSION IN 2004
- INITIAL CREW SIZE OF 4 GROWING TO 8
- SIGNIFICANT SCIENCE RESEARCH CAPABILITY (ASTRONOMY, PLANETARY SCIENCE, OTHER)
- REUSABLE SPACE TRANSPORTATION VEHICLES (LOX/LH_2 PROPULSION)
- AEROBRAKING AT EARTH FOR RETURN VEHICLES
- PROPELLANT PRODUCTION FROM LUNAR RESOURCES
  - FUEL LUNAR ASCENT/DESCENT VEHICLES (INITIALLY OXYGEN ONLY)
- ANNUAL LIMIT ON MASS TO LOW EARTH ORBIT FOR PURPOSES OF COMPARISON WITH THE MARS EVOLUTION CASE

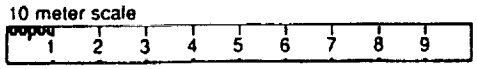
Lunar Evolution -- Case Study 4.1



Lunar Piloted Vehicle

Aerobrake Dia. = 15.49 m
Max. Height = 11.57 m
Tank Envelope Dia. = 10.44 m
Crew Cab Dia. = 5.31 m
Crew Cab Height = 2.19 m



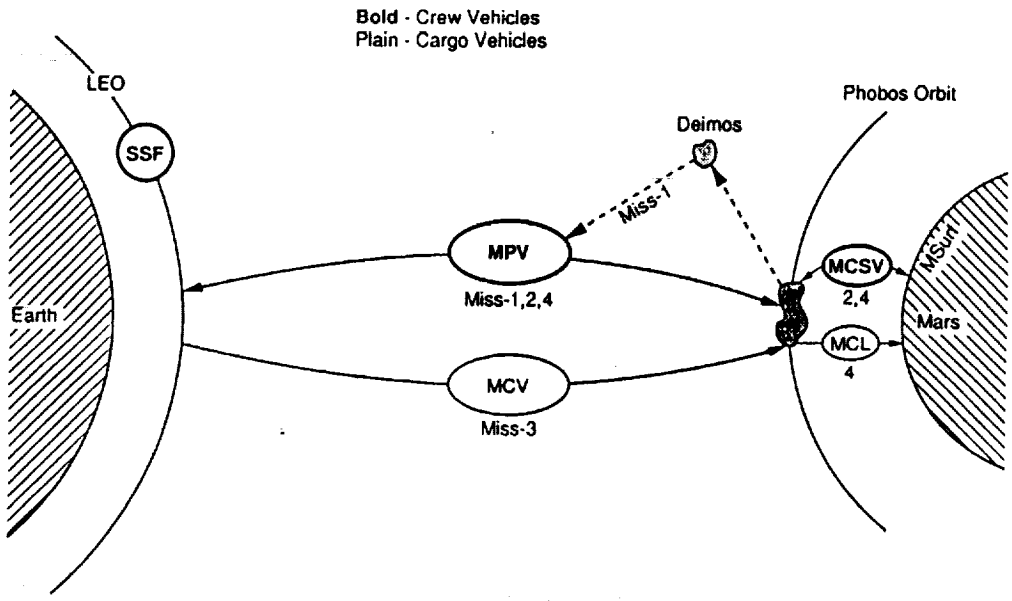


1989 EXPLORATION CASE STUDIES

MARS EVOLUTION CASE STUDY

- INITIAL EXPLORATION OF THE MARTIAN MOONS (PHOBOS & DEIMOS), FOLLOWED BY ESTABLISHMENT OF AN INITIAL MANNED HABITAT ON THE MARS SURFACE, AND THE DEVELOPMENT OF A MARTIAN MOON GATEWAY WHICH PRODUCES CRYOGENIC PROPELLANTS. THE GATEWAY SUPPORTS THE BUILDUP OF A PERMANENT, SELF-SUSTAINED MARS BASE.
- FIRST MISSION TO MARTIAN MOONS DEPARTS EARTH IN 2004 (CREW OF 3) – 60 DAY STAY
- FIRST HUMAN EXPLORATION OF MARS SURFACE IN 2006 (CREW OF 3) – 60 DAY STAY)
- MARTIAN MOON (PHOBOS) GATEWAY WITH PROPELLANT PRODUCTION FROM PHOBOS RESOURCES ESTABLISHED IN 2009
  - FUEL MARS CREW SORTIE VEHICLE (LOX/LH_2)
- HUMAN-TENDED MARS OUTPOST ESTABLISHED IN 2010 (CREW OF 3 – 1 YEAR STAY)
- MARS PILOTED VEHICLES FOR CREW/CARGO TRANSFER WILL PROVIDE ARTIFICIAL – G
- SIGNIFICANT SCIENCE RESEARCH CAPABILITY
- REUSABLE SPACE TRANSPORTATION VEHICLES (LOX/LH_2 PROPULSION)
- AEROBRAKING AT MARS AND EARTH
- ANNUAL LIMIT ON MASS TO LOW EARTH ORBIT FOR PURPOSES OF COMPARISON WITH LUNAR EVOLUTION CASE

Mars Evolution -- Case Study 5.0

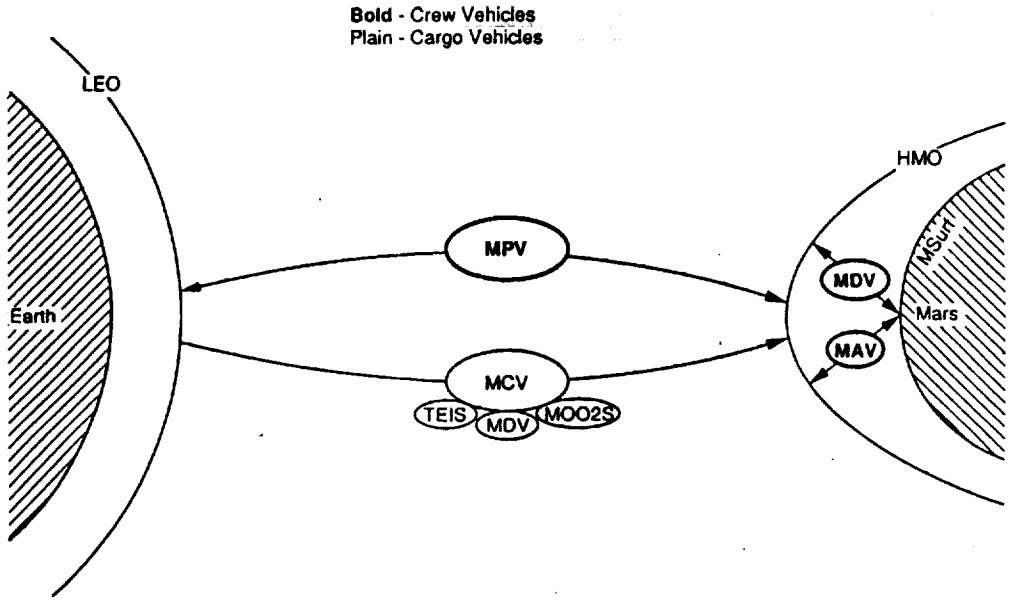


1989 EXPLORATION CASE STUDIES

MARS EXPEDITION CASE STUDY

- PERFORM A MANNED LANDING ON MARS AT THE EARLIEST FEASIBLE OPPORTUNITY
- ONE HUMAN MISSION TO MARS – VEHICLES SIZED FOR 2005/2006 DEPARTURE FROM LOW EARTH ORBIT (INVESTIGATE 2003/2004 OPPORTUNITY)
- CREW SIZE OF 3 (2 CREW TO SURFACE FOR 20 DAYS)
- SPLIT/SPRINT TRAJECTORY FOR TRANSFER OF CARGO AND CREW TO MARS
  - CARGO TRANSFERRED ON A LONGER, LOWER ENERGY TRAJECTORY WHICH MINIMIZES THE LEO MASS REQUIREMENTS
  - SPRINT TRAJECTORY UTILIZED FOR CREW TRANSFER TO REDUCE MISSION TIME (14 MONTHS) THAT CREW WILL BE EXPOSED TO ZERO "G" ENVIRONMENT
- SPACE TRANSPORTATION VEHICLES WILL BE EXPENDABLE (LOX/LH_2 PROPULSION)
- AEROBRAKING AT MARS, DIRECT RETURN AT EARTH
- NO EARTH ORBIT ASSEMBLY FACILITY (TELEROBOTIC & EMERGENCY EVA SUPPORT FROM SPACE STATION FREEDOM)

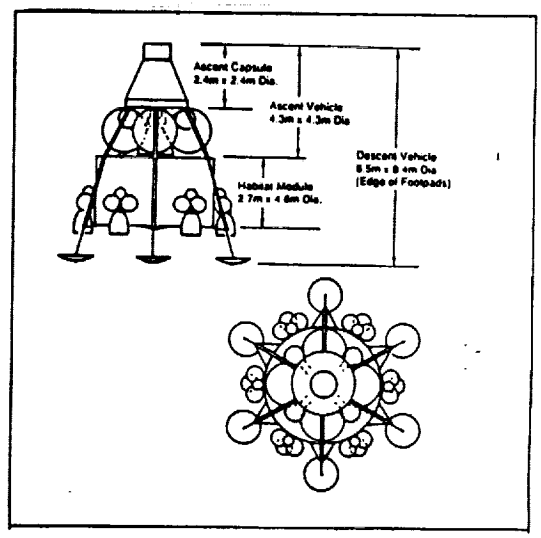
Mars Expedition -- Case Study 2.1



Mars Descent Vehicle (MDV)

CS-2.1

Dry Mass	
(includes wet payload)	*
Payload Mass	*
Payload Volume	
MAV	
(cone - 2.4m rad., 2.4m ht.)	3.1 m^3
HAB Module	
(cyl.- 3.8m rad., 3m ht.)	136 m^3
Propulsion System	
Propellant Type	MMH/N_2O_4
Engines	
Number	6
Type	Shuttle-OMS
Mass (ea.)	134 kg
Thrust (total)	160 kN (36 klbf)
I_{sp} (316 sec)	3.1 kN-s/kg
Propellant Mass	2,320 kg
Tank Mass	700 kg
Initial T/W	0.55
Total Mass	29,750 kg



* See attached sheet

1-804-9-9T

"CONTROLLED TRADE STUDY" DEFINITION

CONTROLLED TRADE STUDIES ARE TECHNICAL INVESTIGATIONS THAT ARE CASE STUDY INDEPENDENT OR THAT AFFECT MORE THAN ONE CASE STUDY. THE RESULTS SUPPORT THE DEVELOPMENT OF NEW CASES STUDIES, THE FURTHER MATURATION OF EXISTING CASE STUDY IMPLEMENTATION STRATEGIES AND OBJECTIVES, OR ENABLE A TECHNICAL "ASSAULT" UPON CASE STUDY CONSTRAINTS.

FY89 CONTROLLED TRADE STUDIES

- LAUNCH/ON-ORBIT PROCESSING STUDY
- EXTRATERRESTRIAL PROPELLANT LEVERAGING STUDY
- EARTH-MOON NODE LOCATION STUDY

1-805-9-9T

LAUNCH/ON-ORBIT PROCESSING STUDY OBJECTIVES

- DEVELOP A GREATER UNDERSTANDING OF THE ISSUES AND TRADE-OFFS INVOLVED IN LAUNCHING, ASSEMBLING, AND SERVICING A SPACE TRANSFER VEHICLE (STV) IN LOW-EARTH ORBIT (LEO). THESE ISSUES AND TRADE-OFFS INCLUDE:
  - ETO LAUNCH VEHICLE PERFORMANCE CAPABILITIES.
  - ON-ORBIT INFRASTRUCTURE AND OPERATIONAL CAPABILITIES.
  - GROUND PROCESSING INFRASTRUCTURE AND OPERATIONAL CAPABILITIES.
  - DESIGN OF THE STV.
  - STV MISSION CHARACTERISTICS AND OBJECTIVES.
- DEFINE THE REQUIRED TASKS TO BE PERFORMED BOTH ON-ORBIT AND ON THE GROUND IN ORDER TO LAUNCH FROM EARTH TO LEO, ASSEMBLE, CHECK-OUT, AND SERVICE IN LEO A STV. IDENTIFY THE SENSITIVITY OF THESE REQUIRED TASKS TO THE ABOVE-MENTIONED ISSUES AND TRADE-OFFS.
- DETERMINE THE LOCATIONS IN THE TRADE SPACE (THE "BREAK POINTS") WHERE CHANGES IN OBJECTIVES OR REQUIREMENTS RESULT IN SIGNIFICANT CHANGES IN THE CAPABILITIES AND/OR FACILITIES NEEDED.
- DEVELOP A METHODOLOGY WHEREBY, GIVEN THE OBJECTIVES AND CHARACTERISTICS OF THE STV's MISSION, THE OPTIMAL BLEND OF THE FOLLOWING CAN BE DERIVED FOR FUTURE CASE STUDIES:
  - ETO LAUNCH VEHICLE CAPABILITIES.
  - DESIGN OF THE STV.
  - ON-ORBIT INFRASTRUCTURE AND CAPABILITIES.
  - GROUND PROCESSING INFRASTRUCTURE AND CAPABILITIES.

1-806-9-9T

LAUNCH/ON-ORBIT PROCESSING STUDY RESPONSIBILITIES

- SPACE TRANSPORTATION INTEGRATION AGENT
  - PROVIDE CONCEPTUAL DESIGN DETAILS OF PILOTED MARS STV DEVELOPED FOR FY89 MARS EVOLUTION CASE STUDY
  - PROVIDE CONCEPTUAL DESIGN DETAILS FOR AT LEAST ONE OTHER STV CONFIGURATION (TBD) AS REQUESTED
- MSFC
  - PERFORM AN ASSESSMENT OF POTENTIAL ETO LAUNCH VEHICLES
  - DEFINE PERFORMANCE CHARACTERISTICS OF ETO LAUNCH VEHICLES INCLUDED IN STUDY SET OPTIONS
  - DEFINE PROXIMITY OPERATIONS SUPPORT CAPABILITIES (e.g., OMV)
  - ASSESS FEASIBILITY ISSUES ASSOCIATED WITH AEROBRAKE DESIGNS AND REUSABILITY FOR EACH SET OF STUDY OPTIONS

1-807-9-9T

EXTRATERRESTRIAL PROPELLANT LEVERAGING STUDY OBJECTIVES

- DEVELOP A GREATER UNDERSTANDING OF THE RELATIONSHIP BETWEEN EXTRATERRESTRIAL RESOURCES AND MANNED EXPLORATION OF THE SOLAR SYSTEM.
- DEVELOP THE METHODOLOGY AND GENERATE THE SUPPORTING DATA TO DETERMINE, FOR A GIVEN SERIES OF MISSION CONSTRAINTS AND OBJECTIVES:
  - WHERE IN THE EARTH-MOON-MARS SYSTEM IT MAKES SENSE TO PRODUCE PROPELLANTS/RESOURCES,
  - WHERE IT IS MOST EFFECTIVE TO USE THEM,
  - WHICH EXTRATERRESTRIAL PROPELLANTS/RESOURCES TO PRODUCE, AND
  - WHEN SUCH PRODUCTION AND USE IS BENEFICIAL.
- DEVELOP A PRIORITIZED CATALOG OF THE KNOWN PROPELLANTS AND RESOURCES IN THE EARTH-MOON-MARS SYSTEM, INCLUDING THEIR LOCATIONS, QUANTITIES, AND USEFUL CHARACTERISTICS.
- DEVELOP A PRIORITIZED CATALOG OF CHEMICAL PROPULSION SYSTEMS WHICH USE ONE OR MORE OF THE EXTRATERRESTRIAL PROPELLANTS PRODUCED IN THE EARTH-MOON-MARS SYSTEM. DEFINITION OF THE SYSTEMS WILL INCLUDE:
  - PERFORMANCE CHARACTERISTICS,
  - REUSABILITY CONSIDERATIONS,
  - VEHICLE/ENGINE LIFETIME, AND
  - PROPELLANT STORAGE/TRANSFER CONSIDERATIONS.
- DEVELOP A PRIORITIZED CATALOG OF THE POTENTIAL PROPELLANT AND RESOURCE EXTRACTION/PRODUCTION PROCESSES FOR USE IN THE EARTH-MOON-MARS SYSTEM, INCLUDING THEIR PRODUCTION CAPACITY/PLANT SIZE RATIOS, PLANT OVERHEAD, PLANT RESUPPLY REQUIREMENTS, AND POTENTIALLY USEFUL BY-PRODUCTS.
- DETERMINE THE EFFECTS OF DIFFERENT TRANSPORTATION SYSTEM TECHNOLOGIES ON EXTRATERRESTRIAL PROPELLANT/RESOURCE PRODUCTION AND USE.

1-808-9-9T

EXTRATERRESTRIAL PROPELLANT LEVERAGING STUDY RESPONSIBILITIES

- SPACE TRANSPORTATION INTEGRATION AGENT
  - PROVIDE CONCEPTUAL DESIGN DETAILS OF STVs (INCLUDING CHEMICAL, NTR, NEP, SEP DESIGNS) AND LANDERS NEEDED FOR THE STUDY
  - DEFINE VEHICLES CAPABLE FO UTILIZING ADVANCED CHEMICAL PROPULSION SYSTEMS DEFINED BY LeRC

1-809-9-9T

EARTH-MOON NODE LOCATION STUDY

STUDY OBJECTIVES

THE OBJECTIVE OF THIS STUDY IS TO CONTINUE THE WORK INITIATED IN FY88. THIS INCLUDES PROVIDING THE RATIONALE FOR USE OF AN EARTH-MOON SYSTEM NODE AND DETERMINING A NODE LOCATION. FUNCTIONS AND OPERATIONS ARE TO BE DEFINED TO INCLUDE ASSEMBLY, STAGING, STORAGE, CREW HABITATION, REFUELING, AND LAUNCHING ASSOCIATED WITH THE AGGREGATION OF MISSION SUPPORT ELEMENTS FOR OEXP HUMAN EXPLORATION CASE STUDIES.

STUDY RESPONSIBILITIES

- SPACE TRANSPORTATION INTEGRATION AGENT
  - DEFINE LUNAR SURFACE TO NODE AND EARTH TO NODE DELIVERY DATA INCLUDING VEHICLES, LUNAR ORBIT LOCATION, NODE FUNCTIONS, STV, TRANSFER TUG (e.g., OTV)
  - IDENTIFY CONCERNS
- CODE M
  - DEFINE ETO VEHICLE CAPABILITIES
  - IDENTIFY CONCERNS

NASA

TRANSPORTATION PLANNING OVERVIEW

PRESENTATION TO THE HIGH ENERGY AEROBRAKING WORKSHOP AT AMES RESEARCH CENTER

BARBARA ASKINS
STV PROGRAM MANAGER

JANUARY 31, 1989

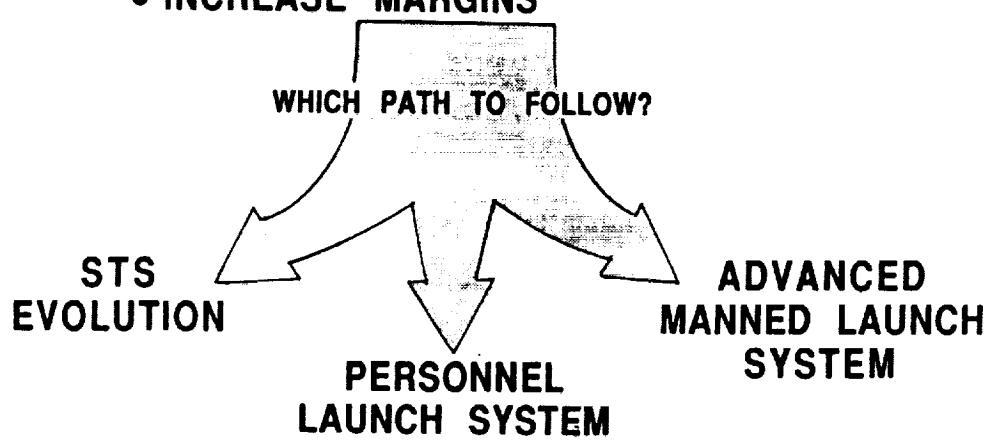
Office Of Space Flight

5436-#90123 001-GG

NASA

THE NEXT MANNED SPACECRAFT

- SATISFY PEOPLE/PAYLOAD REQUIREMENTS
- IMPROVE COST/EFFECTIVENESS
- INCREASE RELIABILITY
- INCREASE MARGINS



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NASA

THE NEXT MANNED SPACECRAFT

STS EVOLUTION

- EXPLOIT NEW TECHNOLOGIES
- BUILD ON EXISTING ENGINEERING DATA BASE
- MINIMIZE MOLD-LINE/ CONFIGURATION CHANGES
- COUNTER OBSOLESCENCE
- INCREASED PEOPLE CARRYING CAPABILITY

ADVANCED MANNED LAUNCH SYSTEM

- FULLY EXPLOIT NEW TECHNOLOGIES
- IMPROVED DESIGN MARGINS
- CONFIGURATION/SIZE OPEN
- PEOPLE ONLY OPTION AVAILABLE

PERSONNEL LAUNCH SYSTEM

- WINGED OR BLUNT BODY
- INCREASED DESIGN MARGINS
- ELV LAUNCHED
- CONFIGURATION/SIZE OPEN
- LIMITED RETURN CARGO CAPABILITY
- UP PAYLOAD ON CARGO VEHICLE

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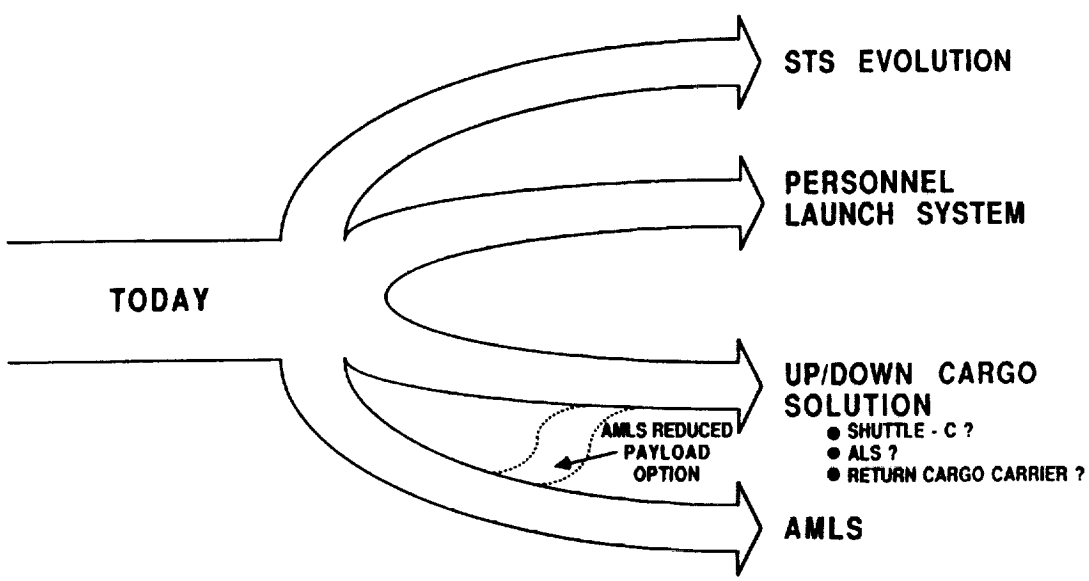
NASA

THE NEXT MANNED SPACECRAFT

ROAD MAP



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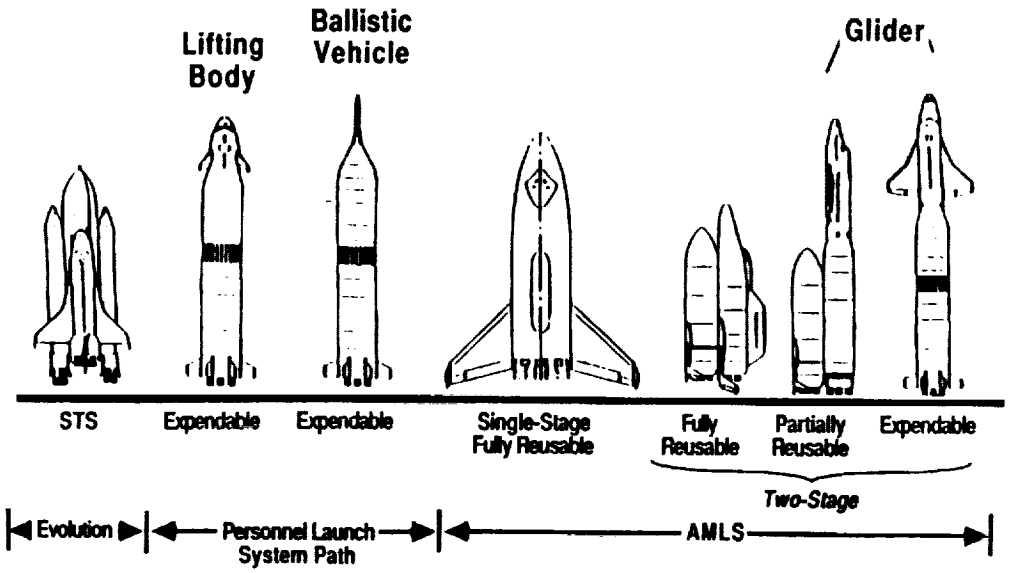
NASA

THE NEXT MANNED SPACECRAFT

CONCEPTS



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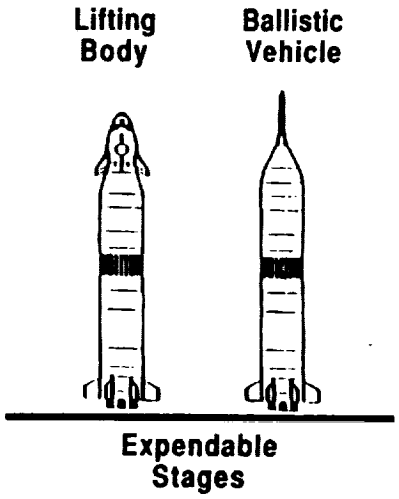
NASA

THE NEXT MANNED SPACECRAFT

PERSONNEL LAUNCH SYSTEM PATH



Study Schedule and Resources are TBD

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NASA

ADVANCED LAUNCH SYSTEM (ALS)

OBJECTIVE

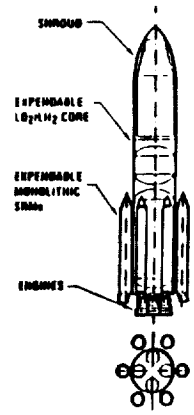
- LOWER COST OF SPACE TRANSPORTATION
- PROVIDE A FLEXIBLE SYSTEM
- PROVIDE INCREASED RELIABILITY

USE

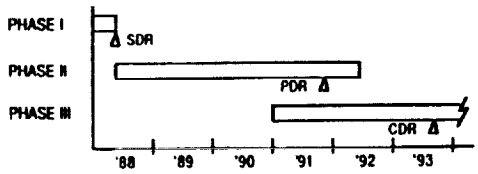
- TRANSPORT DoD AND CIVIL PAYLOADS TO SPACE

COMPANION / PARALLEL STUDIES

- AMLS
- PERSONNEL LAUNCH SYSTEM
- SHUTTLE EVOLUTION STUDY
- SHUTTLE-C



SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*			
SDI	$225M	$150M	$100M
AF			$100M

* For Planning Purposes Only

Office Of Space Flight

5436-890123-002-GG

NASA

SHUTTLE-C

OBJECTIVE

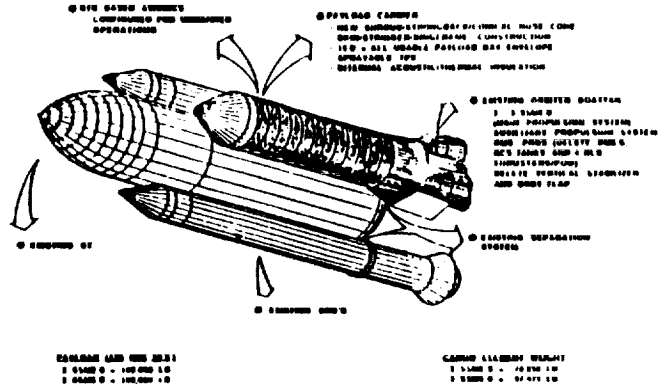
- TO DEFINE A NEAR-TERM UNMANNED CARGO VEHICLE UTILIZING STS ELEMENTS

USE

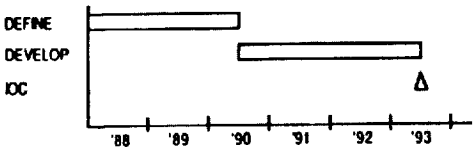
- SPACE STATION ASSEMBLY
- TEST BED FOR NEW NSTS ELEMENTS
- PLANETARY

COMPANION / PARALLEL STUDIES

- SHUTTLE EVOLUTION STUDIES
- ALS
- ALS ADVANCED DEVELOPMENT
- AMLS



SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*		$4.5M	
MANPOWER			
CIVIL SERVICE			

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NASA

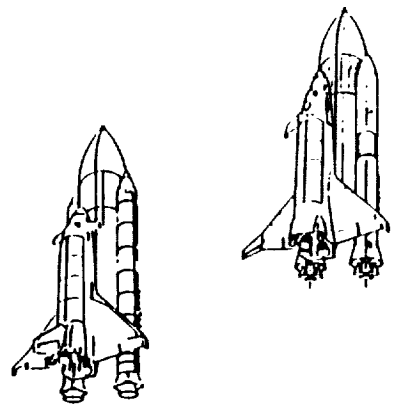
SHUTTLE EVOLUTION

OBJECTIVE

- ASSESS PRACTICALITY OF EVOLVING CURRENT DESIGN
- TO DEFINE STS "BLOCK UPGRADE" CONCEPTS
  - RELIABILITY / SAFETY
  - OPERATIONS COST / EFFECTIVENESS
  - IMPROVED MARGINS

USE

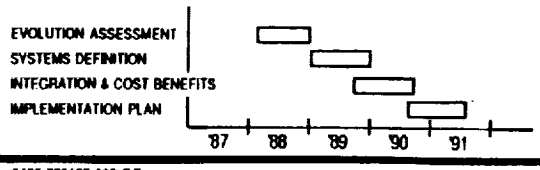
- PROLONG SYSTEM LIFE
- CREW TRANSFER / RETURN
  - SPACE STATION
  - TRANSPORTATION NODE
- CARGO TRANSPORT / RETURN
- SERVICING



COMPANION / PARALLEL STUDIES

- AMLS
- ALS (MAN-RATED)
- SHUTTLE-C
- ALS ADVANCED DEVELOPMENT
- CSTI (OAST)

SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*	$1.0M	$1.75M	$3.4M
MANPOWER			
CIVIL SERVICE	5	8	8

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NASA

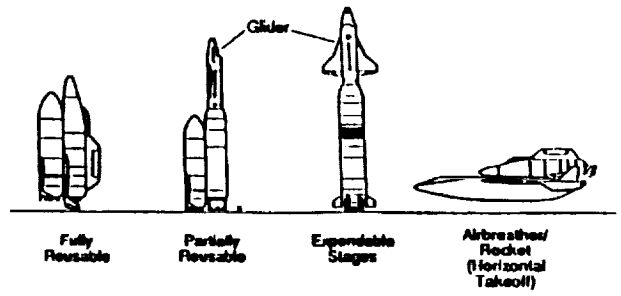
ADVANCED MANNED LAUNCH SYSTEM (AMLS)

OBJECTIVE

- TO DEFINE A SECOND GENERATION ADVANCED MANNED LAUNCH SYSTEM

USE

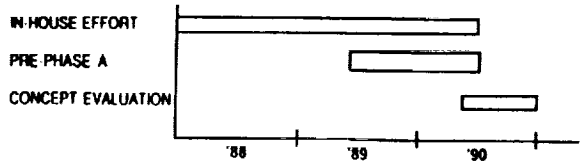
- CREW TRANSFER / RETURN
  - SPACE STATION
  - TRANSPORTATION NODES
- CARGO TRANSPORT / RETURN
- SERVICING



COMPANION / PARALLEL STUDIES

- SHUTTLE EVOLUTION STUDIES
- SYSTEMS ANALYSIS (CODE RS)
- ALS (MAN-RATED)
- NASP
- ALS ADVANCED DEVELOPMENT
- CSTI (OAST)

SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*	$0.6M	$1.5M	$2.2M
MANPOWER			
CIVIL SERVICE	5	5	5

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5436-8901223-005-GG

NASA

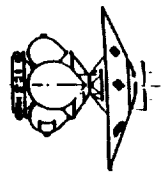
SPACE TRANSFER VEHICLE

OBJECTIVE

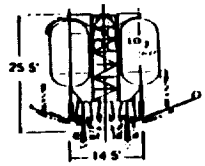
- DEFINE HIGH PERFORMANCE UPPER STAGE TO ACCOMMODATE MISSIONS REQUIRING MORE CAPABILITY THAN CENTAUR PROVIDES
  - INITIAL VEHICLE IOC LATE 1990'S
  - EVOLUTION TO INCREASED CAPABILITIES AS REQUIRED

USE

- UNMANNED PLANETARY MISSIONS
  - MARS ROVER SAMPLE RETURN
  - COMET NUCLEUS SAMPLE RETURN
- MISSION TO PLANET EARTH
  - GEO PLATFORM
- EVOLVE TO SUPPORT HUMAN EXPLORATION



SPACE-BASED STV

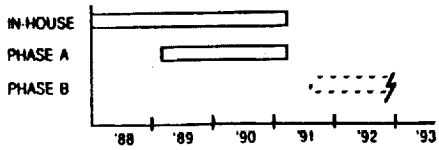


SPACE-BASED MANNED STV

COMPANION / PARALLEL STUDIES

- SPACE TRANSPORTATION INFRASTRUCTURE STUDY
- CENTAUR UPGRADES
- SPACE TRANSFER CONCEPTS AND ANALYSES FOR EXPLORATION MISSIONS (OEXP)
- LONG-TERM CRYOGENIC STORAGE FACILITY SYSTEMS STUDY
- MSFC IN-HOUSE CONCEPT DEFINITION

SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*	$0.25M	$2.5M	$2.5M
MANPOWER CIVIL SERVICE	3	4	4

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5436 890123-006 GG

NASA

ASSURED CREW RETURN CAPABILITY (ACRC)

OBJECTIVE

- STUDY FEASIBILITY OF SYSTEMS FOR SAFE RETURN OF CREW FROM SPACE STATION

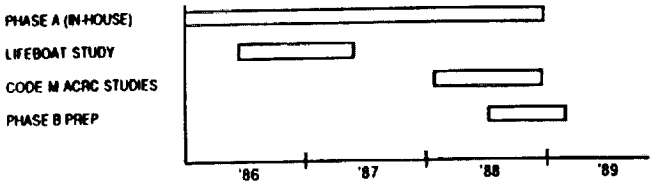
USE

- CREW EMERGENCY RETURN
  - NSTS DOWN
  - SPACE STATION CATASTROPHIC EVENT
  - CREW INJURY / ILLNESS

COMPANION / PARALLEL STUDIES

- PRECISION RECOVERY
- PROPULSION / AVIONICS MODULE

SCHEDULE



RESOURCES (FY)	1987	1988
FUNDING (NOA)*	$3.0M	$2.0M
MANPOWER CIVIL SERVICE	12	12

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5436 890123 007 GG

NASA

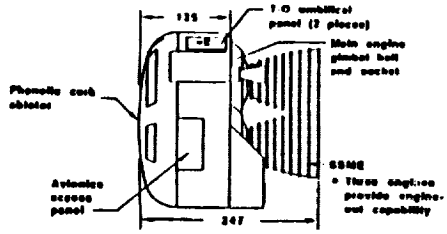
PROPULSION / AVIONICS MODULE

OBJECTIVE

- DETERMINE FEASIBILITY OF PACKAGING AND RECOVERY OF PROPULSION AND AVIONICS COMPONENTS FOR REUSE

USE

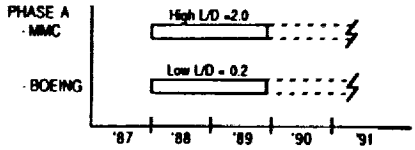
- ADVANCED LAUNCH SYSTEM
  - CORE P/A MODULE
  - BOOSTER ENGINE
- SHUTTLE-C EVOLUTION



COMPANION / PARALLEL STUDIES

- PRECISION RECOVERY
- SHUTTLE-C DEFINITION
- ALS CONCEPT DEFINITION

SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*	$1.0M	$0.7M	$1.0M
MANPOWER			
CIVIL SERVICE	1	1	1

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5436-890123-008-GG

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NASA

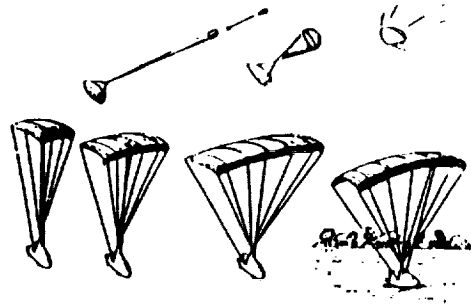
PRECISION RECOVERY

OBJECTIVE

- DEFINE AND DEMONSTRATE FEASIBILITY FOR SOFT LAND RECOVERY OF HIGH COST COMPONENTS

USE

- RECOVERY OF FULLY AND PARTIALLY REUSABLE SUBSYSTEMS AND VEHICLES
  - PROPULSION / AVIONICS (P/A) MODULE (60 K LBS)
  - ACRC



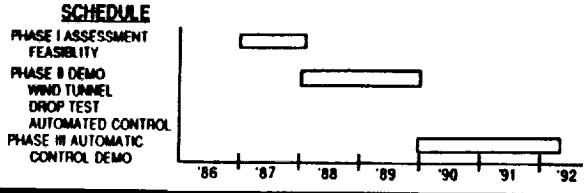
COMPANION / PARALLEL STUDIES

- P/A MODULE
- ACRC
- SHUTTLE-C DEFINTION

INSTITUTIONAL RESOURCES

- AMES 80 X 120 FT WIND TUNNEL

SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*			
MD	$1.0M	$1.0M	$1.7M
ALS "DOD"	$2.0M	$2.5M	$3.25M
MANPOWER			
CIVIL SERVICE	5	5	5

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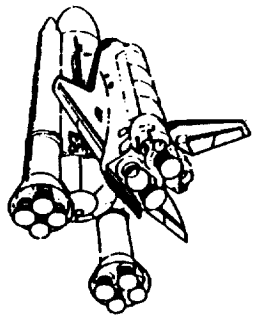
NASA

LIQUID ROCKET BOOSTER (LRB)

OBJECTIVE

- ASSESS FEASIBILITY / COMPARISON OF PRESSURE FED & PUMP FED LRB SYSTEMS FOR STS AND OTHER APPLICATIONS
  - PERFORMANCE (STS GROWTH)
  - COST (LCC)
  - SAFETY (ENHANCE ABORT OPTIONS)
  - IMPROVE MARGINS (LOWER SSME POWER LEVELS)



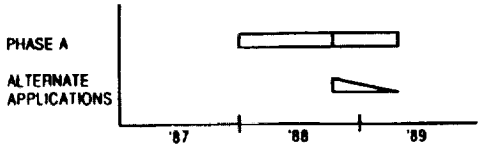
USE

- SRM REPLACEMENT ON STS

COMPANION / PARALLEL STUDIES

- HYBRID RC T FEASIBILITY STUDIES (CODE R)
- ALS ENGINE DEFINITION STUDIES

SCHEDULE



RESOURCES (FY)	1987/88	1989	1990
FUNDING (NOA)*	$12.0M	$0	$0
MANPOWER CIVIL SERVICE	8	4	0

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5436-890123-010-GG

NASA

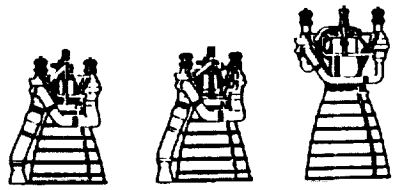
SPACE TRANSPORTATION MAIN ENGINE (STME) SPACE TRANSPORTATION BOOSTER ENGINE (STBE)

OBJECTIVE

- TO EVALUATE AND DEFINE CANDIDATE ENGINE CYCLES AND CONFIGURATIONS FOR ADVANCED LAUNCH VEHICLE SYSTEMS.
- TO EVALUATE ROM DDT&E AND PRODUCTION COSTS (LCC)

USE

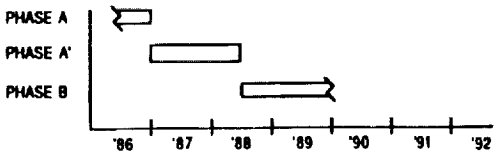
- ALS
- SHUTTLE-C
- AMLS



COMPANION /PARALLEL STUDIES

- ALS VEHICLE CONCEPT AND SYSTEMS DEFINITION

SCHEDULE



RESOURCES (FY)	1988	1989	1990
FUNDING (NOA)*			
MD	$2.8M		
ALS "DOD"	$3.6M	$9.0M	$19.5M
MANPOWER CIVIL SERVICE	1	4	4

* For Planning Purposes Only

Office Of Space Flight

5436-890123-011-GG

NASA

SPACE TRANSPORTATION INFRASTRUCTURE STUDY

OBJECTIVE

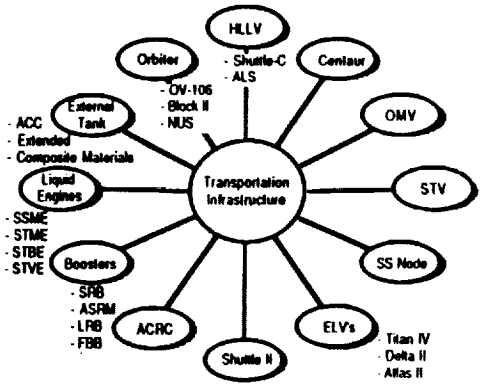
- ASSESS HUMAN EXPLORATION TRANSPORTATION INFRASTRUCTURE REQUIREMENTS
- ASSESS CONCEPT FEASIBILITY OF NEW TRANSPORTATION SYSTEM ELEMENTS AND ASSOCIATED TRADE STUDIES
- OPTIMIZE LEO AND ORBIT-TO-ORBIT TRANSPORTATION ELEMENTS

USE

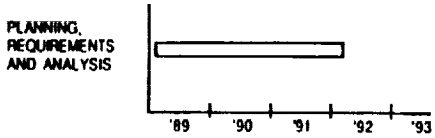
- TRANSPORTATION ANALYSIS OF CIVIL SPACE LEADERSHIP INITIATIVES
- IDENTIFY TECHNOLOGY REQUIREMENTS

COMPANION / PARALLEL STUDIES

- STV CONCEPT DEFINITION STUDIES
- SPACE TRANSFER CONCEPTS / ANALYSES FOR EXPLORATION MISSIONS
- ALS
- SHUTTLE-C
- SHUTTLE EVOLUTION / FOLLOW-ONS
- AMLS
- OPERATIONALLY EFFICIENT LAUNCH SITE (OELS)



SCHEDULE



RESOURCES (FY)	1988	1989	1990	1991
FUNDING (NOA)*	$0.8M	$1.75M	$1.5M	$1.5M
MANPOWER CIVIL SERVICE	3	4	4	4

* For Planning Purposes Only

Office Of Space Flight

5436 890123 012 GG

"HUMAN TOLERANCE TO HIGH ENERGY AEROBRAKING"

PRESENTATION TO HIGH ENERGY AEROBRAKING WORKSHOP

BY

MALCOLM M. COHEN, PH.D.

LIFE SCIENCE DIVISION

AMES RESEARCH CENTER

JANUARY 31, 1989

"HUMAN TOLERANCE TO HIGH ENERGY AEROBRAKING"

- AEROBRAKING UTILIZES ATMOSPHERIC DRAG ON THE VEHICLE TO REDUCE VELOCITY WITHOUT THE APPLICATION OF ADDITIONAL POWER AND THE UNNECESSARY USE OF FUEL.
- THE ACCELERATIVE FORCE (G) ACTING ON THE VEHICLE DETERMINES THE RATE AT WHICH VEHICLE VELOCITY IS REDUCED.
- OPTIONS EXIST WHEREBY G MAGNITUDE CAN BE TRADED OFF AGAINST G DURATION TO ATTAIN A GIVEN REDUCED VELOCITY.
- TRADE-OFFS BETWEEN G MAGNITUDE AND DURATION WILL HAVE A MAJOR IMPACT ON HUMAN TOLERANCE.

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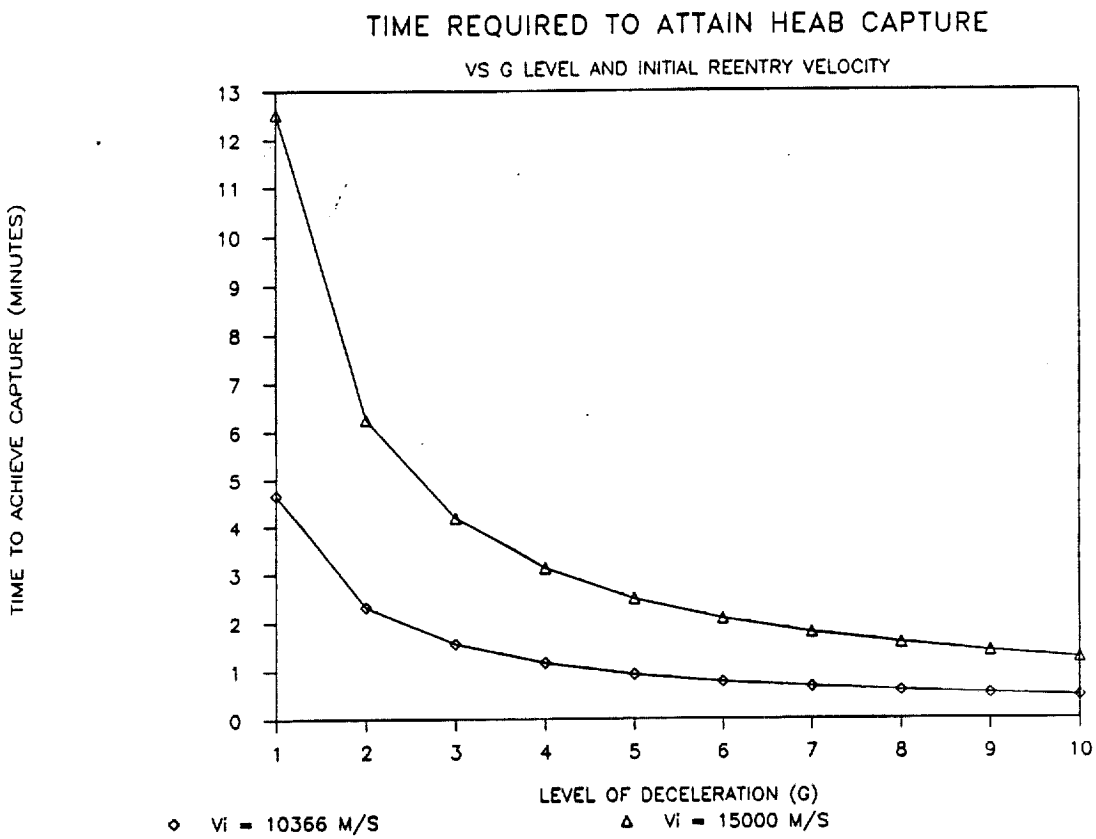


"HUMAN TOLERANCE TO HIGH ENERGY AEROBRAKING"

- FOR A NORMAL INDIVIDUAL WE CAN SPECIFY THREE CARDINAL HUMAN BODY AXES ALONG WHICH LINEAR ACCELERATIVE FORCES CAN ACT:

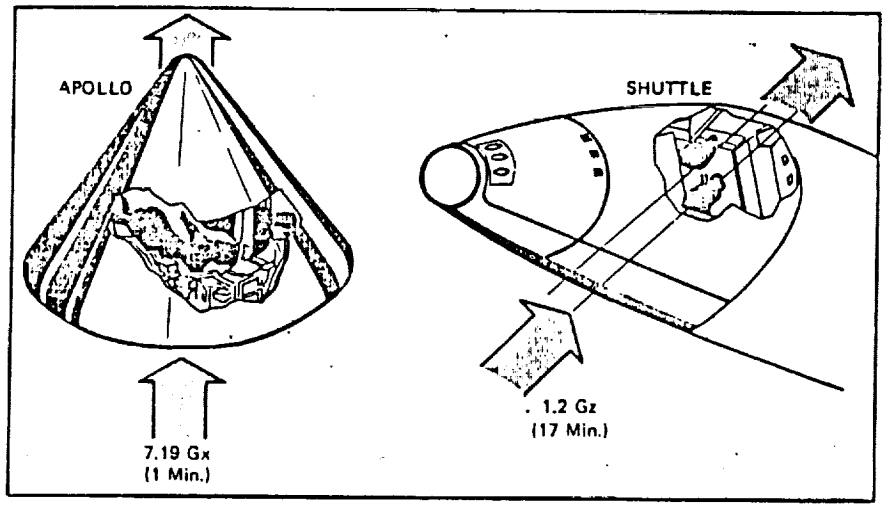
  +Gx = FORCE RESULTING FROM A SPINE TO CHEST ACCELERATION OF THE BODY; THE REACTIVE FORCE DISPLACES INTERNAL ORGANS FROM CHEST TO SPINE.

  +Gz = FORCE RESULTING FROM A FOOT TO HEAD ACCELERATION OF THE BODY; THE REACTIVE FORCE DISPLACES INTERNAL ORGANS FROM HEAD TO FEET.

  +Gy = FORCE RESULTING FROM A LEFT TO RIGHT ACCELERATION OF THE BODY; THE REACTIVE FORCE DISPLACES INTERNAL ORGANS FROM RIGHT TO LEFT.*

***NOTE:**

(Some authors do not maintain the polarity of the convention in the y axis, and designate the force that results from a left to right acceleration as - Gy.)



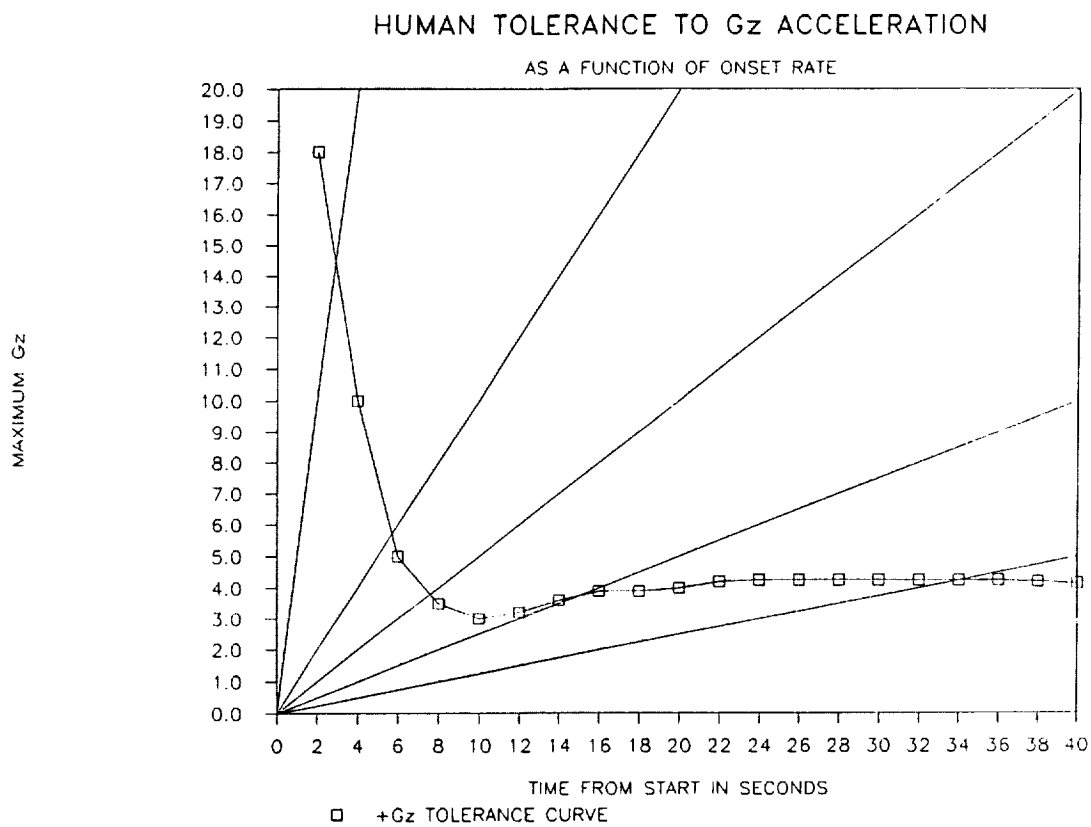
"HUMAN TOLERANCE TO HIGH ENERGY AEROBRAKING"

- TOLERANCE TO ACCELERATION DEPENDS ON THE ORIENTATION OF AN INDIVIDUAL WITH RESPECT TO THE G FORCES ACTING ON HIS/HER BODY.
- IN THE NORMAL SEATED ORIENTATION, THE LIMITING FACTOR FOR SUSTAINED APPLICATION OF Gz FORCES IS THE DELIVERY OF ADEQUATE OXYGENATED BLOOD TO THE BRAIN.
- THE WEIGHT OF THE BLOOD IN THE HEART-BRAIN COLUMN CAN EXCEED THE CAPABILITY OF THE HEART'S PUMPING ACTION IN THE RANGE OF 3.0 TO 8.4 Gz OVER A PERIOD OF SEVERAL SECONDS.
- BEFORE BLOOD SUPPLY TO THE BRAIN IS SIGNIFICANTLY REDUCED, THE BLOOD SUPPLY TO THE EYES CEASES DUE TO INTEROCULAR PRESSURE; VISION NORMALLY FAILS FIRST.

HUMAN TOLERANCE TO HIGH SUSTAINED Gz FORCES

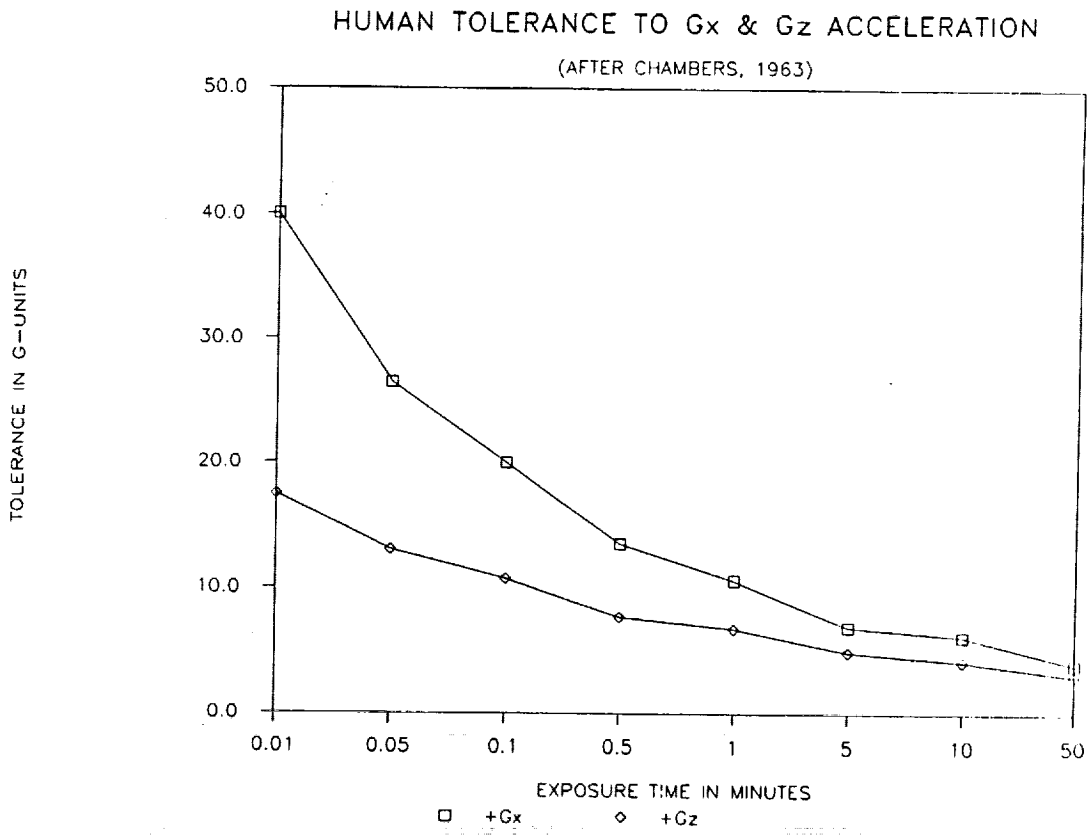
CRITERION	MEAN THRESHOLD	STANDARD DEVIATION	RANGE
LOSS OF PERIPHERAL VISION	4.1	±0.7	2.2 - 7.1
LOSS OF VISION (BLACKOUT)	4.7	±0.8	2.7 - 7.8
LOSS OF CONSCIOUSNESS	5.4	±0.9	3.0 - 8.4

NOTE: 1G = 9.81 METERS/SEC^2



"HUMAN TOLERANCE TO HIGH ENERGY AEROBRAKING"

- G TOLERANCE CAN BE GREATLY ENHANCED BY APPLYING THE FORCES ALONG THE +Gx AXIS (I.E., FROM CHEST TO SPINE, WITH THE INDIVIDUAL SUPINE WITH RESPECT TO G).
- IN THIS CASE, THE LIMITATION BECOMES ONE OF RESPIRATION AND MOVEMENT OF THE CHEST; RESPIRATION CAN BE MAINTAINED FOR SEVERAL SECONDS OVER A RANGE OF 8 TO 14 Gx.
- BECAUSE OF THE GREAT EFFORT INVOLVED, FATIGUE BECOMES A MAJOR CONSIDERATION.
- WE WILL NOT CONSIDER THE Gy AXIS HERE BECAUSE OF THE DIFFICULTY IN PROVIDING ADEQUATE RESTRAINT, AND THE RESULTING DISCOMFORT.



"HUMAN TOLERANCE TO HIGH ENERGY AEROBRAKING"

- THE PHYSIOLOGICAL CONDITION OF AN INDIVIDUAL CAN DRAMATICALLY INFLUENCE HIS/HER TOLERANCE TO ACCELERATIVE FORCES.

- THE TOLERANCE LIMITS AND ACCELERATION VALUES PRESENTED HERE ARE GENERALLY DERIVED FROM ADULT MALE HUMANS ON EARTH WHO ARE IN GOOD PHYSIOLOGICAL CONDITION.

- LONG DURATION EXPOSURE TO MICROGRAVITY CAN LEAD TO APPRECIABLE PHYSIOLOGICAL DECONDITIONING THAT RESULTS IN ORTHOSTATIC INTOLERANCE, BONE DEMINERALIZATION, AND MUSCLE ATROPHY.

- THESE CHANGES CAN SIGNIFICANTLY INCREASE THE RISK OF FAINTING, BREAKING ONES, AND BEING INCAPABLE OF LOCOMOTING UPON RETURN TO A GRAVITATIONAL FIELD.

- ALTHOUGH COUNTERMEASURES IN FLIGHT AND UPON RE-ENTRY CAN BE USED TO MINIMIZE THE DECONDITIONING, OBJECTIVE DATA ARE EXTREMELY LIMITED.

- COUNTERMEASURES CURRENTLY IN USE INCLUDE DIET, EXERCISE AND SPECIAL GARMENTS IN FLIGHT, AND BOTH FLUID LOADING AND ANTI-G SUITS UPON RE-ENTRY.

- THE USE OF ARTIFICIAL GRAVITY IN LONG DURATION MISSIONS IS ALSO CONTEMPLATED, AND ALTHOUGH IT MAY PREVENT THE PHYSIOLOGICAL DECONDITIONING OF WEIGHTLESSNESS, IT WILL IMPACT VEHICLE DESIGN.

- ENGINEERING, BIOMEDICAL RESEARCH, AND OPERATIONAL TRADE-OFF STUDIES WILL BE NEEDED TO ASSESS THE EFFECTIVENESS OF EACH CONTEMPLATED COUNTERMEASURE AND ITS INTERACTIVE EFFECTS WITH MISSION PERFORMANCE IN VARIOUS MISSION SCENARIOS.

- VARIOUS MISSION SCENARIOS PROJECT H.E.A.B. VELOCITY CHANGES RANGING FROM 9,000 TO 24,200 FEET PER SECOND (2,744 TO 7,379 METERS/SEC). IF THESE DECELERATIONS CAN BE ACCOMPLISHED IN THE RANGE OF 2.5 TO 10 MINUTES, THE ACCELERATION LOADS ON THE VEHICLE AND ITS OCCUPANTS WILL BE WELL WITHIN HUMAN TOLERANCE LIMITS.

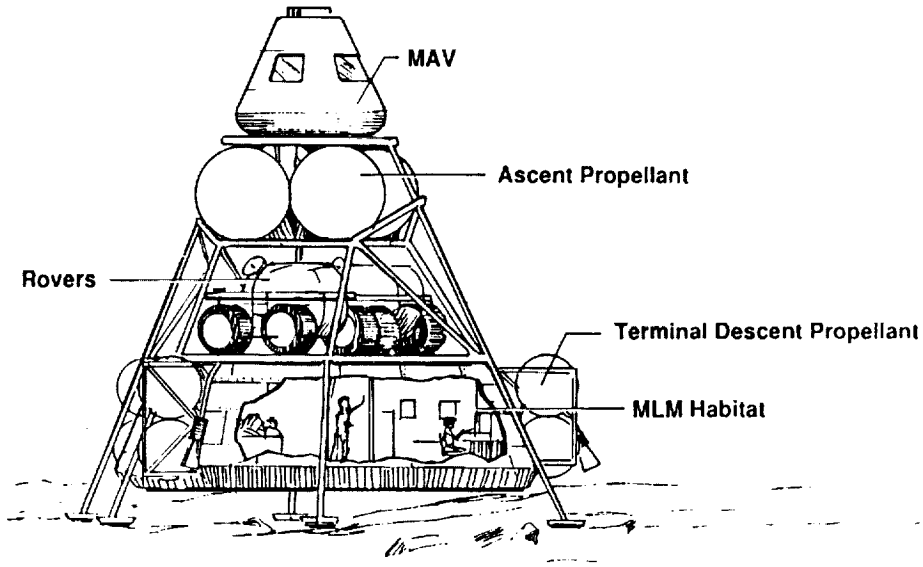
- DESPITE THE CAUTIONS CITED HERE, HIGH ENERGY AEROBRAKING IS POTENTIALLY USEFUL FOR BOTH MANNED AND UNMANNED SPACE MISSIONS.

REVIEW OF MARTIN MARIETTA STUDIES OF SPACE TRANSPORTATION VEHICLE CONCEPTS

B. Clark
Martin Marietta
1/31/89

Landed Configuration

Vehicle Designs



Mars Descent Vehicle (MDV)

Vehicle Designs

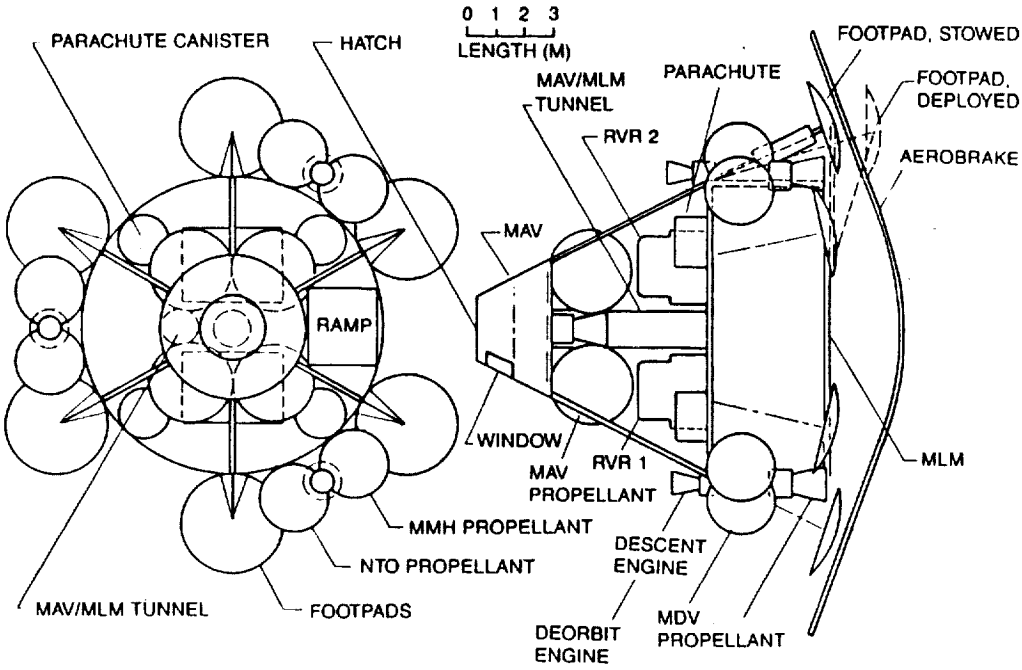
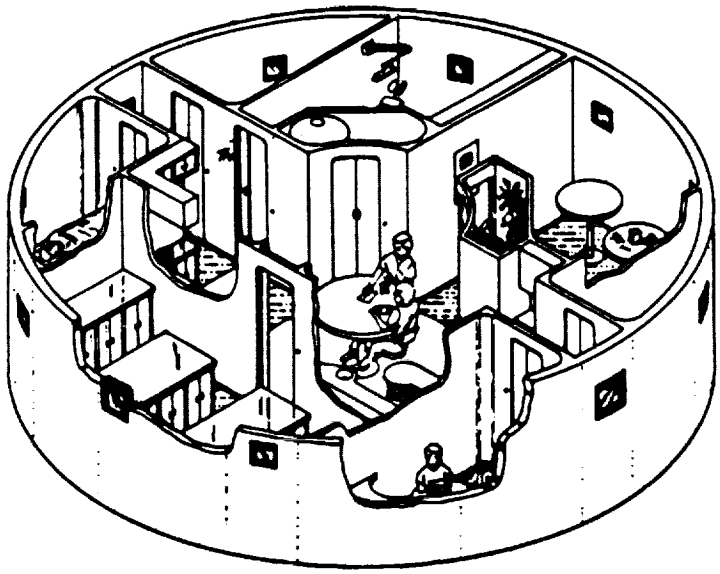
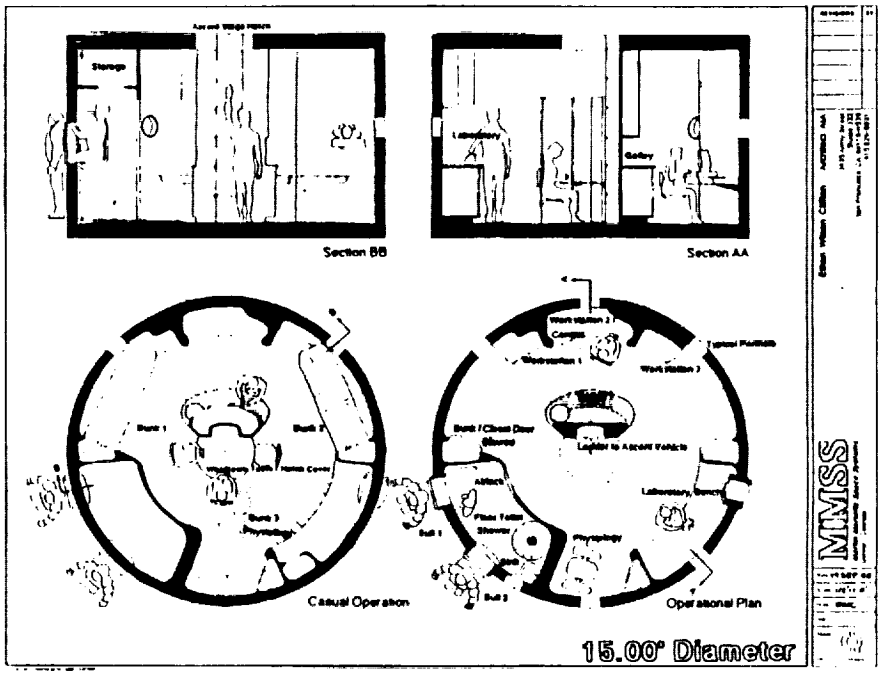


Figure 2.1.2.1-9a Mars Landed Mission Module (MLMM), Designed by Ethan Clifton



Mars Lander Hab Module (MLMM on MDV)

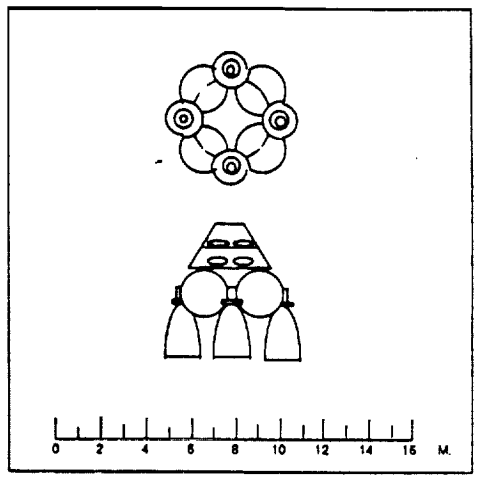
Habitats



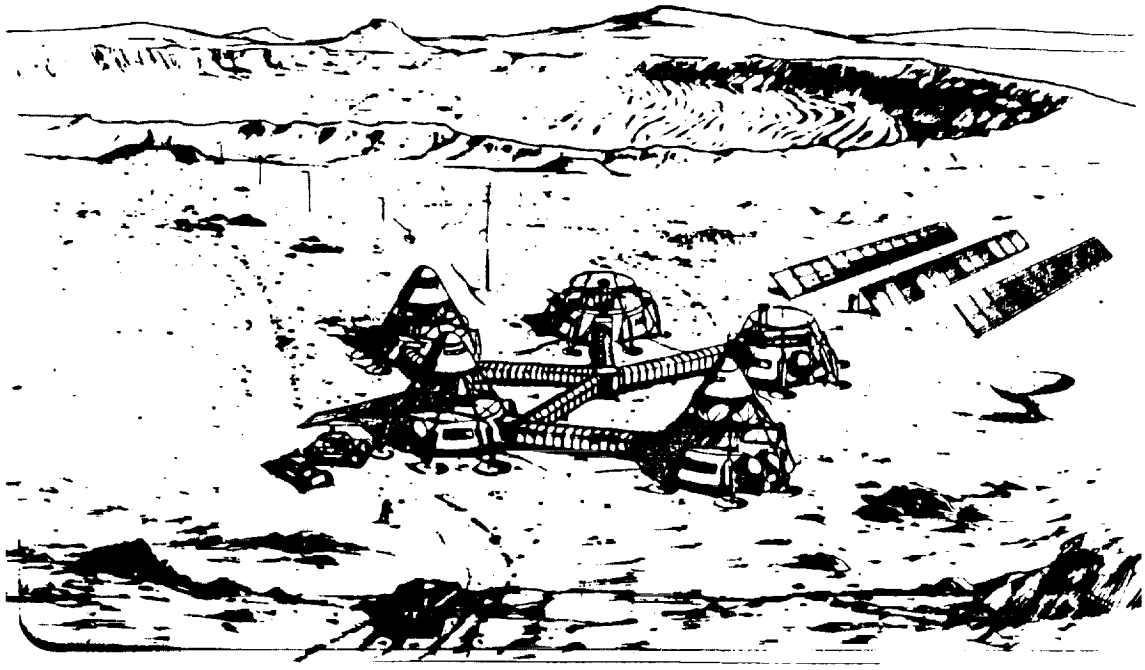
MARTIN MARIETTA V-011.MMSS-42 Gateway Quick Turn, 11/11/88

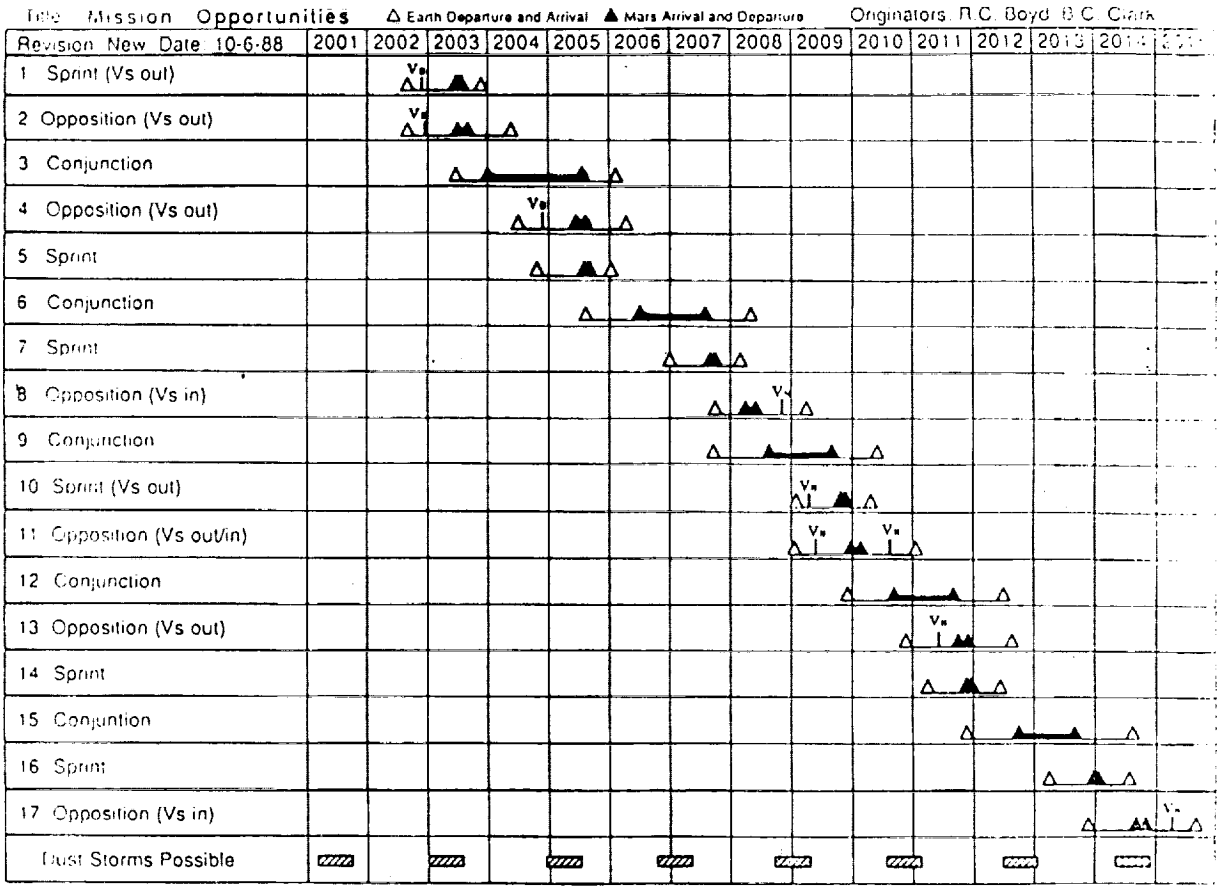
Mars Ascent Vehicle (MAV)

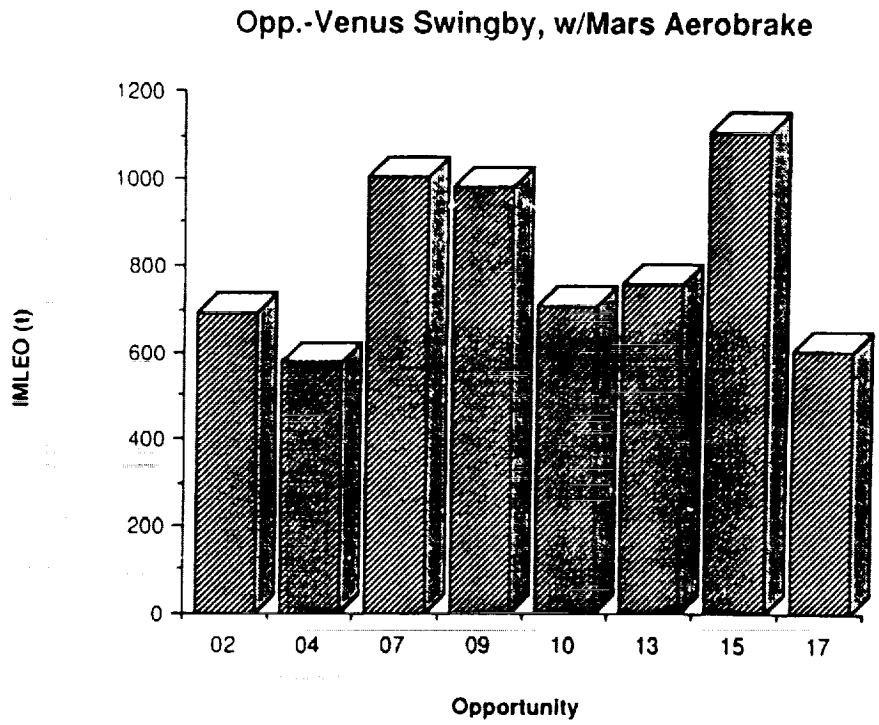
Dry Mass	
(includes payload)	3,758 kg
Payload Mass	
(crew & supplies)	470 kg
Payload Volume	
MAV	
(cone - 1.8m rad., 2.3m ht.)	8 m^3
Propulsion System	
Propellant Type	MMH/N_2O_4
Engines	
Number	4
Type	Delta
Mass (ea.)	100 kg
Thrust (total)	178 kN (40.0 klbf)
I_{sp} (320 sec)	3.14 kN-s/kg
Propellant Mass	19,422 kg
Tank Mass	1,942 kg
Initial T/W	2.55
Mass Fraction	
Ascent to 24.66 hr elliptical orbit	0.183
Total Mass	23,180 kg

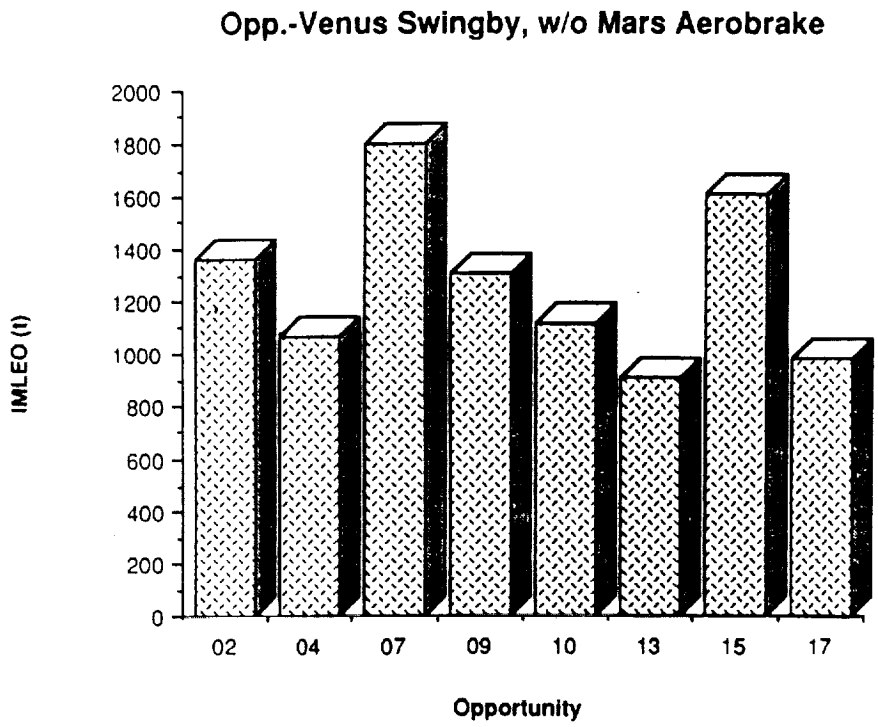


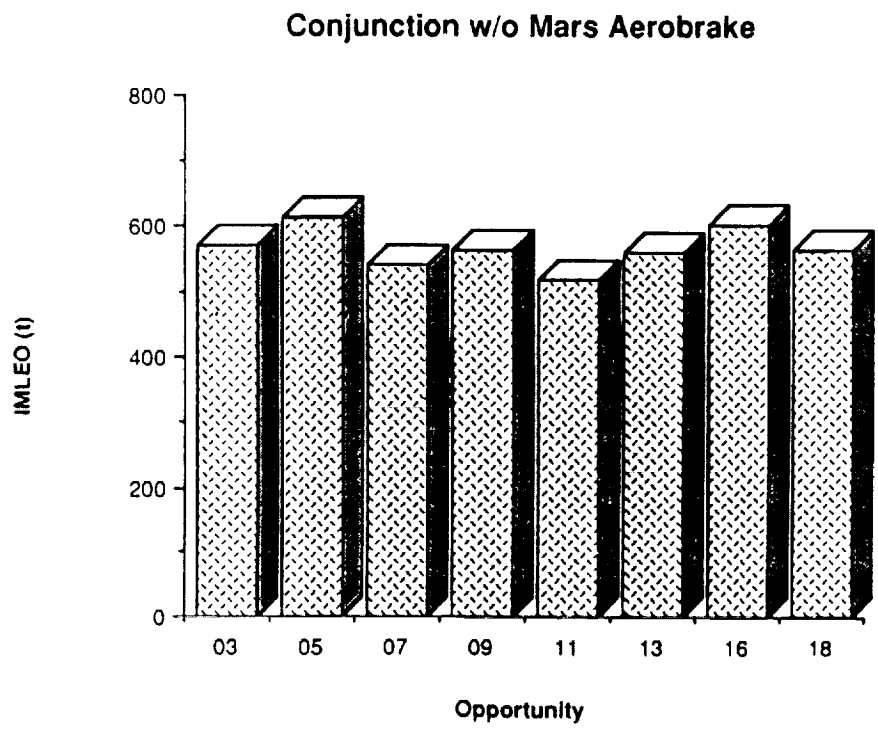
MARTIN MARIETTA C3-Vehicles.MMS5 11/12/88

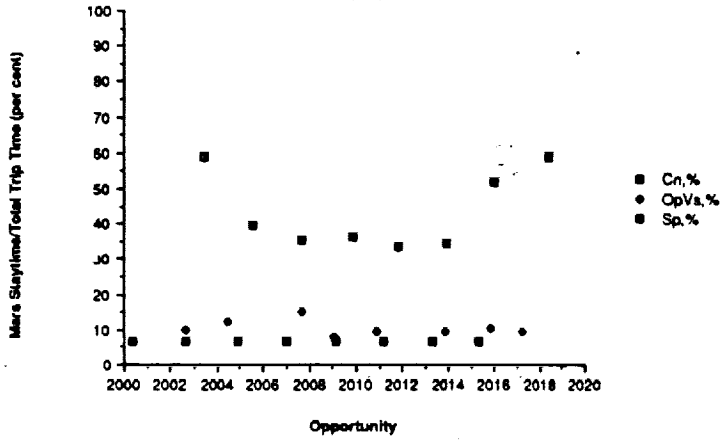



Title Mission Opportunities
Earth Departure and Arrival
Mars Arrival and Departure
Originators R.C. Boyd B.C. Clark
Revision New Date 10-6-88
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
1 Sprint (Vs out)
2 Opposition (Vs out)
3 Conjunction
4 Opposition (Vs out)
5 Sprint
6 Conjunction
7 Sprint
8 Opposition (Vs in)
9 Conjunction
10 Sprint (Vs out)
11 Opposition (Vs out/in)
12 Conjunction
13 Opposition (Vs out)
14 Sprint
15 Conjuntion
16 Sprint
17 Opposition (Vs in)
Dust Storms Possible


Opp.-Venus Swingby, w/Mars Aerobrake
IMLEO (t)
1200
1000
800
600
400
200
0
02
04
07
09
10
13
15
17
Opportunity


Opp.-Venus Swingby, w/o Mars Aerobrake
IMLEO (t)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
02
04
07
09
10
13
15
17
Opportunity


Conjunction w/o Mars Aerobrake
IMLEO (t)
800
600
400
200
0
03
05
07
09
11
13
16
18
Opportunity



Crew Size

Human Factors

Crew Skills and Personalities Needed

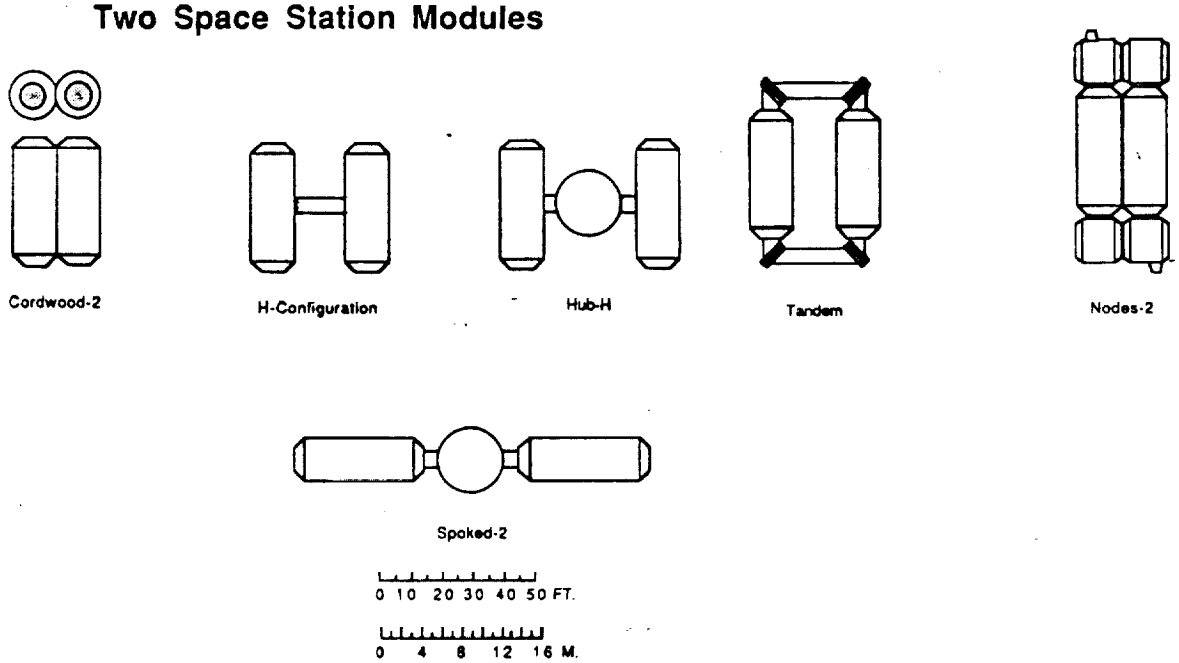
the Doer: pilot, emergency rescuer, procedure follower, technician, builder
the Healer: general practitioner, surgeon, dentist, EMT, psychologist; exobiologist, biochemist
the Fixer: maintenance/repair man, handyman, engineer
the Hacker: computer program craftsman (all others are computer users), mathematician
the Inquirer: scientist, explorer, Sherlock, synthesizer (geographer, planetary geologist, astrophysicist, exobiologist, climatologist, chemist, geophysicist)
the Stabilizer: decision-maker, social leader, communicator with home base, guardian angel (safety), the Coach

Crew Number and Responsibilities

	Title	Primary Responsibility	Backup Responsibility
1.	Commander	the Stabilizer, the Doer	Engineer
2.	1st Engineer	the Fixer	Cmdr, Software
3.	Medical Officer	the Healer	Scientist
4.	Scientist	the Inquirer	Engineer, Software, Medical
5.	Pilot	the Doer	Cmdr, Engr
6.	Medical Specialist	Healer's assistant/back-up	Medical, Scientist
7.	Field Scientist	additional Inquirer	Pilot, Engineer
8.	Technical Specialist	1st Engr's assistant/back-up	Scientist, Med Specialist
9.	Software Engineer	the Hacker	Engineer, Scientist

Mars Descent Crew:
Lander commander (Engineer or Pilot), Scientist, Field Scientist, Medical specialist
(Note: Commander and Medical Officer must "stay with the ship." Scientists needed most on surface.)

Zero Gravity Configurations: Two Space Station Modules



Zero Gravity Configurations: Five and Six Space Station Modules

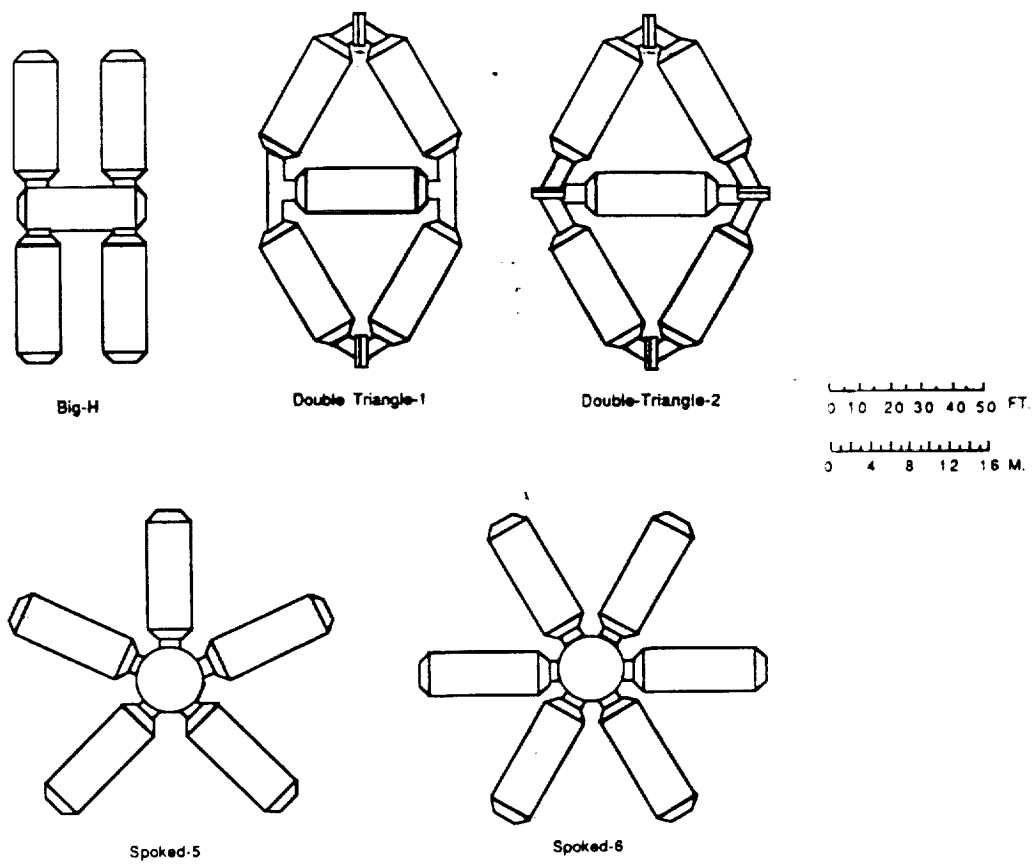
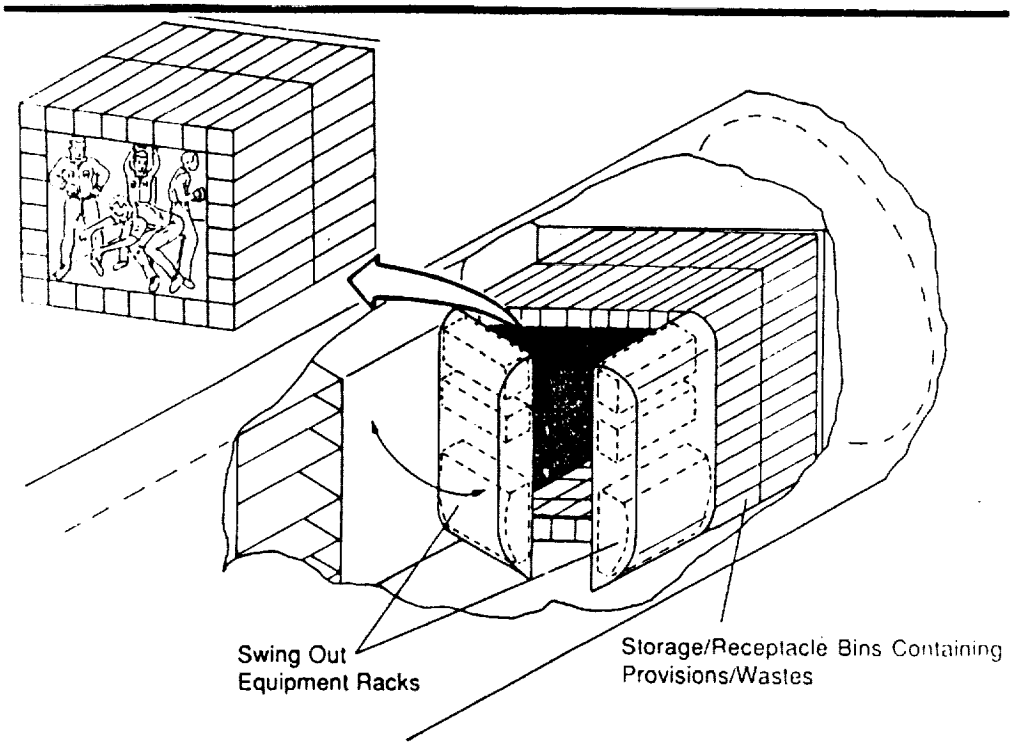


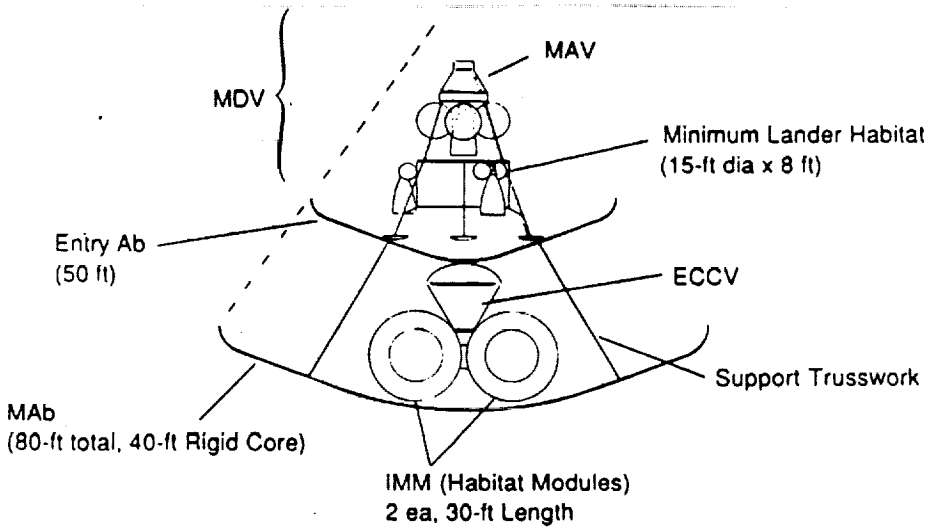
Figure 1.1.2.1-3a **Radiation Shelter Situated at Habitat Module End**



1-19

Configuration C

IMM for 4 Crew, MDV for 3 Crew, 20 Sol. Stay



Human Expedition to Phobos

MARTIN MARIETTA V-G15.MMSS-1 6/16/88

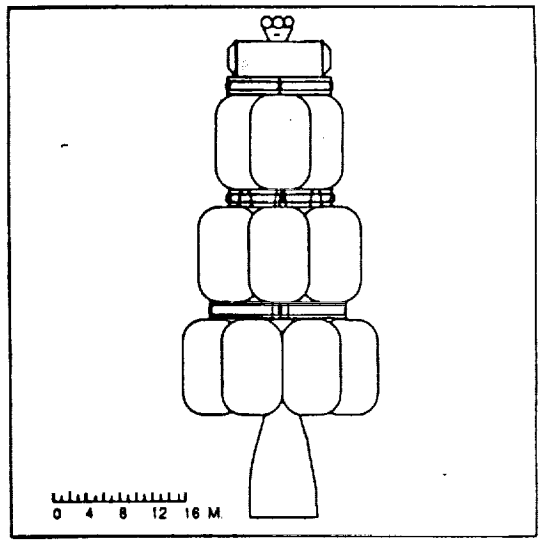
Table 1.3.-3 Alternatives Mass Summary—Case Study 1

TIC i.d. Concept	Alternatives	IMLEO Hum	IMLEO Car	IMLEO Total	File Miss	File Ref
TIC-1R	Reference (all-prop.480/460/320; nom tank (0.15); low boil; separate PhEV, 9.8 t; 7 t MRSR; ECCV direct entry, 619m/s)	1311.3	467.0	1778.3	m-FD	m-DG
TIC-1A	Mars aerobrakes (MAb's) for piloted and cargo	452.9	311.7	764.6	m-ES	m-DU
TIC-1A-b	Next later opportunity	817.5	275.1	1092.6	m-ET	m-DW
TIC-1A-f	Venus probes	463.7	311.7	775.4	m-GD	m-ES
TIC-1A-m	2-stg TMIS	416.0	311.6	727.6	m-EU	m-DX
-1A-bm	2-stg TMIS, next opportunity	737.9	275.1	1013.0	m-EV	m-DY
-1A-dm	adv. prop. (485/470/340), 2 stg	403.0	298.6	701.6	m-EW	m-DZ
-1A-fdm	Venus probes, plus preceding	412.7	298.6	711.3	m-EX	m-EA
-1A-gh	v. conserv. LH2/LOX propulsion (0.206 tanks), high boil	717.2	538.8	1256.0	m-EY	m-DU
-1A-hi	Hydrocarbon/LOX for TEI (395), high boil	454.9	320.0	774.9	m-EZ	m-DU
-1A-u	adv technol. cryoprop (tankage 0.075)	367.5	248.9	616.4	m-FZ	m-ES
-1A-u1	adv technol. cryoprop (tankage 0.075), no boiloff	357.5	234.8	592.3	m-GB	m-ES
TIC-1B	Nuclear Thermal Rocket (NTR) for TMI only	771.1	317.4	1088.5	m-FE	m-EB
TIC-1B-p	all propulsive, TMI for all (TMI, DSM, MOO, TEI)	538.2	314.0	852.2	m-FF	m-EC
TIC-1B-ph	same, but high boiloff	1004.9	555.8	1560.7	m-FG	m-ED
TIC-1AB	NTR+MAb	284.2	225.9	510.1	m-FA	m-EE
-1AB-h	NTR+MAb, high boiloff	321.4	276.3	597.7	m-FB	m-EF
-1AB-p	NTR for TEI also	281.9	214.8	496.7	m-FC	m-EG
1-AB-hu	NTR+MAb, adv cryoprop (tankage 0.075), high boiloff	302.6	244.6	547.2	m-GI	m-FB

MARTIN MARIETTA CS-1.MMSS-13 1-46 9/22/88

Fig. 1.1.2.1-6a Trans-Mars Injection System (TMIS)

Dry Mass (includes payload)	499,850 kg
Payload Mass (MTV)	377,030 kg
Propulsion System	
Propellant Type	LOX/LH_2
Engines	
Number	1
Type	SSME-derivative
Mass (ea.)	3,175 kg
Thrust (total)(543 klbf)	2,415 kN
I_{sp} (480 sec)	4.71 kN-s/kg
Propellant Mass	811,490 kg
Initial T/W	0.19
Mass Fraction	
Total	0.38
Total Mass	1,311,340 kg



ETO Manifest -- Case Study 1 (91 t HLLV)

Launch	Date	Item	Mass
1. HLLV-1	Apr '00	Mars transfer vehicle (MTV) minus	90.6 t
2. HLLV-2	Jun '00	TMIS Tank #1	91.0 t
3. HLLV-3	Aug '00	TMIS Tank #2	91.0 t
4. HLLV-4	Oct '00	TMIS Tank #3	91.0 t
5. HLLV-5	Nov '00	TMIS Tank #4 (small tank)	42.2 t
6. STS-1	Dec '00	Crew for teleoperated assembly of	
7. HLLV-6	Feb '01	TEIS (fully loaded)	58.7 t
Teleoperated docking of TEIS and MCV from Earth . Launch Apr '01 via Earth command.			
8. HLLV-7	Apr '01	MTV, minus MOCS	81.1 t
9. STS-2	May '01	Crew #1; initial boarding and checkout	
10. HLLV-8	Jul '01	MOCS Tank #1	91.0 t
11. HLLV-9	Aug '01	MOCS Tank #2 plus engine, PA	87.1 t
12. STS-3	Sep '01	Changeout to crew #2	
13. HLLV-10	Oct '01	TMIS Tank #1	91.0 t
thru	thru	thru	91.0 for 5
19. HLLV-16	Apr '02	TMIS Tank #7	51.5 t
20. STS-4	May '02	Deliver final assembly hardware and crew #3	
21. STS-5	Jun '02	Crew changeout to flight crew (#1, #2, or #3)	

Requirements and Assumptions -- Case Study 1

Mission		--- Total --- Crew	Time	Launch Date	Destination	User Accommodation Mass (t)	Type(s)	---Surface --- Crew	Time	LEO Mass (t)
CS-1	Car-1	--	800 d	4-01	Phobos	20	Phobos science	--	--	< 410
	Hum-1	4	440 d	8-02	Phobos	5	MRSR (2 ea.)	2	20 d	<320
						0.1	User accomm.			

Other Requirements:

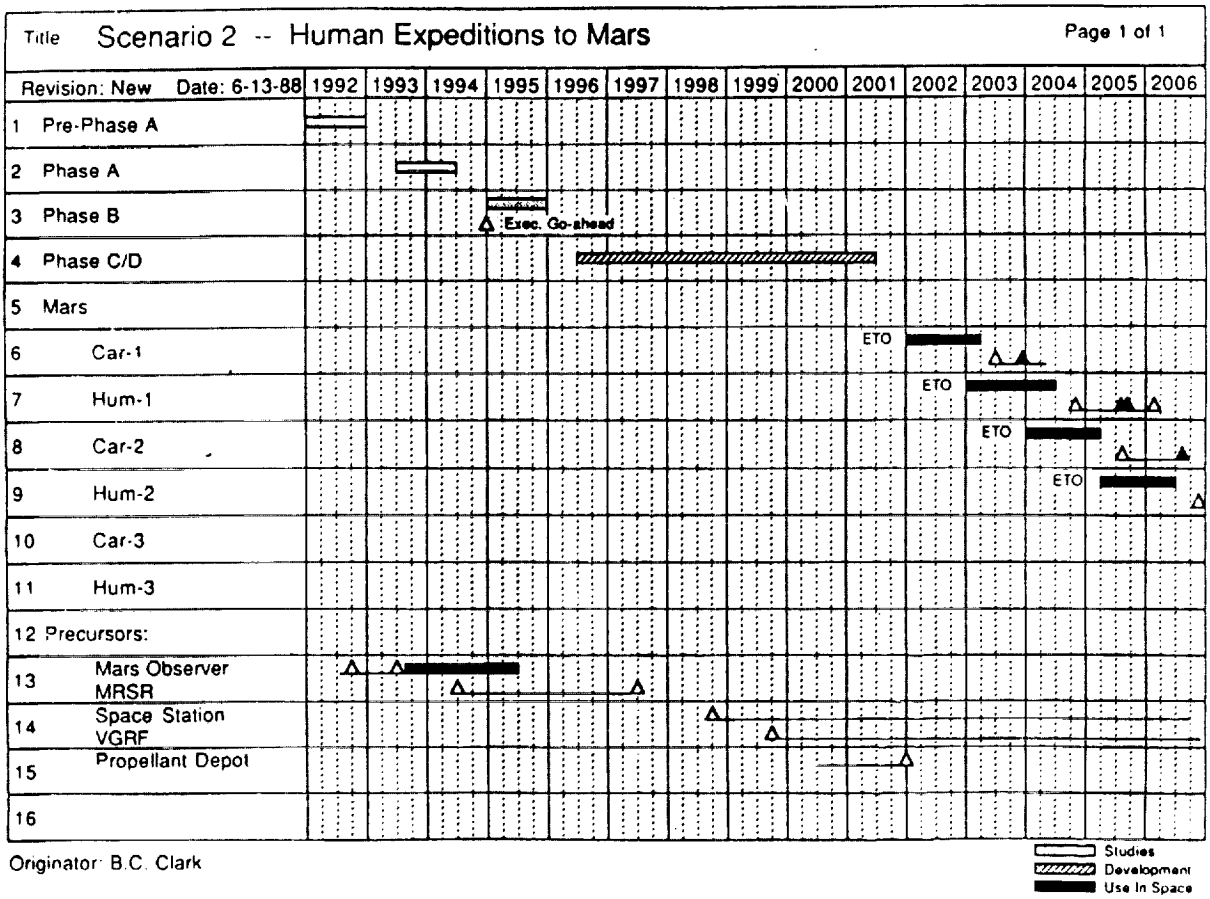
- 20-30 days at Phobos, close prox, "but not land per se". Dock with a previously planted "drogue". will require "crew stability/mobility aids" for EVA work on Phobos
- No SS assembly. Split:sprint/conj
- Man-rate xport hardware 3 yr before launch.
- Four 6-hr EVAs. (3.1.1)
- Fly-around aborts.
- EOC to LEO node (3.1.1)
- 1-2 yr in-LEO demo/verif of process requirements (3.3.2)
- Payloads: MRSR, PNL, balloon robots (3-4): 15 t. Venus probes: 3 t. (A.1)

Assumptions for Baseline:

- Mars aerobraking; ECCV for crew recovery at Earth
- Engine performance: I_{sp}=460s for cryo; 320 for storable biprop
- Propulsion: Cryo for TMI, TEI; Biprop for DSM XXX, MOC, MOO, RCS
- Mars parking orbit: 250 km x 1 sol; Phobos excursion vehicle (PhEV)
- No Venus probes
- Two SS-derived modules; "H" configuration

Trade Studies:

- max use of existing hardware; earlier departure window; direct earth entry (3.1.2)



Originator: B.C. Clark

Figure 2.1.1-2 Reference Mission Options

Scenario CS-2 TIC-1R

	OPTIONS (proven or under development → unproven, or must be developed / analyzed)							Options Selected (Date & Your Name)
Earth departure location	LEO	HEO	GEO	L1,L2				
On-orbit assembly	SS, attached	SS, free-flyer	Min. SS	no SS req'd				
Hardware staging	integrated	split, MDV	split, MRSR	split, TEIS				
Trajectory type	flyby	conjunction	opposition	sprint	low thrust	cycler		
Launch dates	1990's	2000's	2010's	2020's	2030's			
Crew size, total	3	4	5	6	7	8	9-11	12-24
Cabin pressure	4.3 psi	14.7 psi	10.2 psi					
Gravity environment	microgravity	artificial, .38 g	artificial, 0.6 g	artificial, 1 g	hybrid			
Rotation rate	0 rpm	1 rpm	2 rpm	4 rpm	6 rpm			
Radiation protection	none	one storm shelter	two storm shelters	GCR shield				
Hab/Lab modules	SS modules (15' dia.)	ET derived (25' dia.)	large dia. (31' dia.)	inflatables				
Science equipment	interplanetary	Mars orbit	Mars surface	Phobos	Deimos			
ECLSS, spaceborne	consumables	SS ECLSS	water recycling	low mass/power	CELSS			
TMI launch propellant	hybrid chemical	LH2/LOX	Hc/LOX	waste/LOX	SEP	NTR	NEP	solar sail
engines, cryo	RL-10 growth	F1 derived	SSME derived	advanced cryo				
growth	max.-sized tank	stretch	cluster					
reusability	non-recoverable	engines, avionics	all recoverable					
recovery method	none	turn-around	re-encounter					
Cryoprop storage	passive	active, refrigeration	active, reliquifaction	from H2O				
Power,spaceborne	PVPA	fuel cells	RTGs	nucl. reactor	DIPS	solar th.-dy		
TM abort capabilities	Mars swingby	propulsive abort						
Mars orbit	LMO	8.2 hr. ellip.	24.6 hr. ellip.	Phobos	Deimos	GMO		
Mars orbit capture	propulsive braking	prop/aero hybrid	aerobraking					
Satellites Relay Com	none	LMO	24.6 hr	12.3 hr	Molniya	GMO		
Mars Science Orbiters	none	polar	circ.	elliptical				
Unmanned Landers	none	penetrator(s)	rover(s)	sample return				
Fr. De telecperators	none	Phobos	Deimos					
Number of MDV's	none	one	two					
Time on surface	0	1 wk.	3 wk	6wk.	6 mo	1 yr.	PMP	
Crew size, landed	0	2	3	4	5	6-20		
Propellants, MDV	LH2/LOX	Biprop	H2O2	CH4/LOX				
MELS	de-orbit prop.	parachutes	aerobraking	terminal prop.	hover/translate	airbags		
Landing hazard	large, safe areas	pinpoint landing	terminal H.A.					
Power generation	RTG	fuel cells	PVPA	DIPS	nucl. reactor	solar th.-dy.		
Power storage	batteries, Ni-H	Regen. FC	HEDRB					
ECLSS, Mars landed	consumables	SS ECLSS	low mass/power	ISCP	CELSS			
MLSE	RVR	analyt. eq.	geopys. pkg.	meteorol. pkg.	biol. eq.	drilling		
MLOE mass	none	0.5 t	1 t	2 t	4 t	8 t	16 t	
RVR, manned	none	unpressurized	press., 5 sol	press., 20 sol				
ISPP	none	CO2	CO	H2O2	LOX	CH4/LOX		
ISRU demos	water	food	H2O2	buffer gas	GOX	fertilizer	MLOX	
Propellants, MAV	UDMH/N2O4	solids	ISPP					
Recovery ETV	not recovered	Ab EOC	propulsive capture	prop/Ab hybrid				
ECCV	none	Ab EOC	prop. capture	prop/Ab hybrid	direct entry			
Orbital retrieval	STS to SS	STV to SS	STS to Earth					

Form Revised by M. Thornton 6-12-89

Human Expedition to Mars

MARTIN MARIETTA CS-2.MMSS-1 11/12/88

Mars Cargo Vehicle (MCV)

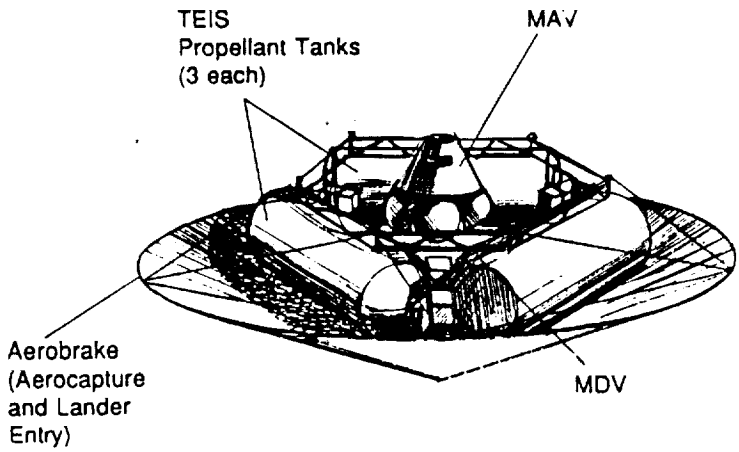


Figure 2.1.2.1-1a **Mars Spaceship, Case Study 2**

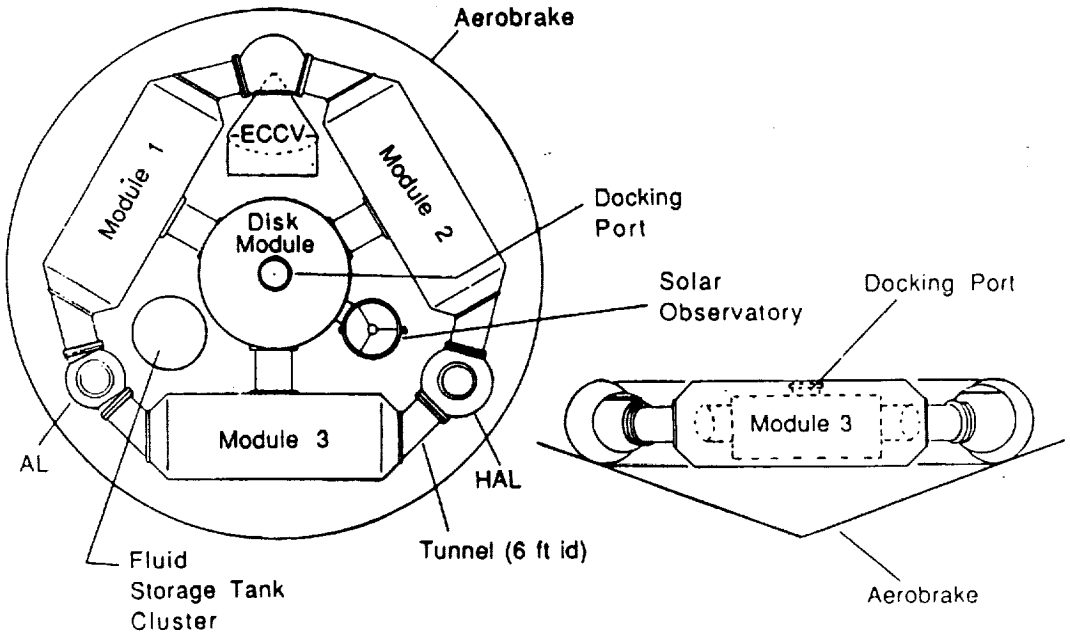


Figure 2.1.2.1-5a **Mars Transfer Vehicle (MTV) (Piloted)**

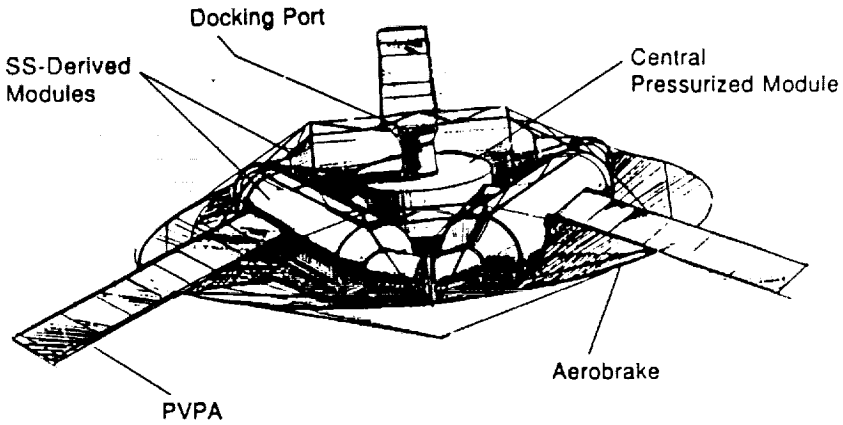
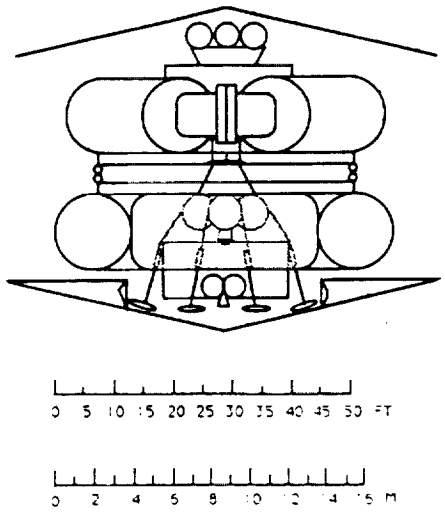
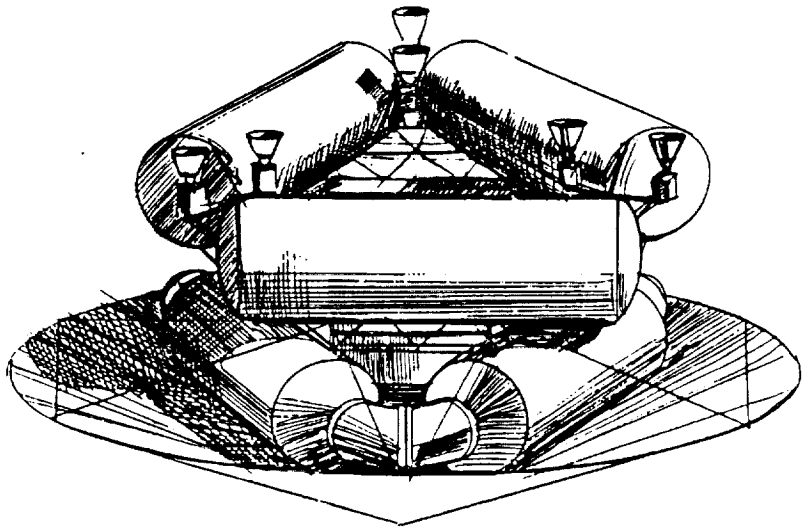


Fig. 2.1.2.1-7
Mars Orbital Operations, Step 2 - Docking of TEIS and MDV



Mars Orbiting Vehicle (MOV)



(After TEIS Transfer)

Table 2.1.4-2 Options Mass Summary—Case Study 2

TIC i.d.		-------- IMLEO --------			----- File -----	
Concept	Trade/Option	Hum	Car	Total	Miss	Ref
TIC-1R	Reference (MAb, 2-TMIS, (485/470/320), nom. tank, low boiloff, PhTele, ECCV)	1124.5	503.3	1627.8	c-HG	c-HG
TIC-1R-a	Next earlier opportunity (2002)	641.1	552.6	1193.7	m-GJ	c-HG
TIC-1R-b	Next later opportunity (2006) ("fallback")	1747.1	708.1	2455.2	m-GK	c-HG
TIC-1R-c	Conservative propulsion performance (480/470/320)	1139.5	509.0	1648.5	m-GL	c-HG
TIC-1R-d	Very conservative performance (480/460/320)	1168.7	519.3	1688.0	m-GM	c-HG
TIC-1R-h	High boiloff	1226.3	568.6	1794.9	m-GN	c-HG
TIC-1R-g	V. conservative tankage (.256), low boiloff	1516.7	665.7	2182.4	m-GO	c-HG
TIC-1R-gh	V. conservative tankage, high boiloff	1682.6	768.3	2450.9	m-GP	c-HG
TIC-1R-u	Advanced tankage (0.075)	916.0	417.1	1333.1	m-GR	c-HG
TIC-1R-ul	Advanced tankage, no boiloff	889.3	402.3	1291.6	m-GS	c-HG
TIC-1R-i	Hydrocarbon/LOX for TEI	1132.9	525.1	1658.0	m-GT	c-HG
TIC-1R-m	1-stg TMIS	1242.7	503.2	1745.9	m-GU	c-HG
TIC-1R-n	Nominal MAb (10%)	1034.3	445.0	1479.3	m-GW	c-HG
TIC-2R	Reference for 2nd mission (Launch 2006)	1769.7	741.8	2511.5	c-HQ	c-HQ
TIC-3R	Reference for 3rd mission (Launch 2009)	1511.8	1113.3	2625.1	m-HH	m-HH
TIC-2R-s	no PhEV on mission 2, but Phobos teleoperator	1748.2	707.5	2455.7	m-HE	c-HQ
TIC-3R-s	no PhEV or DeEV on mission 3, but teleoperators	1482.4	1048.7	2531.1	m-HF	c-HP

Artificial Gravity Scaling

ARTIFICIAL GRAVITY SCALING

Spin rate	Acceleration	Radius	
1 rpm	1.0 gee	900 m	[2950']
	0.38	340	[1115']
2 rpm	1.0	225.6	[740']
	0.38	83.8	[275']
4 rpm	1.0	56.4	[185']
	0.38	21.3	[70']
6 rpm	0.675	16.8	[55']
4.5	0.38	16.8	[55']

Figure 2.2.3-3f Artificial Gravity Concept, with 1 MDV

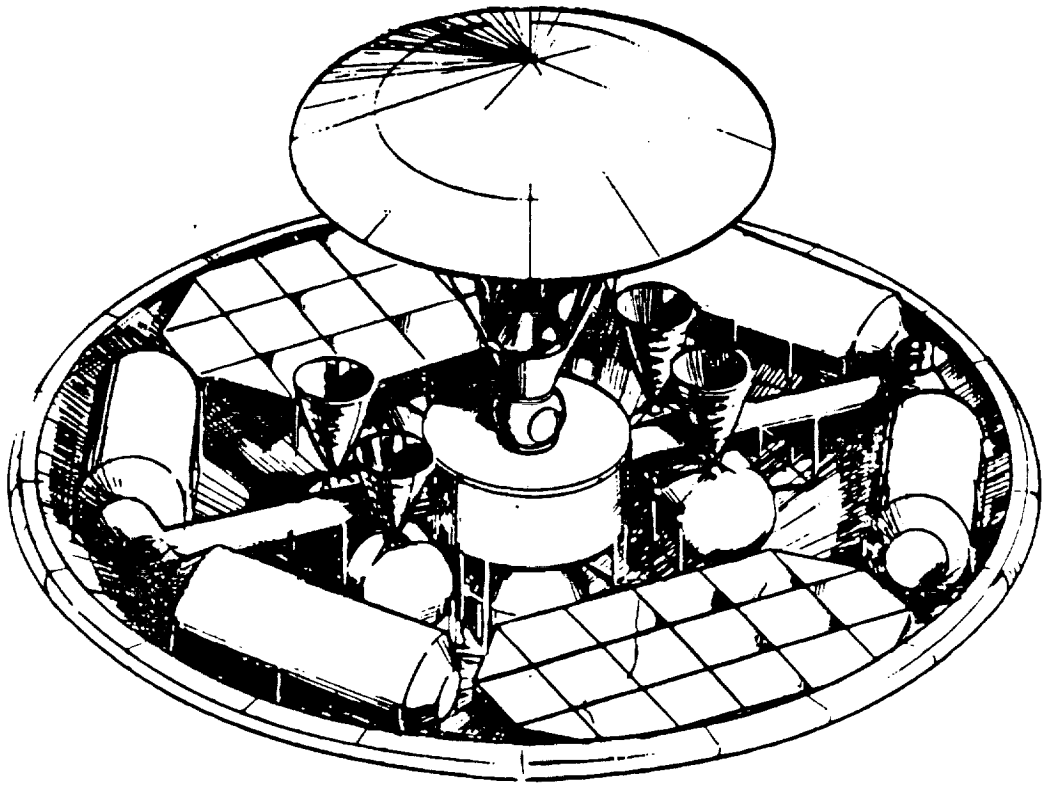


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Figure 2.2.3-3c Artificial Gravity Concept

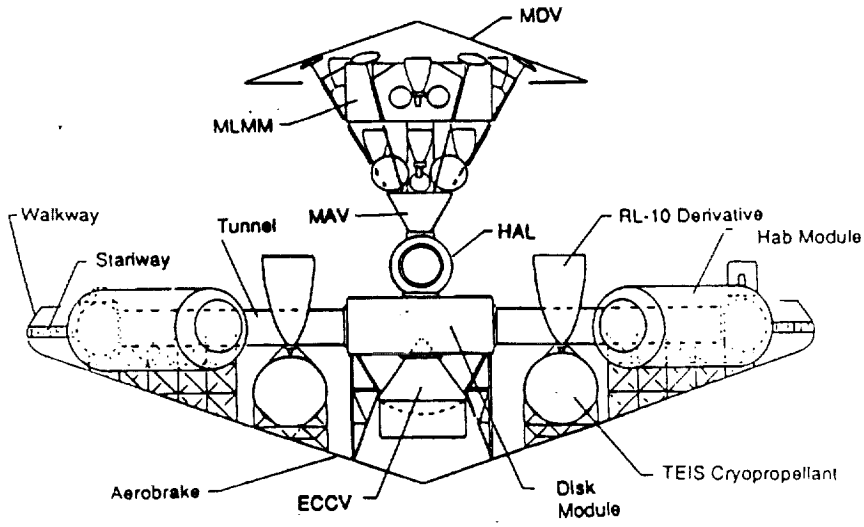

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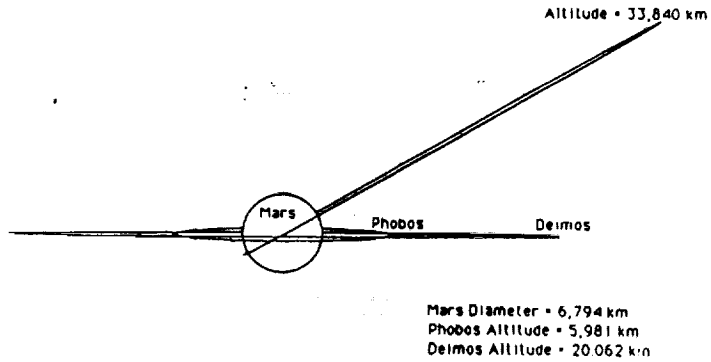
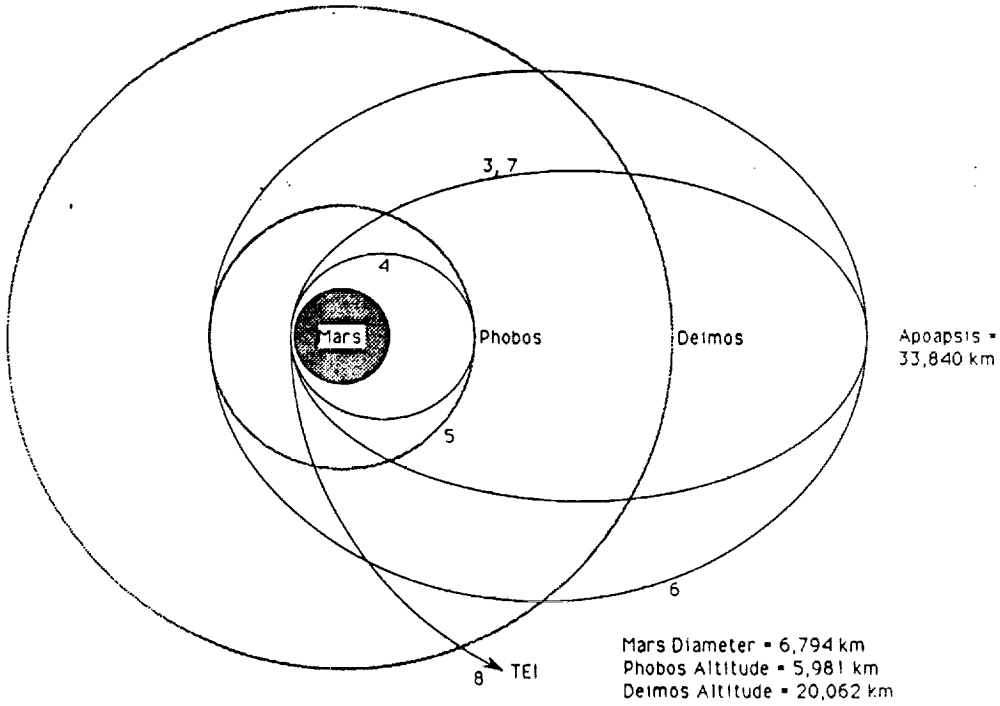
Figure 1.1.1-1
Post Aerobrake Orbit and Orbits of Phobos and Deimos



Phobos Excursion Maneuvers and Mars Escape



Trade Study for Phobos Excursion Vehicle

PhEV

Trade: Should the Mars Orbiting Vehicle (MOV) be sent directly to Phobos, or should the astronauts utilize a small, dedicated Phobos Excursion Vehicle (PhEV) to depart from and then return to the MOV mother ship which remains in a fixed orbit.

Issues:
- Optimum orbit for MOV is not the Phobos orbit
- Operations at Phobos
- Mission risk and astronaut safety

Analysis:
- Large propulsion systems are required to send the entire mother ship (MOV) into Phobos rendezvous orbit, resulting in significant IMLEO penalties:
  IMLEO summary: E-P6 increases from 337.8 to 573.1 t (70 %) [c-KO, c-KS]
- Operations at Phobos require added propulsion mass to prevent a landing of the MOV (or PhEV). (Design and qualification testing of the MOV as a Phobos Lander is major development penalty and negates concept of Phobos mission as quick, early, and minimum technology)
- Because of low surface gravity (roughly 0.001 g), loose dust and rubble may abound. A co-orbiting debris cloud associated with Phobos has not been detected, but some material may be present. Any craft in the near-vicinity or on the surface of Phobos may need capability to survive particle and boulder impact, solar occultations up to 2 hours, and dust contamination.
- From a mission safety viewpoint, it is better to risk only a portion of crew to the challenges of Phobos visit, surface exploration, and major Mars orbital maneuvers and rendezvous operations. Yet safer would be to conduct Phobos exploration with robotic vehicles teleoperated by the astronauts remaining on the mother ship (MOV).

Conclusion: Use of PhEV allows division and isolation of mission risk, as well as major reductions in IMLEO. To minimize design complexity and reduce cost, EVA to the Phobos surface is recommended over landing the PhEV.

Phobos LOX Utilization

Phobos LOX, ISRP

Question: Does utilization of Phobos LOX provide a net savings (reduction of IMLEO)

Issues:
a) Replacement of TEIS LOX
b) Replacement of MDV+MAV LOX
c) Transport of materials from Mars surface to Earth (gold shipments??)

ΔV penalties for plane change and circularizing to Phobos orbit and for escaping Mars' gravitational well from Phobos orbit must be considered along with realistic mission profiles.

Analysis:
For mission #2 (Conjunction class, 2007 launch from Earth)

	IMLEO (t)		
	LOX from Earth	PhLOX	Savings
a) TEIS LOX	702.7	624.0	11.2 %
b) MDV+MAV LOX	660.4	621.4	5.9 %
c) MAV+TEIS LOX	661.8	555.9	16.0 %

Note: Derived by scaling, using m-OO. MOV is in 250 km x 1 sol orbit.

Conclusion: Phobos resource utilization is not cost-effective, except for export of high-value commodities from Mars. Private sector resources would presumably develop PhLOX production plants and Mars prospecting and mining, should water be shown to exist on Phobos and valuable resources be shown to exist on Mars.

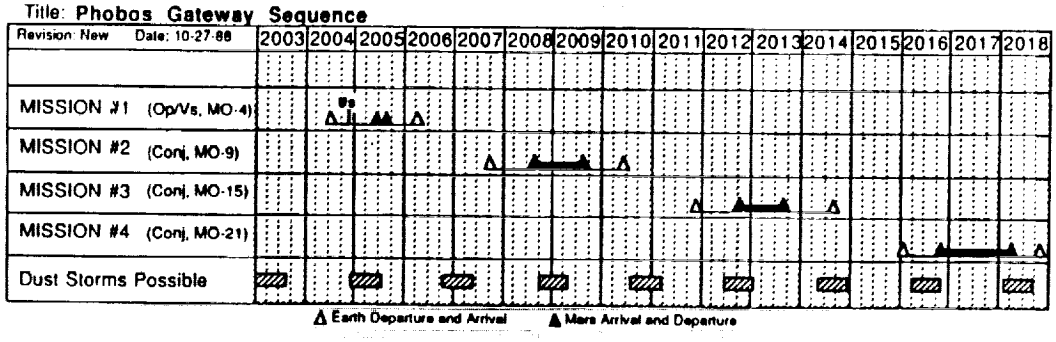
Phobos Excursion Astrodynamics

Mission Profile for 2004 Opposition Class mission (MO-4)
MOV orbit at Mars: 300 x 58,014 km, i = 37°

	ΔV (m/s)
Plane change to equatorial orbit.	178
Raise periapsis to Phobos altitude	149
Lower apoapsis to Phobos altitude (circularize)	678
Rendezvous with Phobos	100
Subtotal, MOV orbit to Phobos	1105
Phobos sorties	
(four 6-hr hover periods)	825
(20 days at 100 km distance)	134
Subtotal, Phobos sorties	959
Raise apoapsis to 58,014 km	678
Lower periapsis to 300 km	149
Plane change to 37° orbit	178
Rendezvous and dock with MOV	100
Subtotal, Phobos to MOV orbit	1105
Round Trip Total	**3169**

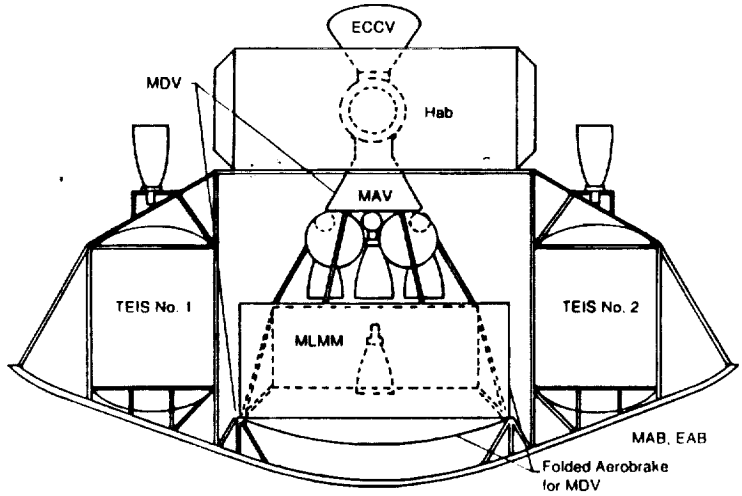
Mission Sequence, Phobos Gateway

Title: **Phobos Gateway Sequence**



Phobos Gateway, Mars Transfer Vehicle (MTV)

Vehicle



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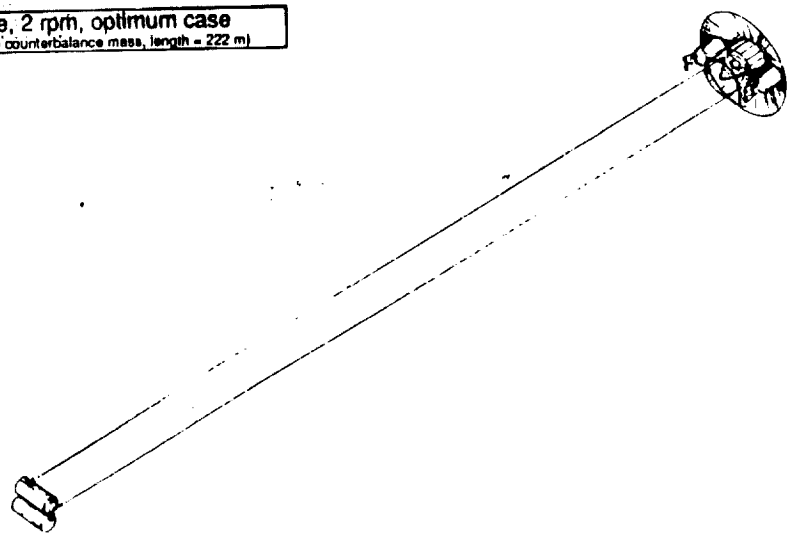
Tether Artificial Gravity, Phobos Gateway

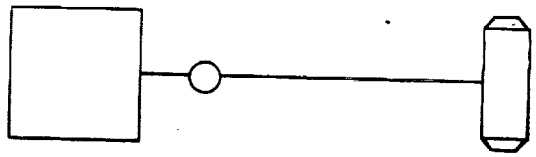
Artificial Gravity

1.0 gee, 2 rpm, optimum case
(maximum counterbalance mass, length = 222 m)

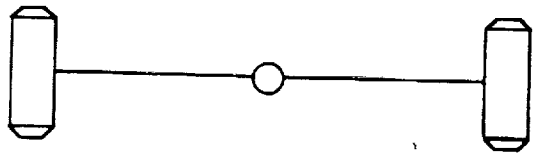


MARTIN MARIETTA V-G11.MMSS-27 Gateway Quick-Turn, 11/11/88

Artificial Gravity Configurations: Tethered Systems



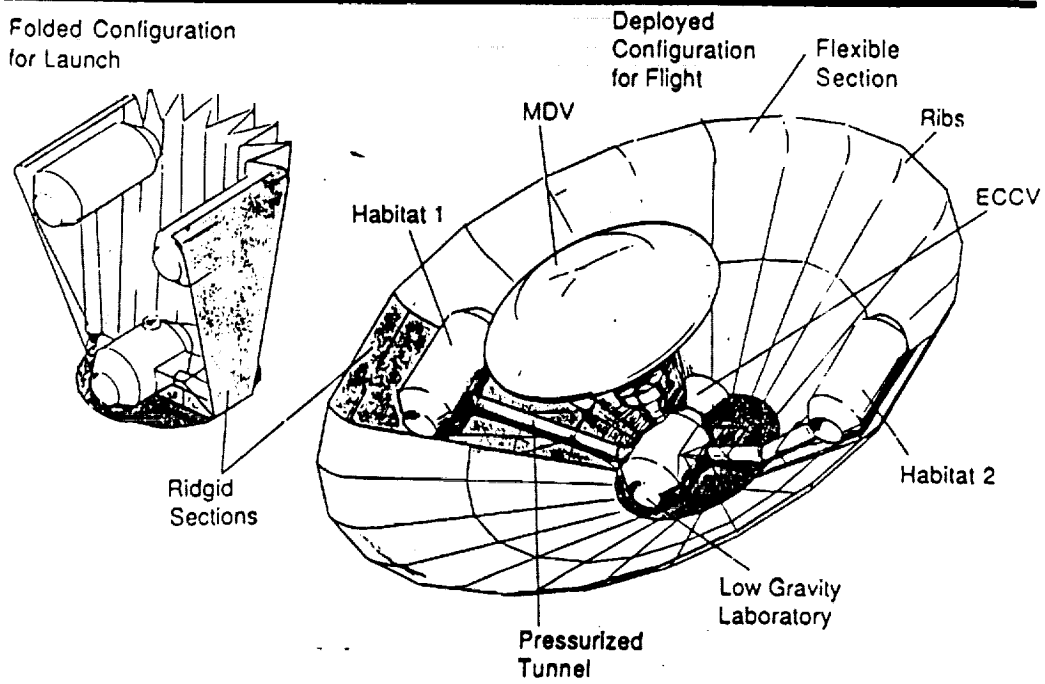
Counter-weight



Symmetrical

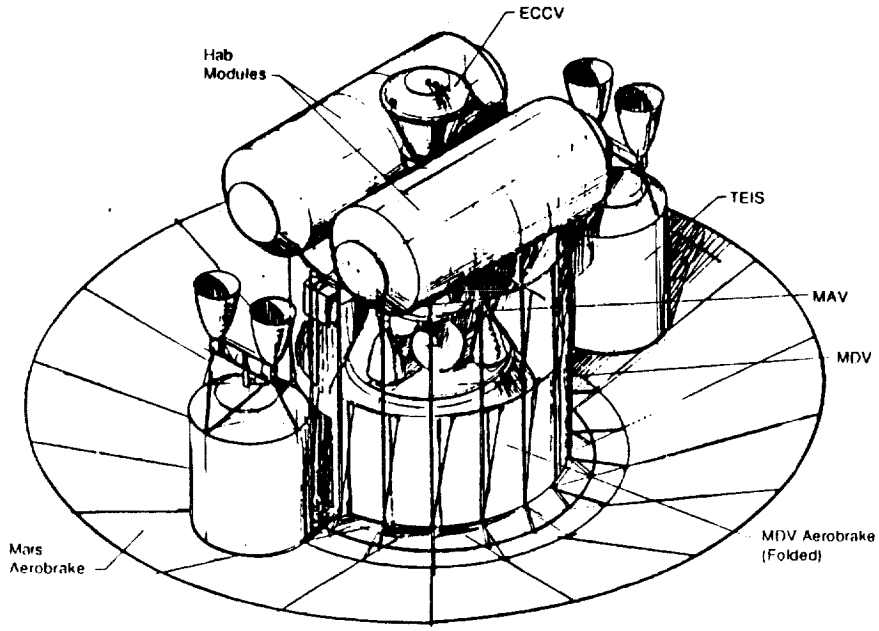
Stacked Disks

Deployable Aerobrake Configuration



Phobos Gateway, Mars Transfer Vehicle (MTV)

Vehicle



Mass Summary

Mass Breakdown

Mission	Traj	Code	TMIS	TEIS	MOOS	MTV-	MDV/ PhEV	ECCV (CERV)	Total IMLEO	MTV--a
Reference missions										
#1 ref*	OpVs	m-ON	373.5	41.8	5.8	114.7	22.8/10.1	5.6	575.9	87.5
#2 ref	Cn	m-OO	430.2	37.3	13.0	158.7	54.6/0	7.0	702.7	112.6
#3 ref	Cn	m-OP	387.2	29.3	12.6	158.2	54.6/0	7.0	650.8	111.1
#4 ref	Cn	m-OQ	373.6	29.3	12.4	154.1	54.6/0	7.0	632.9	110.1
Options										
#1a PhEV		m-OU	309.8	39.2	4.9	106.2	0/10.1	5.6	477.3	80.9
#1b MDV-		m-OV	668.7	58.0	118.5	157.2	22.8/0	5.6	1033.1	119.3
#1c MOV to Phobos		m-OW	542.2	52.5	95.2	139.6	0/0	5.6	837.1	105.8
#2a cryo descent		m-OX	429.2	37.3	12.9	158.4	54.1/0	7.0	700.8	112.4
#2b cryo ascent		m-OY	405.3	36.5	12.2	154.5	44.4/0	7.0	661.8	109.5
#2c cryo descent/ascent		m-OZ	404.4	36.5	12.2	154.4	44.1/0	7.0	660.4	109.4
#2d all prop		m-PB	749.2	57.6	201.1**	142.1	54.6/0	7.0	1211.6	81.0
#4p 120 t Phobos cargo		m-OS	251.6	-	22.1	-	-	-	422.6	
#4p' ditto, i=45°		m-OT	275.9	-	36.6	-	-	-	463.6	

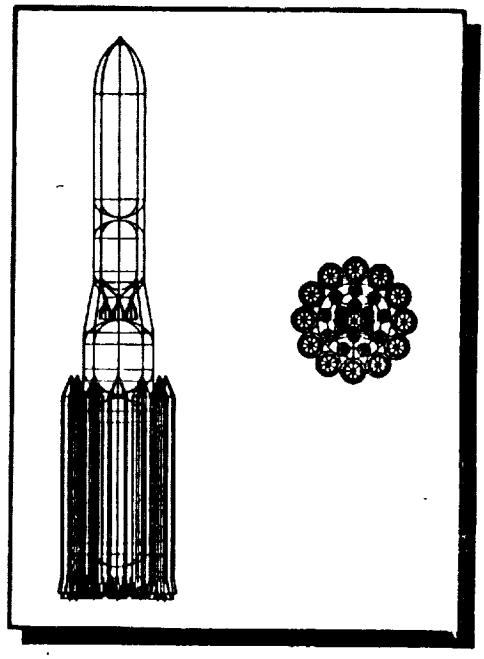
MTV- is MSS less TMIS, TEIS, MOOS, MOCS, MDV, PhEV, ECCV
MTV-- is MTV- less consumables, MOSE
MTV--a is MTV-- less artificial gravity propellant
MDV- is a MDV without a MAV

* "Forward Deployment" option (Mars habitat landed unmanned -- no MAV on MDV), with PhEV
** MOCS + MOOS + EOCS propulsion systems

575 t Super Magnum Tanker

Delivered Propellant	575 t [1267 Klbs]
GLOM	10589 t
Height	112.7 m
Orbit	407 x 407 Km 28.5°, ETR
Stage-1	12 ASRM's
Stage-2	13.7 m diameter 16 SSME's 2375 t prop 152 t dry
Stage-3	10 m diameter 4 SSME's 1294 t prop 67 t dry

Stage-2 SSME's ignited at liftoff



Shuttle-CZ

HLLV

Definition: A Shuttle-CZ is a launch vehicle which capitalizes on Shuttle-C design by addition of an upper stage which can be reused as a TMI propulsion system and/or to augment the lift-capability for launch of preassembled transfer vehicle hardware (dry) and cryopropellant.

Purpose: The Shuttle-CZ is viewed as a means of capturing selected minimum mass missions to Phobos, the martian surface, or the moon without development of an all-new HLLV system.

Groundrules:
- The system should be compatible with SSME and ASRM engine technology, and ET cryotankage technology [caveat: low boiloff tanks for TEI and TMI (possibly) are new designs].
- Payload shrouds up to 40-ft diameter should be the design objective
- Minimum modification to VAB, Pad 39B, and Michoud mfg. facilities is a design objective

Analysis: The following preliminary vehicle designs (based upon use of the Fly-It software tool to examine point design concepts -- full optimizations not complete) demonstrate payload-to-orbit capacity for various engine configurations:

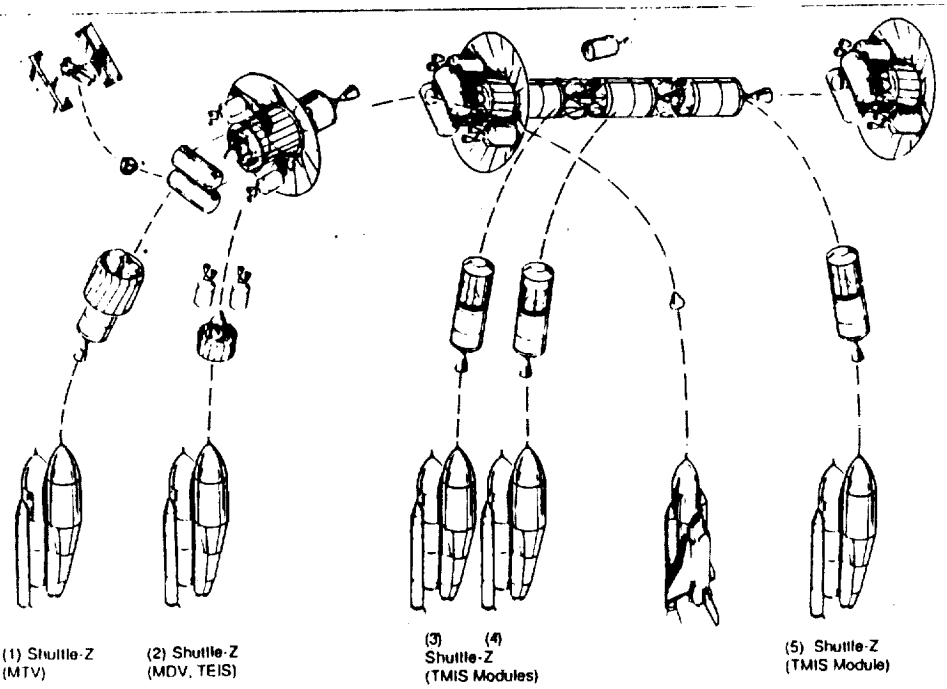
		Mass (t)			
ASRM's	SSME's	GLOM	Payload	Stg-3 dry	Total-to-orbit*
2	3 @ 100%	2208	108.2	11.7	119.9
2	3 @ 103 %	2213	112.7	11.7	124.4
2	3 @ 109 %	2220	120.7	11.7	132.4
2	4 @ 100 %	2243	139.7	11.7	151.4
2	8 @ 100 %	2970	175.0	45.0	220.0
2	8 @ 109%	2834	175.0	45.0	220.0

These designs result in vehicle stack heights compatible with VAB vertical clearances. Engine numbers may/should be compatible with flame trench capacity.

* Note: For a dual-use TMIS, the stage 3 mass should be added to "payload" mass to obtain the total useful mass delivered to orbit. For concerns with respect to the TMIS dual-use approach, see separate view-graph.

Manifest Sequence, Phobos Gateway

Manifest



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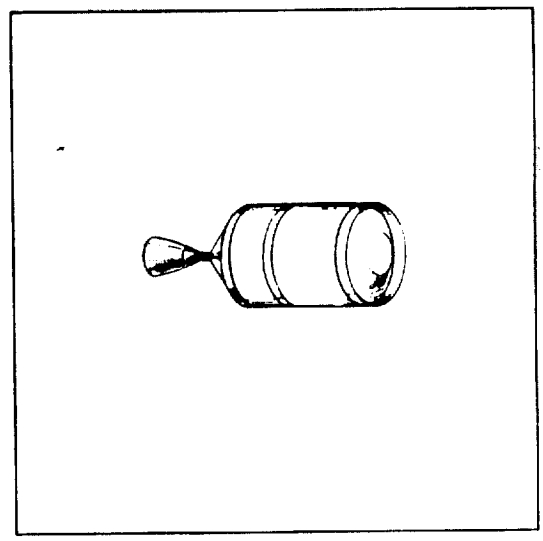
TMIS Propulsion Module and Shuttle-Z Stage 3

Propulsion: Rockets

Dry Mass	13,000 kg
Payload Mass	variable
Propulsion System	
Propellant Type	LOX/LH_2
Engines	
Number	1
Type	SSME/HE
Mass	3,630 kg
Size	
Length, extended [40-ft]	12.2 m
Length, nested [14-ft]	4.3 m
Exit diameter [24.5-ft]	7.5 m
Thrust @ 100% [498 klbf]	2,206 kN
I_{sp} (478 s)	4.68 kN-s/kg
Propellant Capacity	127,000 kg
Tank Mass	8,920 kg
Tankage factor	7.0 %
Total Mass (Wet)	140,000 kg



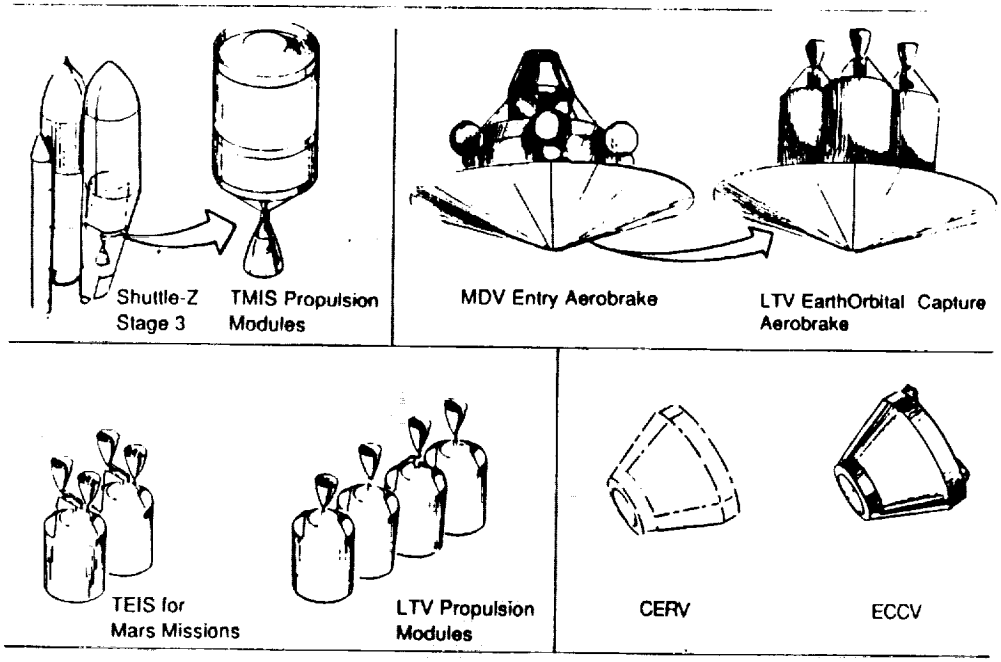
MARTIN MARIETTA V-G11.MMSS-45 Gateway Quick-Turn, 11/11/88

Mission #1 as Trailblazer

- **First Flag and Footprints, on Phobos**
- **Use of Phobos Excursion Vehicle (PhEV)**
  - Dramatic savings in LEO mass (IMLEO) and launch vehicle requirements
  - PhEV is a derivative of the Mars Ascent Vehicle (MAV)
  - Demonstration of MAV-type operations in Mars orbit -- rendezvous and docking
- **Landing of "Forward Deployment" Mars Descent Vehicle (MDV), unmanned**
  - Demonstration of safe landing of man-rated vehicle onto Martian surface
  - Robotic exploration of surface
  - Serves as surface-planted beacon for navigation and radio-guided pinpoint landings
  - First foothold on Mars. Could serve as a nucleus of future Mars Base
- **Reduced Risk Exposure of First Mission**
  - Opposition Class mission is shorter duration than Conjunction
  - 3 crew vs 5 crew members at risk
  - No manned landings or ascents, but
    - Demonstration of MAV orbital operations remote from Earth
    - Demonstration of MDV automated landing
    - Option: unmanned MAV could accomplish a sample return from the MDV, further demonstrating ascent capability
- **Science Bonus -- Venus**
  - Drop probes off at Venus during gravity-assisted turn (minor IMLEO penalty)

Note 1: milli-gee of Phobos makes walking impossible. Footprint by MMU-assisted feet-first flight into Phobos?
Note 2: Opposition class mission requires special thermal considerations because of initial sunward flight and Venus flyby
Note 3: 2004 Opposition/Venus swingby is an unusually favorable Opposition class opportunity

Commonality Candidates

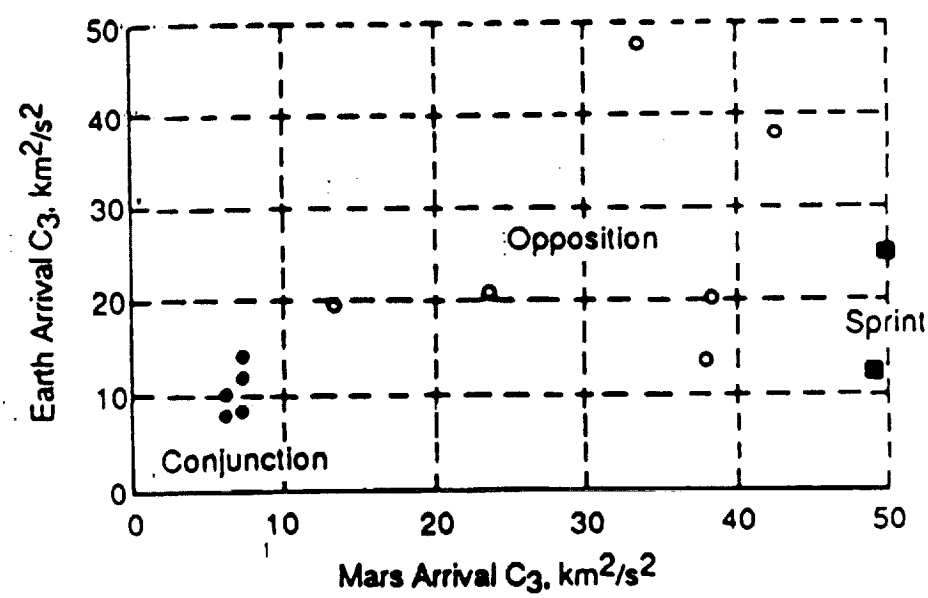


Applications -- MAV

Application	Propulsion System Mass (t)
Mars Ascent (MAV)	21.8
Lunar Ascent (LAV)	7.0*
Phobos Excursion (PhEV)	8 to 25**
Round-trip, SSF to GEO	42.8***
Round-trip, SSF to Mir	124
Round-trip, SSF to polar orbiting platform	not possible

Basis: Constant crew cab volume and mass (except for radiation shielding). Storable biprop (I_{sp}=320)

* Includes allowance for 1 t radiation shielding added to LAV
** Depends upon orbit of mother ship
*** Includes allowance for 0.5 t radiation shielding added for GEO excursion



Encounter Energetics

Astrodynamics

Preliminary

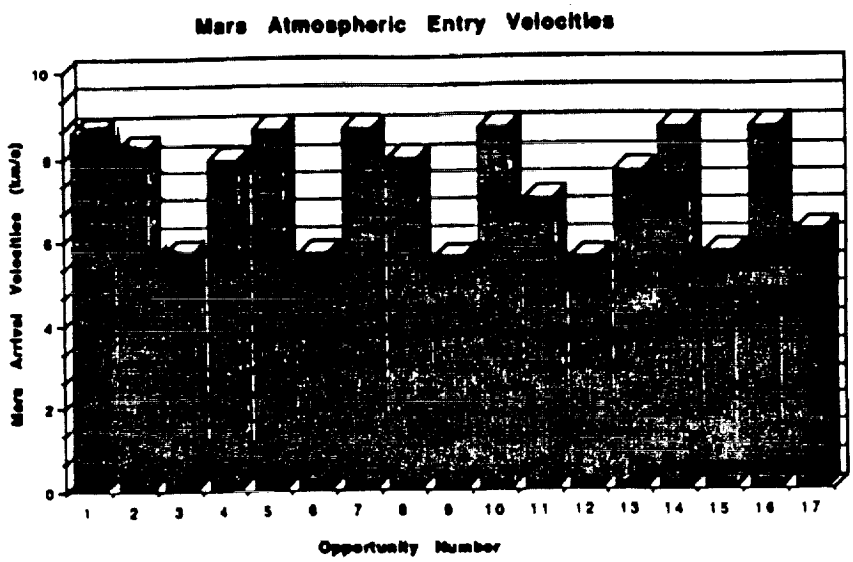
Opp. No.	Trajectory Class	Mars Arrival	C_3 (km^2/s^2)	Earth Arrival	C_3 (km^2/s^2)
1	Sprint	31-May-03	49.22	12-Nov-03	12.36
2	Opposition	21-Jun-03	42.63	20-Apr-04	38.03
3	Conjunction	29-Dec-03	7.28	13-Jan-06	12.07
4	Opposition	14-May-05	37.98	28-Mar-06	13.94
5	Sprint	01-Jul-05	**50.00**	23-Dec-05	25.00
6	Conjunction	12-Jun-06	7.10	27-Apr-08	8.56
7	Sprint	06-Aug-07	50.00	24-Feb-08	25.00
8	Opposition	01-Mar-08	38.51	17-Mar-09	20.47
9	Conjunction	10-Aug-08	6.03	23-May-10	8.02
10	Sprint	01-Oct-09	50.00	13-Apr-10	25.00
11	Opposition	07-Dec-09	23.62	21-Jan-11	21.06
12	Conjunction	19-Aug-10	6.07	25-Jun-12	10.25
13	Opposition	27-Sep-11	33.48	29-Aug-12	**47.71**
14	Sprint	14-Nov-1	50.00	25-May-12	24.97
15	Conjunction	11-Sep-12	7.31	28-Jul-14	14.21
16	Sprint	23-Dec-13	50.00	03-Jul-14	24.96
17	Opposition	18-Aug-14	13.40	15-Aug-15	19.86

Entry Velocities, Mars Arrival

Astrodynamics

Mars Atmospheric Entry Velocities (km/s)

Opportunity Number	Trajectory Class	Mars Arrival	Mars Entry Velocities	
1	Sprint	31-May-03	8.626 km/s	[28300 fps]
2	Opposition	21-Jun-03	8.235 km/s	[27017 fps]
3	Conjunction	29-Dec-03	5.699 km/s	[18697 fps]
4	Opposition	14-May-05	7.948 km/s	[26076 fps]
5	Sprint	01-Jul-05	8.671 km/s	[**28448** fps]
6	Conjunction	12-Jun-06	5.682 km/s	[18642 fps]
7	Sprint	06-Aug-07	8.671 km/s	[28448 fps]
8	Opposition	01-Mar-08	7.981 km/s	[26184 fps]
9	Conjunction	10-Aug-08	5.588 km/s	[18333 fps]
10	Sprint	01-Oct-09	8.671 km/s	[28448 fps]
11	Opposition	07-Dec-09	6.986 km/s	[22920 fps]
12	Conjunction	19-Aug-10	5.591 km/s	[18343 fps]
13	Opposition	27-Sep-11	7.659 km/s	[25128 fps]
14	Sprint	14-Nov-11	8.671 km/s	[28448 fps]
15	Conjunction	11-Sep-12	5.701 km/s	[18704 fps]
16	Sprint	23-Dec-13	8.671 km/s	[28448 fps]
17	Opposition	18-Aug-14	6.212 km/s	[20380 fps]

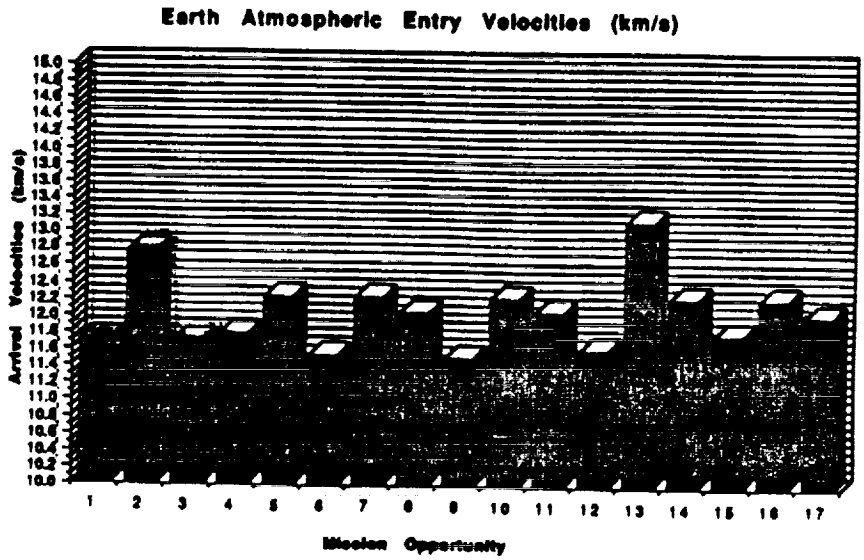


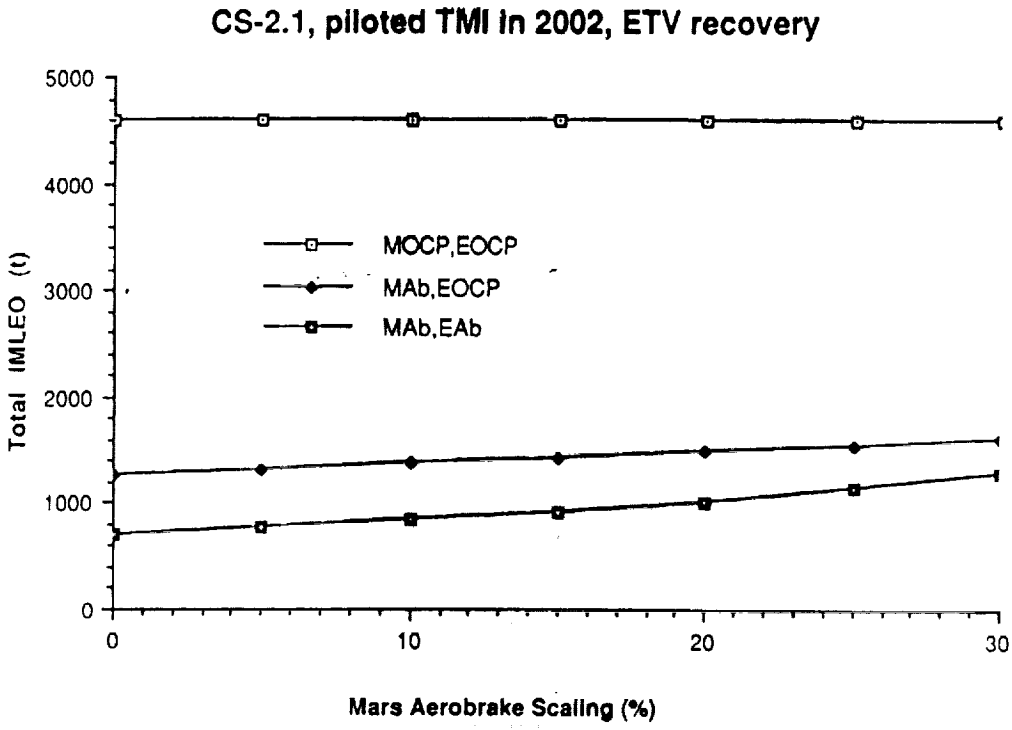
Entry Velocities, Earth Arrival

Astrodynamics

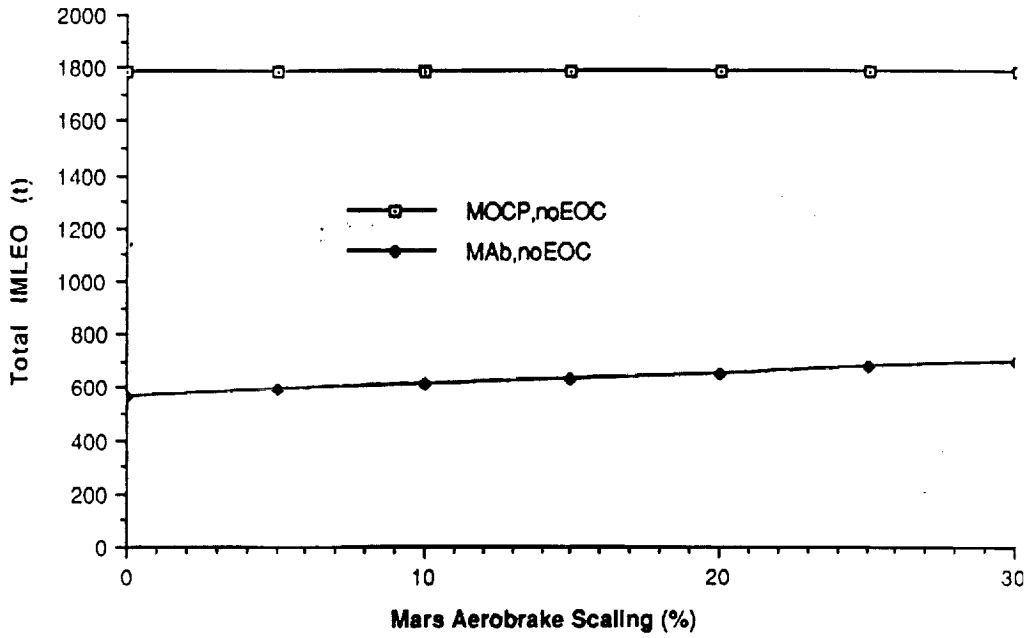
Earth Atmospheric Entry Velocities (km/s)

Opportunity Number	Trajectory Class	Earth Arrival	Earth Entry Velocities	
1	Sprint	12-Nov-03	11.713 km/s	[38428 fps]
2	Opposition	20-Apr-04	12.762 km/s	[41870 fps]
3	Conjunction	13-Jan-06	11.700 km/s	[38385 fps]
4	Opposition	28-Mar-06	11.780 km/s	[38648 fps]
5	Sprint	23-Dec-05	12.241 km/s	[40160 fps]
6	Conjunction	27-Apr-08	11.549 km/s	[37890 fps]
7	Sprint	24-Feb-08	12.241 km/s	[40160 fps]
8	Opposition	17-Mar-09	12.054 km/s	[39547 fps]
9	Conjunction	23-May-10	11.526 km/s	[37815 fps]
10	Sprint	13-Apr-10	12.241 km/s	[40160 fps]
11	Opposition	21-Jan-11	12.079 km/s	[39629 fps]
12	Conjunction	25-Jun-12	11.622 km/s	[38130 fps]
13	Opposition	29-Aug-12	13.135 km/s	[43093 fps]
14	Sprint	25-May-12	12.239 km/s	[40154 fps]
15	Conjunction	28-Jul-14	11.791 km/s	[38684 fps]
16	Sprint	03-Jul-14	12.239 km/s	[40154 fps]
17	Opposition	15-Aug-15	12.029 km/s	[39465 fps]

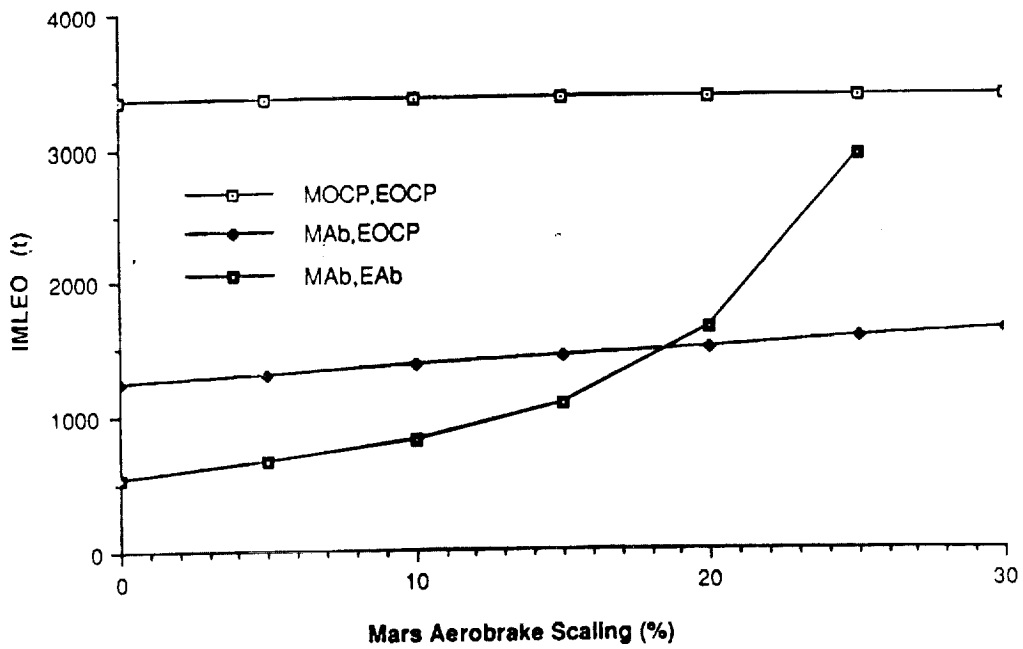

Earth Atmospheric Entry Velocities (km/s)
Arrival Velocities (km/s)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Mission Opportunity

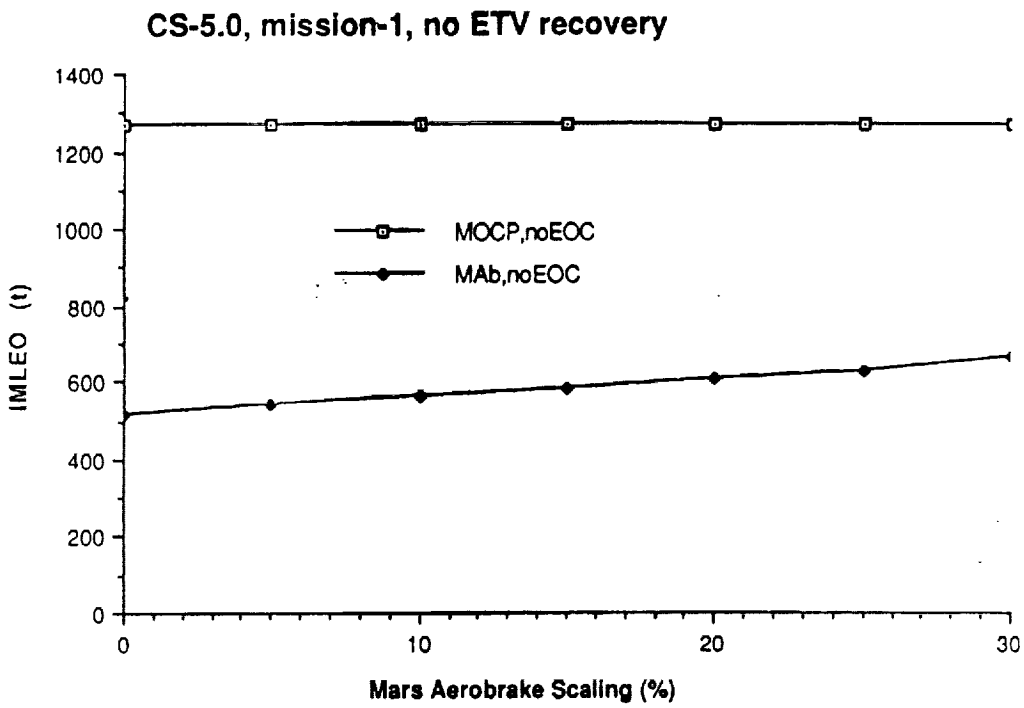

CS-2.1, piloted TMI in 2002, ETV recovery
Total IMLEO (t)
5000
4000
3000
2000
1000
0
MOCP,EOCP
MAb,EOCP
MAb,EAb
0
10
20
30
Mars Aerobrake Scaling (%)

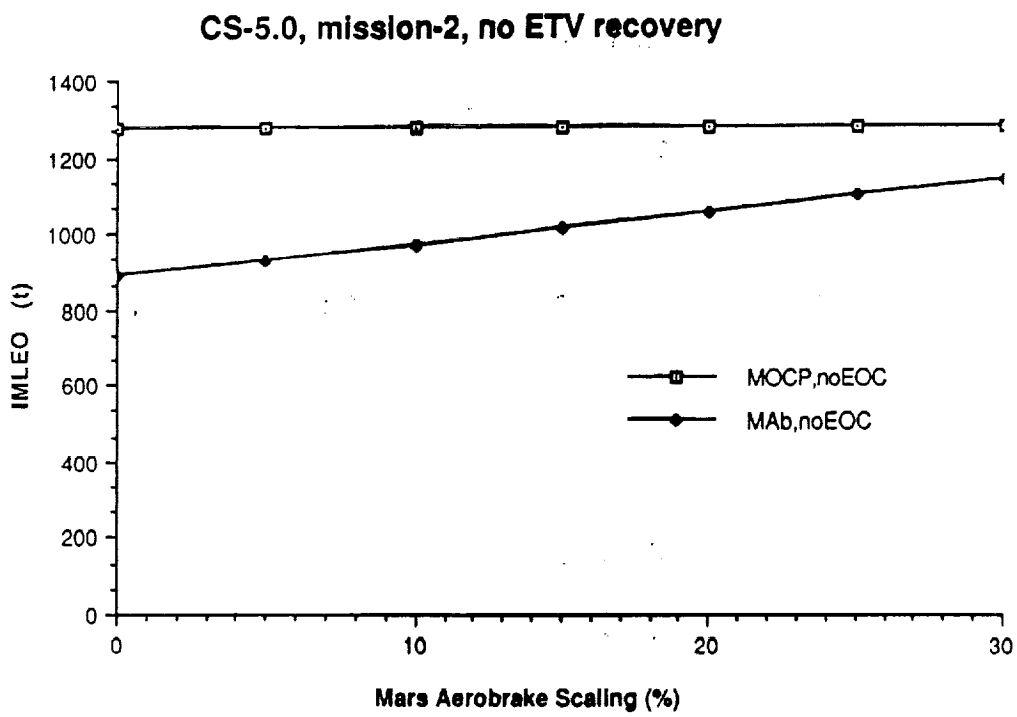
CS-2.1, piloted TMI in 2002, no ETV recovery

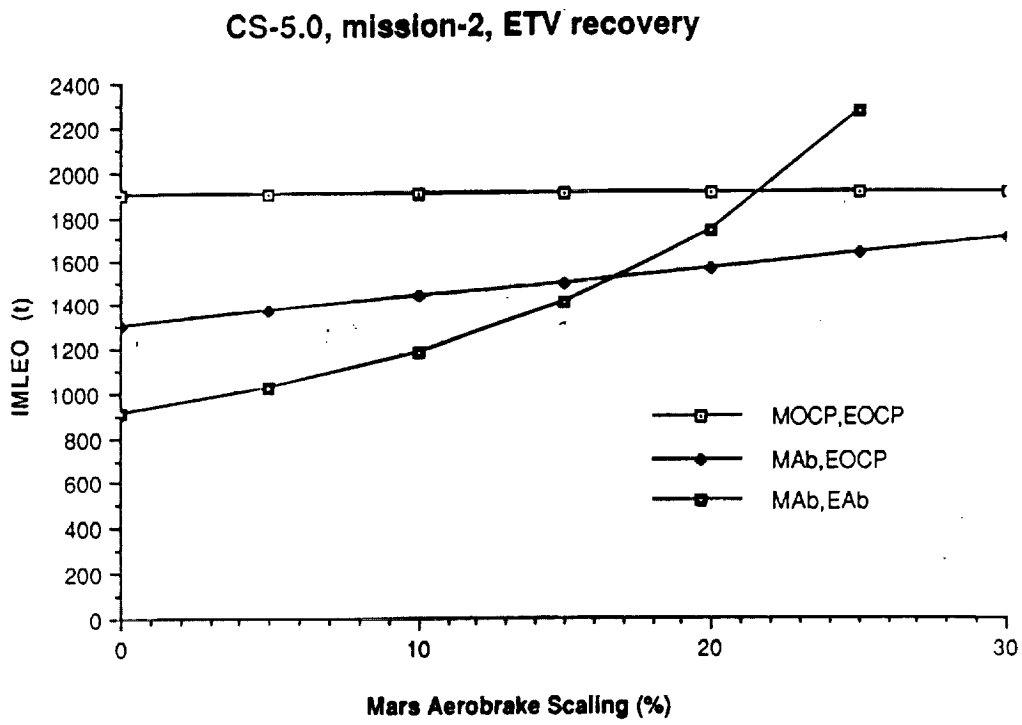


CS-5.0, mission-1, ETV recovery

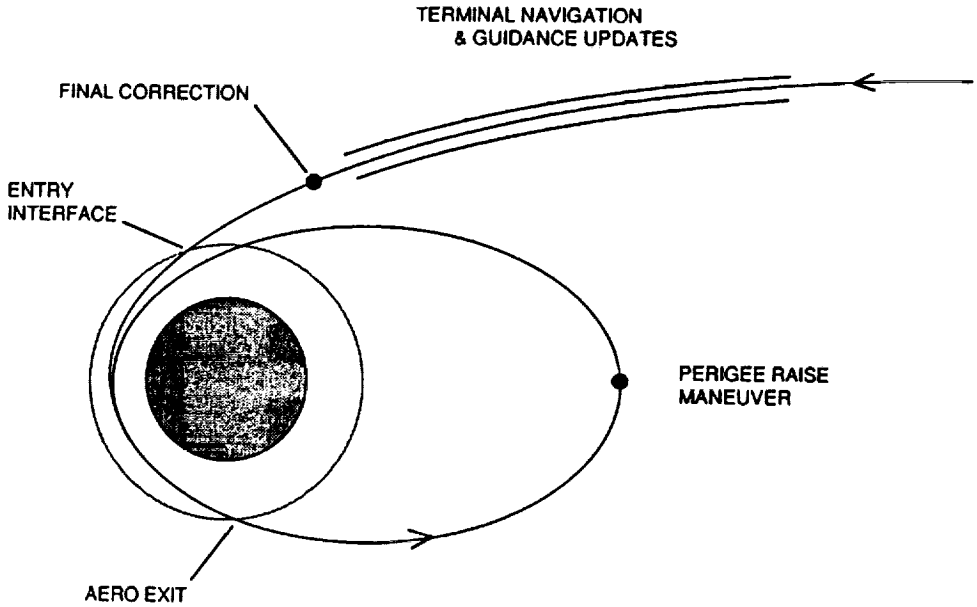



CS-5.0, mission-1, no ETV recovery
1400
1200
1000
800
600
400
200
0
IMLEO (t)
MOCP,noEOC
MAb,noEOC
0
10
20
30
Mars Aerobrake Scaling (%)


CS-5.0, mission-2, no ETV recovery
1400
1200
1000
800
600
400
200
0
IMLEO (t)
MOCP,noEOC
MAb,noEOC
0
10
20
30
Mars Aerobrake Scaling (%)


CS-5.0, mission-2, ETV recovery
IMLEO (t)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
Mars Aerobrake Scaling (%)
MOCP,EOCP
MAb,EOCP
MAb,EAb

AEROASSIST OVERVIEW



MARTIN MARIETTA

CURRENT AEROASSIST APPLICATIONS

- AERODYNAMIC FLIGHT EXPERIMENT (AFE) - 1992
  - STS PAYLOAD OF OPPORTUNITY
  - VERIFY AEROASSIST TECHNIQUE & THERMAL MODELS
- ORBITAL TRANSFER VEHICLE (OTV) - 1996(?)
  - RE-USABLE CRYOGENIC UPPER STAGE
  - AEROASSIST MAXIMIZES VEHICLE EFFICIENCY
- MARS ROVER / SAMPLE RETURN MISSION (MRSR) - 1998 (?)
  - AEROCAPTURE AT MARS AND EARTH RETURN
  - PINPOINT LANDING ON SURFACE OF MARS
- CIVIL SPACE LEADERSHIP INITIATIVES (CSLI)
  - 3 OF 4 INITIATIVES DEPEND ON AEROASSIST:
    LUNAR BASE
    UNMANNED PLANETARY
    MANNED PLANETARY

MARTIN MARIETTA

MANNED VS UNMNANNED MARS AEROCAPTURE

DIFFERENT REQUIREMENTS DRIVE DIFFERENT ANSWERS FOR AEROCAPTURE AT MARS

SUMMARIZED BELOW ARE MARS SAMPLE RETURN (MRSR) AND PATHFINDER MANNED MARS REQUIREMENTS THAT DRIVE L/D

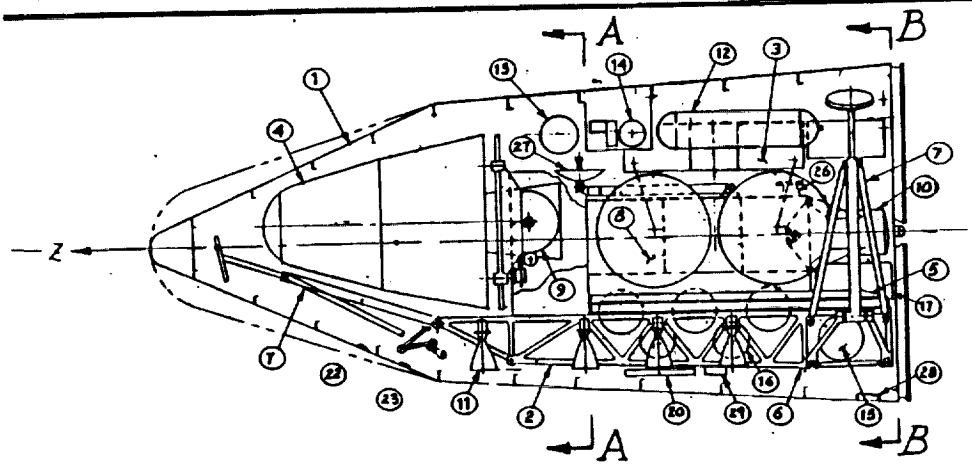
	MRSR	MANNED MARS
LAUNCH DATE	1996-1998	2004+
ON-ORBIT ASSEMBLY	NO	PROBABLY
ENCOUNTER NAVIGATION	EARTH BASED	VEHICLE-BASED (MAN-RATING)

MRSR CONSTRAINED BY NAV ACCURACY AND LAUNCH PACKAGING ===> MID L/D SOLUTION

MANNED MARS FREE TO UTILIZE WIDE RANGE OF L/D'S

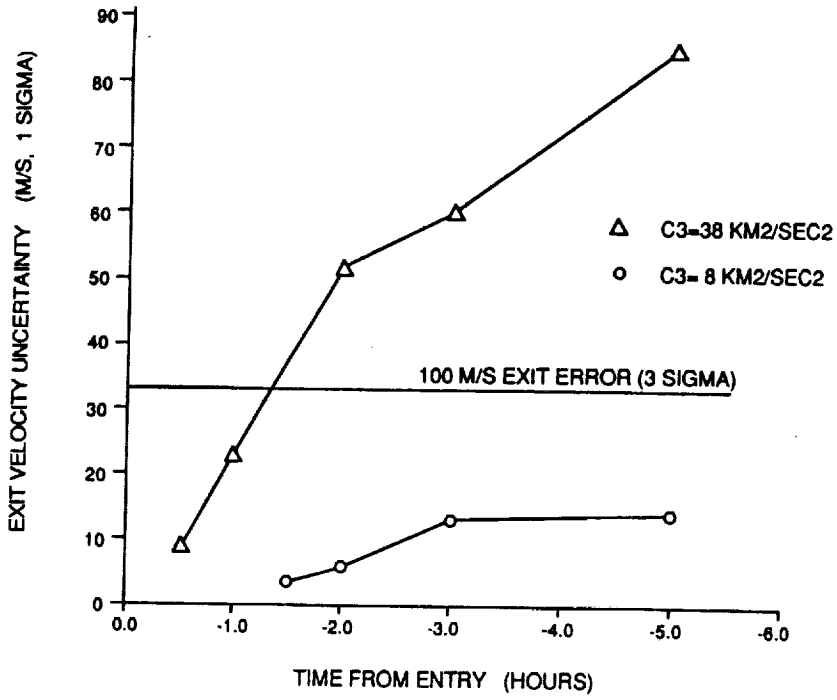
MARTIN MARIETTA

CONFIGURATION D1 - CRUISE PHASE



1. AEROSHELL
2. LANDER
3. ROVER
4. ASCENT VEHICLE (MAV)
5. ROVER EXIT RAMP
6. LANDER STRUCTURE
7. LANDING LEG ASSY (3)
8. EQUIPMENT COMP'T
9. MAV ROTATION/REL. SYS.
10. PARACHUTE/REL. SYS.
11. TERM. DESCENT 12000 ENG. (9)
12. AEROSHELL PROP. TANK (2)
13. AEROSHELL PRESS. TANK (2)
14. REACTION WHEELS (4)
15. LANDER PROP. TANK (4)
16. LANDER PRESS. TANK (2)
17. LANDER RTG
18. LANDER SEPARATION MECH (4)
19. GUIDE RAIL/ROLLERS (2)
20. TERM. DESCENT LANDING RADAR
21. HAZARD AVOID. OPTICS

MARTIN MARIETTA

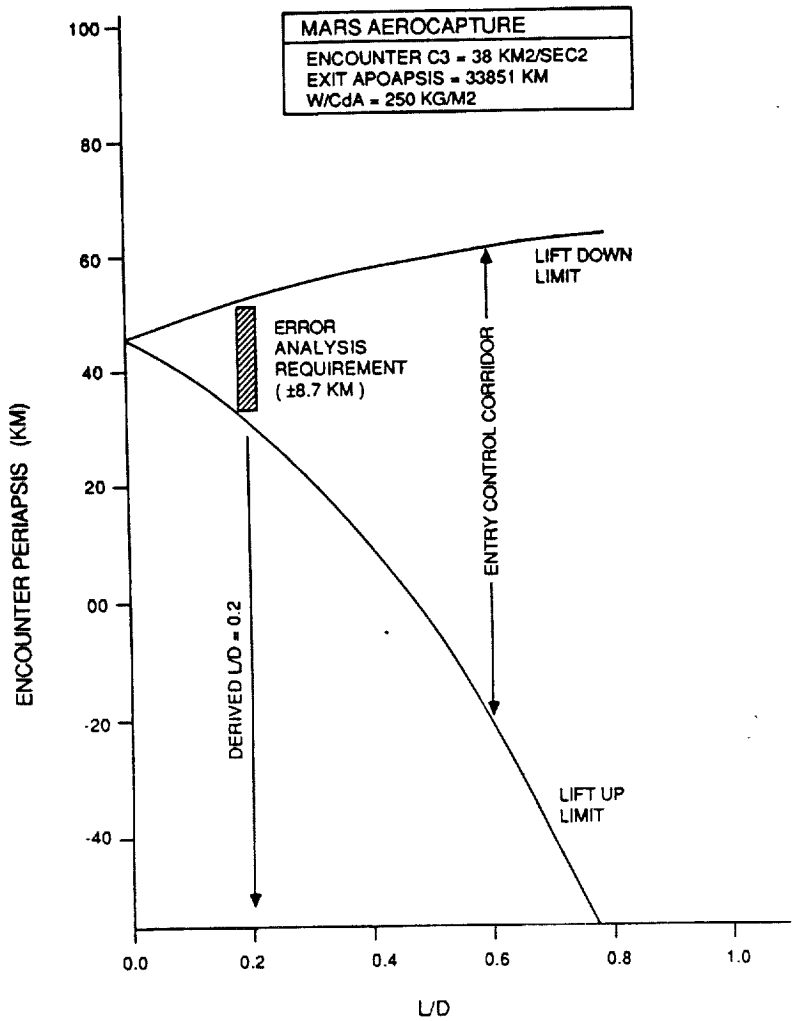


1) MARS CAPTURE, SPACE SEXTANT TYPE MEASUREMENTS (1 ARC SEC)

MANNED MARS ERROR ANAL

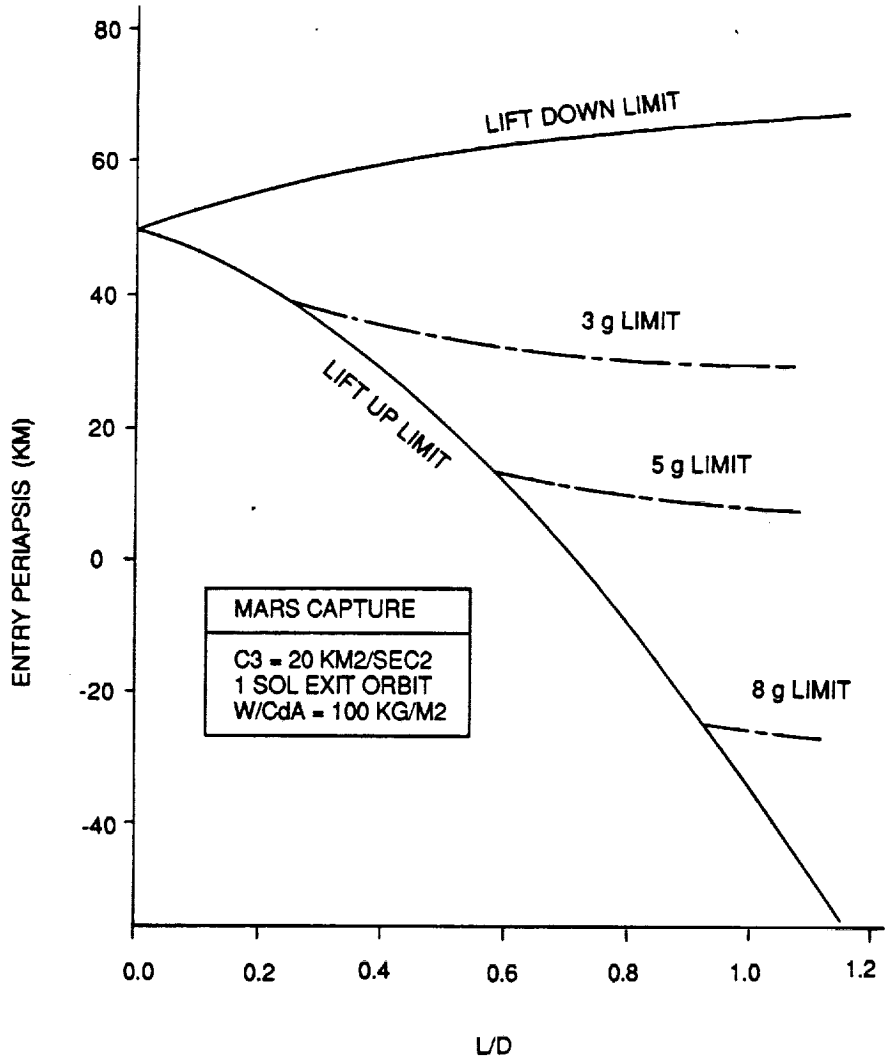
	EQUIVALENT PERIAPSIS VARIATION (KILOMETERS)	EQUIVALENT PERIAPSIS VARIATION (FLT PATH ANG AT125 KM)	COMMENTS
TARGETING ERRORS			
FINAL MIDCOURSE (E-5 HR)			MIDCOURSE EXECUTED AT ENTRY - 5 HRS
EXECUTION ERRORS	±1.09 KM	±0.08°	
NAV ERRORS	±2.36 KM	±0.16°	
FINAL NAV ERRORS (E-1 HR)	±1.22 KM	±0.08°	NAV SIGHTINGS TERMINATE AT ENTRY - 1 HOUR
AERODYNAMIC VARIATION			
ATMOSPHERIC VARIATION	±4.72 KM	±0.33°	±50% DENSITY VARIATION
L/D UNCERTAINTY	±3.78 KM	±0.26°	±2.0° AT 12° ANGLE OF ATTACK (±17% L/D)
RSS OF VARIATIONS	±6.70 KM	±0.46°	
RSS + 30%	±8.70 KM	±0.61°	

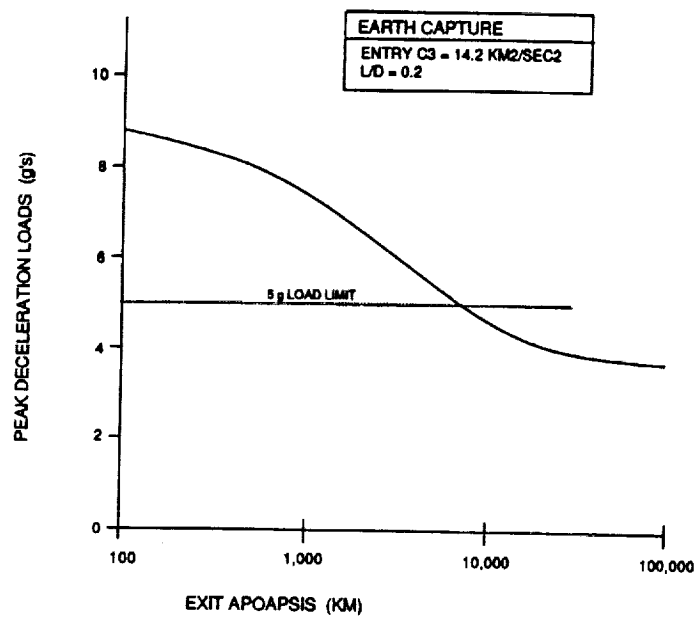
FOR C3=38 KM2/SEC2, 0.2 L/D IS REQUIRED



DERIVATION OF MINIMUM L/D FROM ERROR ANALYSIS REQMTS

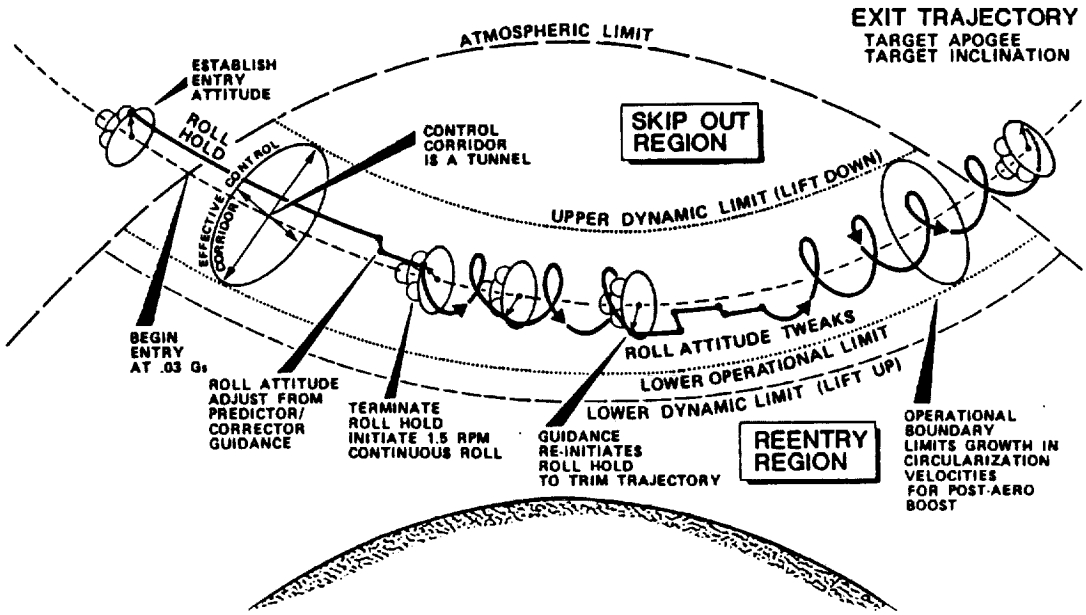
ENTRY CTRL PARAMS C3=38, MKS



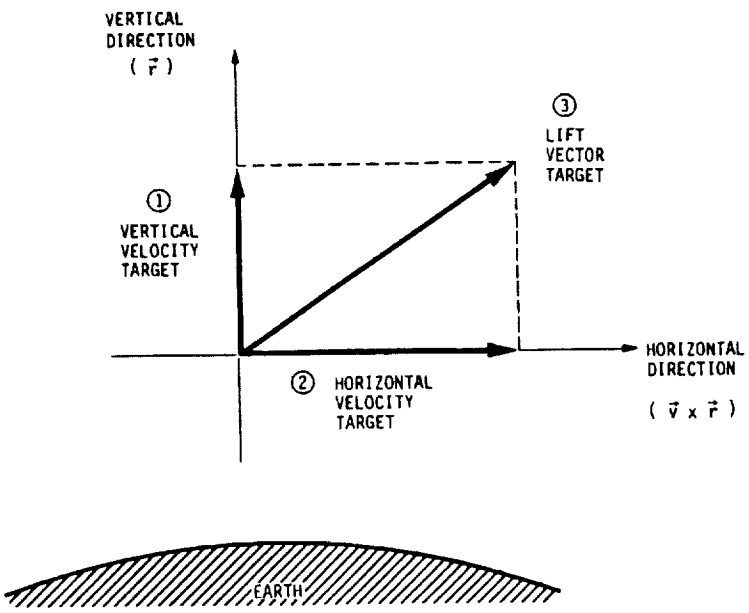


EARTH CAPTURE g LOADS VS EXIT APOAPSIS

AERO-ENTRY OVERVIEW



LIFT VECTOR TARGETING



VIEW LOOKING FORWARD INTO DIRECTION OF TRAVEL

VERTICAL VELOCITY TARGET ① FROM APOGEE GUIDANCE LOGIC

HORIZONTAL VELOCITY TARGET ② FROM INCLINATION GUIDANCE LOGIC

VECTOR ADDITION OF ① AND ② YIELDS LIFT VECTOR TARGET ③

LIFT TARGET DIRECTION DETERMINES ROLL ATTITUDE

LIFT TARGET MAGNITUDE DETERMINES HOLD DURATION

MARTIN MARIETTA

MARS CAPTURE, L/D=0.20, W/CdA=250 KG/M2, C3=38 KM2/SEC2
PERFECT NAVIGATION

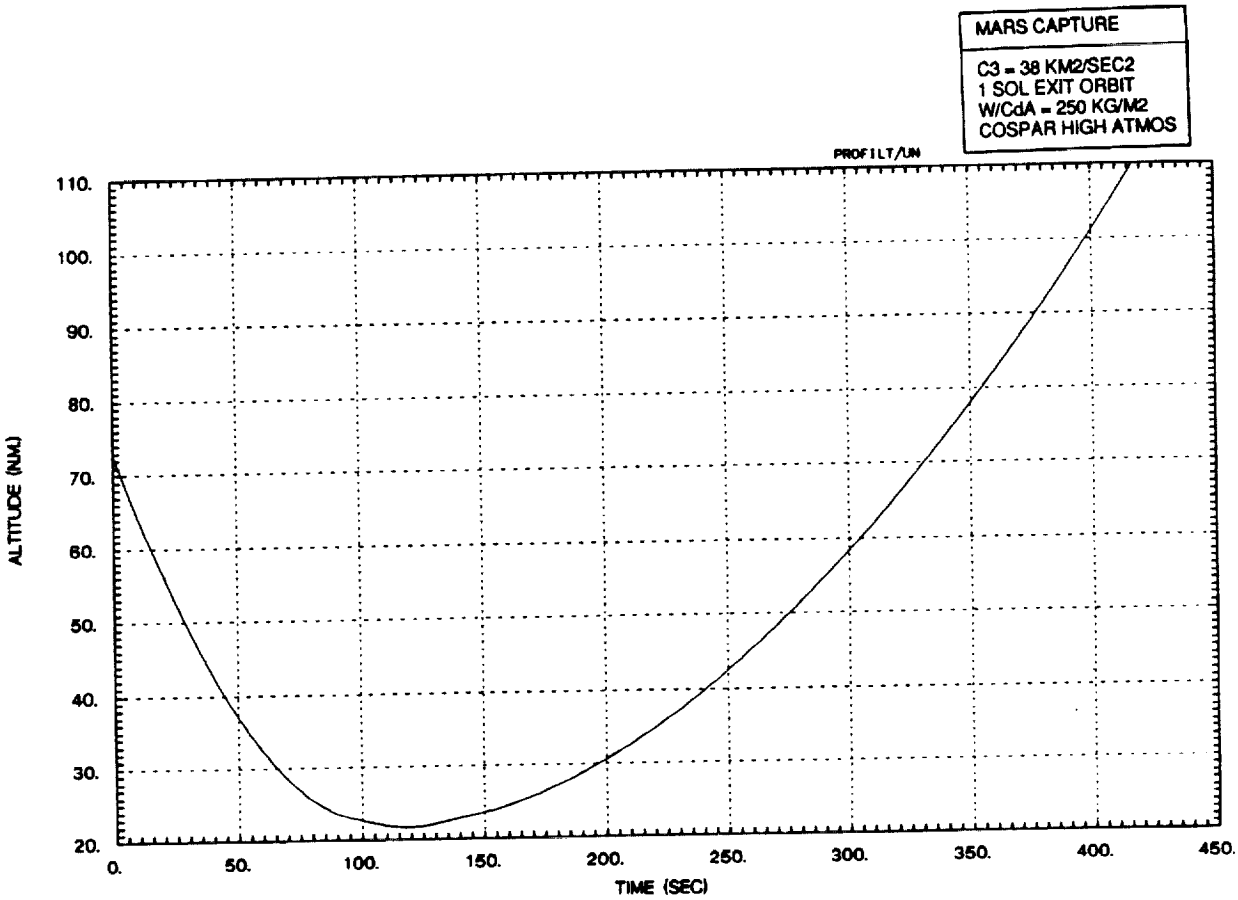
DISPERSION	EXIT ORBIT PERIAPSIS (KM)	EXIT ORBIT APOAPSIS (KM)	ΔV TO REACH PARK ORBIT (MPS)**	PEAK LOADS (g's)
NOMINAL	34.8	33849.2	12.4	4.22
LOW PRES ATMOS	36.3	36561.4	26.1	4.26
HIGH PRES ATMOS	34.4	32018.9	24.3	3.99
VIKING 1 ATMOS	36.5	36640.5	26.0	4.24
VIKING 2 ATMOS	38.7	35339.3	19.7	4.39
ΔPER = +2.59 km*	34.8	33849.7	12.4	4.23
ΔPER = -2.59 km*	34.8	33853.1	12.4	4.22
Δ ALPHA = +2.0°	35.0	33839.2	12.5	4.31
Δ ALPHA = -2.0°	34.4	33844.4	12.5	4.12
RMS OF DELTAS FROM NOMINAL	1.6	1609.3	8.4	0.11

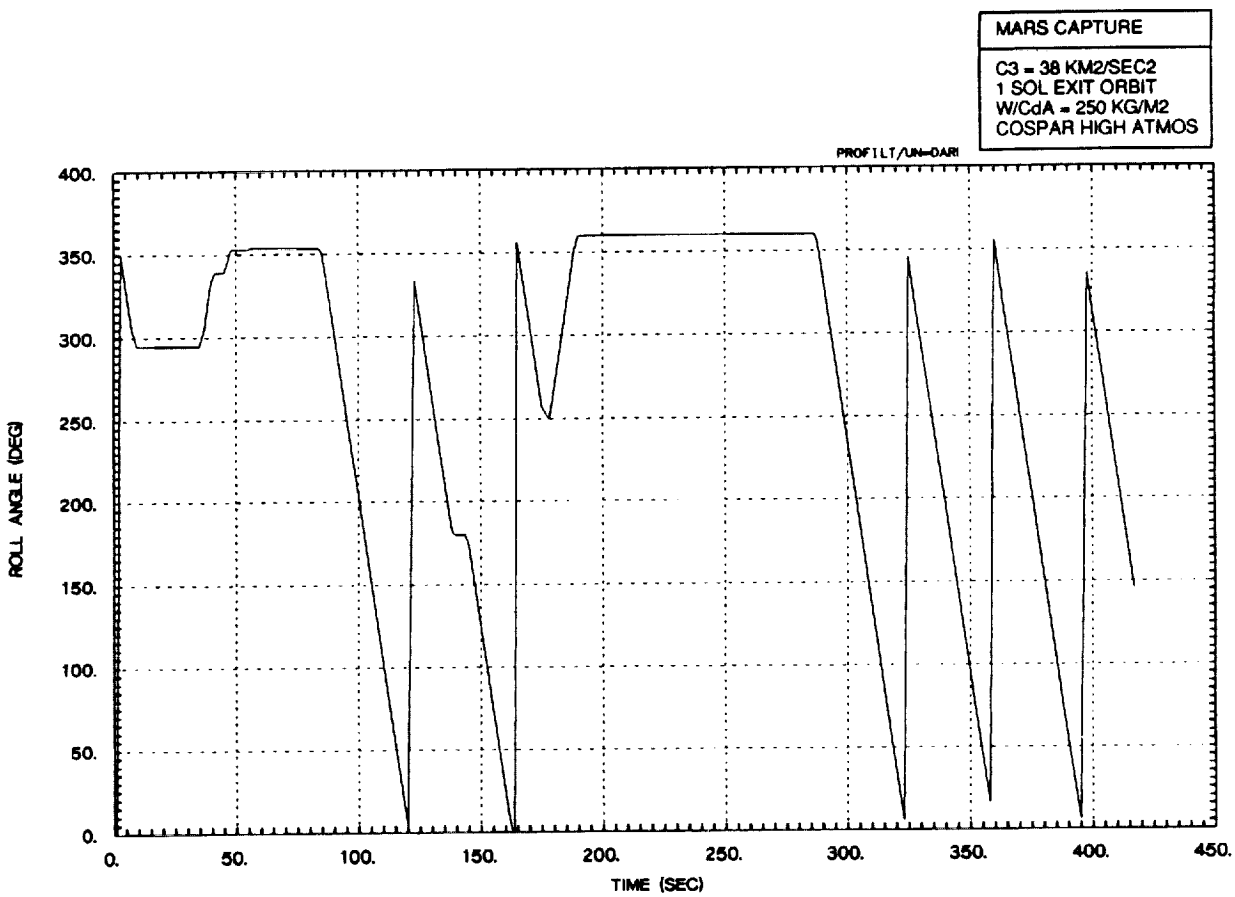
* DELTA FLIGHT PATH ANGLE = ±0.17° (AT 125 KM)
** FINAL PARK ORBIT OF 250 X 33851 KM IS REACHED VIA
ΔV1 AT APOAPSIS FOLLOWED BY ΔV2 AT PERIAPSIS (ΔV=ΔV1+ΔV2)

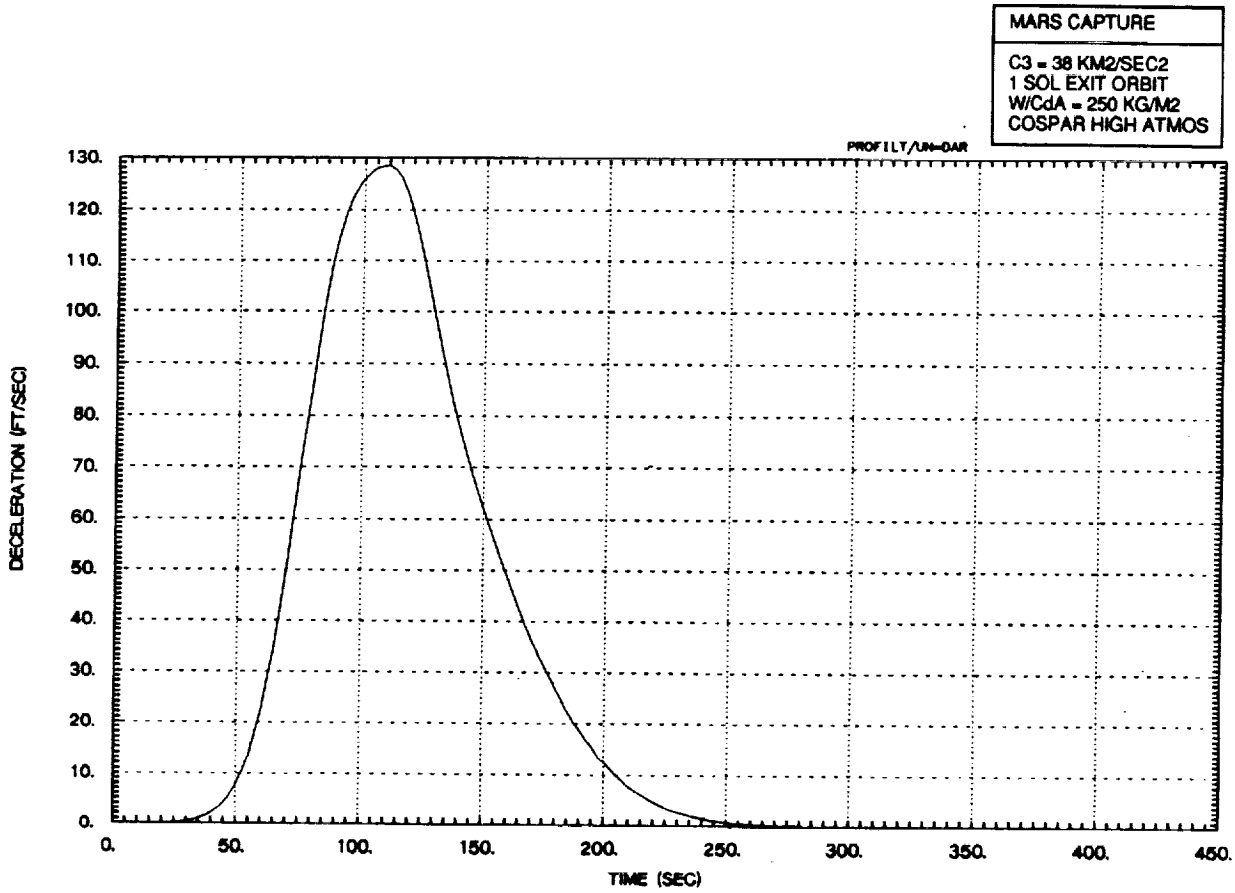
MARS CAPTURE, L/D=0.20, W/CdA=250 KG/M2, C3=38 KM2/SEC2
NAVIGATION FOR ENTRY MINUS 1 HOUR TERMINATION

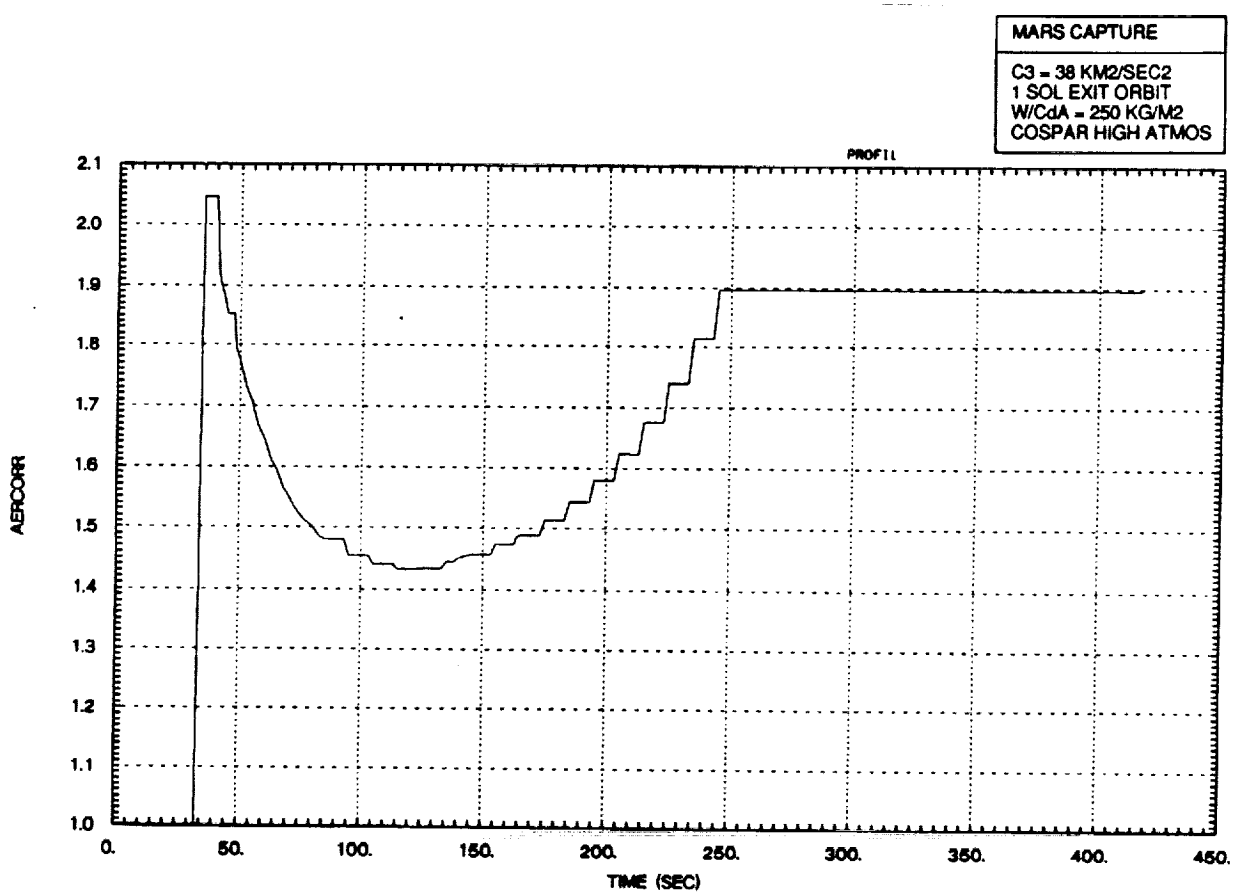
DISPERSION	EXIT ORBIT PERIAPSIS (KM)	EXIT ORBIT APOAPSIS (KM)	ΔV TO REACH PARK ORBIT (MPS)**	PEAK LOADS (g's)
NOMINAL	34.8	33849.2	12.4	4.22
LOW PRES ATMOS	30.9	25826.9	71.1	4.07
HIGH PRES ATMOS	28.3	22808.3	101.7	4.18
VIKING 1 ATMOS	32.4	26159.9	68.0	4.20
VIKING 2 ATMOS	28.9	24085.4	88.1	4.58
ΔPER = +2.59 km*	29.1	24894.4	80.0	4.40
ΔPER = -2.59 km*	28.2	23390.0	95.4	4.38
Δ ALPHA = +2.0°	21.9	24816.2	81.3	4.50
Δ ALPHA = -2.0°	26.1	20508.9	129.7	4.27
RMS OF DELTAS FROM NOMINAL	7.2	9936.4	79.2	0.19

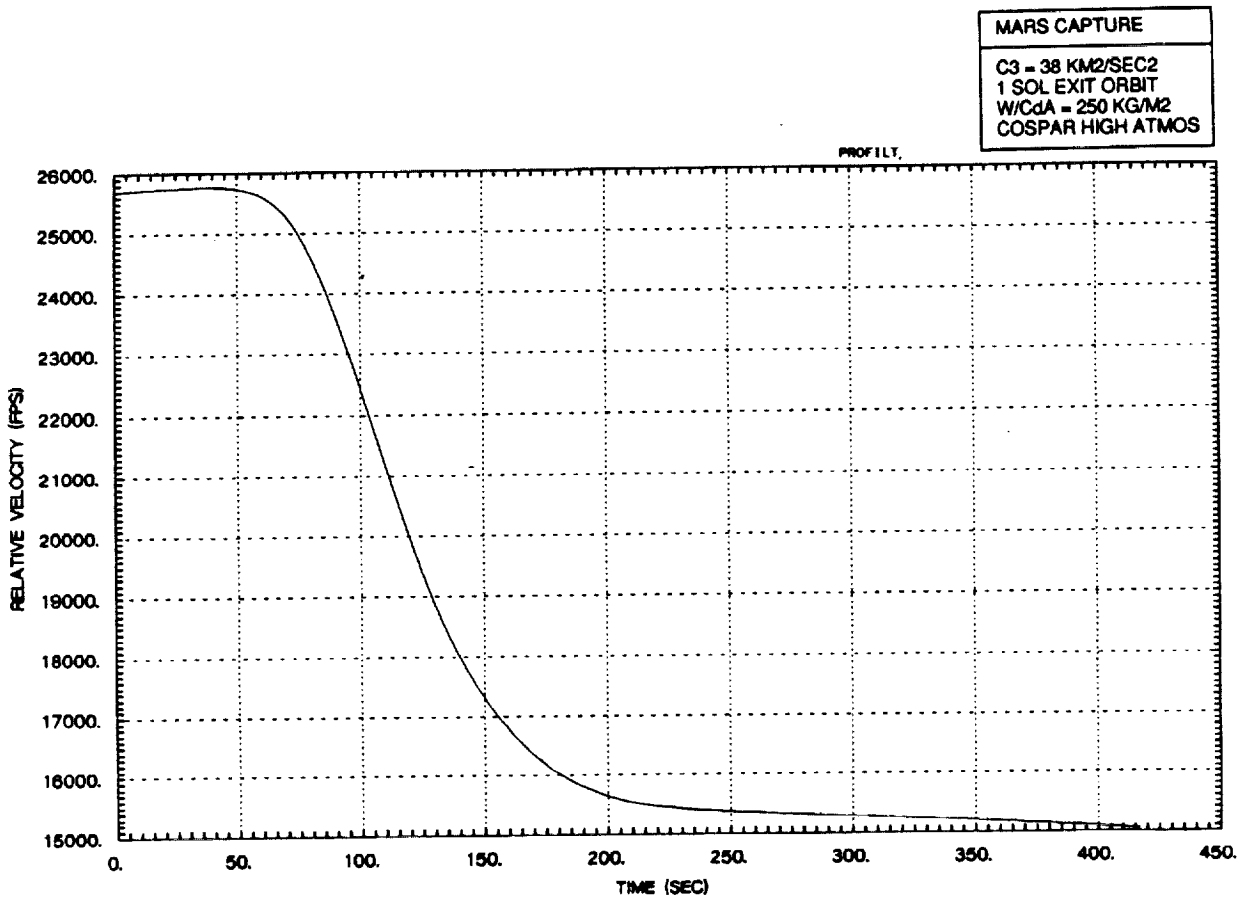
* DELTA FLIGHT PATH ANGLE = ±0.17° (AT 125 KM)
** FINAL PARK ORBIT OF 250 X 33851 KM IS REACHED VIA
ΔV1 AT APOAPSIS FOLLOWED BY ΔV2 AT PERIAPSIS (ΔV=ΔV1+ΔV2)

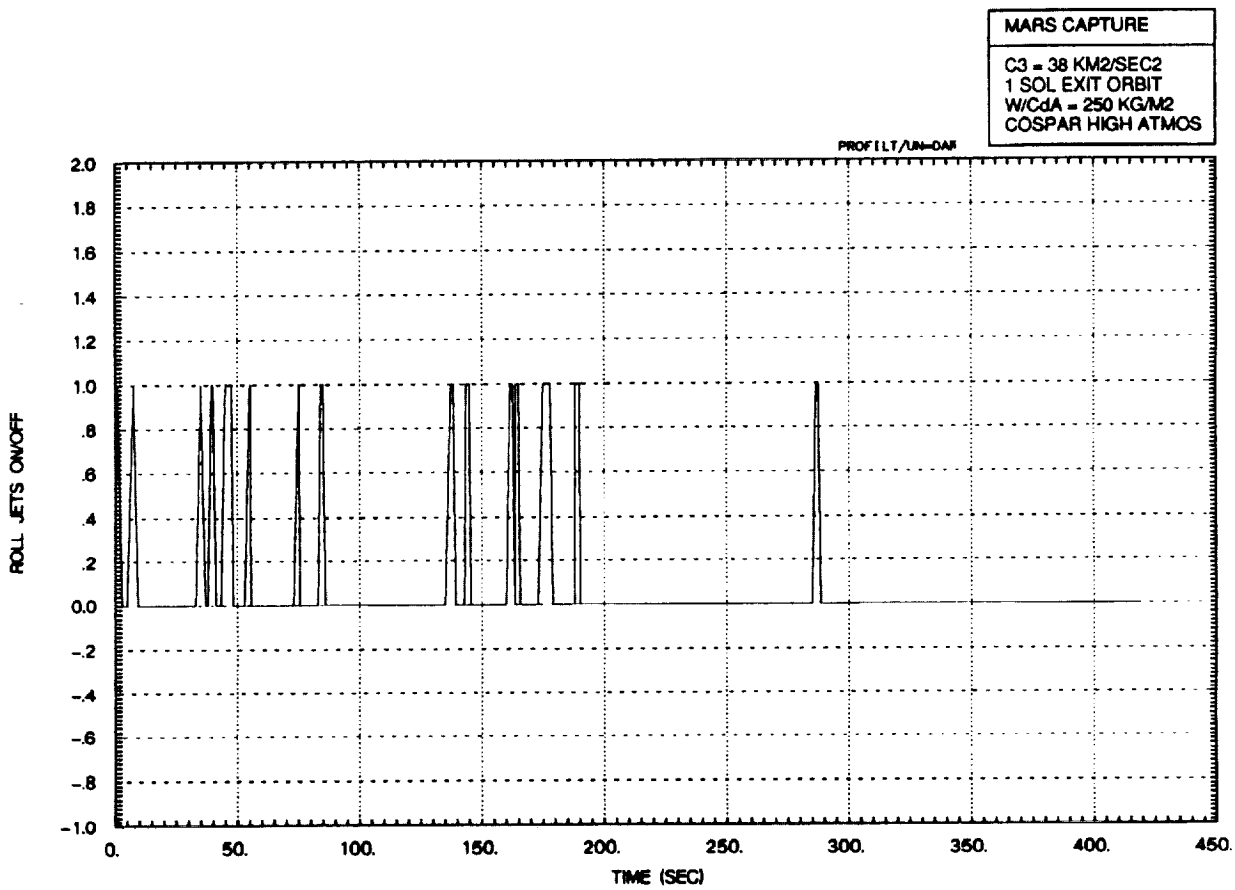

MARS CAPTURE
C3 = 38 KM2/SEC2
1 SOL EXIT ORBIT
W/CdA = 250 KG/M2
COSPAR HIGH ATMOS
PROFILT/UN
ALTITUDE (NM)
110.
100.
90.
80.
70.
60.
50.
40.
30.
20.
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
TIME (SEC)


MARS CAPTURE
C3 = 38 KM2/SEC2
1 SOL EXIT ORBIT
W/CdA = 250 KG/M2
COSPAR HIGH ATMOS
PROFILT/UN-DARI
ROLL ANGLE (DEG)
400.
350.
300.
250.
200.
150.
100.
50.
0.
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
TIME (SEC)

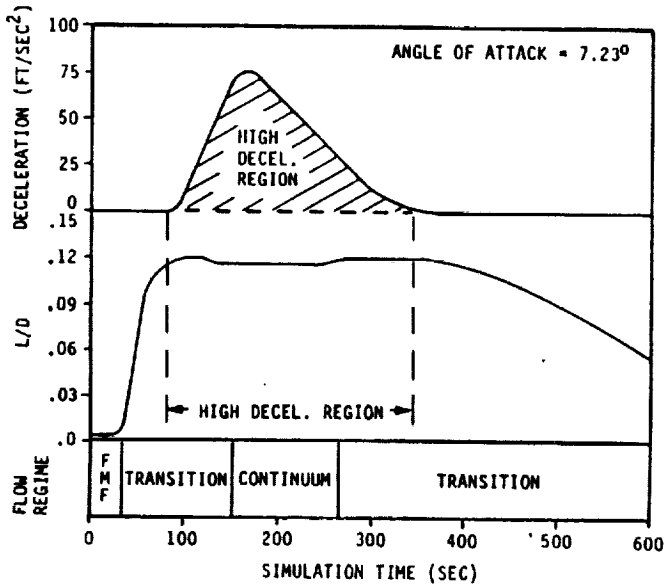

MARS CAPTURE
C3 = 38 KM2/SEC2
1 SOL EXIT ORBIT
W/CdA = 250 KG/M2
COSPAR HIGH ATMOS
PROFILT/UN-DAR
DECELERATION (FT/SEC)
130.
120.
110.
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
TIME (SEC)


MARS CAPTURE
C3 = 38 KM2/SEC2
1 SOL EXIT ORBIT
W/CdA = 250 KG/M2
COSPAR HIGH ATMOS
PROFIL
AERCORR
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
TIME (SEC)


MARS CAPTURE
C3 = 38 KM2/SEC2
1 SOL EXIT ORBIT
W/CdA = 250 KG/M2
COSPAR HIGH ATMOS
PROFILT,
RELATIVE VELOCITY (FPS)
26000.
25000.
24000.
23000.
22000.
21000.
20000.
19000.
18000.
17000.
16000.
15000.
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
TIME (SEC)


MARS CAPTURE
C3 = 38 KM2/SEC2
1 SOL EXIT ORBIT
W/CdA = 250 KG/M2
COSPAR HIGH ATMOS
PROFILT/UN-DAR
ROLL JETS ON/OFF
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.0
-.2
-.4
-.6
-.8
-1.0
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
TIME (SEC)

FREE MOLECULAR FLOW IMPACT ON L/D

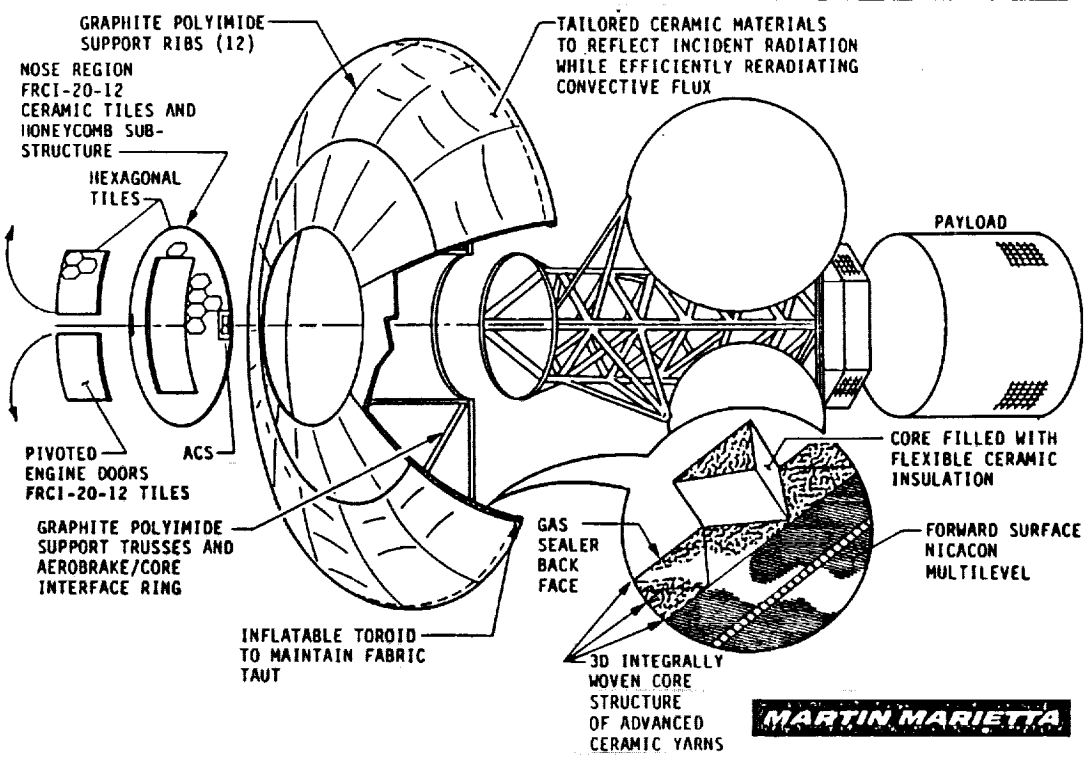


- FREE MOLECULAR FLOW (FMF) REGIME DEGRADES LIFT CAPABILITY
- LIFT DEGRADATION IS ONLY SIGNIFICANT IN THE LOW DECELERATION PORTIONS (PROFILES LEFT)
- ACS HAS NO PROBLEM MAINTAINING DESIGN ATTITUDE IN FREE MOLECULAR AND TRANSITION FLOW REGIMES
- IMPLEMENT FMF PREDICTOR IN GUIDANCE TO IMPROVE AERO DENSITY FEEDBACK

- CONCLUSION: FMF LIFT DEGRADATION HAS NO SIGNIFICANT TRAJECTORY IMPACT FOR OTV

MARTIN MARIETTA

OTV RIGID/FLEX TPS AEROBRAKE



MARTIN MARIETTA

AEROBRAKE DESIGN DETAIL

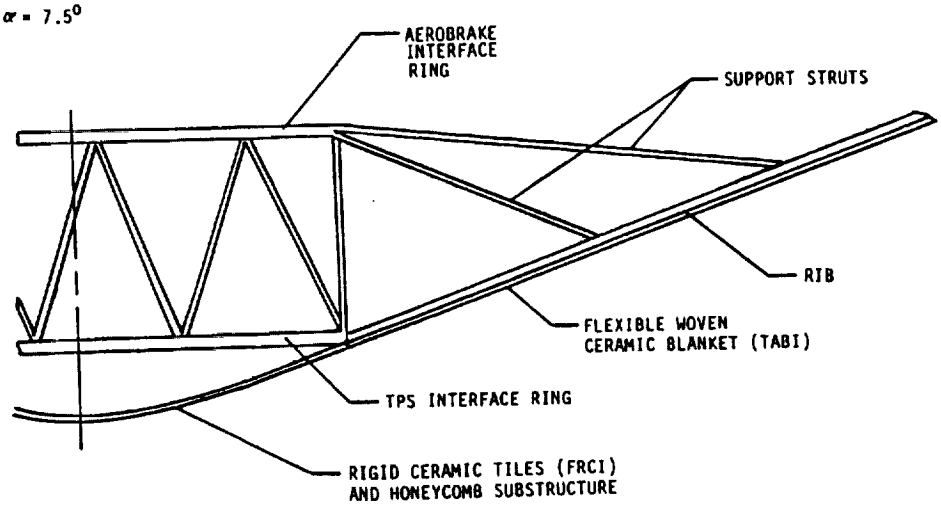
$W/C_D A = 6.0$

$D_B = 44$ FT

$R_N = 11$ FT

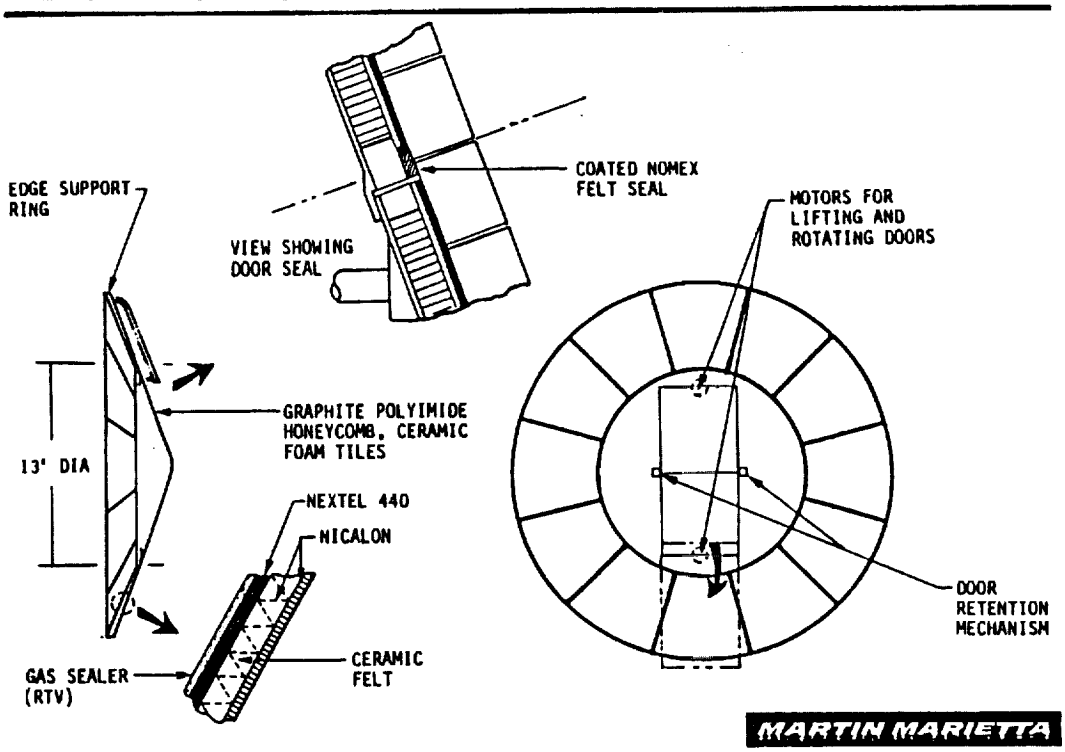
$L/D = 0.12$

$\alpha = 7.5^o$



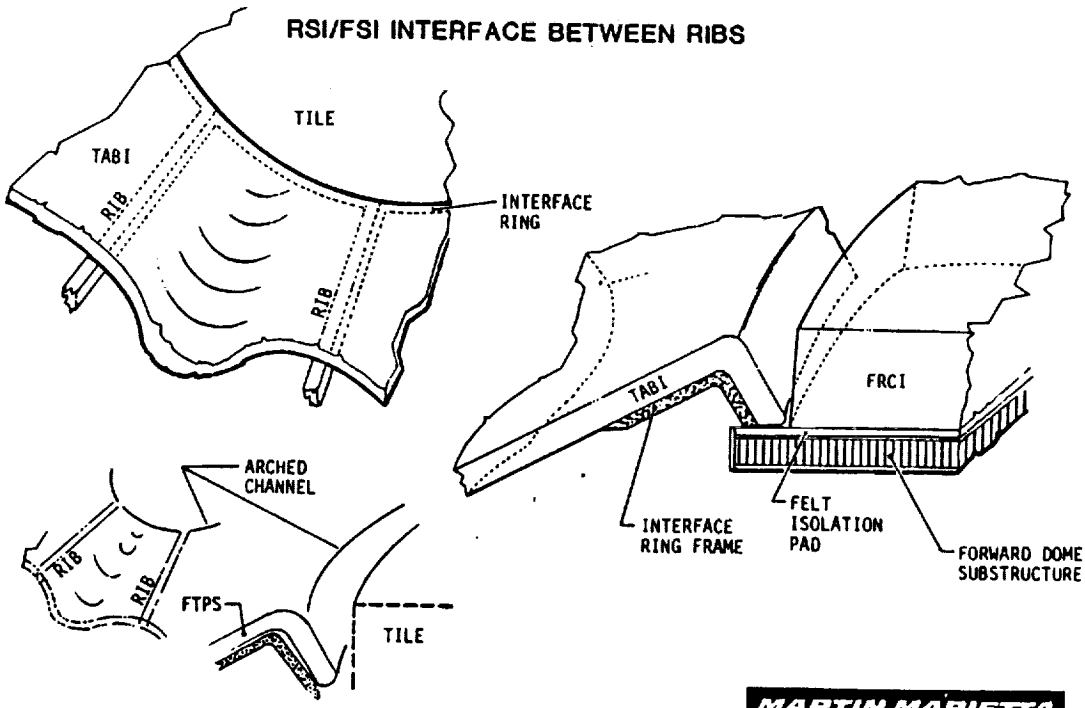
MARTIN MARIETTA

AEROBRAKE TPS AND ENGINE COVER MECHANISM



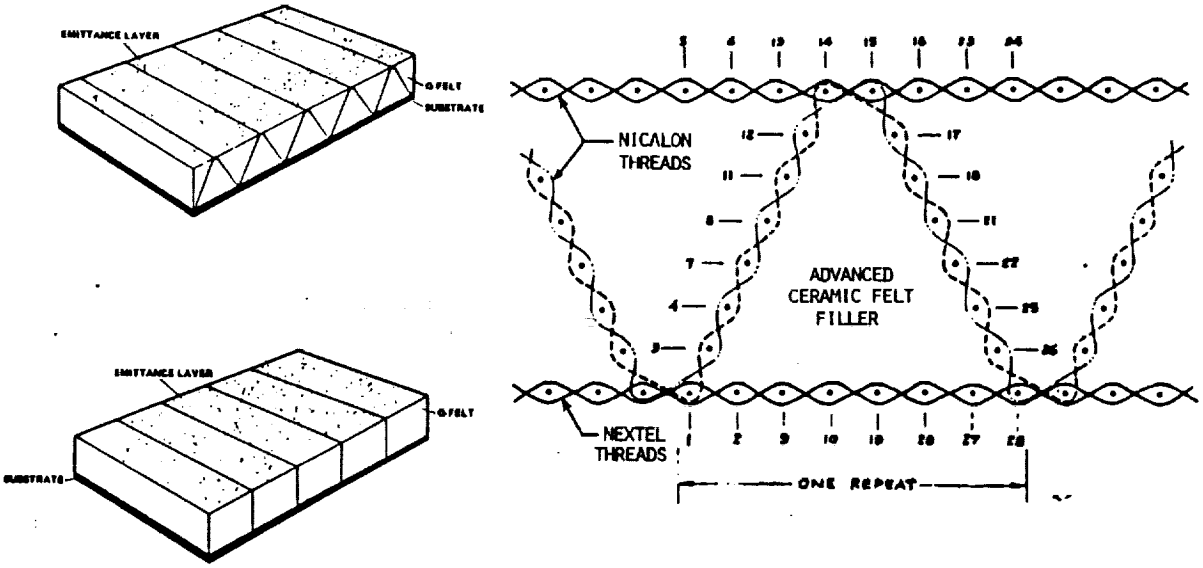
MARTIN MARIETTA

GROUND BASED AEROBRAKE DEPLOYMENT



MARTIN MARIETTA

TAILORABLE ADVANCED BLANKET INSULATION (TABI)



MARTIN MARIETTA

TAILORABLE ADVANCED CERAMIC MATERIALS

TEMPERATURE CAPABILITY

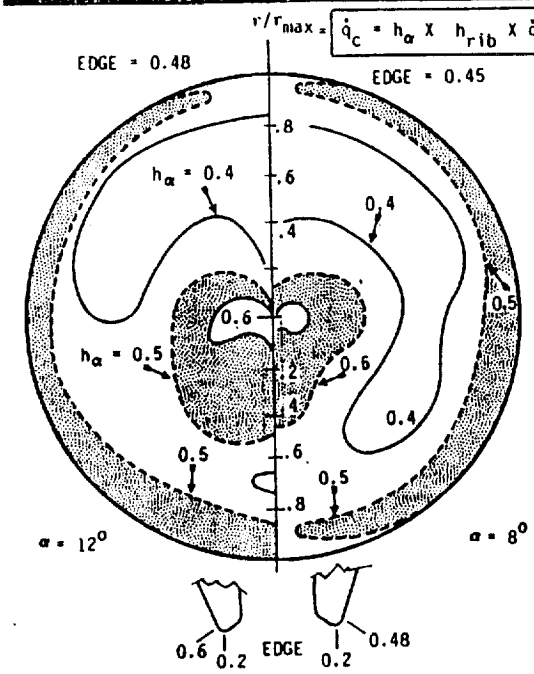
	SINGLE FLIGHT	MULTIPLE FLIGHT	MANUF CONT LIMIT	MAX HEAT FLUX
SILICA (CURRENT AFRSI)	> 2000	1500	1800	4
NEXTEL 312 (ALUMINOBOROSILICATE)	> 2200	> 1800	2200	9
NEXTEL 440	?	?	2800	> 9
SILICON CARBIDE (NICALON)	> 2600	> 2000	2300	34

- TEMPERATURES IN ^{o}F
- HEAT FLUXES IN BTU/FT^2-SEC (HEATING LIMIT WHEN FABRIC CONDITION BECOMES BRITTLE)

MARTIN MARIETTA

HEAT TRANSFER DISTRIBUTION OF THE VIKING SHAPED AEROBRAKE

r/r_{max} = $\dot{q}_c = h_\alpha \times h_{rib} \times \dot{q}_o$, WHERE $\dot{q}_o$ IS STAG. PT. HEAT TRANSFER RATE OF BRAKE NOSE RADIUS.



TPS DESIGN PARAMETERS

	FSI	RSI
S/R	0.3	0.0
h_α	0.50	0.65
h_{rib}	1.15	1.00
R_N	11.0	11.0
k	0.7	0.7
α_λ	0.3	0.3

REF: MMC TP-3720318 & AEDC-TR-73-195

MARTIN MARIETTA

	MARS EXPLORATION	
	BRAKE 1	BRAKE 2
BRAKE TYPE	FLEX FABRIC	ALL-RIGID
MISSIONS	MARS CAPT C3=38 WT= 285.5 MT EARTH CAPT C3=14.2 WT=36 MT	MARS CAPT C3=38 WT= 285.5 MT EARTH CAPT C3=14.2 WT=36 MT
PEAK G LOAD	6.0	6.0
BRAKE DIA	31 M	23 M
NUMBER OF RADIAL BEAMS	28	20
INTERFACE RING DIA	11 M	11 M
RSI TPS WEIGHT	421 KG	2121 KG
FSI TPS WEIGHT	1975 KG	0 KG
TOTAL TPS WEIGHT	2396 KG	2121 KG
TOTAL STRUCTURE WEIGHT	8725 KG	34900 KG
TOTAL BRAKE WEIGHT + 15%	12789 KG	42574 KG
BRAKE/(BRAKE+VEHICLE)%	4.3%	13.0%

PRELIMINARY DATA

CONCLUSIONS TO DATE

LOW L/D, FLEX-FABRIC BRAKE SHOWS PROMISE FOR ADVANCED MANNED MISSIONS

- LOW WEIGHT
- LARGE PACKAGING VOLUME AVAILABLE
- SIMPLE ON-ORBIT ASSEMBLY

SIGNIFICANT TECHNICAL ISSUES NEED RESOLUTION

- HYPERSONIC FLUTTER & DYNAMIC LOADING
- NON-EQUILIBRIUM RADIATION HEATING
- RE-USE EMBRITTLEMENT
- LONG-TERM SPACE EXPOSURE

MARTIN MARIETTA

Review of Boeing Studies of Pathfinder Missions Involving High Energy Aerobraking

January 31, 1989

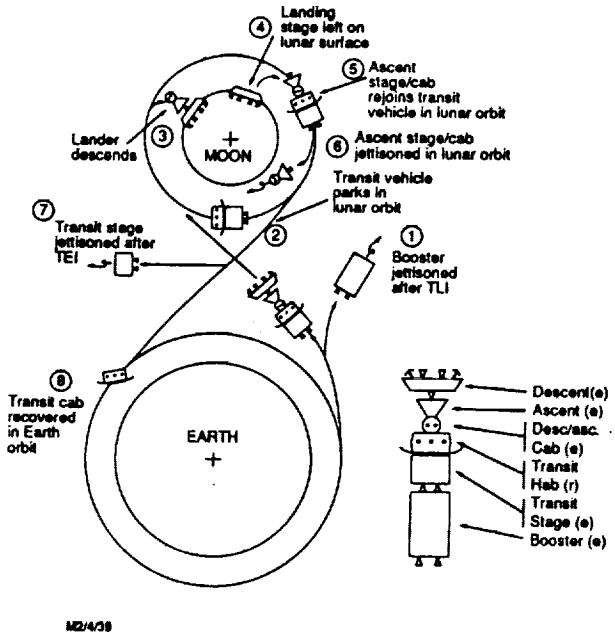
Code R/Z/M/Industry High Energy Aerobraking Workshop

ADVANCED CIVIL SPACE SYSTEMS

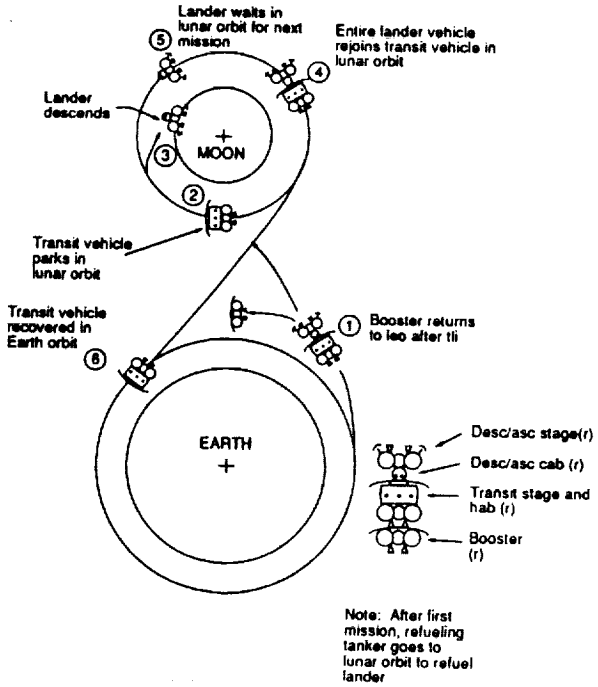
Lunar Vehicle Design Approaches (LOR Mode)

BOEING

Minimum Mass Approach



Maximum Reuse Approach



Note: After first mission, refueling tanker goes to lunar orbit to refuel lander

M2/4/38

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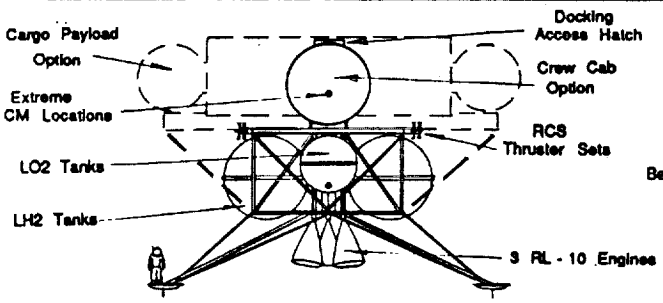
Lunar Evolution Set Configuration

BOEING

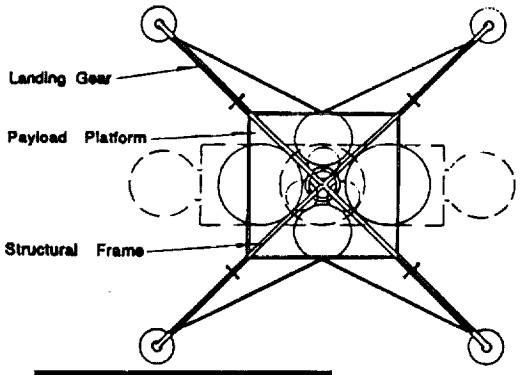


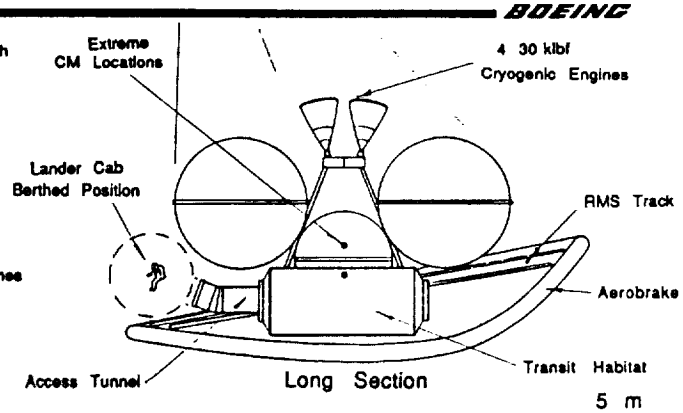
Side Elevation

5 m

Lander

Sectioned Plan



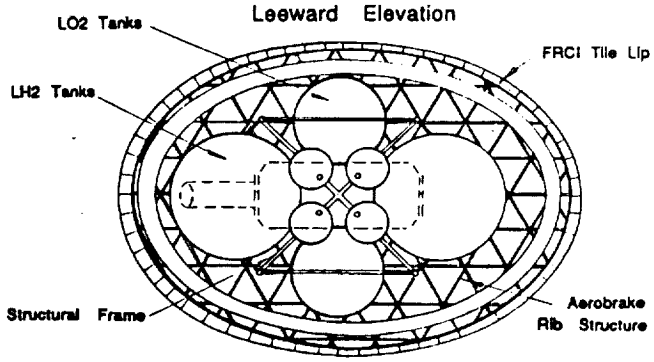


Long Section

5 m

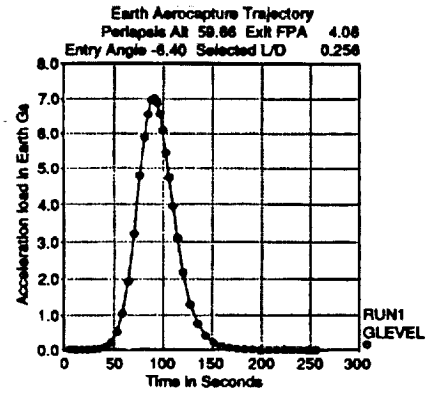
Transit Vehicle

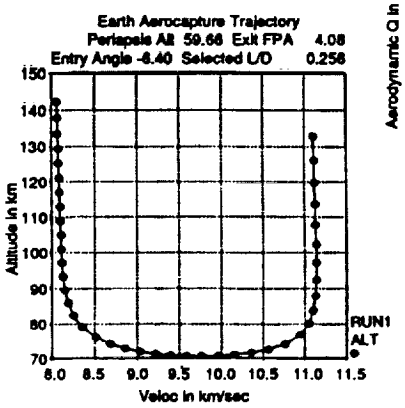
Leeward Elevation

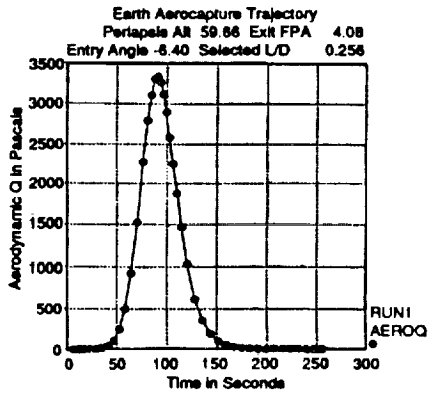


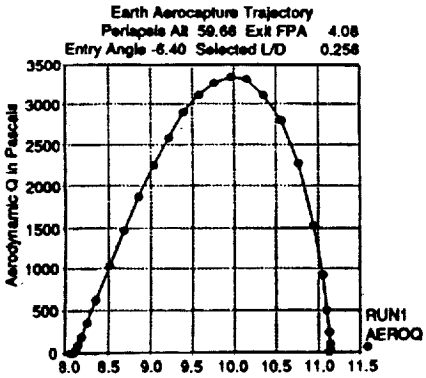
Earth Aerocapture from Lunar Trajectories

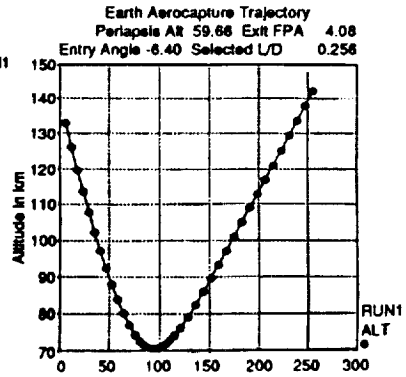
BOEING



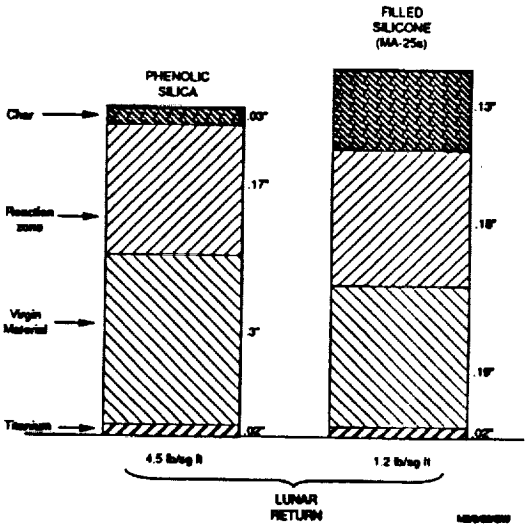


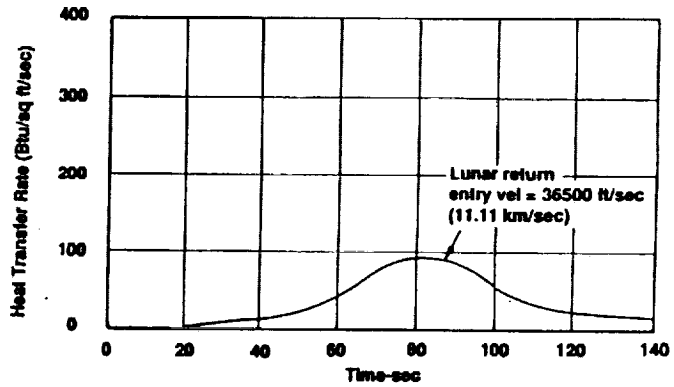




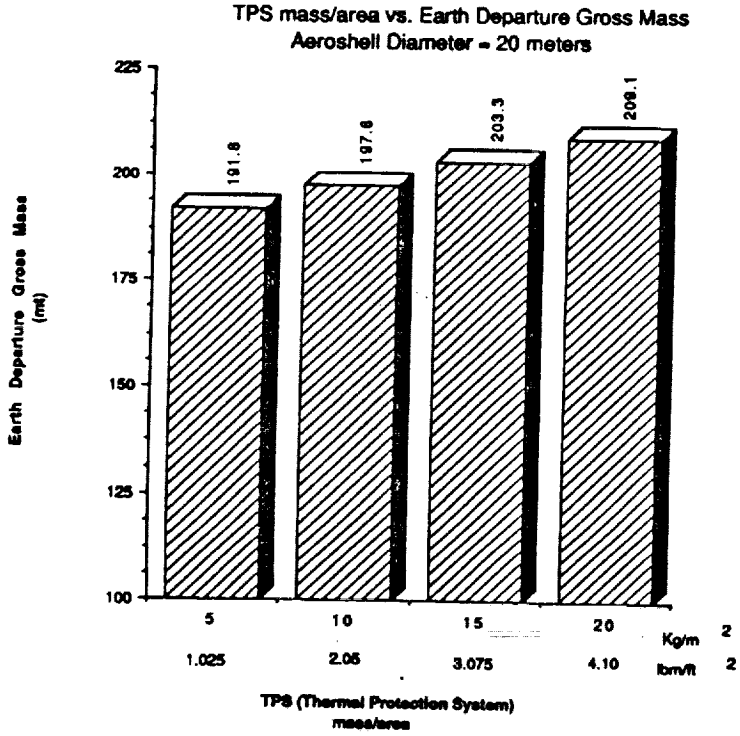


Earth Return From Moon Thermal Environment





Lunar TPS Trade

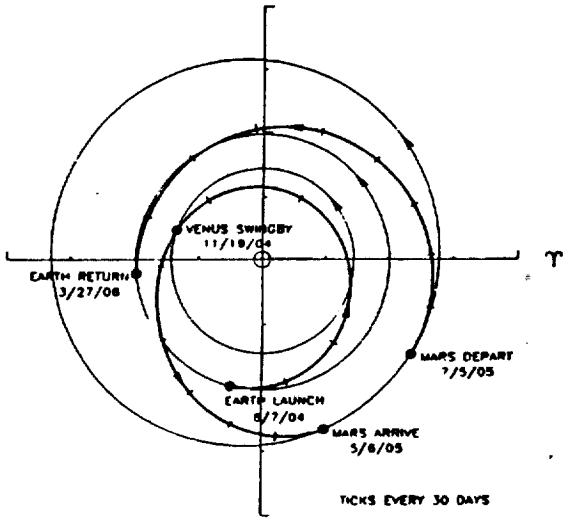


Lunar Return Aerothermal Assessment

- Current predictions exceed reradiative capability
- Could fly cooler trajectory; reradiative probably OK
- Uncertainty in radiation heating
- Need AFE results to make final design decisions

Mars Opportunity Profiles

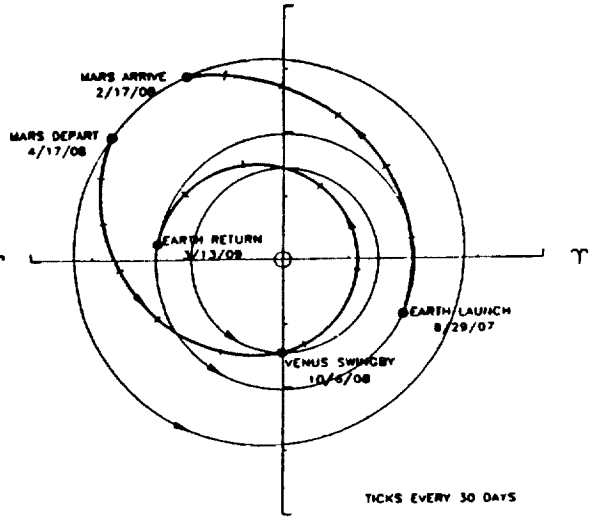
TRAJECTORY PROFILE FOR 2004 OPPOSITION CLASS MARS MISSION WITH OUTBOUND VENUS SWINGBY



DAYS FROM LAUNCH	BODY	ΔV(KM/S)
0.0	EARTH	4.096
165.5	VENUS	0.000
333.4	MARS	0.000
393.4	MARS	1.473
658.6	EARTH	0.000

TOTAL		5.569

TRAJECTORY PROFILE FOR 2007 OPPOSITION CLASS MARS MISSION WITH INBOUND VENUS SWINGBY

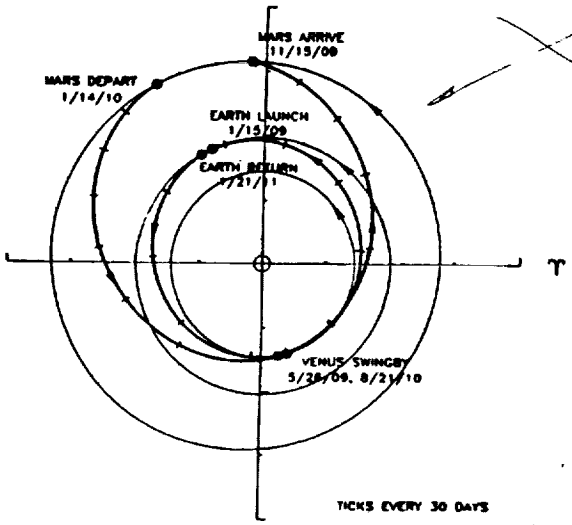


DAYS FROM LAUNCH	BODY	ΔV(KM/S)
0.0	EARTH	4.744
172.1	MARS	0.000
232.1	MARS	3.152
403.5	VENUS	0.000
561.9	EARTH	0.000

TOTAL		7.897

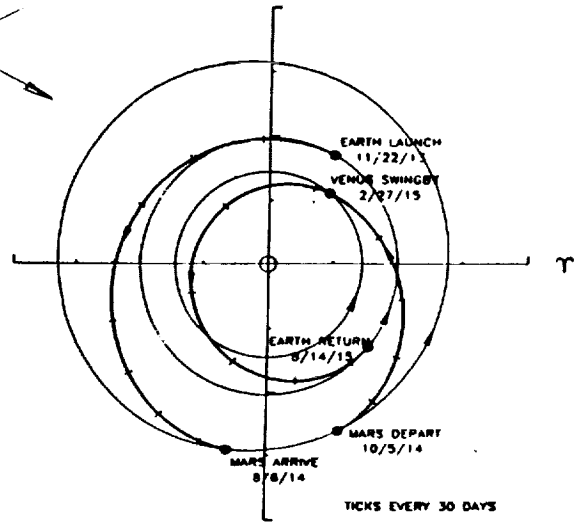
Mars Opportunity Profiles

TRAJECTORY PROFILE FOR 2009 OPPOSITION CLASS MARS MISSION WITH INBOUND VENUS SWINGBY



DAYS FROM LAUNCH	BODY	ΔV(KM/S)
0.0	EARTH	3.936
130.3	VENUS	1.099
303.3	MARS	0.000
363.3	MARS	2.060
583.2	VENUS	0.000
735.8	EARTH	0.000
TOTAL		7.095

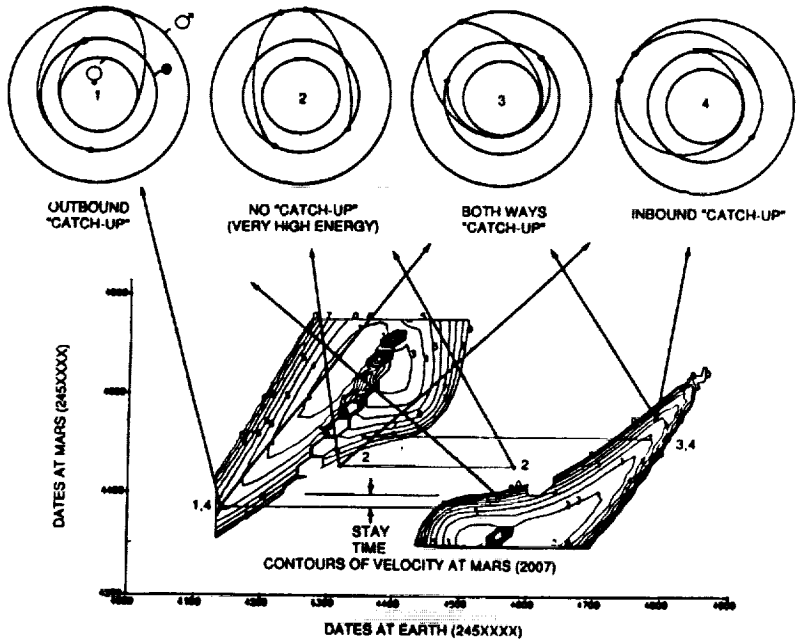
TRAJECTORY PROFILE FOR 2013 OPPOSITION CLASS MARS MISSION WITH DOUBLE VENUS SWINGBY



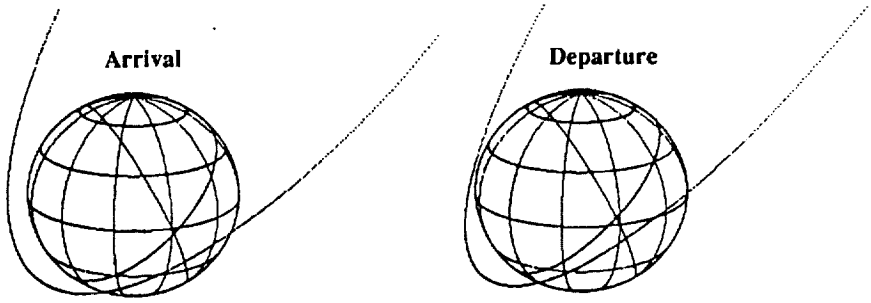
DAYS FROM LAUNCH	BODY	ΔV(KM/S)
0.0	EARTH	3.749
257.5	MARS	0.000
317.5	MARS	3.256
462.1	VENUS	0.000
630.1	EARTH	0.000
TOTAL		7.005

Opposition-Class Trajectories Types

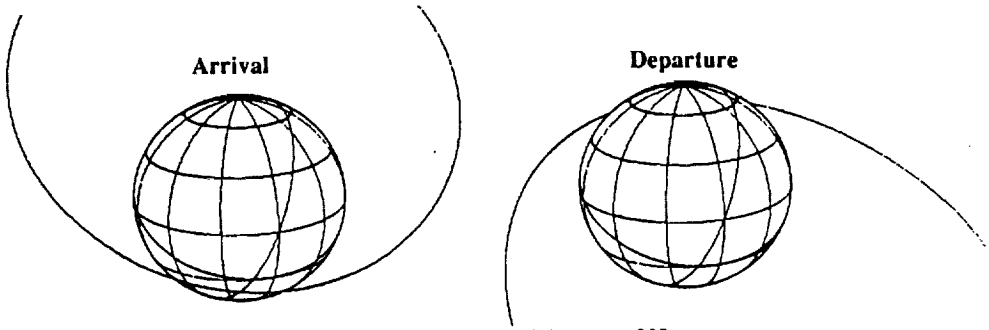
TRAJECTORY TYPES



Parking Orbits Comparison

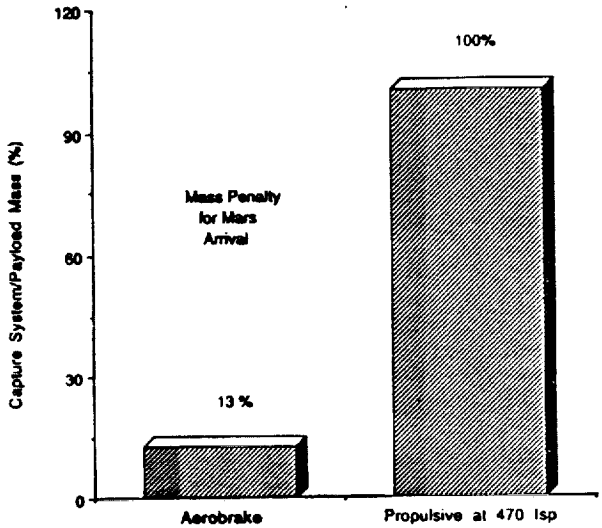


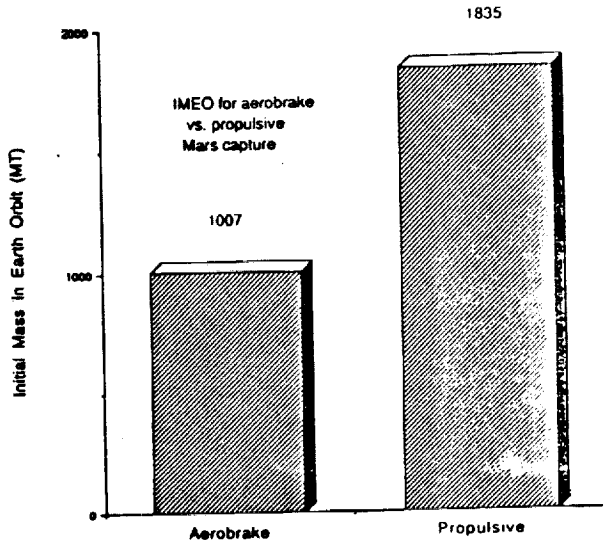
Strategy 2 selected orbit = 24.6 hrs, 45°
Nodal Regression about 10° in 60 days



Strategy 7 selected orbit = 8.2 hours, 30°
Nodal regression 360° in 450 days
Periapsis advance 207°

Aerobrake and Propellant Mass as a Percentage of Payload Mass for Mars 2007 Case



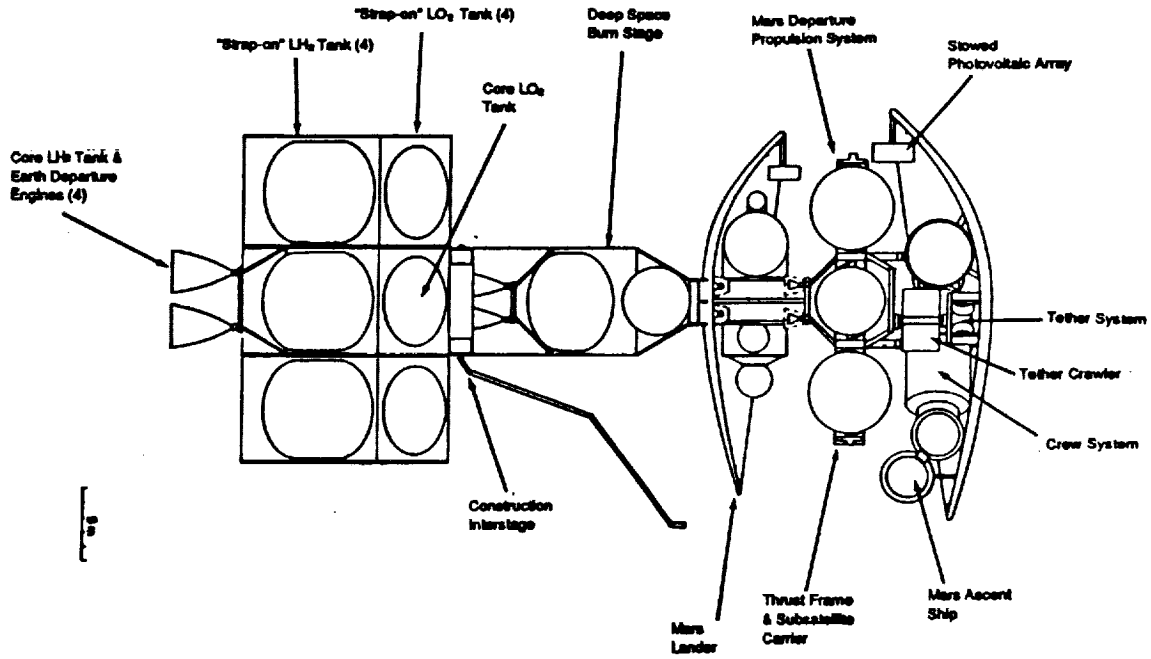


- Aerobrake may be used again for landing
- Aerobrake high leverage technology: Structures; TPS; assembly vs. deployment

ADVANCED CIVIL SPACE SYSTEMS

Mars Baseline Full-up Configuration Keel Section

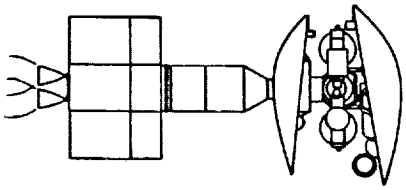
BOEING



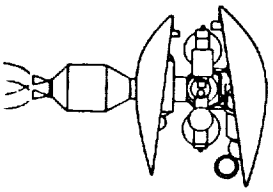
ADVANCED CIVIL SPACE SYSTEMS

Mars Baseline Mission Sequence Earth Departure

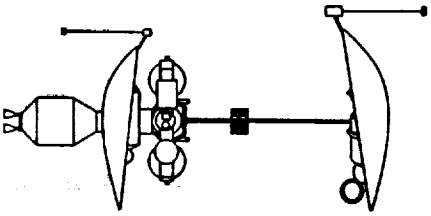
BOEING



1. Earth Departure



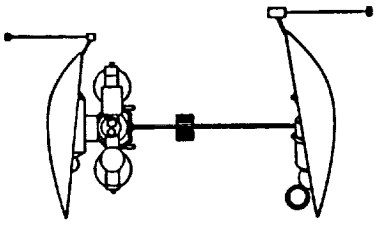
3. Deep Space Burn



2. Outbound Artificial g

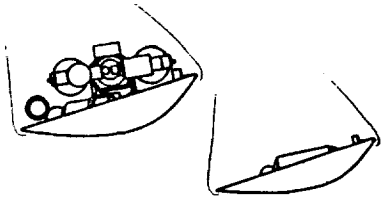
Mars Baseline Mission Sequence

Mars Arrival



4. Post-DSB Artificial g

7. Surface Operations

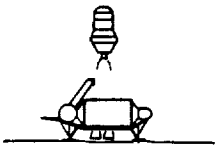


5. Mars Aerocapture

6. Lander Aero-entry

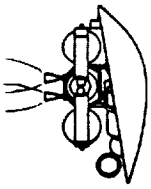
Mars Baseline Mission Sequence

Return

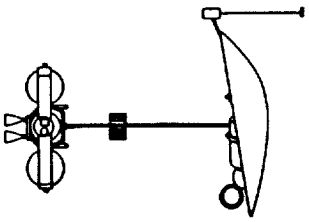


8. Ascent Ship Launch

11. Earth Aerocapture

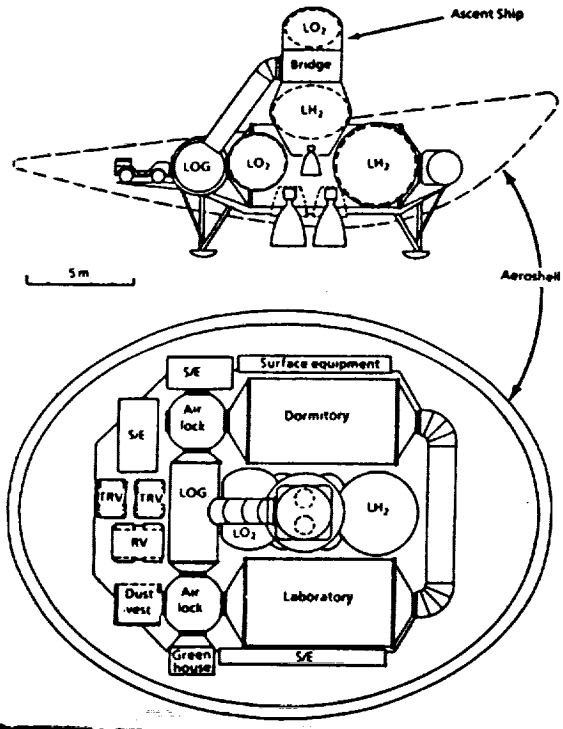


9. Mars Departure



10. Inbound Artificial g

Mars Lander Configuration



Vehicle Mass Summary

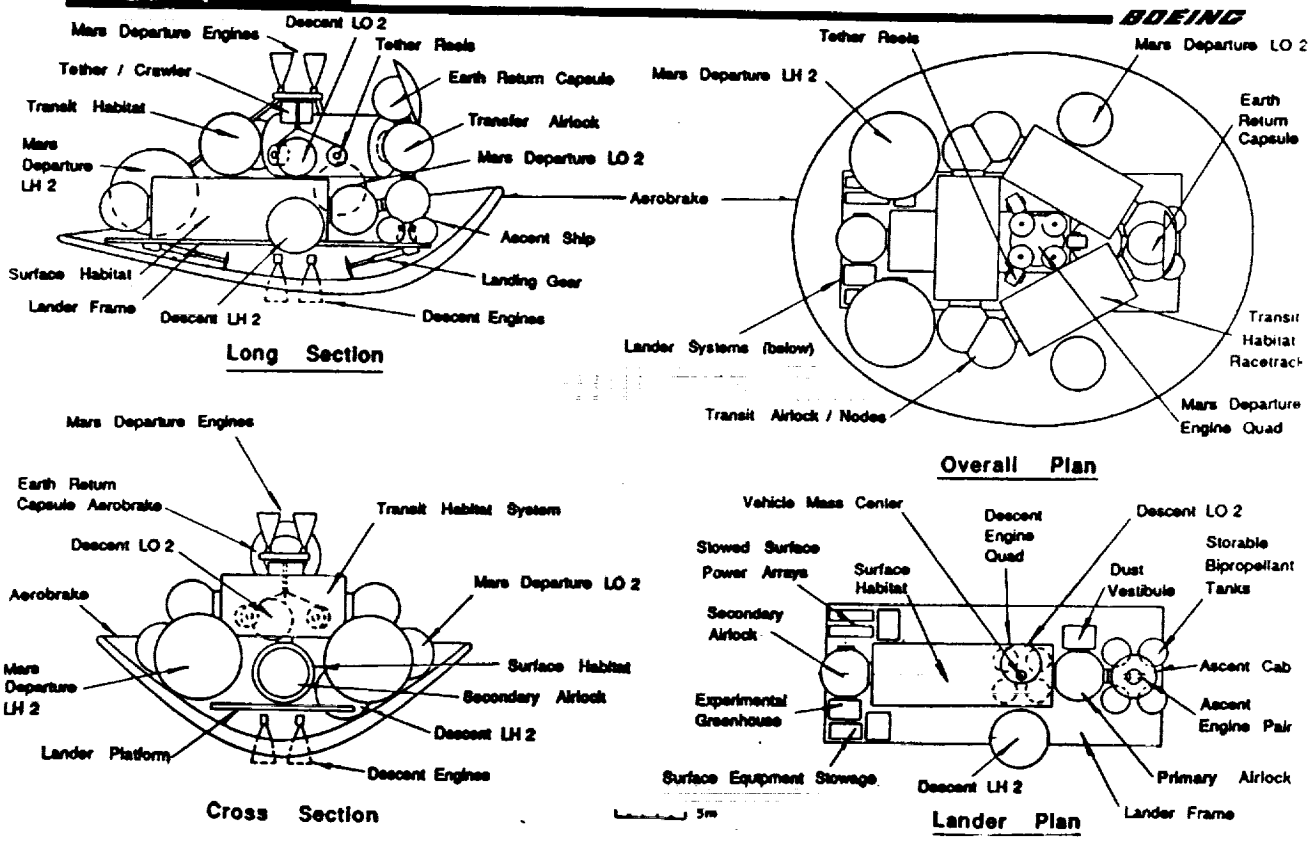
Ascent

Crew cab	1.7
Inert mass	2.0
Prop load	8.9
Total	12.6 mt

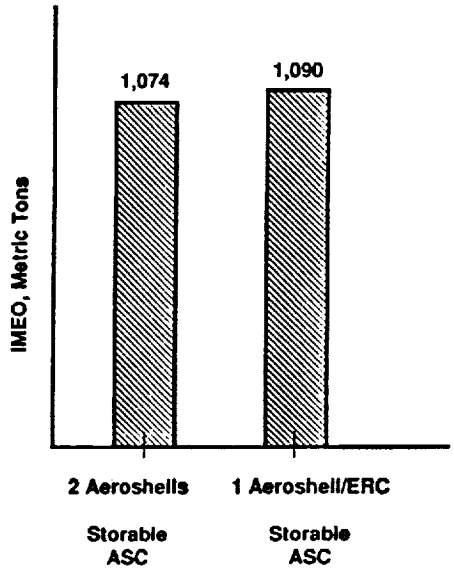
Lander

Ascent vehicle	12.6
Surface hab sys	29.8
Inert mass	7.2
Prop load	12.1
Lander aeroshell	4.2
Total	65.9 mt

Single Aerobrake Configuration



Single Aerobrake Trade Conclusions

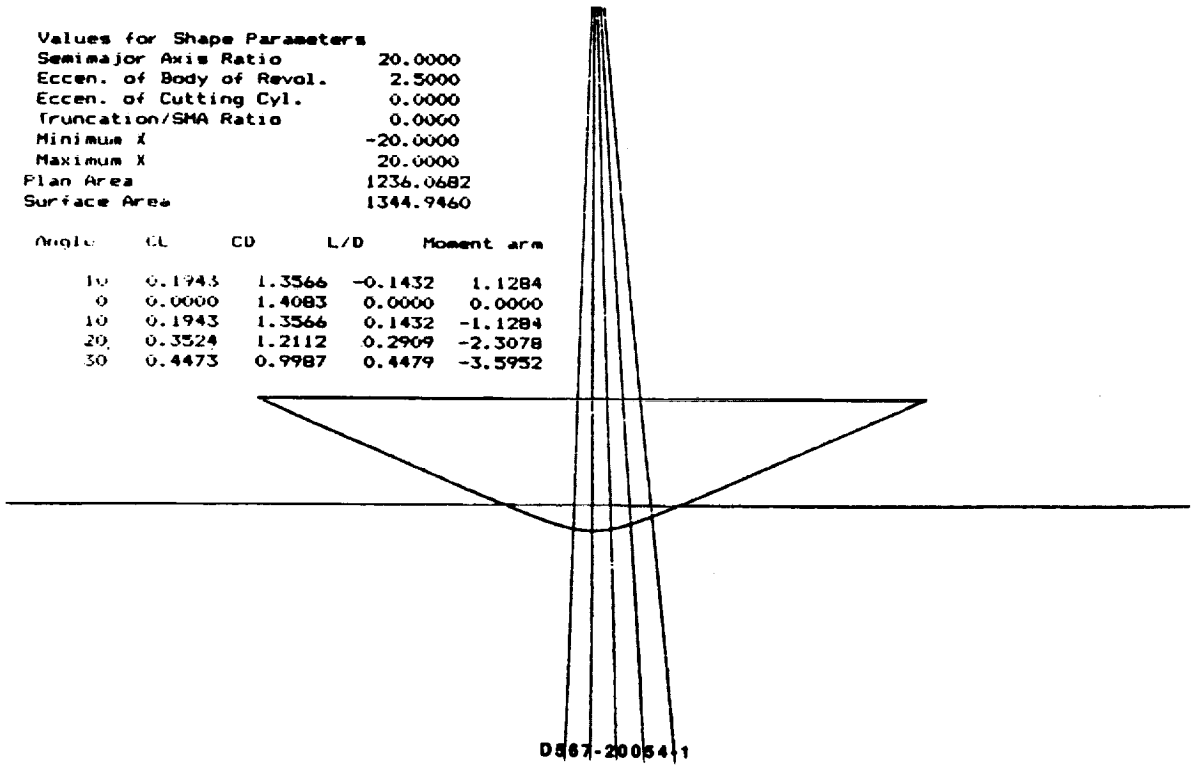


- Mass trade is about even
- Single brake configuration more complex; requires larger launch vehicle shroud
- Drives configuration toward storable Mars ascent vehicle
- Cannot recover transit vehicle on Earth return

Aerobrake Aero Characteristics Prediction For Conical Shape

Values for Shape Parameters	
Semimajor Axis Ratio	20.0000
Eccen. of Body of Revol.	2.5000
Eccen. of Cutting Cyl.	0.0000
Truncation/SMA Ratio	0.0000
Minimum X	-20.0000
Maximum X	20.0000
Plan Area	1236.0682
Surface Area	1344.9460

Angle	CL	CD	L/D	Moment arm
10	0.1943	1.3566	-0.1432	1.1284
0	0.0000	1.4083	0.0000	0.0000
10	0.1943	1.3566	0.1432	-1.1284
20	0.3524	1.2112	0.2909	-2.3078
30	0.4473	0.9987	0.4479	-3.5952



ADVANCED CIVIL SPACE SYSTEMS

Entry Vehicle C.G. Trim and Stability

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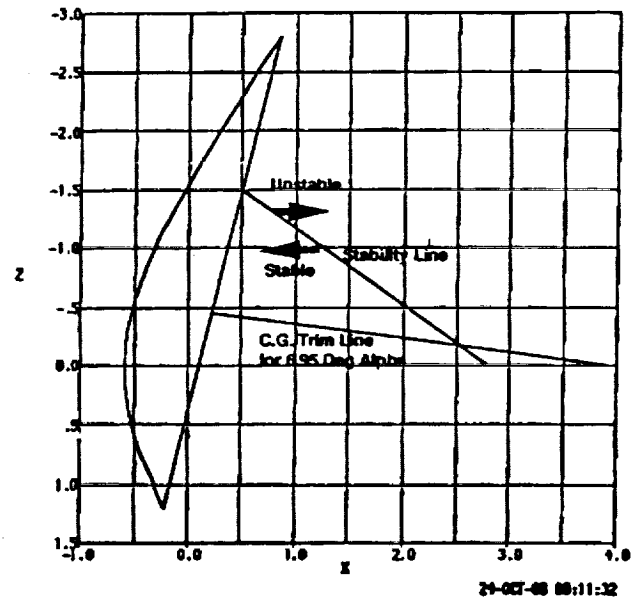

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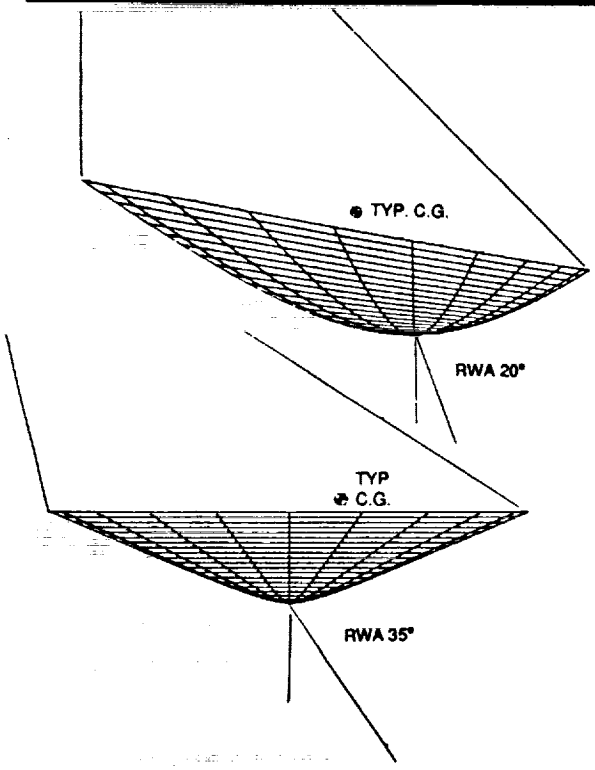
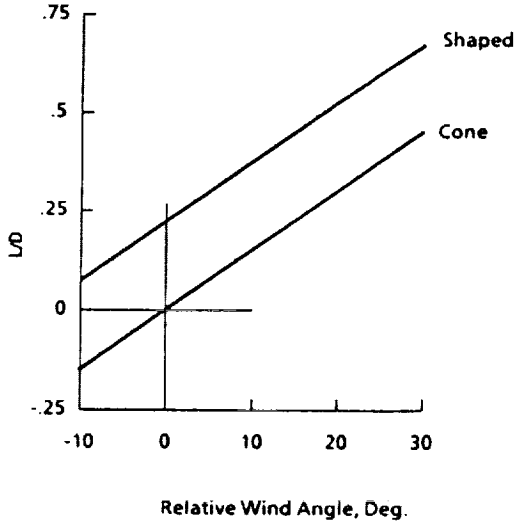
Aerobrake Shape Effects & Protected Area Estimates

BOEING





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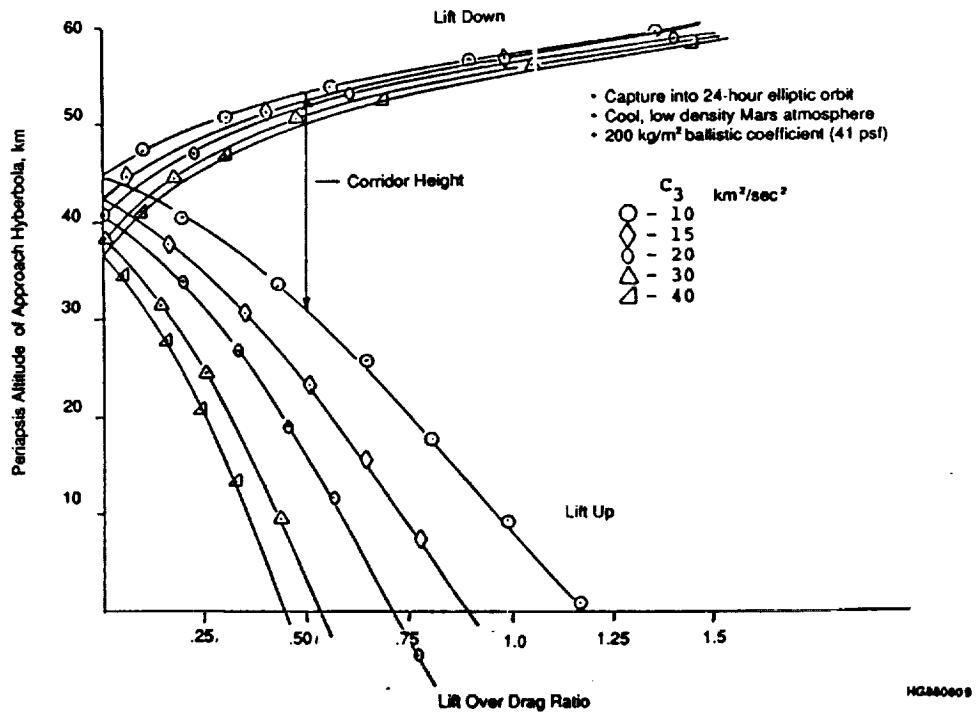
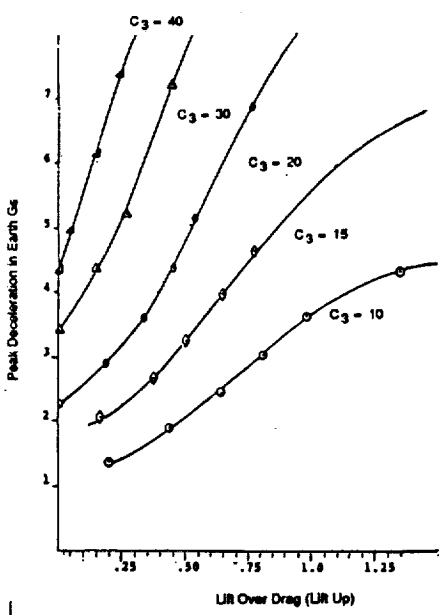
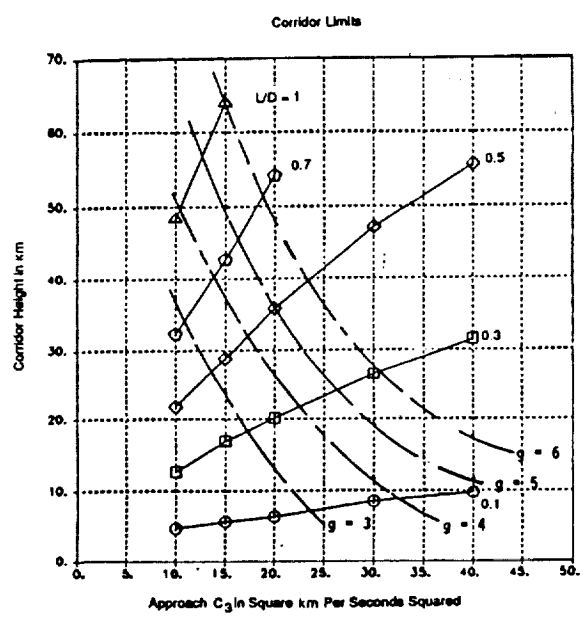
Results of Fixed L/D Aerocapture Simulations



Mars Aerocapture Corridor Height Estimates

- 24-hour elliptic orbit
- Cool, low density atmosphere
- 200kg/m² (40 psf)





NOMINAL TRAJECTORY
WARM, HIGH PRESSURE ATMOSPHERE

ADVANCED CIVIL SPACE SYSTEMS

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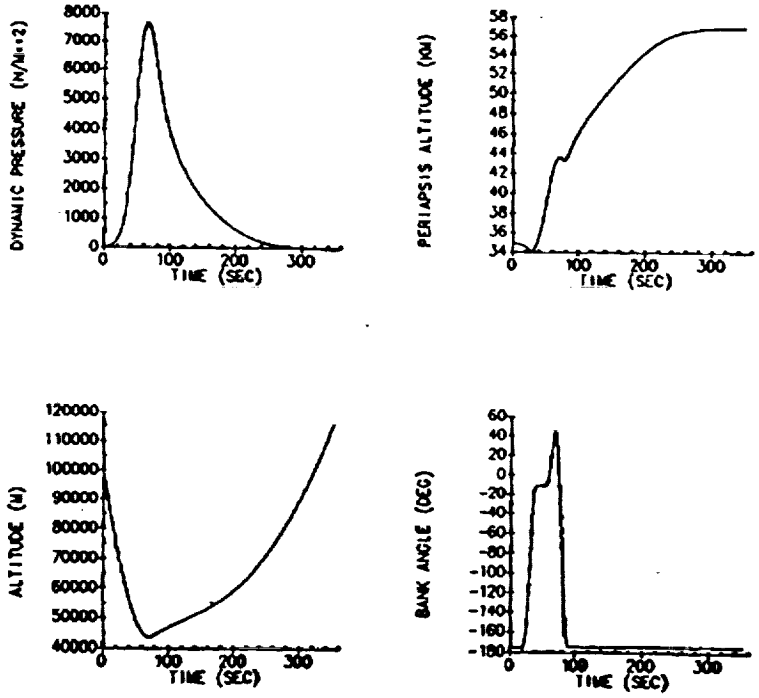

Mars Landing Profiles

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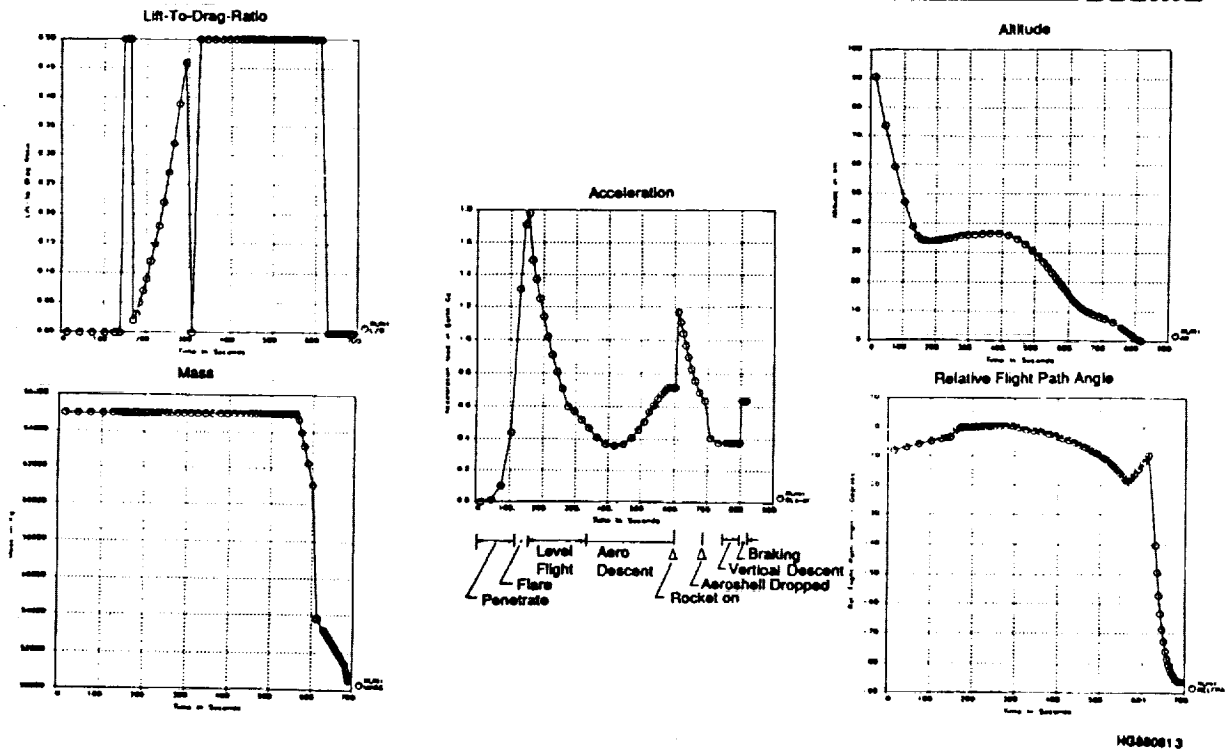
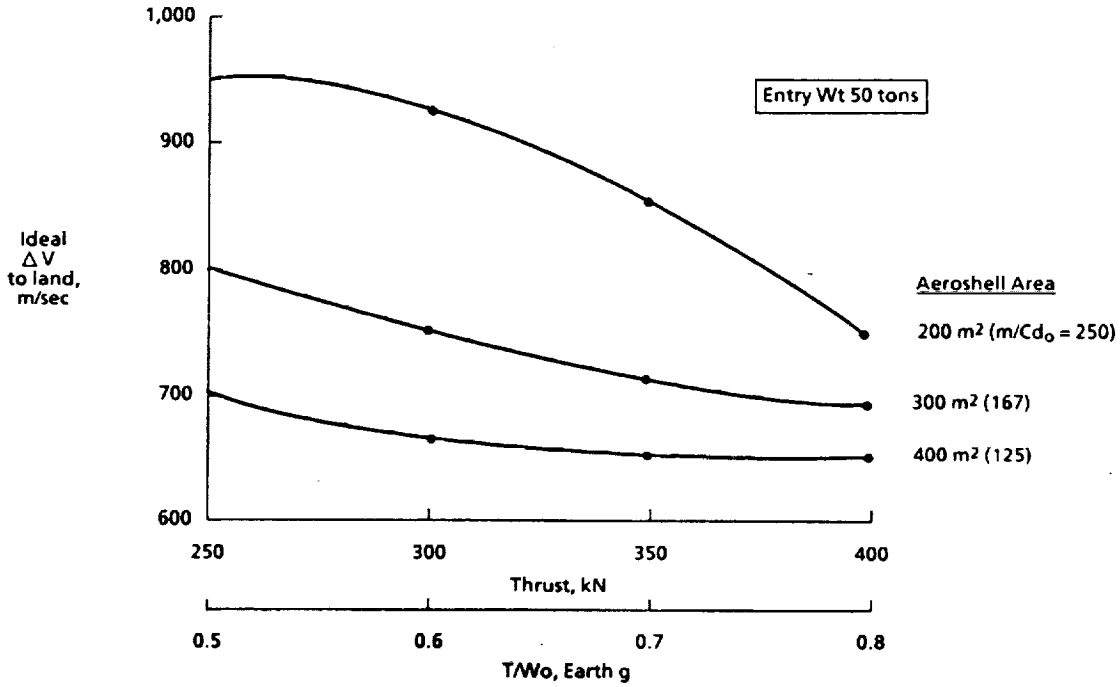
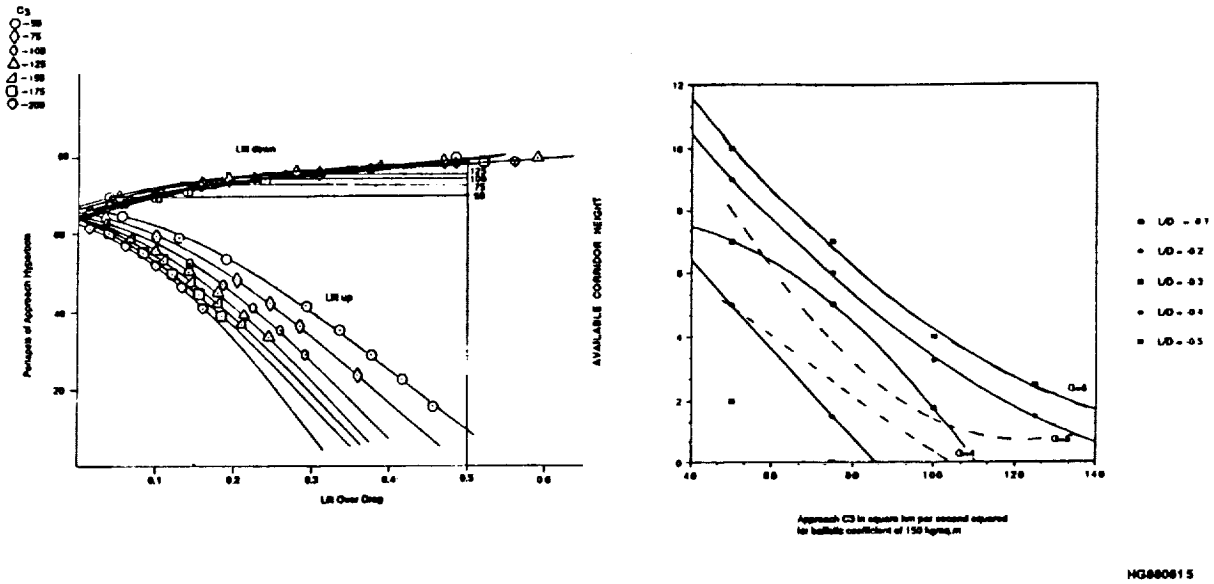


Lunar/Mars Technology Study
Aeroshell and Thrust Effect on Landing Δv



Deceleration - Constrained Corridor Height for Earth Entry



ADVANCED CIVIL SPACE SYSTEMS

MARS AEROCAPTURE
Premininary Guidance Analysis

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Reentry Conditions:
- Altitude = 100 km
- Velocity = 7922.45 m/s
- Latitude = −8.5 deg
- Longitude = 0.0 deg
- Azimuth = 43.94 deg
- Gamma = −10.18 deg

Vehicle parameters
- M/CdA = 200 kg/m**2
- L/D = 0.33
- Max roll rate = 30 deg/sec
- Max roll acceleration = 2 deg/sec**2

Target conditions:
- Apoapsis = 36,500 km
- No plane change
- (Incl = 45.41 deg)
- (RAAN = 8.38 deg)

ADVANCED CIVIL SPACE SYSTEMS

Aerothermal Issues

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- Improved analysis methods needed, particularly with regard to:
  - — Transport properties at very high temperatures
  - — Gas radiation
    - equilibrium
    - non-equilibrium
- Effects of non-equilibrium chemistry and ionization on convective heating
- Engineering tools for treating non-axisymmetric blunt body flow fields

Aerothermal Methods and Assumptions

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- Flow Field - modified Newtonian
- Boundary layer:
  - — laminar - rho-mu
  - — turbulent - Spalding-CHI
  - — transition criteria

$$\frac{R_e}{M_{e\ onset}} = 220$$

$$R_{e,\ turb} = 2R_{e,\ onset}$$

virtual origin at transition onset

- Thermodynamic Properties - Freeman and Oliver, AIAA Journal September 1970
- Transport Properties - Seiff, Advanced Space Research, vol 2, 1982 (warm, high pressure model)
- Trajectory - aerocapture to 36,500 km apoapsis

Stagnation Point Temperatures

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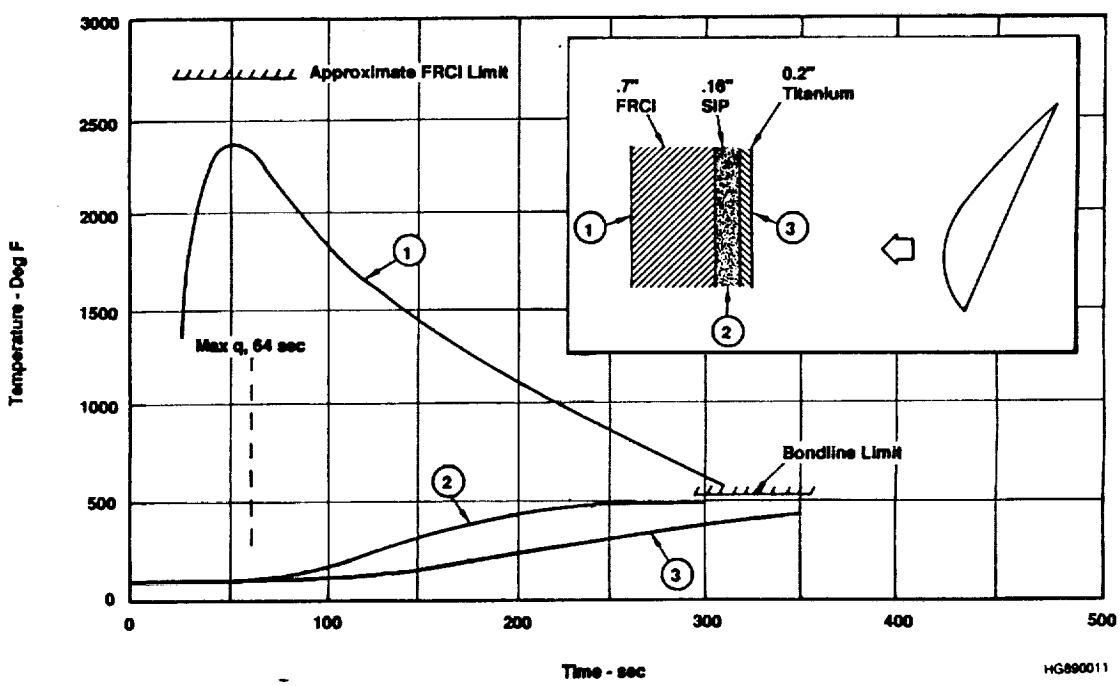
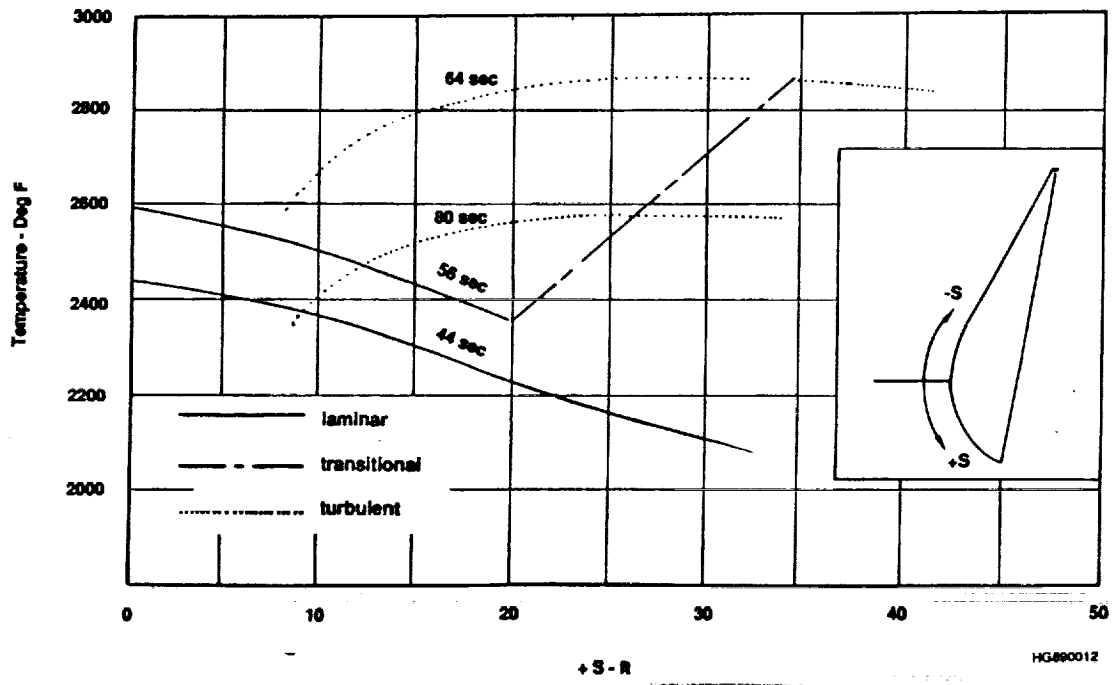


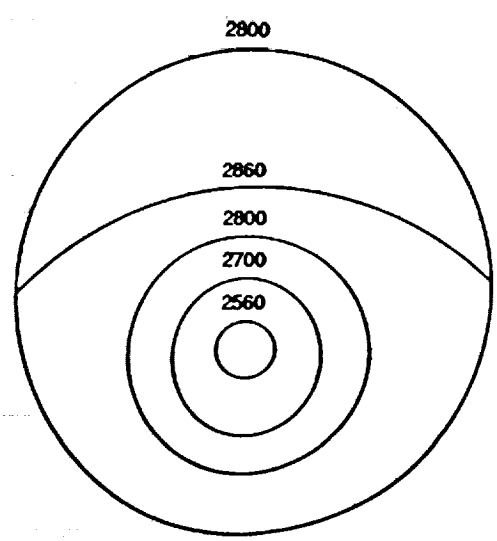
Equilibrium Temperature Distribution



Mars Entry Aerothermal Assessment

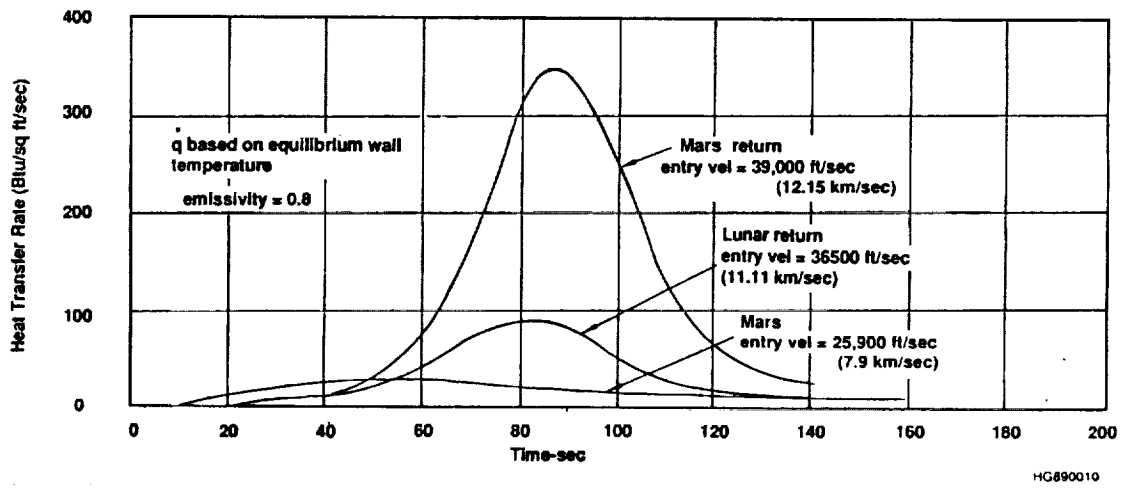
- Peak Stagnation Point Temperatures
  - Stagnation Point 2400° F
  - X = 30 ft 2800° F
- Shuttle tiles useable to 2600° F
  - Sized by tile/SIP bondline constraint
- Preliminary Analyses indicate tile (FRCI) and light weight ablator (MA 255) weights about equal at 1.1 lb./ sq. ft. at this Stagnation Point.
- Preliminary TPS Recommendation
  lightweight ablator
  or advanced reradiative TPS

Emittance = 0.8



Temperatures in ° F

Comparison Of Aerocapture Environments



Earth Aerocapture Flow Conditions

- Time = 80 seconds
- Altitude = 228,500 ft (69.6 km)
- Velocity = 37,820 ft/sec (11.5 km/sec)

<u>Stagnation Conditions</u>

- Fully dissociated flow
- Total enthalpy = 28660. btu/lbm (66 kJ/gm)
- $\frac{\text{Ionization enthalpy}}{\text{Total enthalpy}} = 0.25$
- Total temperature = 20,000 R (11,111 K)
- $\dot{q}$ = 88 btu/sq ft/sec (100 W/cm^2) (convection)
- $\dot{q}$ = 261 btu/sq ft/sec (296 W/cm^2) (radiation)

Earth Aerocapture Thermal Environment

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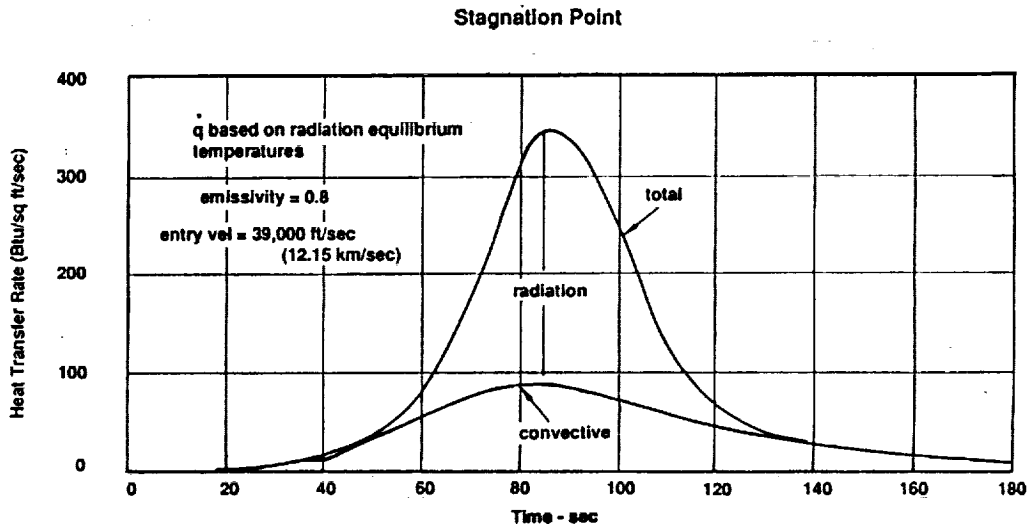

Predicted Ablator Performance At Stagnation Point

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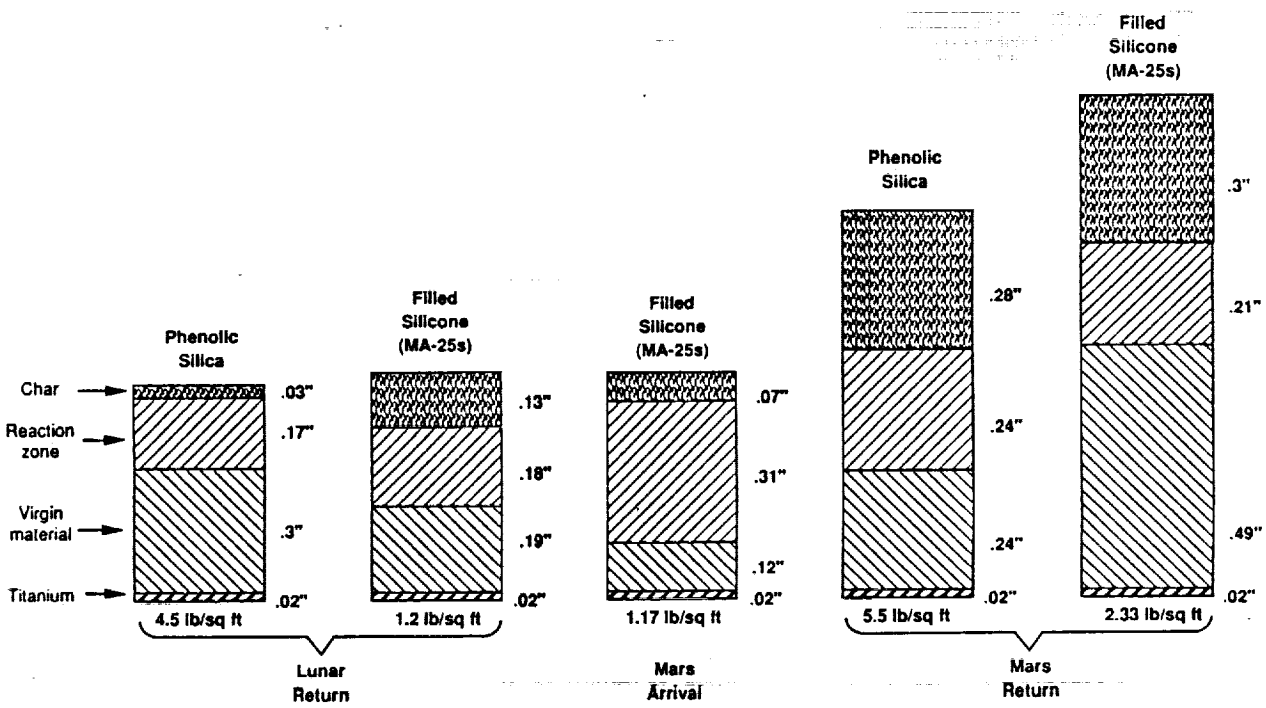
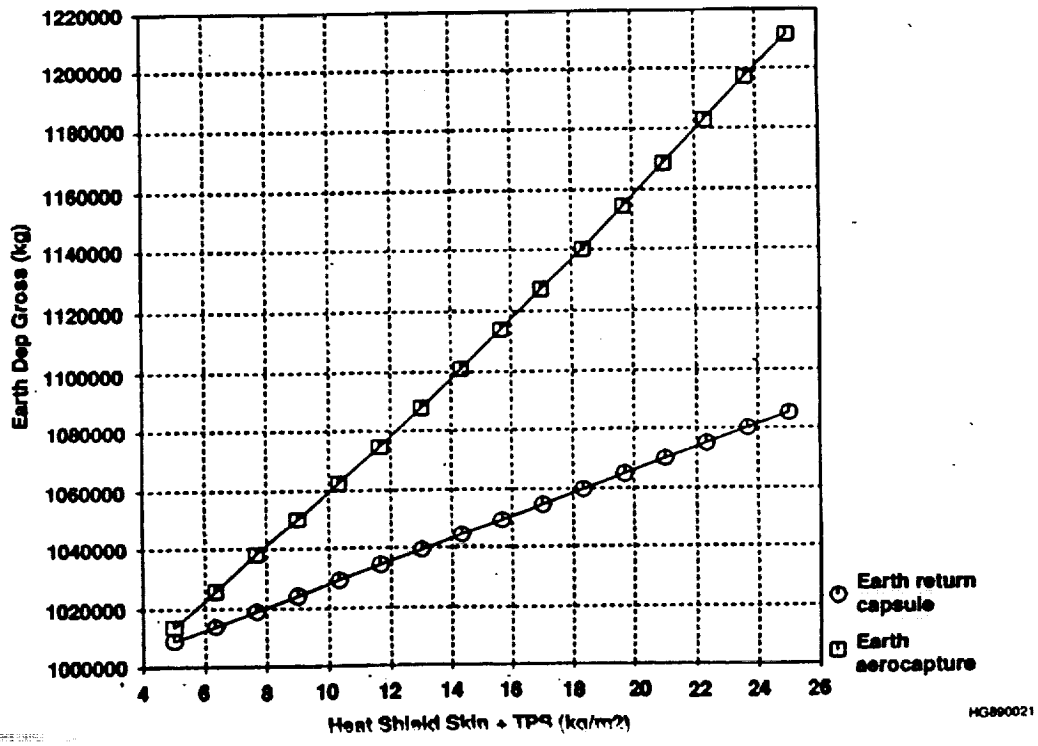


Thermal Protection System Trade Results



Overall Mars Aerothermal Assessment

- Mars aerocapture and landing within reradiative or lightweight ablator capability with C3 < 50 km^2/sec^2

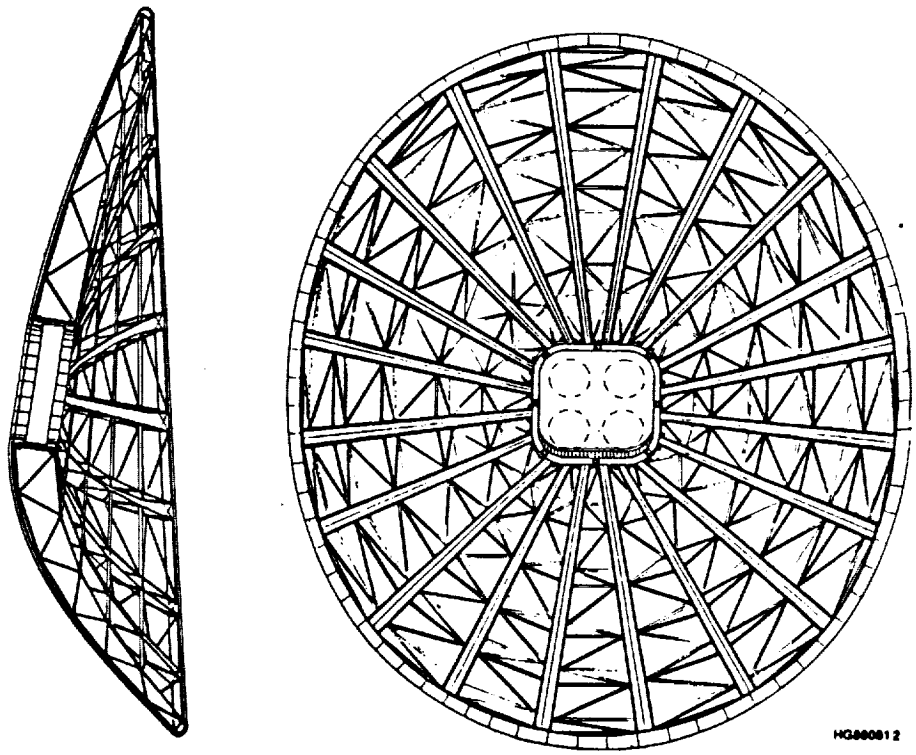
- Earth return from Mars exceeds projected reradiative technology and has large uncertainities in heating predictions
  - Radiation from nonequilibrium ionized shock layer
  - Lightweight ablators not tested at these heating rates
  - May need AFE reflight, especially if Mars transit vehicle to be recovered

- Lightweight TPS essential to make recovery of Mars transit vehicle economical

ADVANCED CIVIL SPACE SYSTEMS

Initial Aeroshell Structure Concept; Basis for Mass Estimating Algorithms

BOEING



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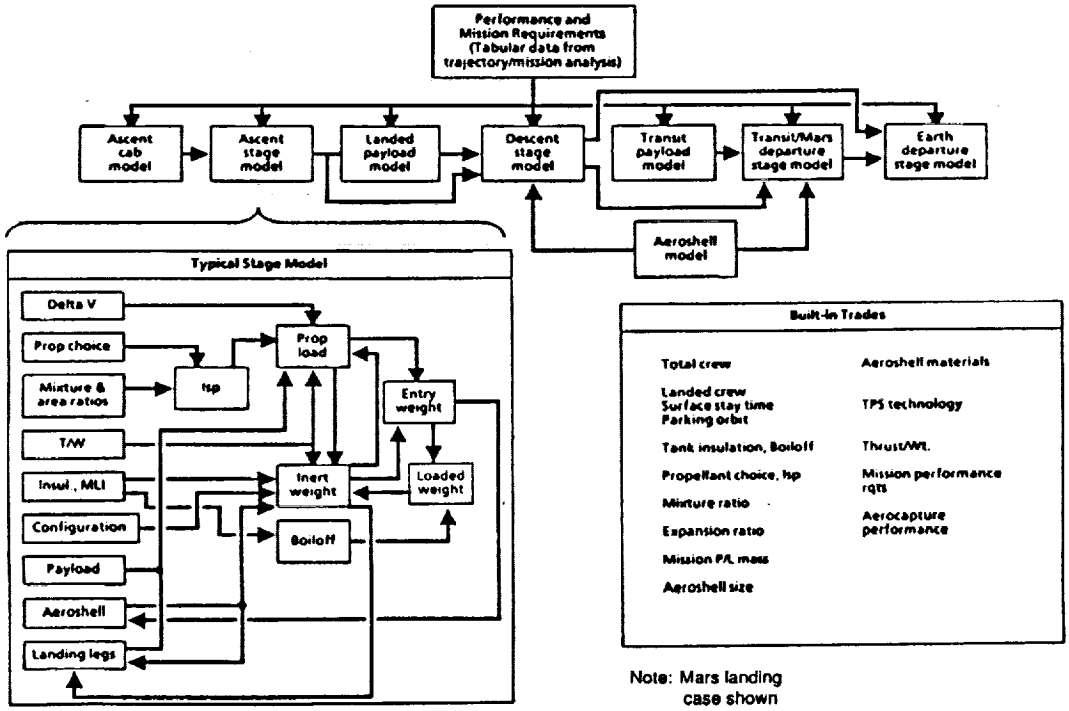
Baseline Synthesis Model Generated Iterated Point Designs For Every Trade Study

BOEING



Note: Mars landing case shown

Earth Return Configuration Selection Sensitivity to Aerobrake/Propulsion Internal Escalation

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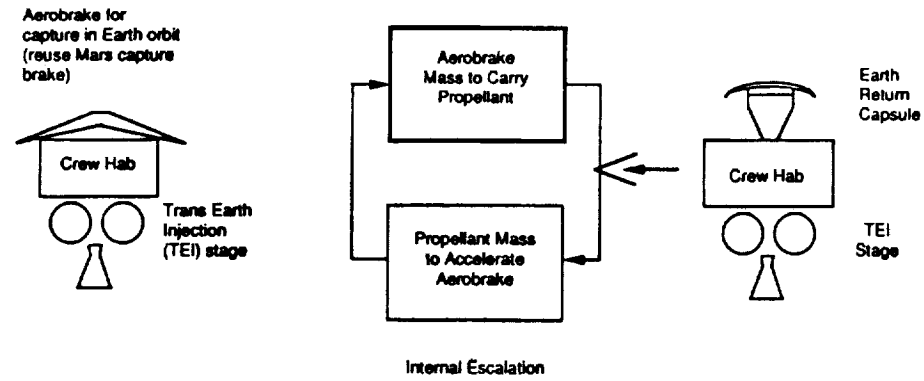

If TEI Delta v is low and Trans Mars Injection (TMI) Delta v is high, this is the least mass configuration and saves the most hardware.

If TEI Delta v is high and TMI Delta v is low, breaking the internal escalation feedback loop provides the least mass configuration

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ADVANCED CIVIL SPACE SYSTEMS

Preliminary Aerobrake Structural Analysis

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Assumptions

Simplified Geometry : 42° Sphere section, 29.3 m span
20.88 m radius of curvature
Constant thickness

Loads : Uniform pressure = 22 kN/m^2
183 MT payload, 12 point touchdown
6 g max acceleration
20 MT distributed brake mass

Model: NASTRAN FEM
108 elements, 85 mesh
340 DOF
Constrained at 12 touchdown points
Grounded to payload by representative stiffnesses

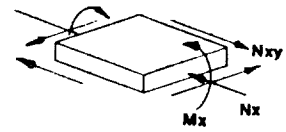
Results

Maximum line loads:

Axial Nx = 623.9 kN/m (3563 lb/in)

Moment Mx = 189.9 Nm/m (42701 in-lb/in)

Shear Nxy = 1552 kN/m (8862 lb/in)



ADVANCED CIVIL SPACE SYSTEMS

Aerobrake Structure Finite-Element Model

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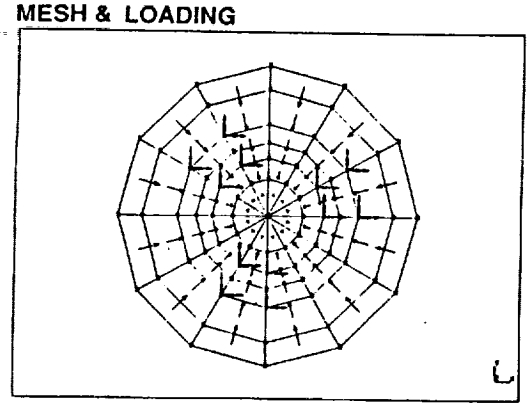
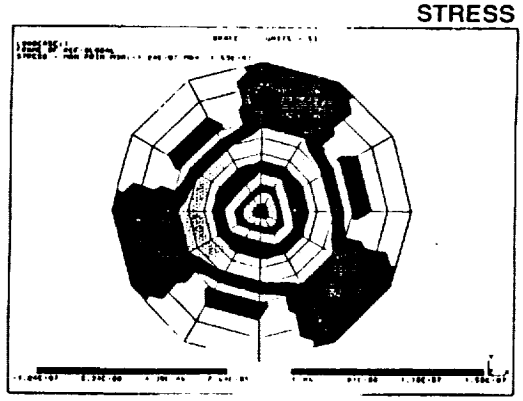
MESH & LOADING



STRESS



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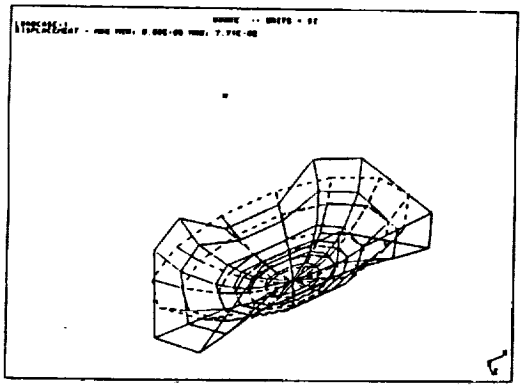

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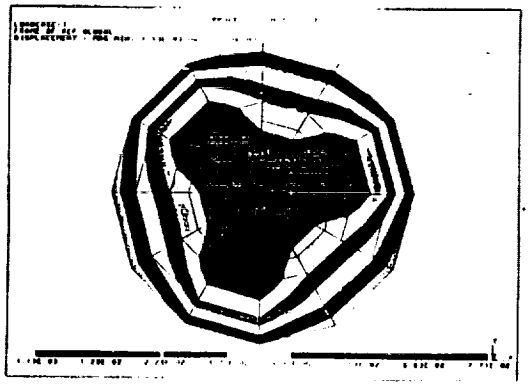

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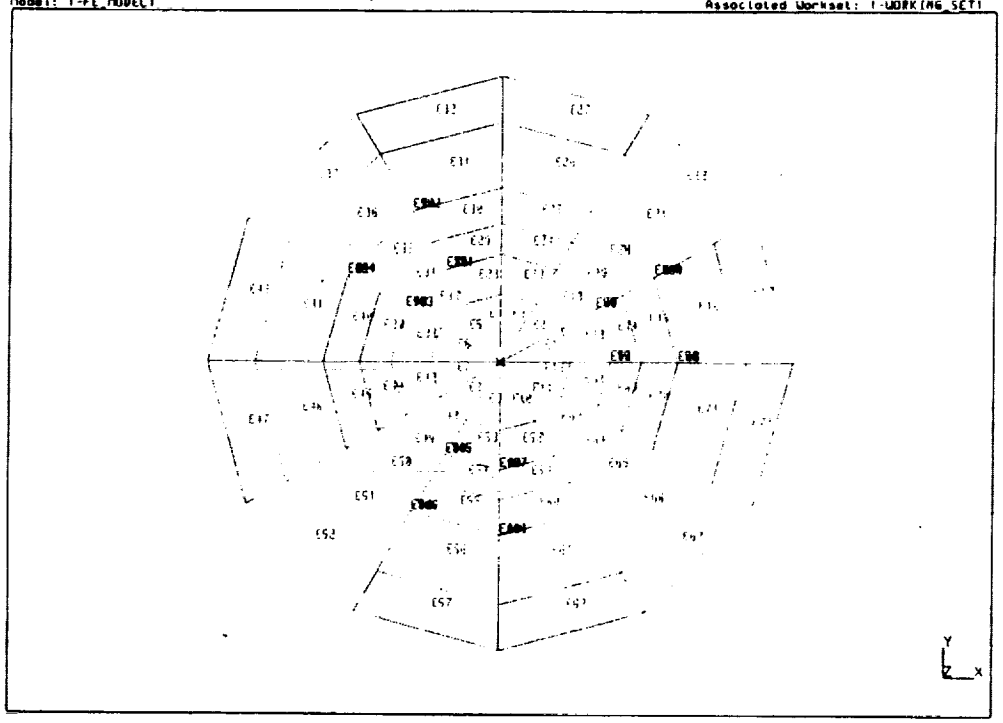

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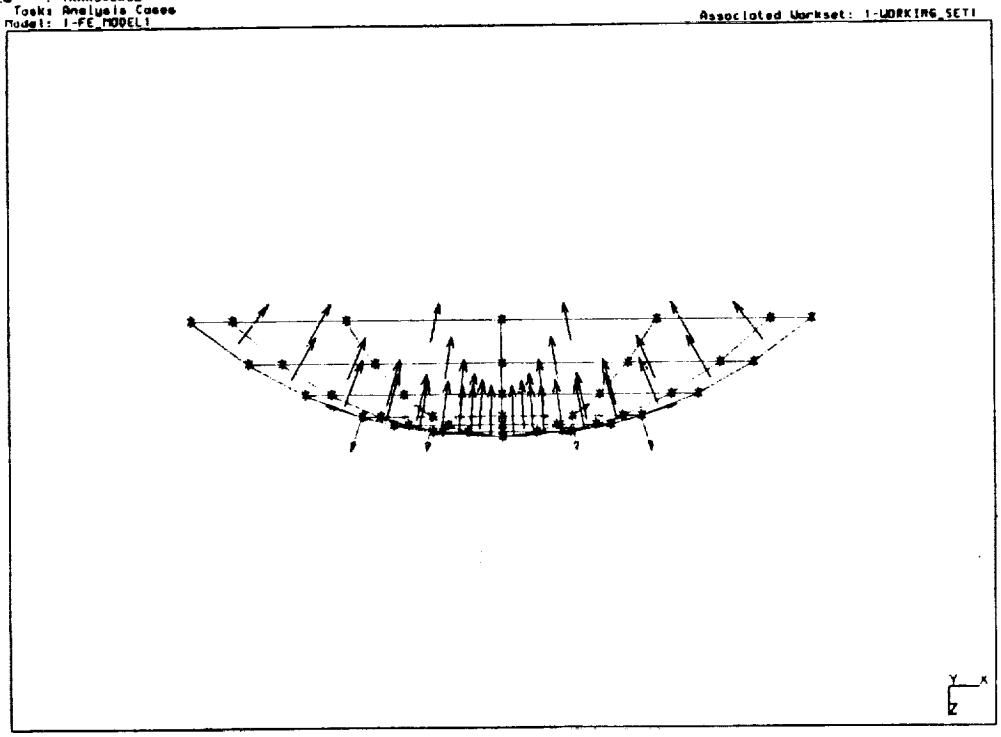

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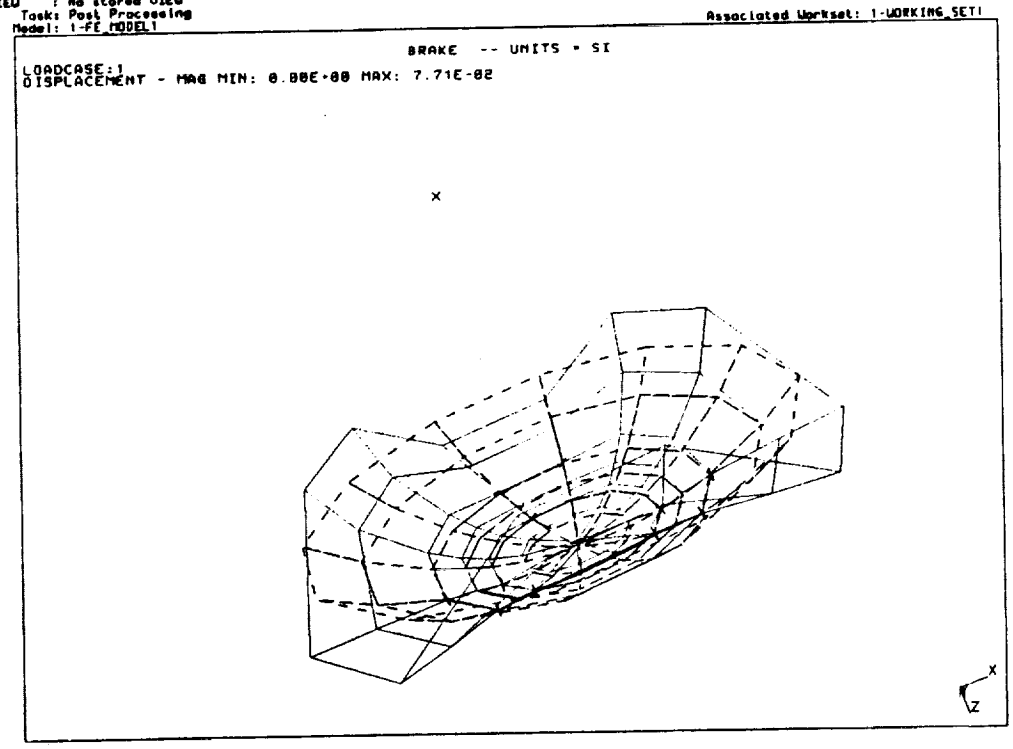

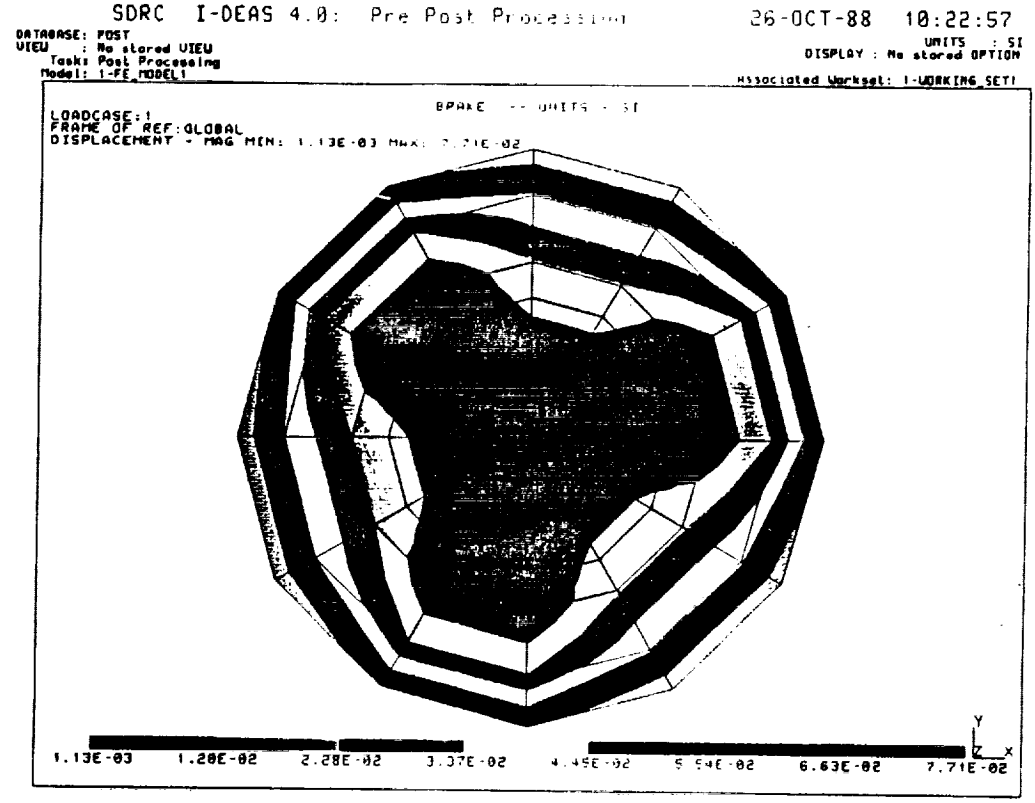
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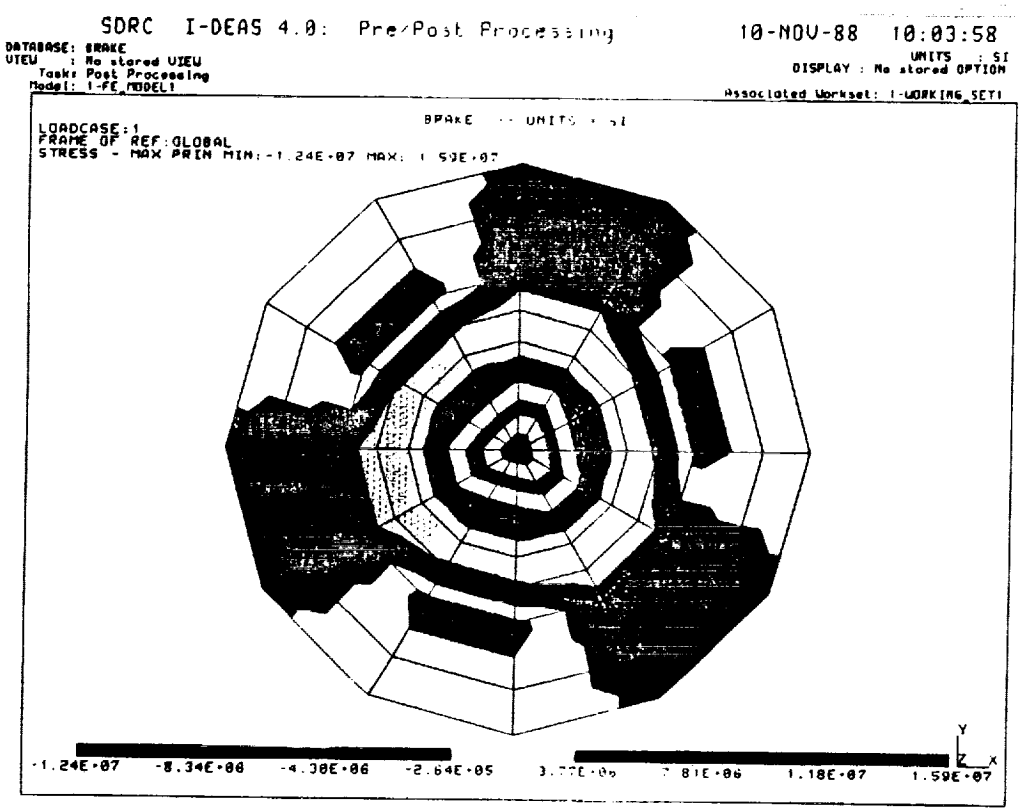
Y
X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-2.64E-05
1.18E-07
1.59E-07
Y
X

Preliminary Aerobrake Structural Design

Procedure

Use maximum line loads, iterate component dimensions to obtain minimum material

Assumptions

Reference structure temperature = 394 K (250 °F)
Factor of safety = 1.6
Uniform Cross Section
Square Grid of ED-Welded, Pultruded C/Mg ribs:

Rib spacing 2m
Rib depth < 1m

E = 270 GPa (39.1 Msi)
F_{Tult} = 459 MPa (66.5 ksi)
ρ = 1830 kg/m^3 (0.066 lb/in^3)

Flat honeycomb panels take all shear loads (design for shear + axial interaction)

Design Procedure: Boeing manual 253.2, 25.3.2, 25.3.5

Ti - 6Al - 4V face sheets:

E = 107 GPa (15.5 Msi)
F_{Cult} = 848 MPa (123.0 ksi)
F_{Cyield} = 779 MPa (113.0 ksi)
ρ = 4430 kg/m^3 (0.16 lb/in^3)

Ti - 3 Al - 2.5V honeycomb: ρ = 64.1 kg/m^3 (4 lb/ft^3)

ADVANCED CIVIL SPACE SYSTEMS

Preliminary Aerobrake Structural Design

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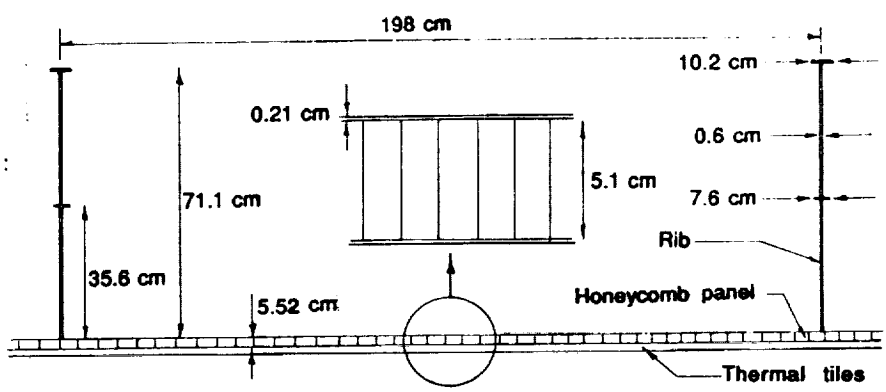
Results

Configuration :



Weights:

Ribs	8796 kg	(19352 lb)
Honeycomb	15594 kg	(34306 lb)
Thermal tiles	3818 kg	(8399 lb)
Total Aerobrake Structure without fasteners (±10% Accuracy)	28 MT	(62000 lb)

ADVANCED CIVIL SPACE SYSTEMS

Aerobrake Structural Conclusions

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Findings

- Shear stress higher than expected
- Simple design yields aerobrake ~ 50% heavier than initial assumption

Lessons

- Distributed loading important to reduce moment
- High strength/weight materials necessary:
  - C/Mg metal-matrix composite ribs
  - Ti/Al honeycomb face panels
- Lightweight TPS critical for Mars ⟶ Earth return
- Triangulated rib grid important to react shear stress, reduce face sheet weight significantly

Future

- Design structure to take full advantage of deep shell geometry
- Avoid sizing entire structure for maximum line loads
- More refined FEM model

ADVANCED CIVIL SPACE SYSTEMS

Aerobrake Assembly Detailing

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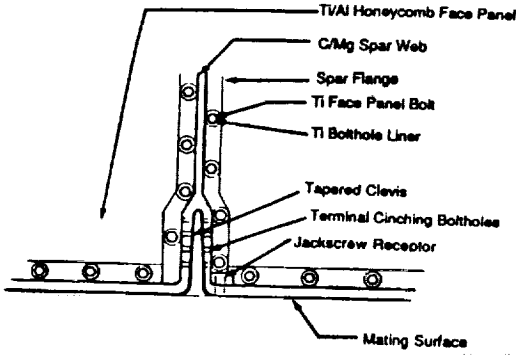
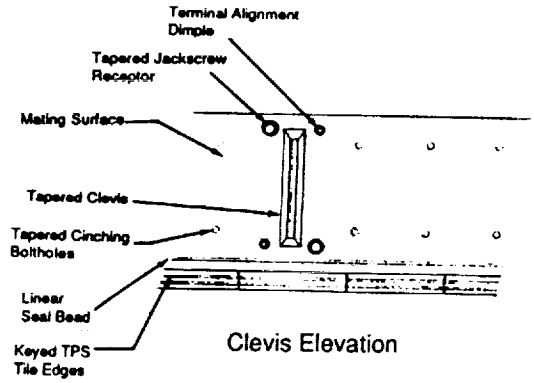
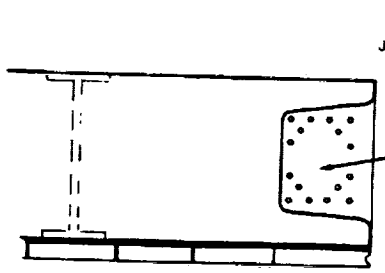


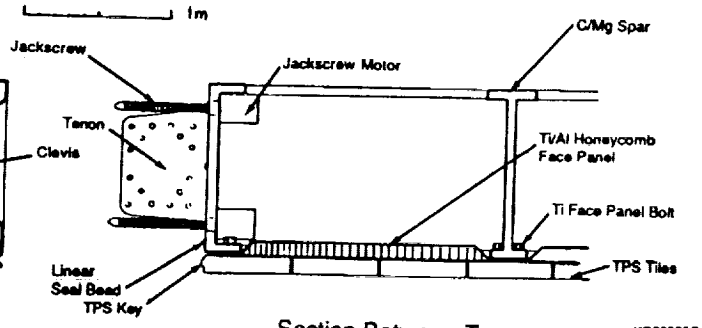
Cross Section Through Clevis



Clevis Elevation



Long Section Through Clevis

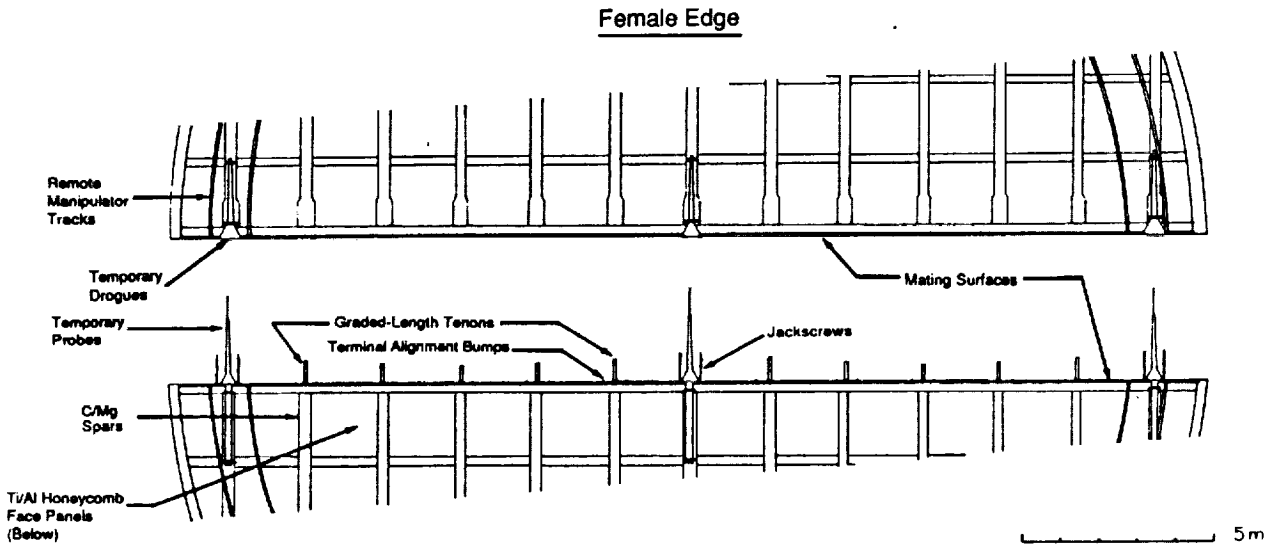


Section Between Tenons

Aerobrake Joint Assembly

ADVANCED CIVIL SPACE SYSTEMS

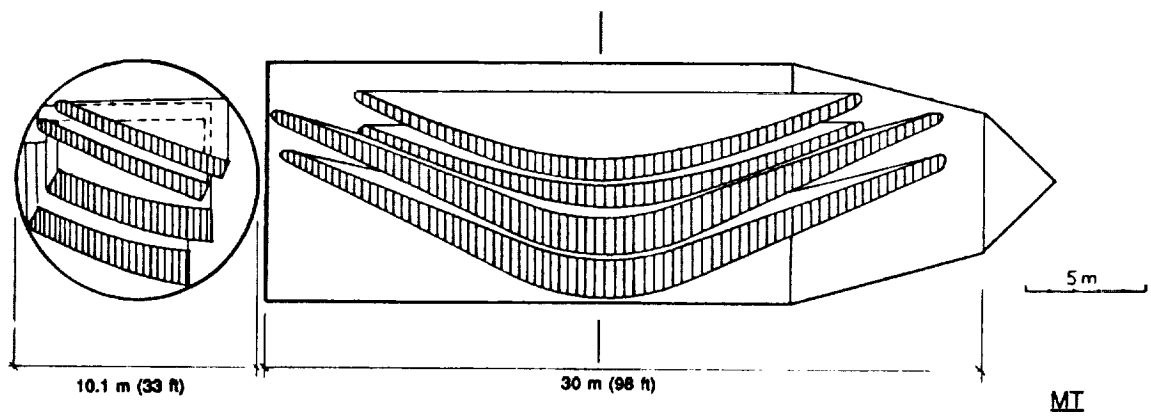
BOEING



Mars Exploration Mission Configuration

ADVANCED CIVIL SPACE SYSTEMS

BOEING



Aeroshell Packaging for Flight #1

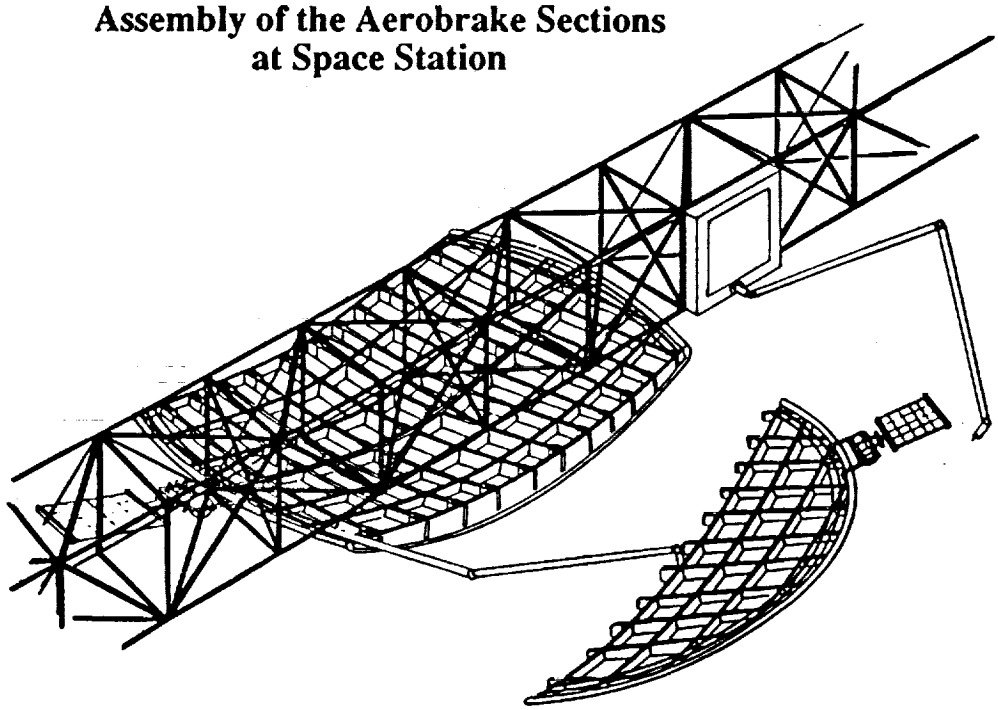
		MT
28 m	Brake in 4 sections	24
5	Holding Arms	2
2	Manipulator Arms	3
2	Rim Rail Carriages	2
3	Housekeeping Modules	5
	+ 20%	
	Σ = 43 MT	

ADVANCED CIVIL SPACE SYSTEMS

Mars Exploration Mission Configuration

BOEING

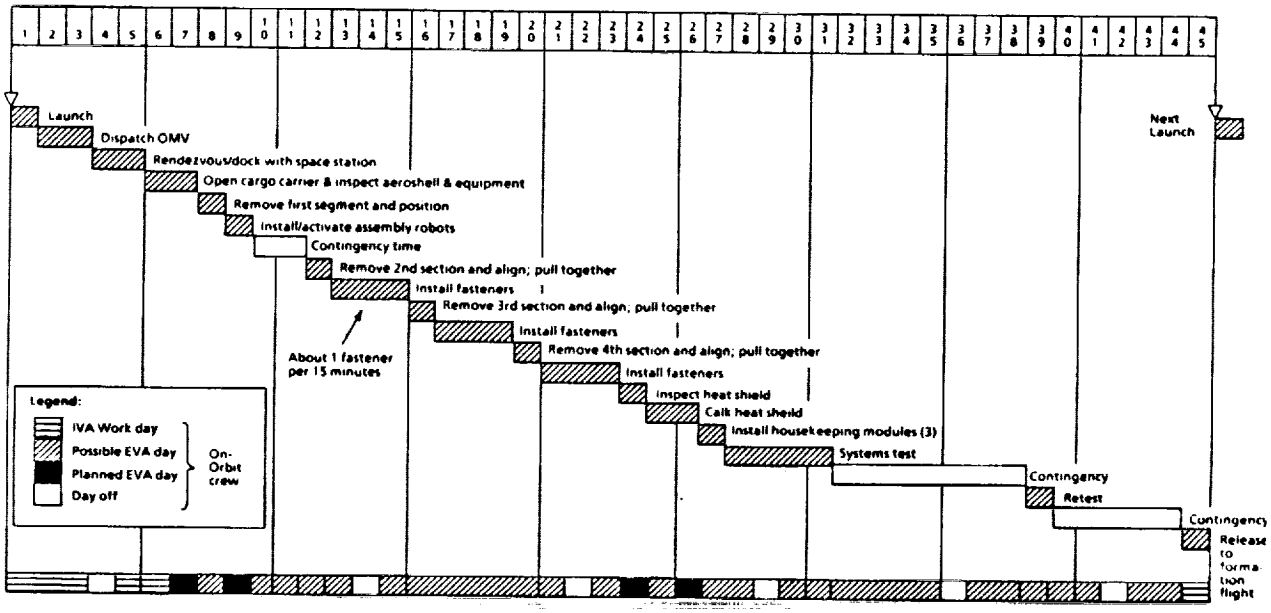
Assembly of the Aerobrake Sections at Space Station



ADVANCED CIVIL SPACE SYSTEMS

45-Day Demand Schedule for Aeroshell Assembly

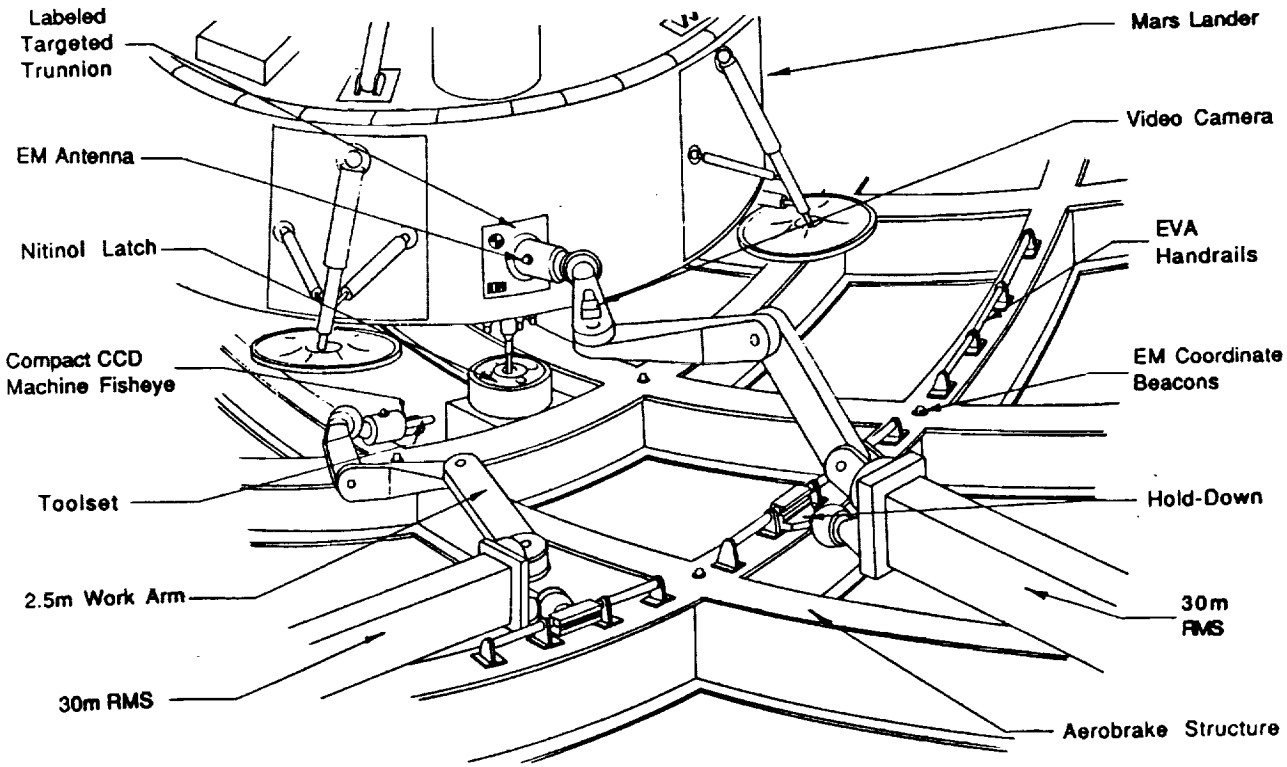
BOEING



ADVANCED CIVIL SPACE SYSTEMS

Robotic Assembly Suite

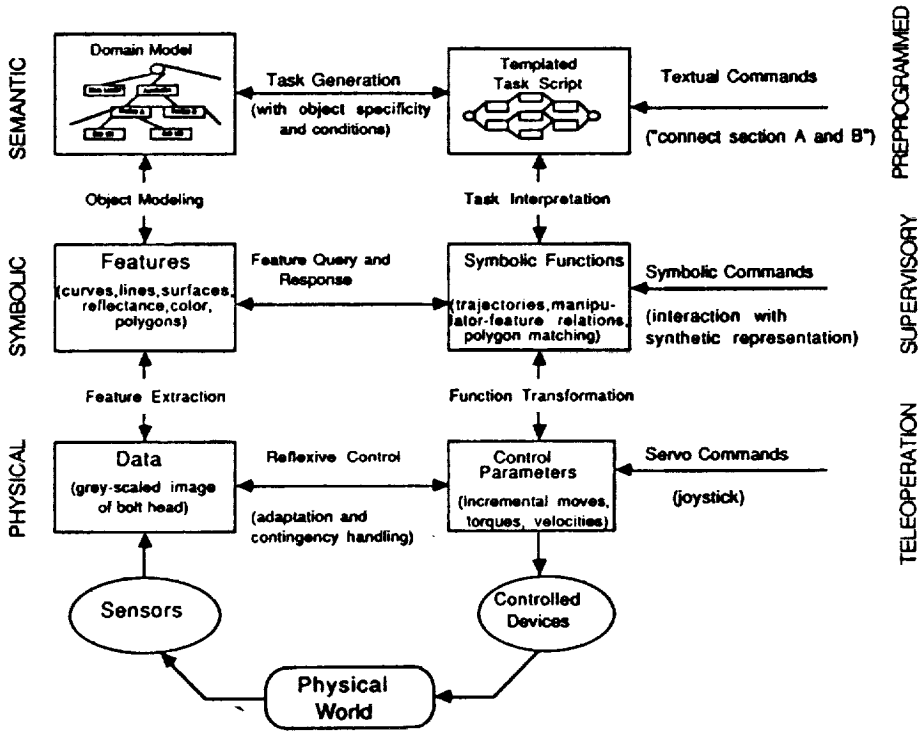
BOEING



ADVANCED CIVIL SPACE SYSTEMS

Software Architecture

BOEING



ADVANCED CIVIL SPACE SYSTEMS

Aerobrake Summary Assessment

BOEING

- L/D 0.3 - 0.6 (corridor height and g limits)
- Ballistic loading 200 kg/m² (40 psf), gives adequate terrain clearance (h_{min} = 30 km) and size compatible with spacecraft.
- Asymmetric lifting shape puts trim c.g. close to middle of protected area.
- Initial controllability runs have not identified any problems.
- Aerobrakes are highly loaded structures and should probably be rigid; assembled.
- Distributed loading and composite materials essential for minimum weight.
- Earth return C_3s up to 50 appear feasible with conventional TPS.

ADVANCED CIVIL SPACE SYSTEMS

Aerothermal Summary Assessment

BOEING

LUNAR RETURN

- Uncertainty in radiation heating, current predictions exceed reradiative capability
  - Trajectory design may reduce problem
  - Need AFE results for final design decisions

MARS RETURN

- (Mars capture and landing within known capability)
- Earth return exceeds projected reradiative technology
  - Large uncertainties in heating predictions
  - Radiation from nonequilibrium ionized shock layer
  - Lightweight ablators not tested at these heating rates
  - May need AFE follow-on
- Lightweight TPS essential to make recovery of Mars transit vehicle economical

NASA-OAST STUDIES OF HIGH ENERGY AEROBRAKING

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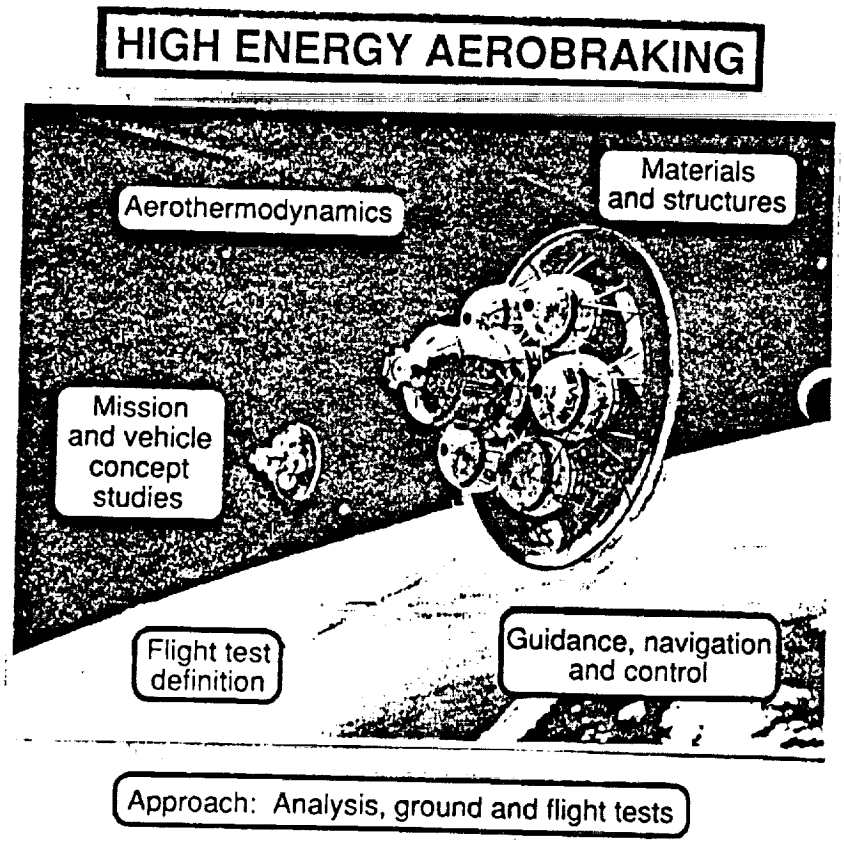
OVERVIEW OF OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY

OAST HIGH ENERGY AEROBRAKING PROGRAM (MANAGEMENT)

S. WANDER



PROJECT PATHFINDER
HIGH-ENERGY AEROBRAKING

OAST

PROGRAM OBJECTIVES

- Develop Critical Technologies For Planetary Aerocapture/Aeromaneuver and Earth Re-entry
- Enable A Factor Of 2-to-3 Reduction In Propellant Mass For Planetary Missions

TECHNOLOGY ISSUES

- Optimization Of Aerobrake Configurations
- Heating Mechanisms Definition
- Development of Thermal Protection Systems
- Need For Real-Time Adaptive/Fault-Tolerant Guidance, Navigation, and Control (GN&C)
- Inadequate Ground Test Facilities

PROJECT PATHFINDER
HIGH-ENERGY AEROBRAKING

OAST

OVERVIEW DESCRIPTION

Research-oriented program in a suite of key disciplines; focused through mission-oriented systems analyses and configuration concept definition. Simulations and discipline-specific milestones planned. Requirements for space flight demonstration to be defined.

RESOURCES REQUIRED

	FY'89	*FY'90*	*FY'91*	*FY'92*	*FY'93*	(Continuing)
FUNDING ($,M)	2.0	4.0	8.0	13.0	20.0	(TBD)
WORKFORCE (WY/Y)	TBD	TBD	TBD	TBD	TBD	(TBD)

PROJECT PATHFINDER
HIGH-ENERGY AEROBRAKING

OAST

TECHNOLOGY DEVELOPMENT PHASE MILESTONES/DELIVERABLES: 1993
• IMPROVED CFD CODES AVAILABLE • EXPANDED ENGINEERING DESIGN CAPABILITY • VALIDATED ADAPTIVE GN&C CAPABILITY • ADVANCED TPS MATERIALS EVALUATED AND DEVELOPED • BASELINE CONFIGURATIONS FOR ROBOTIC AND PILOTED MARS MISSIONS DEFINED • FLIGHT EXPERIMENT(S) DEFINED

PROJECT PATHFINDER
HIGH ENERGY AEROBRAKING

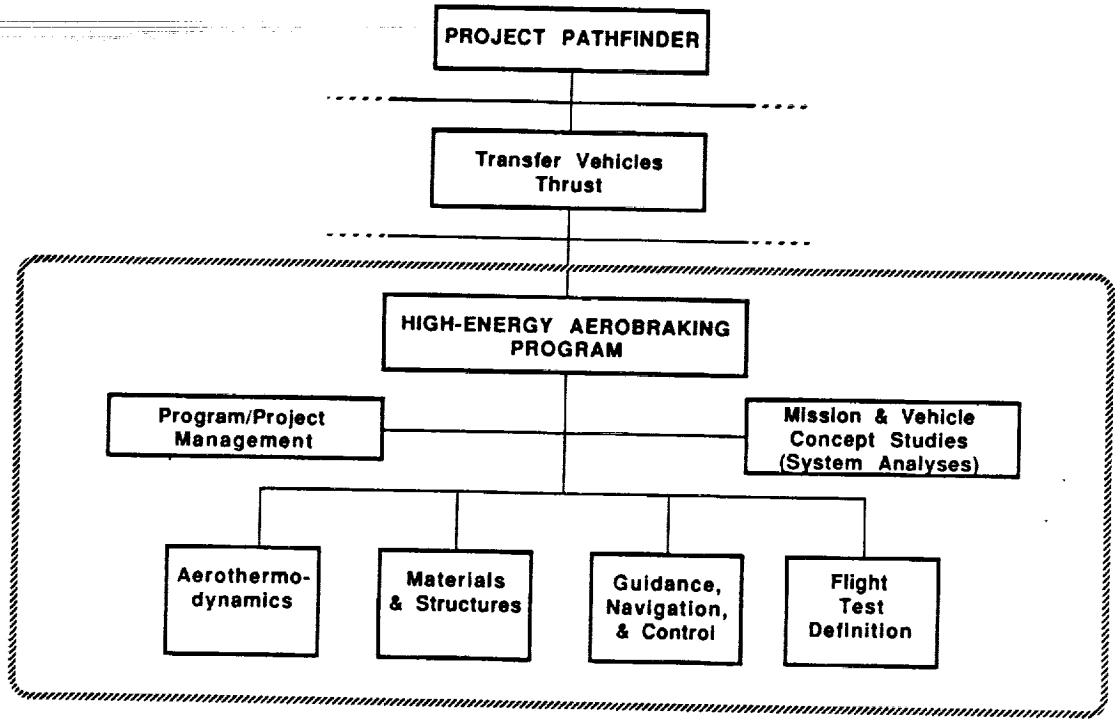
OAST

MULTI-FACETED PROGRAM; INVOLVING MULTIPLE OAST DIVISIONS, MULTIPLE CENTERS

- **MANAGEMENT STRATEGY:**
  - *OAST/RF: PROGRAM MANAGER*
  - *MULTI-DIVISION MANAGEMENT OVERSIGHT COMMITTEE*
  - *INTERCENTER WORKING GROUP*
  - *FIELD CENTER: "PROJECT IMPLEMENTATION MANAGER"*
- **PROGRAM DEFINITION APPROACH:**
  - *INITIAL PLANNING PROCESS APRIL 88 to SEPT.88*
  - *PRODUCT: "High-Energy Aerobraking Program Plan"*
    "H-E-A Technology Project Plan"
  - *ESTABLISH PROGRAM LEAD CENTER & PARTICIPATING CENTERS ROLES AND RESPONSIBILITIES*

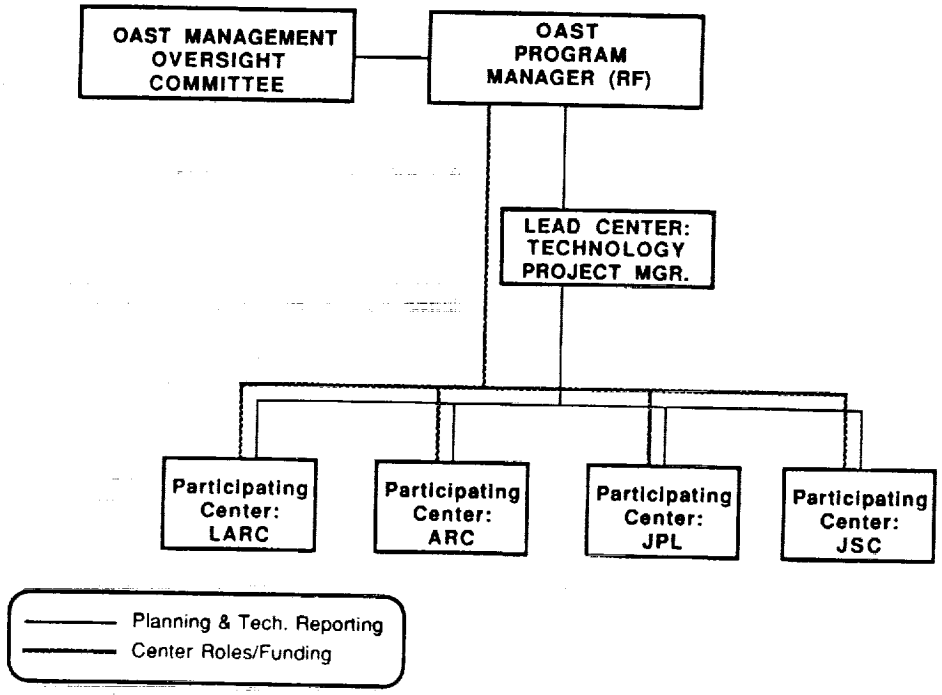
HIGH ENERGY AEROBRAKING WORK BREAKDOWN STRUCTURE

OAST



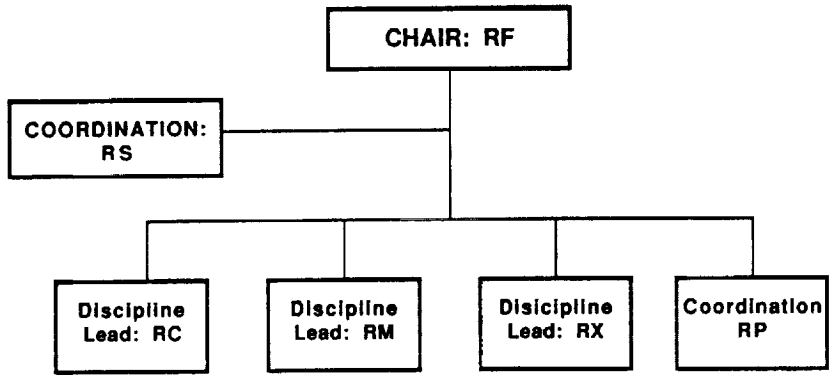
HIGH ENERGY AEROBRAKING PROGRAM MANAGEMENT STRUCTURE

OAST



HIGH ENERGY AEROBRAKING MANAGEMENT OVERSIGHT COMMITTEE

OAST



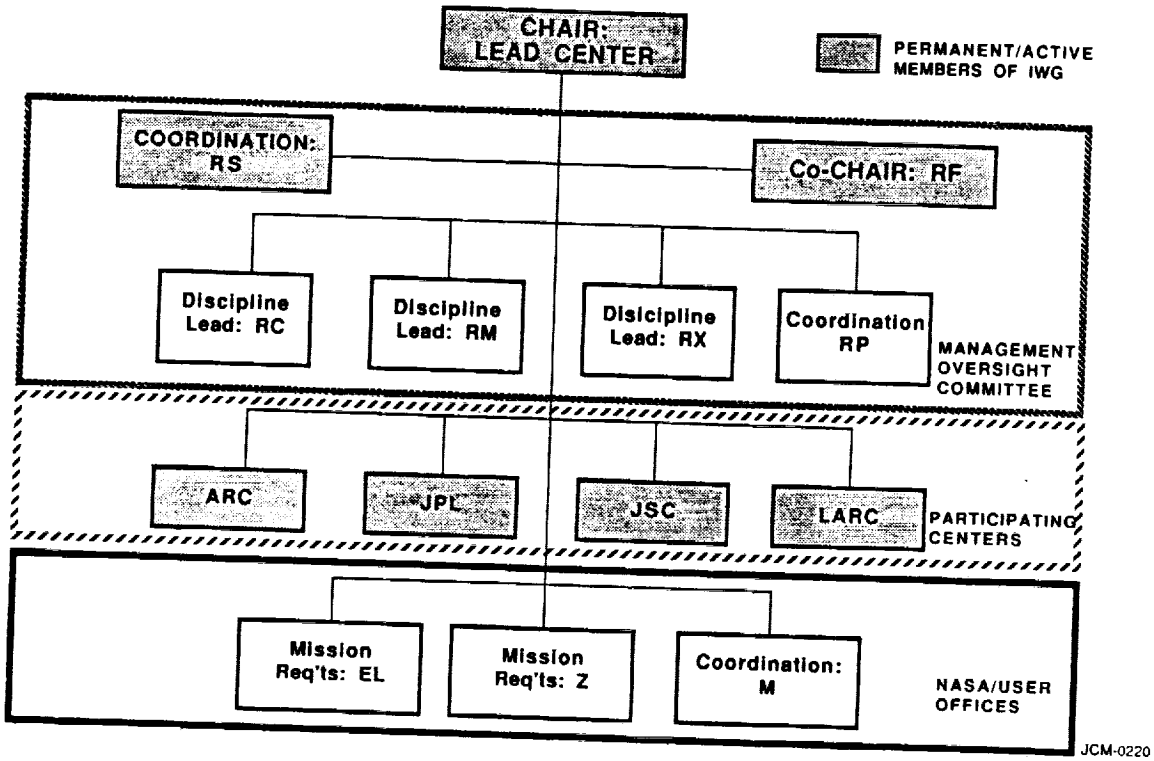
HIGH ENERGY AEROBRAKING MANAGEMENT OVERSIGHT COMMITTEE

OAST

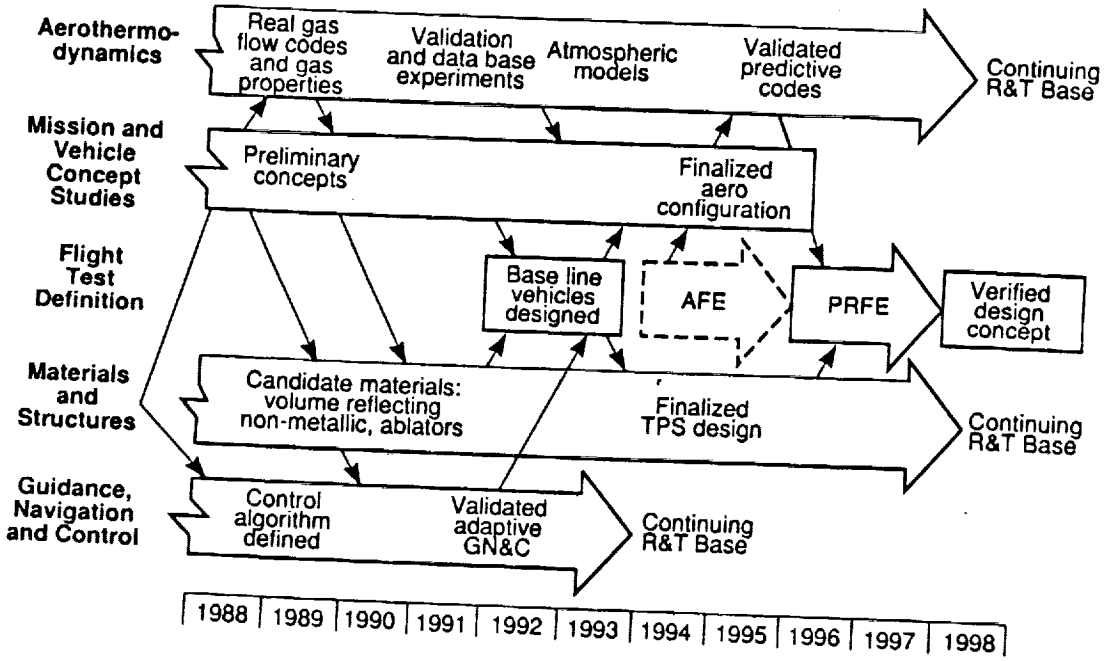
CHAIR: RF	*Responsible For Chairing Oversight Meetings; Aerothermodynamics Discipline/Workpackage Planning; and Plan Integration*
Discipline Lead: RM	*Responsible For Materials & Structures Discipline/Workpackage Planning*
Discipline Lead: RC	*Responsible For GN&C Discipline/Workpackage Planning*
Disicipline Lead: RX	*Responsible For In-Space R&T Experiments Consideration/Planning*
COORDINATION: RS	*Responsible For Cross-Discipline Coordination, and Mission Analyses*

HIGH ENERGY AEROBRAKING INTERCENTER WORKING GROUP

OAST



HIGH ENERGY AEROBRAKING MILESTONES AND DELIVERABLES



SPECIFICS OF AMES' AEROBRAKING EFFORTS: PAST, PRESENT AND PLANNED

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OVERVIEW OF AMES' TRANSATMOSPHERICS PROGRAM

PRESENTED AT THE CODE R/Z/E/INDUSTRY HIGH ENERGY AEROBRAKING HEAB WORKSHOP

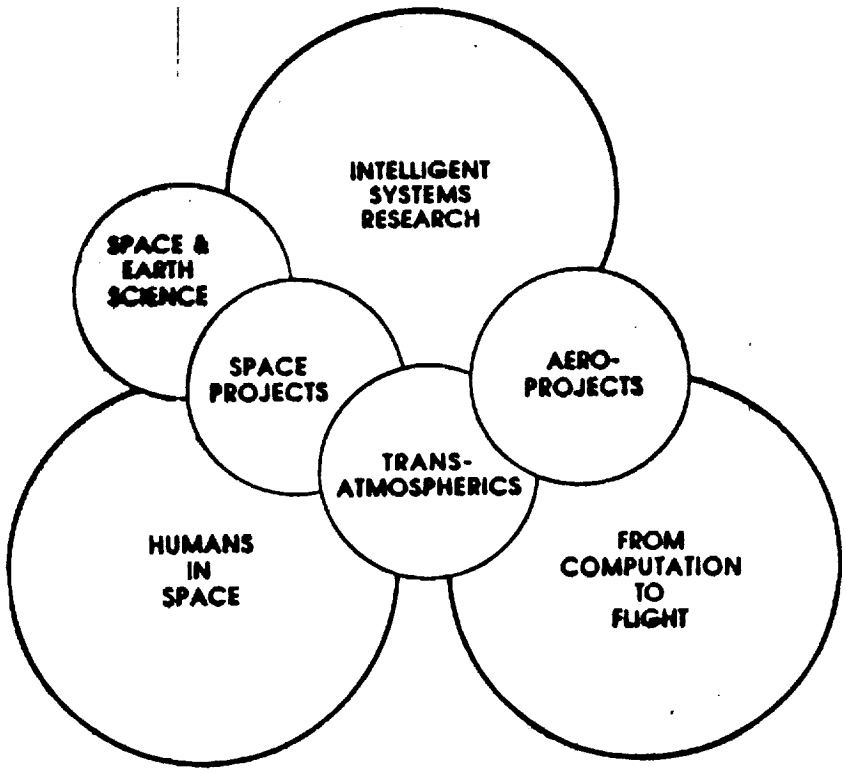
1/31/89

BY

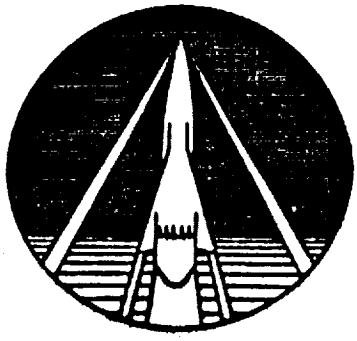
JAMES O. ARNOLD

THE VISION OF AMES (1996)

SPACE ⟷ AERONAUTICS



TRANSATMOSPHERICS



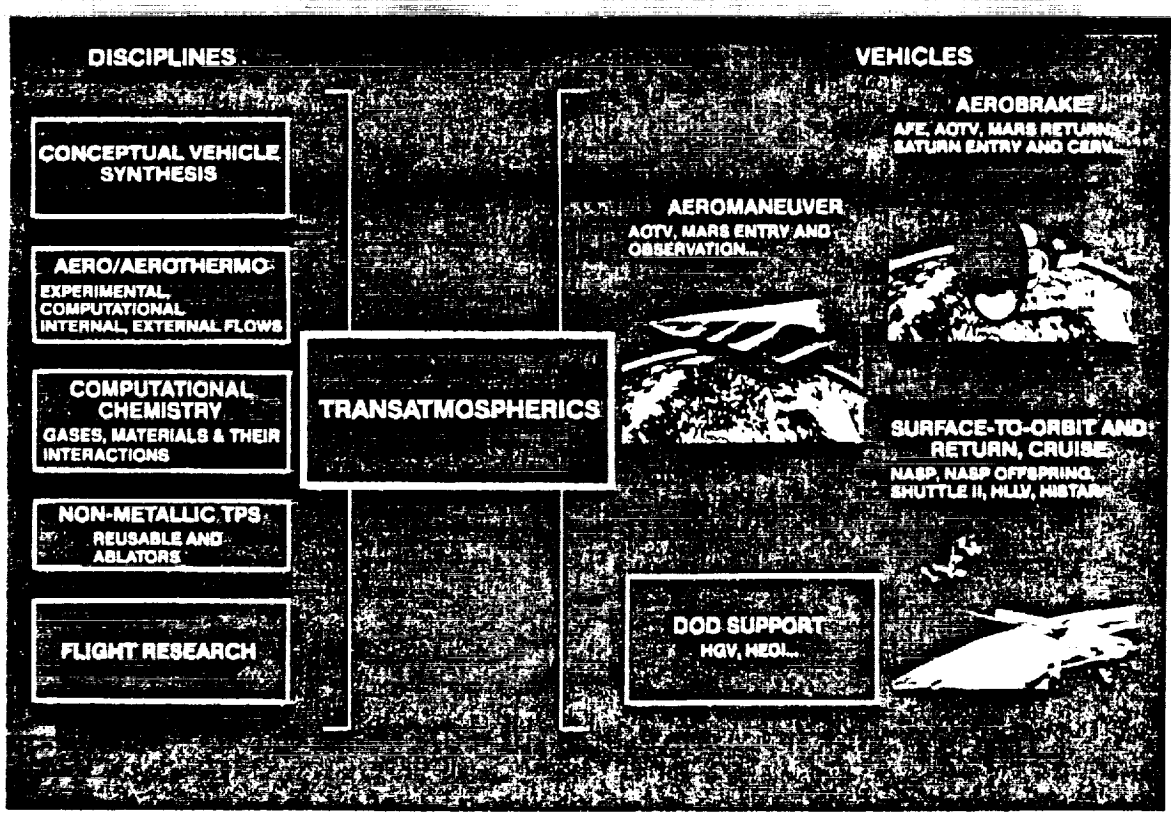
Ames will strengthen its established excellence *in selected areas* of basic research and technology development for aerospace systems that transport humans and materials to and from space and within the atmospheres of other bodies in the solar system.

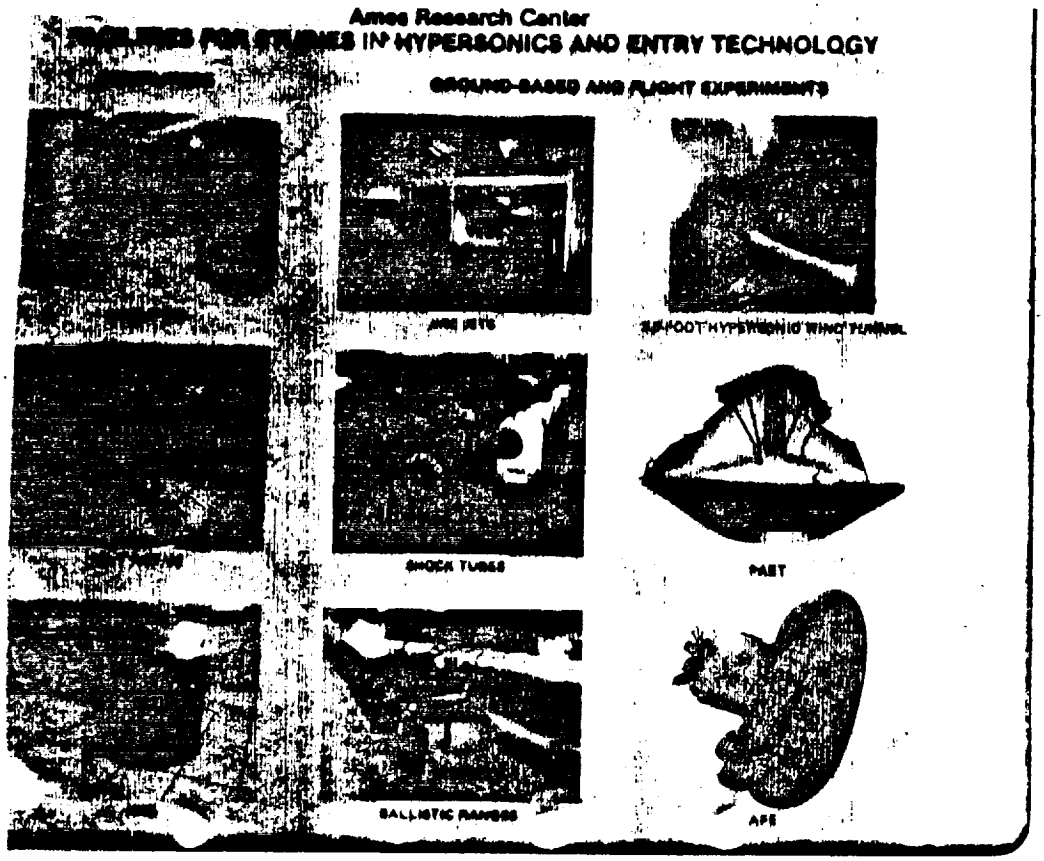
Ames will excel in

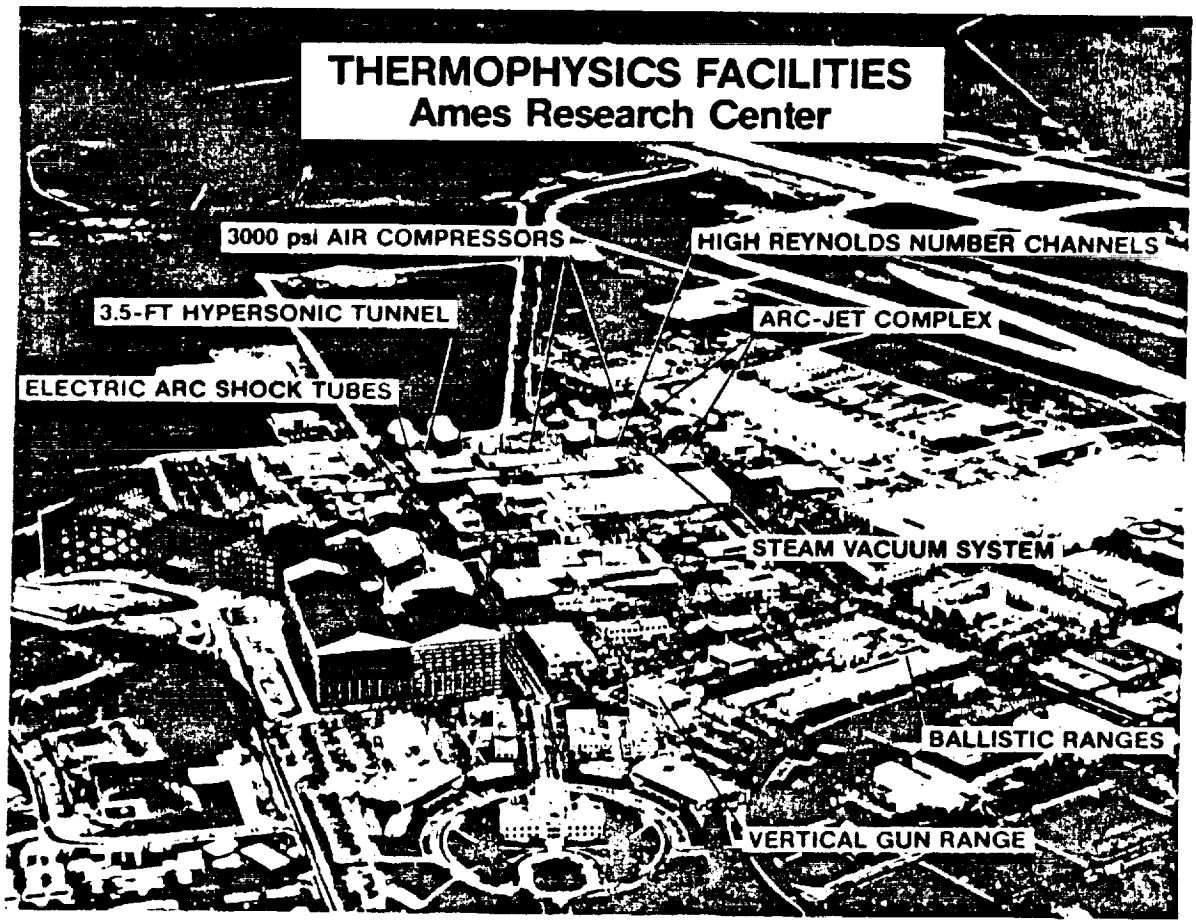
- fluid and thermal physics
- re-entry systems
- hypersonic vehicle flight research

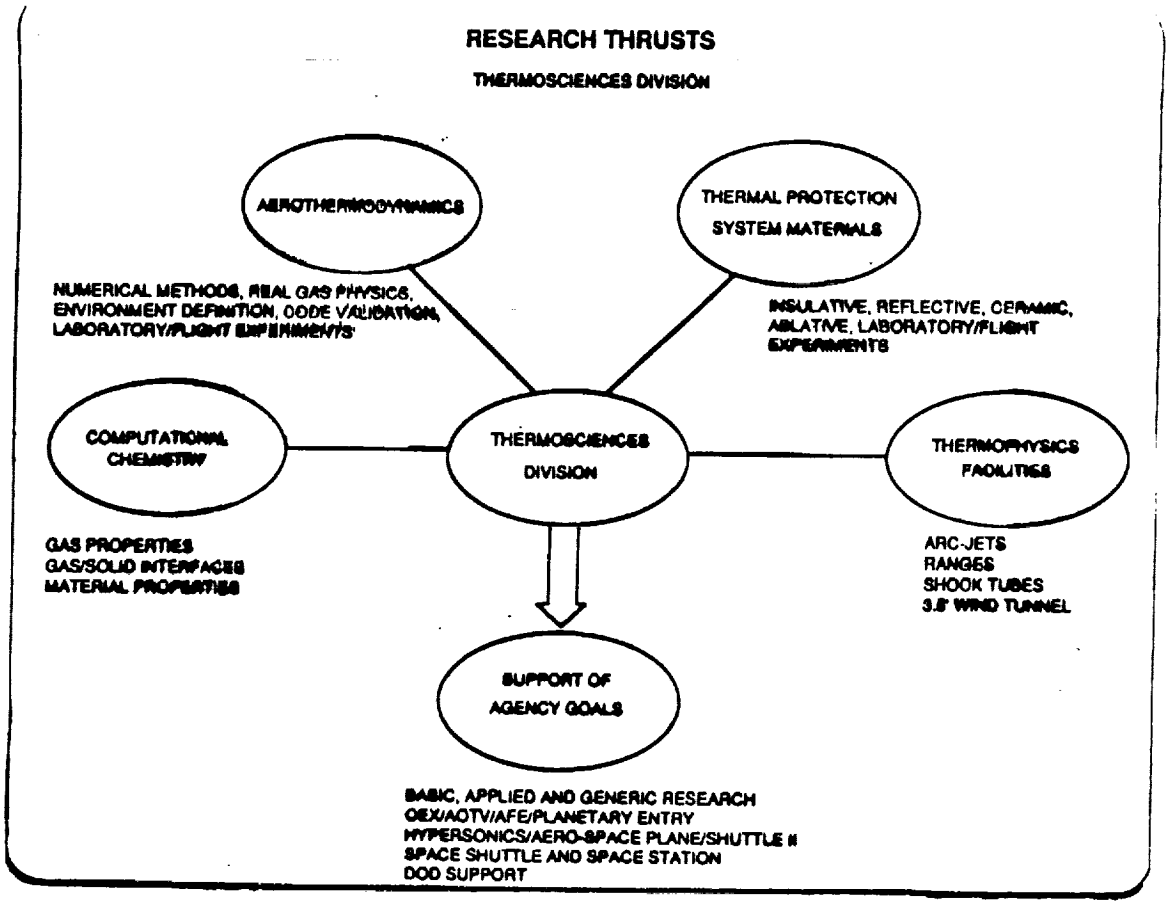
Vehicles to be studied travel at hypersonic Mach numbers and include:

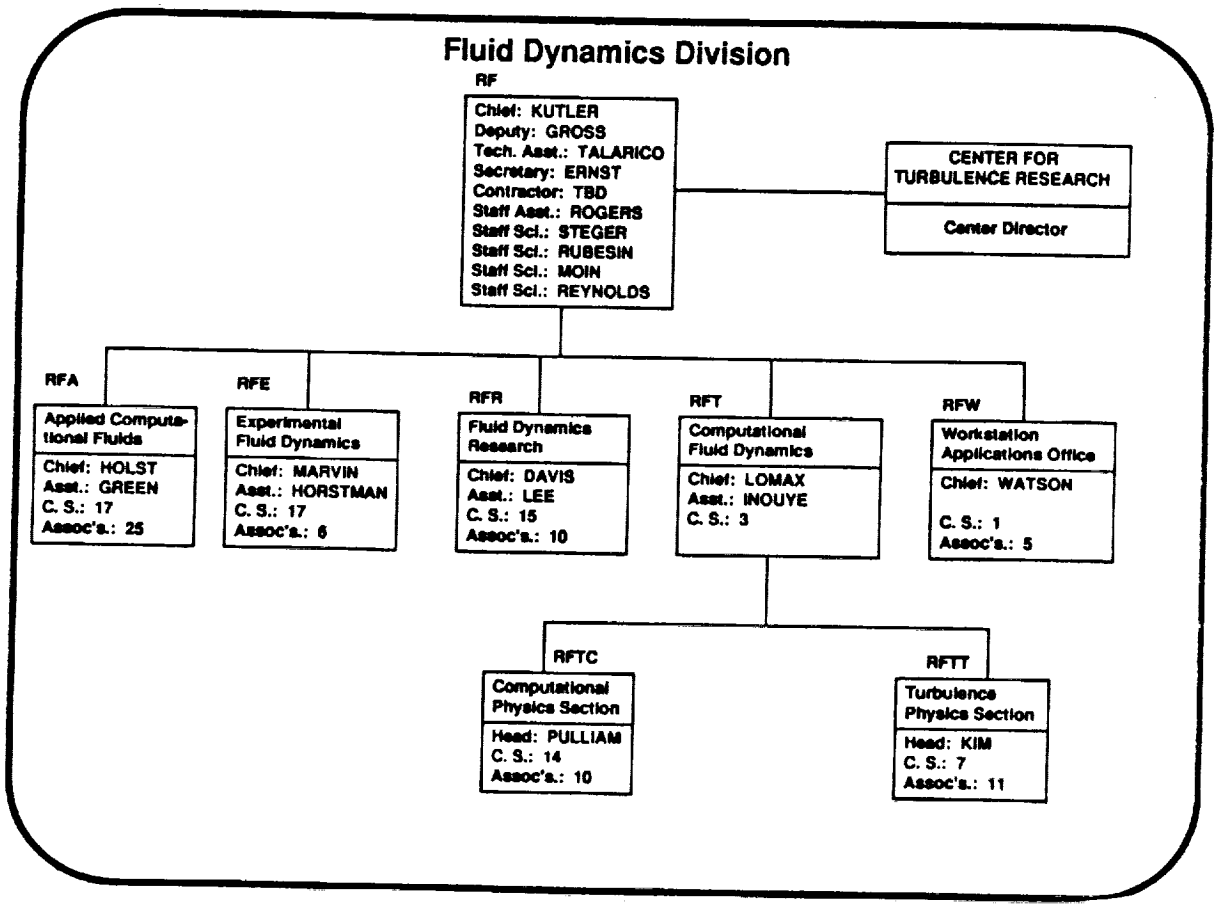
- aerospacecraft
- atmospheric entry probes
- space cargo transports




Ames Research Center
IN HYPERSONICS AND ENTRY TECHNOLOGY
GROUND-BASED AND FLIGHT EXPERIMENTS
ARC JETS
SHOCK TUBES
PAET
BALLISTIC RANGES
APE


THERMOPHYSICS FACILITIES
Ames Research Center
3000 psi AIR COMPRESSORS
HIGH REYNOLDS NUMBER CHANNELS
3.5-FT HYPERSONIC TUNNEL
ARC-JET COMPLEX
ELECTRIC ARC SHOCK TUBES
STEAM VACUUM SYSTEM
BALLISTIC RANGES
VERTICAL GUN RANGE


RESEARCH THRUSTS
THERMOSCIENCES DIVISION
AEROTHERMODYNAMICS
NUMERICAL METHODS, REAL GAS PHYSICS, ENVIRONMENT DEFINITION, CODE VALIDATION, LABORATORY/FLIGHT EXPERIMENTS
THERMAL PROTECTION SYSTEM MATERIALS
INSULATIVE, REFLECTIVE, CERAMIC, ABLATIVE, LABORATORY/FLIGHT EXPERIMENTS
COMPUTATIONAL CHEMISTRY
GAS PROPERTIES
GAS/SOLID INTERFACES
MATERIAL PROPERTIES
THERMOSCIENCES DIVISION
THERMOPHYSICS FACILITIES
ARC-JETS
RANGES
SHOCK TUBES
3.5' WIND TUNNEL
SUPPORT OF AGENCY GOALS
BASIC, APPLIED AND GENERIC RESEARCH
OEX/AOTV/AFE/PLANETARY ENTRY
HYPERSONICS/AERO-SPACE PLANE/SHUTTLE II
SPACE SHUTTLE AND SPACE STATION
DOD SUPPORT


Fluid Dynamics Division
RF
Chief: KUTLER
Deputy: GROSS
Tech. Asst.: TALARICO
Secretary: ERNST
Contractor: TBD
Staff Asst.: ROGERS
Staff Sci.: STEGER
Staff Sci.: RUBESIN
Staff Sci.: MOIN
Staff Sci.: REYNOLDS
CENTER FOR TURBULENCE RESEARCH
Center Director
RFA
Applied Computational Fluids
Chief: HOLST
Asst.: GREEN
C. S.: 17
Assoc's.: 25
RFE
Experimental Fluid Dynamics
Chief: MARVIN
Asst.: HORSTMAN
C. S.: 17
Assoc's.: 6
RFR
Fluid Dynamics Research
Chief: DAVIS
Asst.: LEE
C. S.: 15
Assoc's.: 10
RFT
Computational Fluid Dynamics
Chief: LOMAX
Asst.: INOUYE
C. S.: 3
RFW
Workstation Applications Office
Chief: WATSON
C. S.: 1
Assoc's.: 5
RFTC
Computational Physics Section
Head: PULLIAM
C. S.: 14
Assoc's.: 10
RFTT
Turbulence Physics Section
Head: KIM
C. S.: 7
Assoc's.: 11

SUMMARY

- AMES STRATEGIC PLAN SHOWS LONG-RANGE COMMITMENT TO TRANSATMOSPHERICS, INCLUDING CSTI & ADVANCED MARS MISSIONS.

- AMES IS ADDING STAFF TO MEET THE CHALLENGES OF TRANSATMOSPHERICS AND SOME EXPERIENCED STAFF WILL BE ROLLING OUT OF THE NASP PROGRAM INTO NEW PROGRAMS SUCH AS PATHFINDER HEAB, WHILE COMPLETING PROJECTS SUCH AS AFE.

- AMES EXISTING AND PLANNED COMPUTATIONAL AND EXPERIMENTAL FACILITIES WILL BE SIGNIFICANT TOOLS IN THE TECHNOLOGY BASE FOR THE DEVELOPMENT OF FUTURE TRANSATMOSPHERIC VEHICLES.

MARS MISSION ANALYSIS/SYSTEM STUDIES

CODE R/Z/E/INDUSTRY
HIGH ENERGY AEROBRAKING WORKSHOP

NASA AMES Research Center
January 31 to February 2, 1989

M. E. Tauber
Aerothermodynamics Branch
NASA Ames Research Center

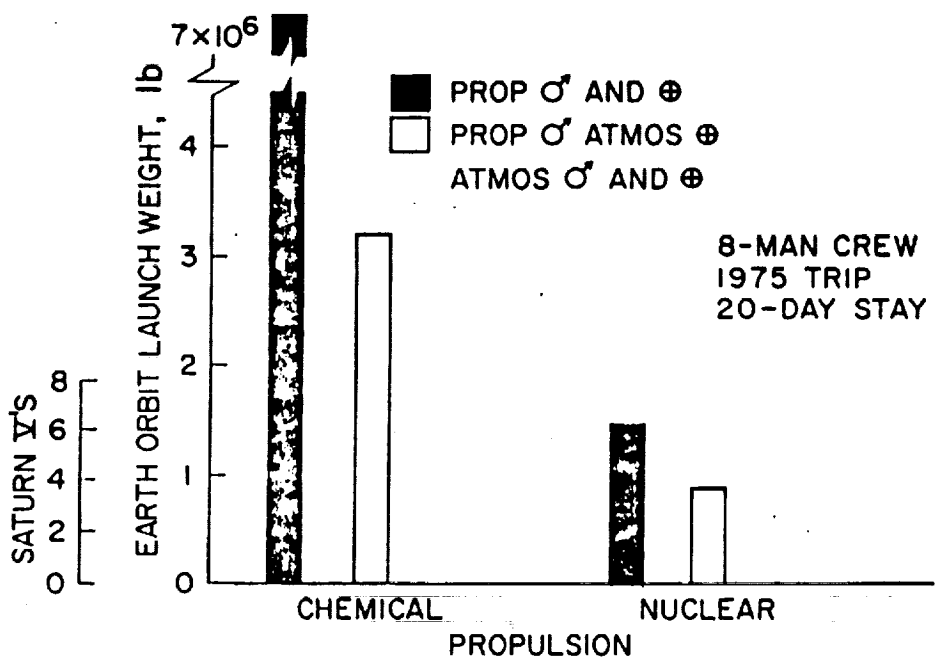
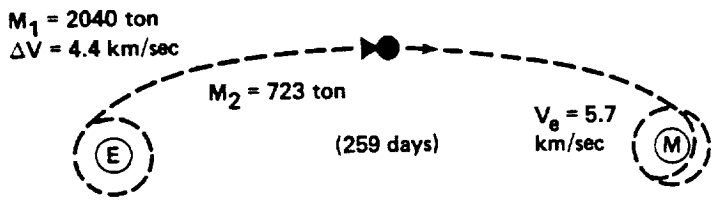


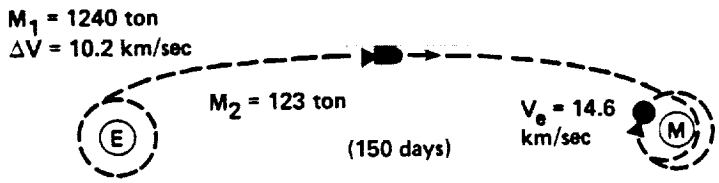
Fig. 6.- Earth orbit launch weights.

OPTIMUM 330 DAY MANNED MARS MISSION

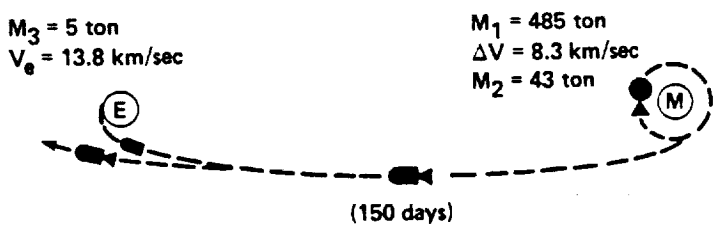
NASA SP-35, 1962



(a) ADVANCED UNMANNED



(b) MANNED EARTH-TO-MARS



(c) MANNED MARS-TO-EARTH

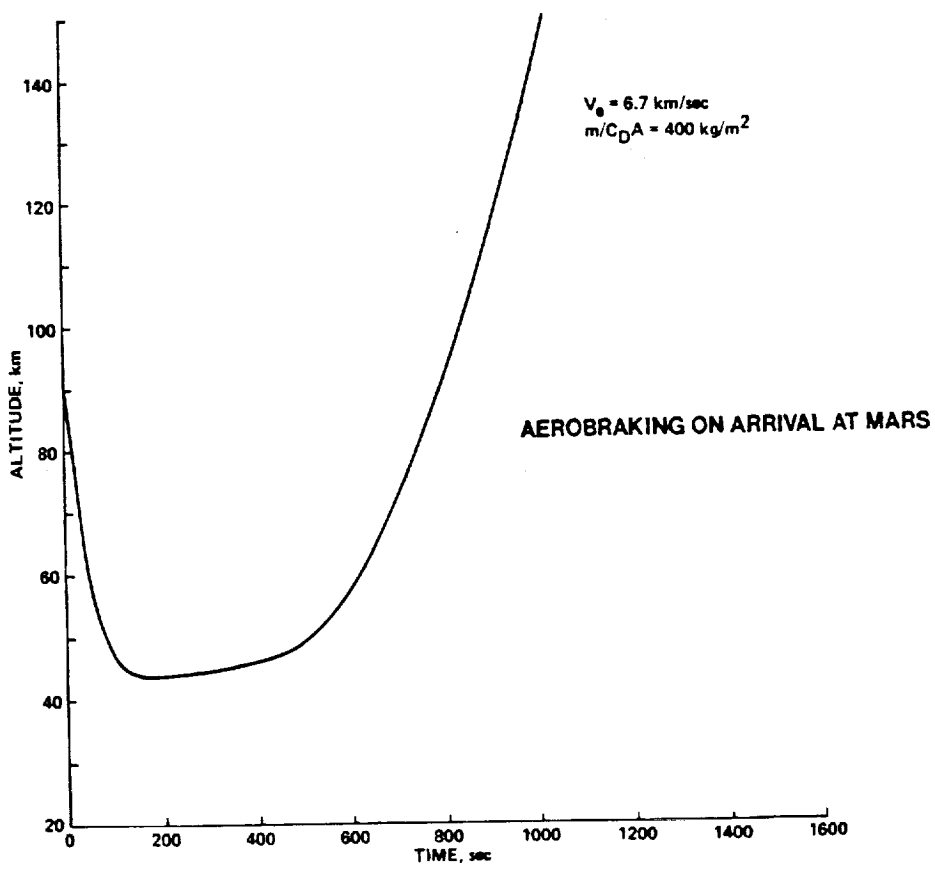
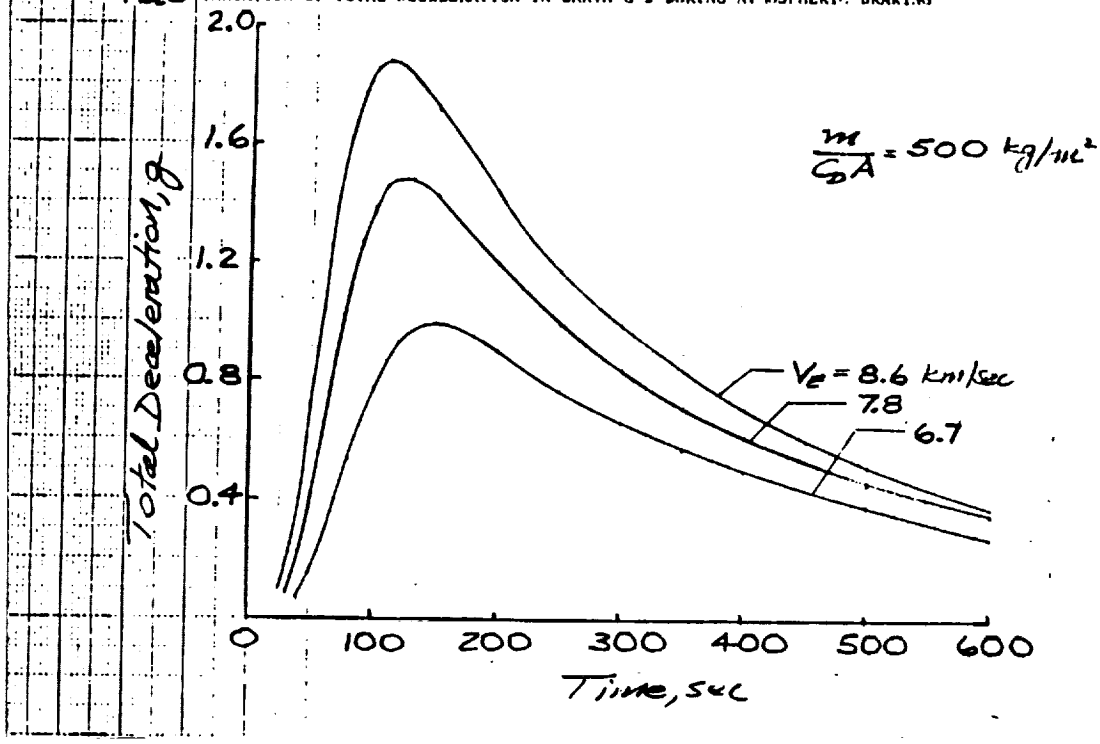
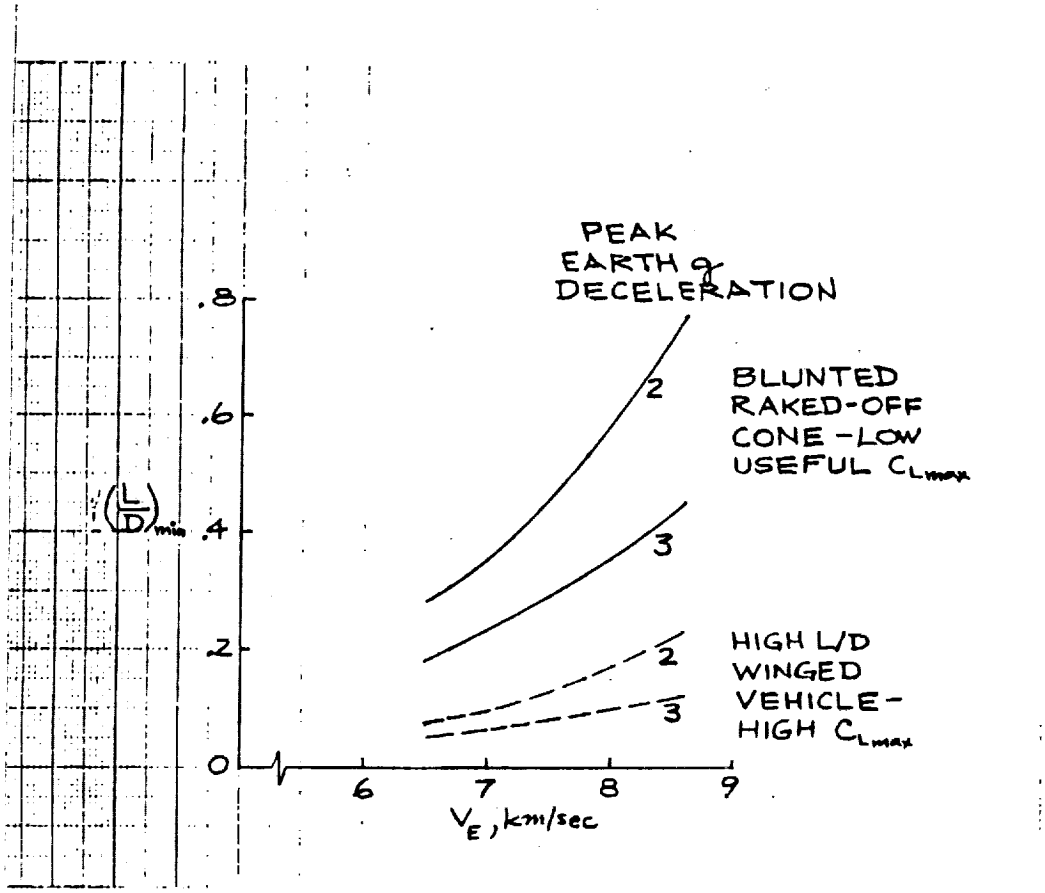
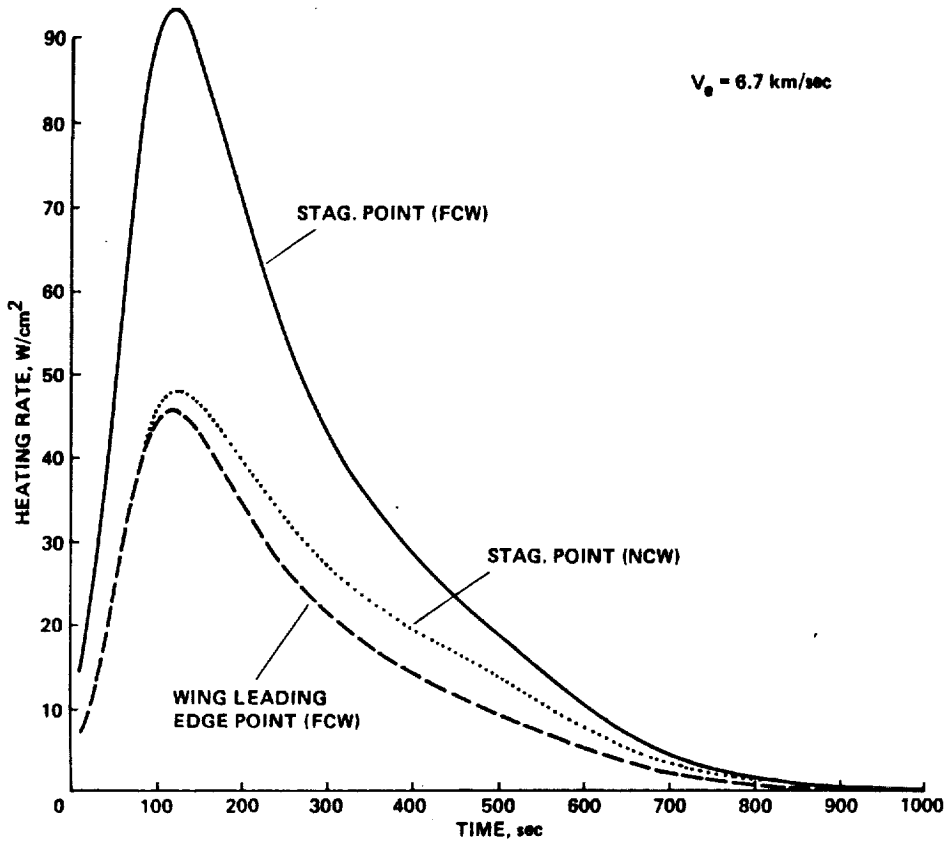


FIG. 5 VARIATION OF TOTAL DECELERATION IN EARTH G's DURING ATMOSPHERIC BRAKING



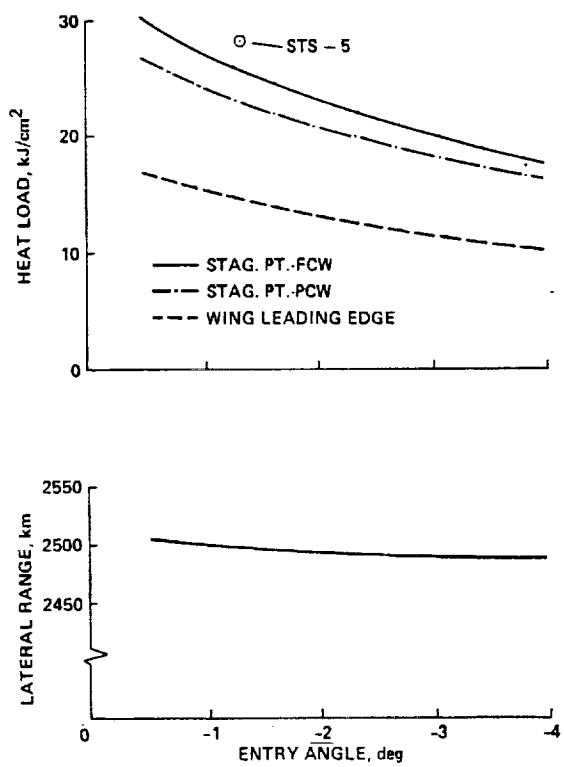


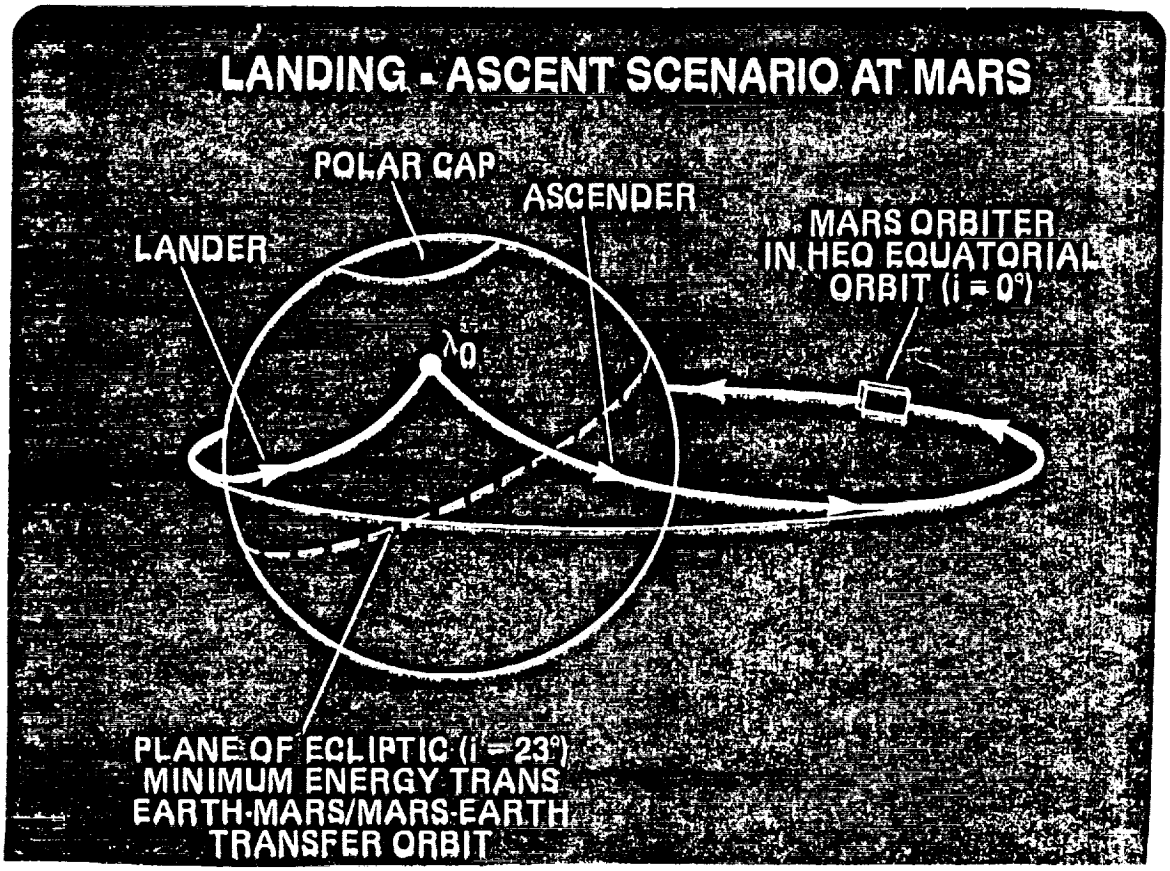
HEATING PULSES DURING AEROBRAKING AT MARS



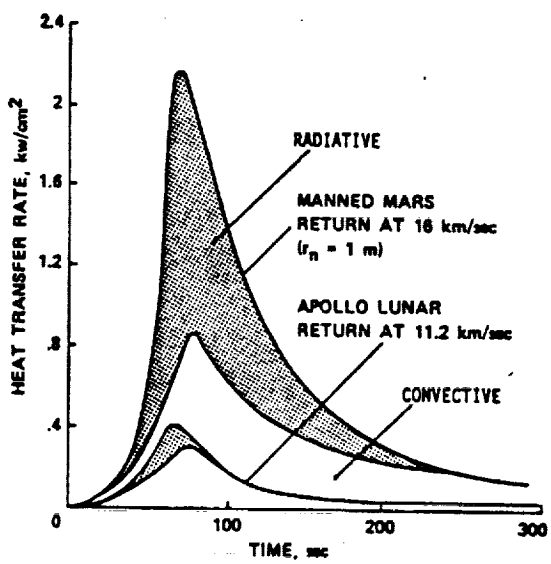
VARIATION OF TOTAL HEAT LOADS AND LATERAL RANGE WITH ENTRY ANGLE

V_E = 3.5 km/sec





STAGNATION POINT HEATING RATES DURING
EARTH ATMOSPHERIC ENTRY
(COLD WALL)



AMES' AEROTHERMODYNAMICS PROGRAM THEORETICAL and EXPERIMENTAL

CODE R/Z/E/INDUSTRY
HIGH ENERGY AEROBRAKING WORKSHOP

NASA AMES Research Center
January 31 to February 2, 1989

G. S. Deiwert
Aerothermodynamics Branch
NASA Ames Research Center

THEORETICAL AEROTHERMODYNAMICS

Real Gas Code Development:

Equilibrium
Finite Rate - Dissociation and Ionization
Thermal Nonequilibrium
Nonequilibrium Radiation

Ablation
Low Density Flows
Particulates
Turbulence
Unsteady

Algorithm Enhancements
Discretization & Graphics

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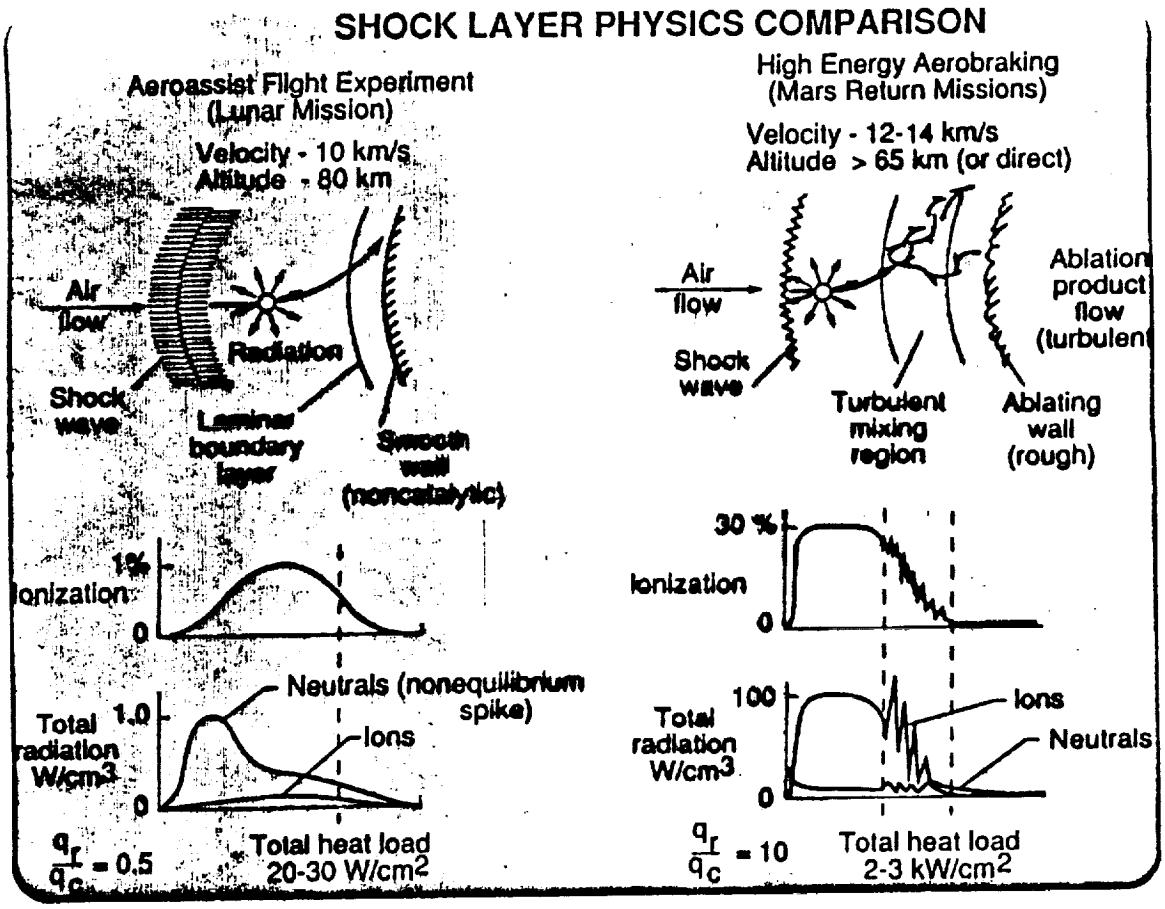


1-D Thermochemical Nonequilibrium Code Development

Objective: Develop the capability to simulate real-gas flows where multi-temperature effects are important

Code: Combined STRAP & SPRAP, explicit 2nd order

Chemistry: 4 elements: (N, O, A, C)
19 species: atoms, diatomic, triatomic, ions, electrons
38 reactions: 7 dissociative, 24 exchange,
3 associative ionization, 4 electron impact ionization

Status: Applied to shock tubes, stagnation streamlines, nozzles
Validated with nonequilibrium radiation spectra (AVCO data)

Future: Add selected hydrogen species
(Titan entry and combustion studies)

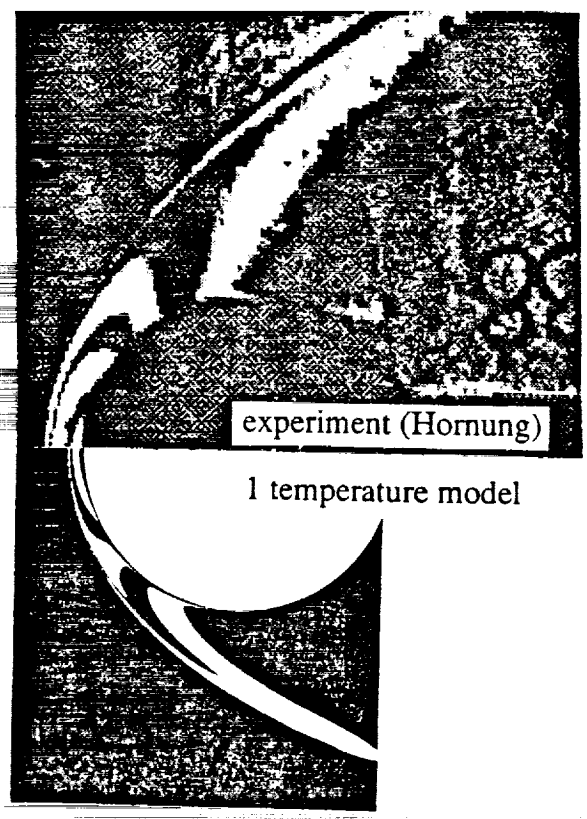
2-D Thermochemical Nonequilibrium Code Development

Objective:	Develop the capability to simulate real-gas flows where multi-temperature effects are important
Code:	Two dimensional, fully implicit, upwind, Gauss-Seidel relaxation scheme.
Chemistry:	Finite rate excitation, reaction, and ionization. Seven species air, six temperatures (1 translational-rotational, 4 vibrational, 1 electron).
Future:	High levels of ionization, Electro-magnetic forces, Improved electron modeling, Extension to three dimensions, Multi-component, thermal and pressure diffusion.

Results – Cylinder

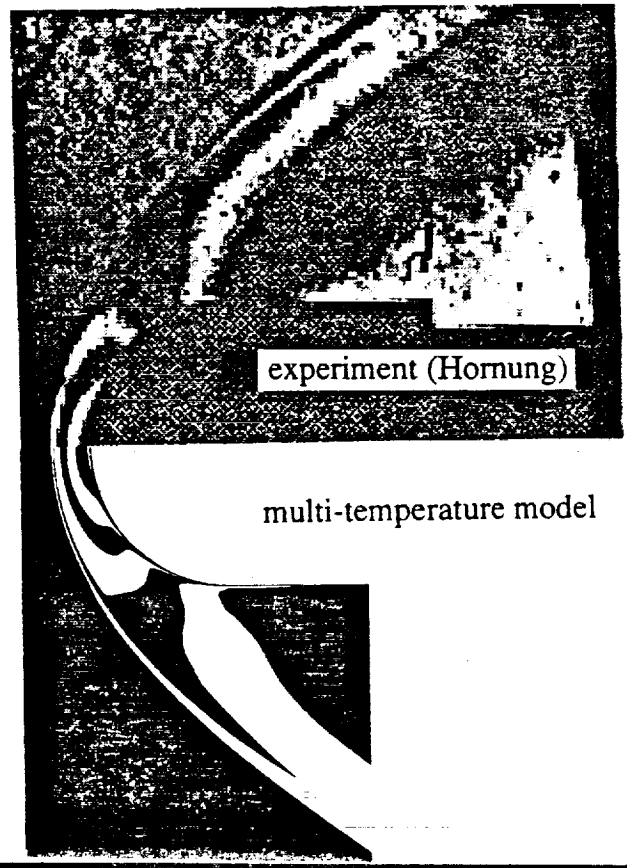
- Interferogram of 2 inch diameter cylinder in N_2 and N.

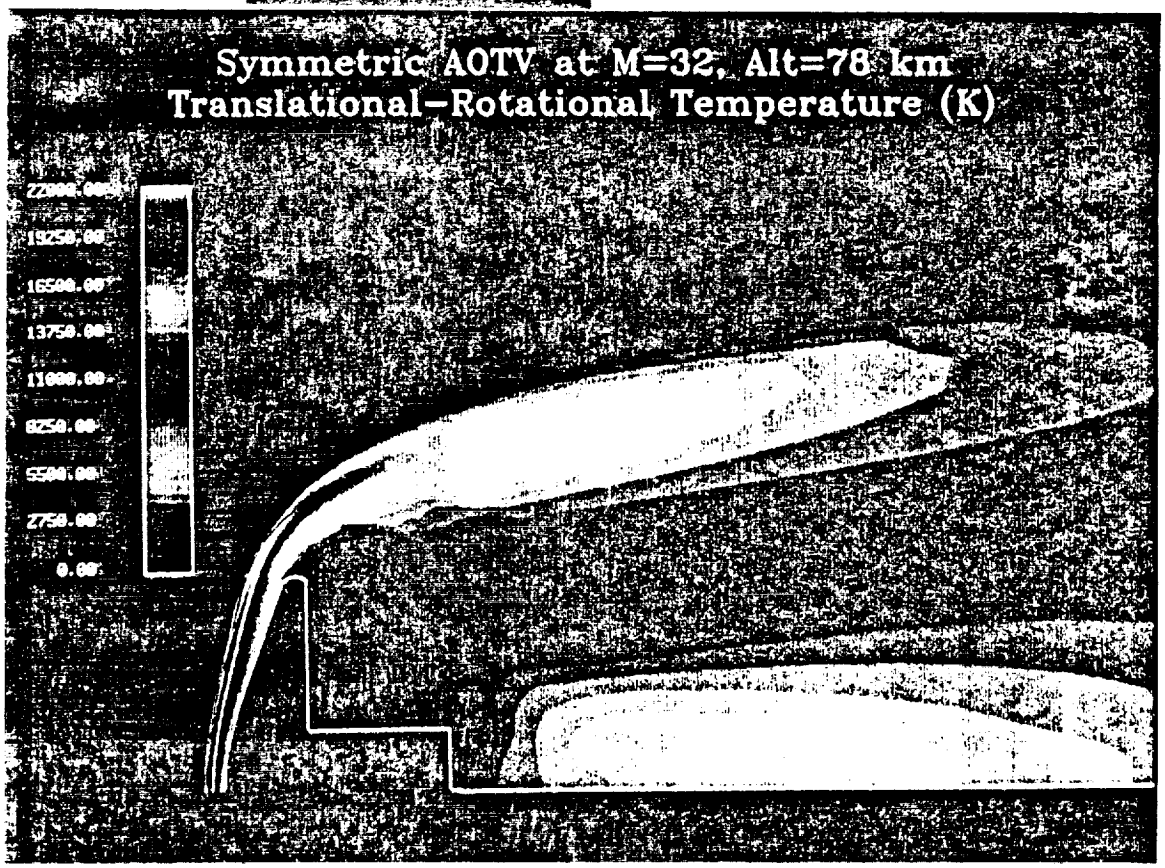
  $u_\infty = 5.59\,\mathrm{km/s}$, $\mathcal{M}_\infty = 6.1$, $Re = 12000$, $\psi = 5.5$.

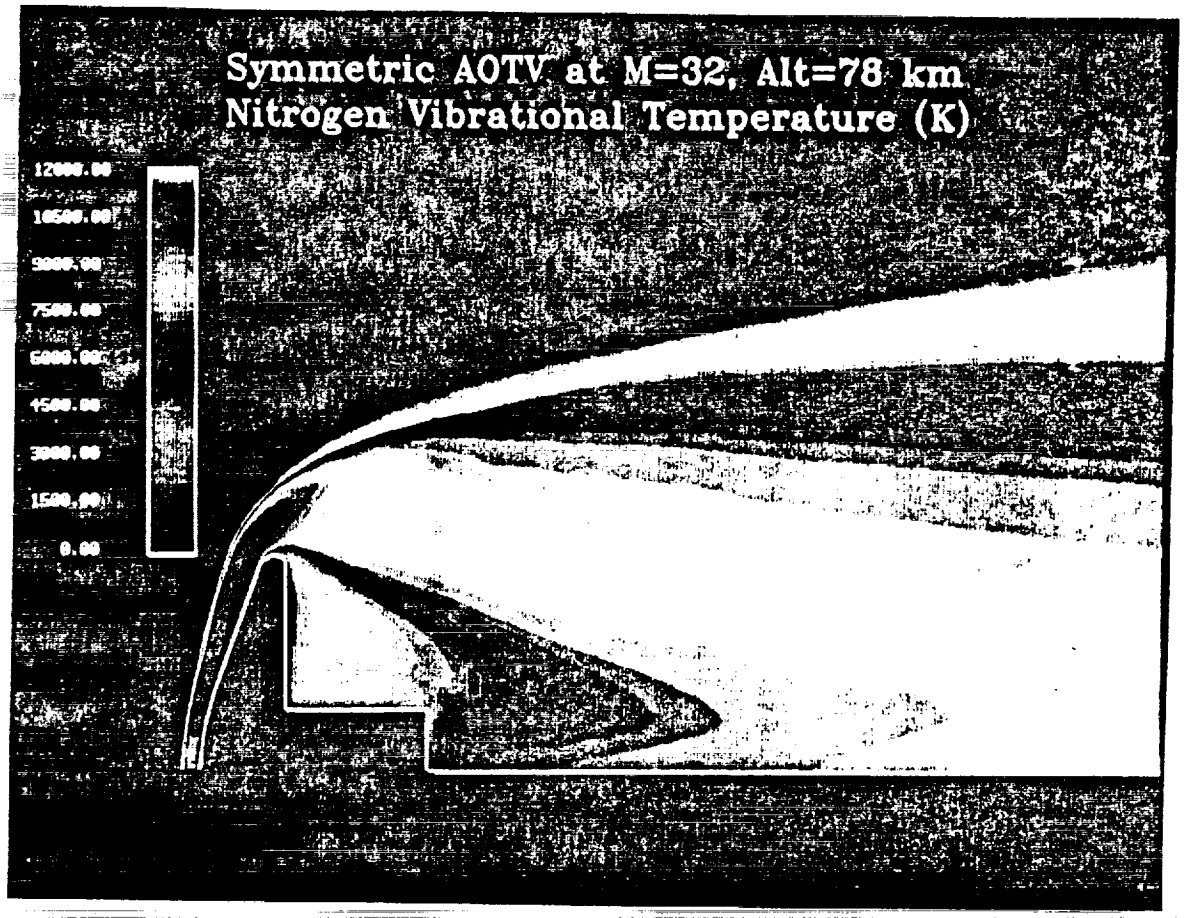


- Interferogram of 1 inch diameter cylinder in N_2 and N.

  $u_\infty = 5.59\,\mathrm{km/s}$, $\mathcal{M}_\infty = 6.1$, $Re = 6000$, $\psi = 2.7$.

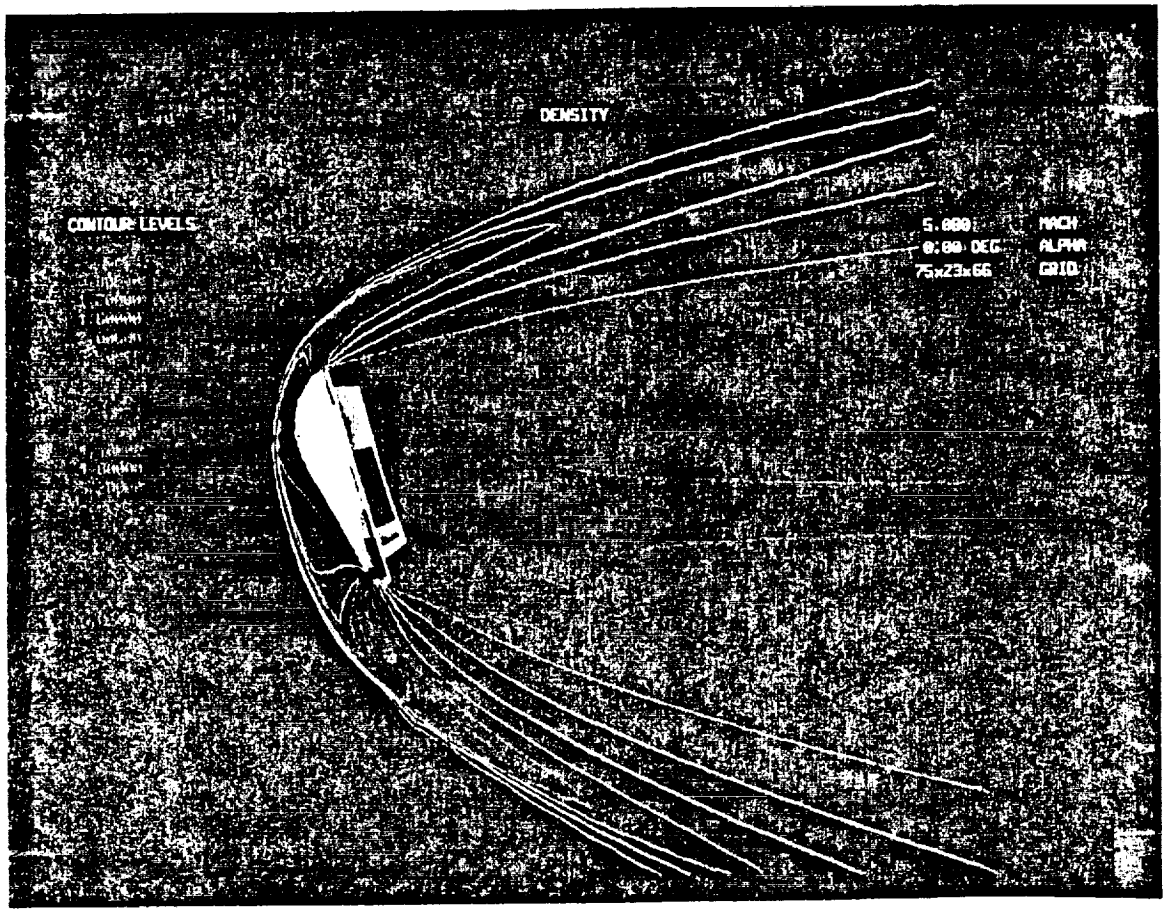






Nonequilibrium Code Development

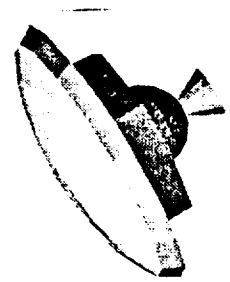
Objective:	Develop capability to simulate flowfields in nonequilibrium air
Codes:	Explicit 3-D, 2nd order accurate upwind, steady flows Implicit 3-D, 2nd order accurate TVD, unsteady flows
Chemistry:	Fully coupled, dissociating/ionizing air
Status:	Explicit code applied to AFE configuration Compared with ballistic range shadowgraph Implicit code under development
Future:	Multi-temperature thermochemical nonequilibrium capability Application to unsteady base flows



Direct Particle Simulation of Hypersonic Flows

Objective:

- Develop the capabilities of a new discrete particle simulation method for rarified hypersonic flows in 3D with non-equilibrium chemistry.



Approach:

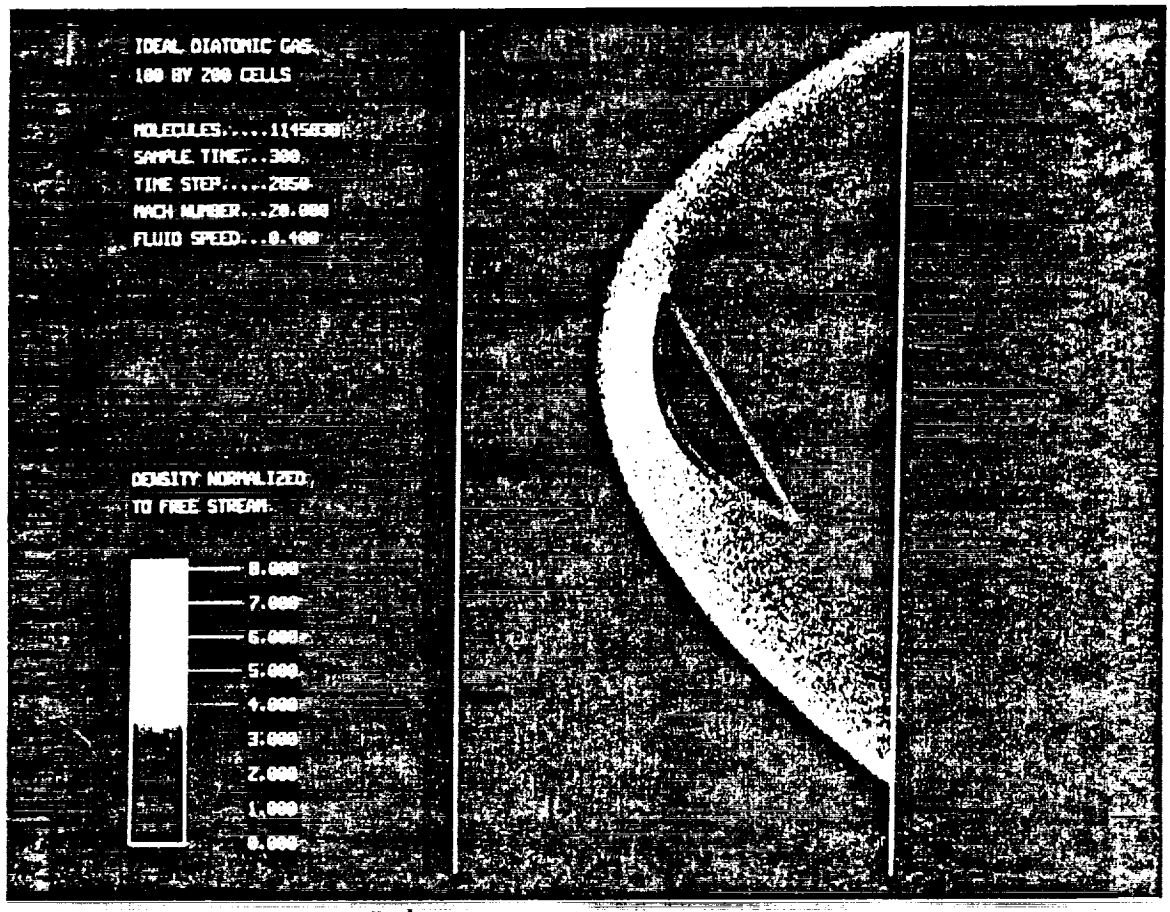
- Fluid is modeled as a large collection of discrete particles that interact with each other through collisions.
- Simplified physical models are used allowing orders of magnitude increase in computational efficiency while enhancing statistical accuracy.

Future Directions:

- Realistic 3D geometries with more general boundary conditions.
- Molecular models are being extended to account for additional internal degrees of freedom, chemistry and wall-particle interaction models.

Payoff:

- Direct particle simulation is applicable at low densities and high Mach numbers beyond the reach of continuum methods.
- Enables particle simulations on a much larger scale than previously possible.
- Provides needed insight in the design of proposed hypersonic vehicles.

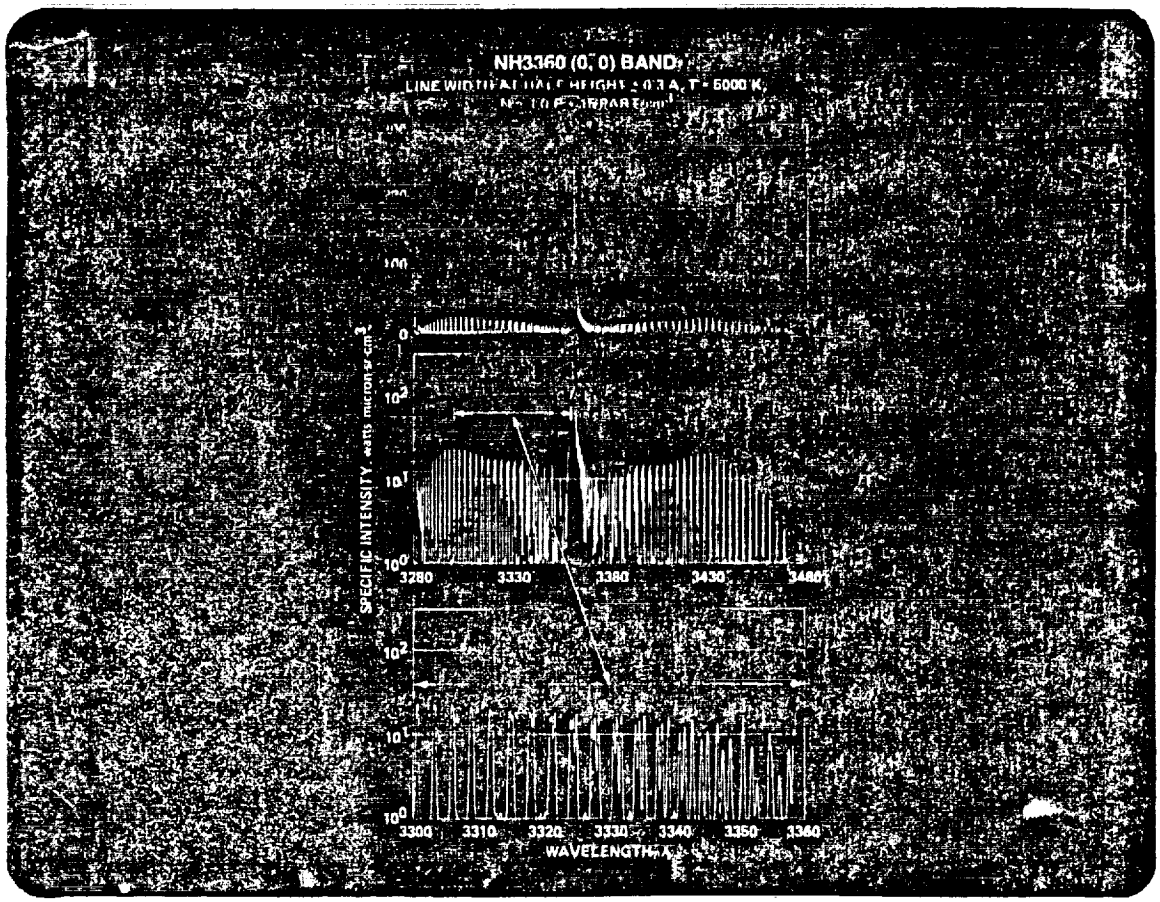


Nonequilibrium Radiation

Objective: Predict point spectra and line of sight radiation in flowfields out of thermochemical equilibrium

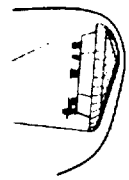
Code (NEQAIR):
- All allowed diatomic transitions.
- Forbidden diatomic transitions.
- High resolution spectra (~ 0.01 A)
  - Rotation distortion to 4th order
  - Spin-orbit, spin-spin, spin-rotation to 1st order
  - Lambda splitting by perturbation
- Realistic radiative transport

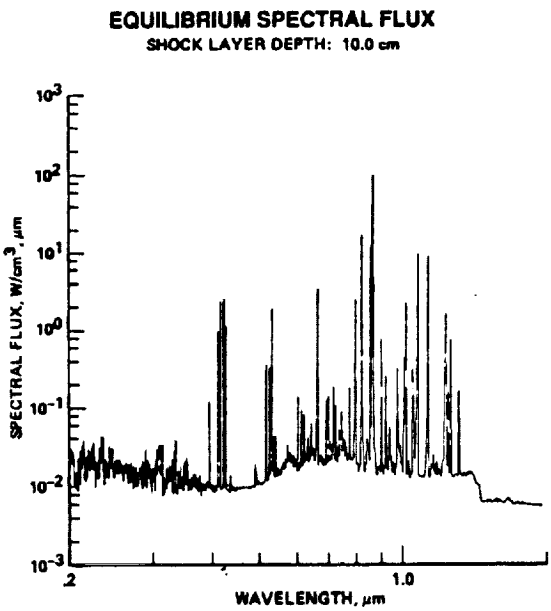
Applications:
- Vacuum UV radiative transport
- Spectroscopic data analysis
- Accurate simulation of radiometric signals

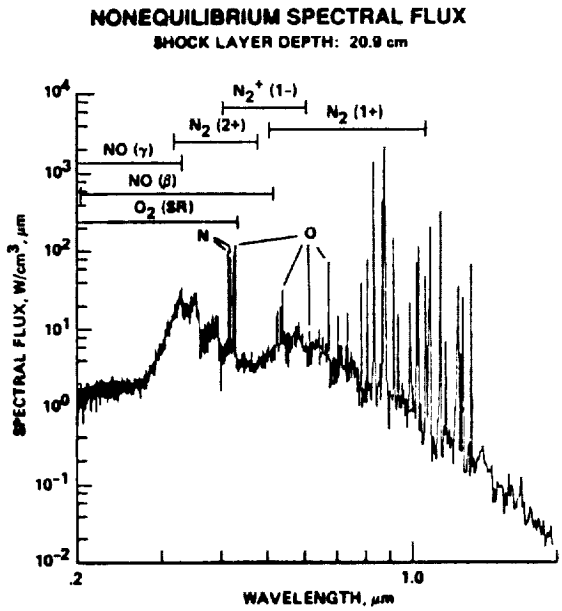


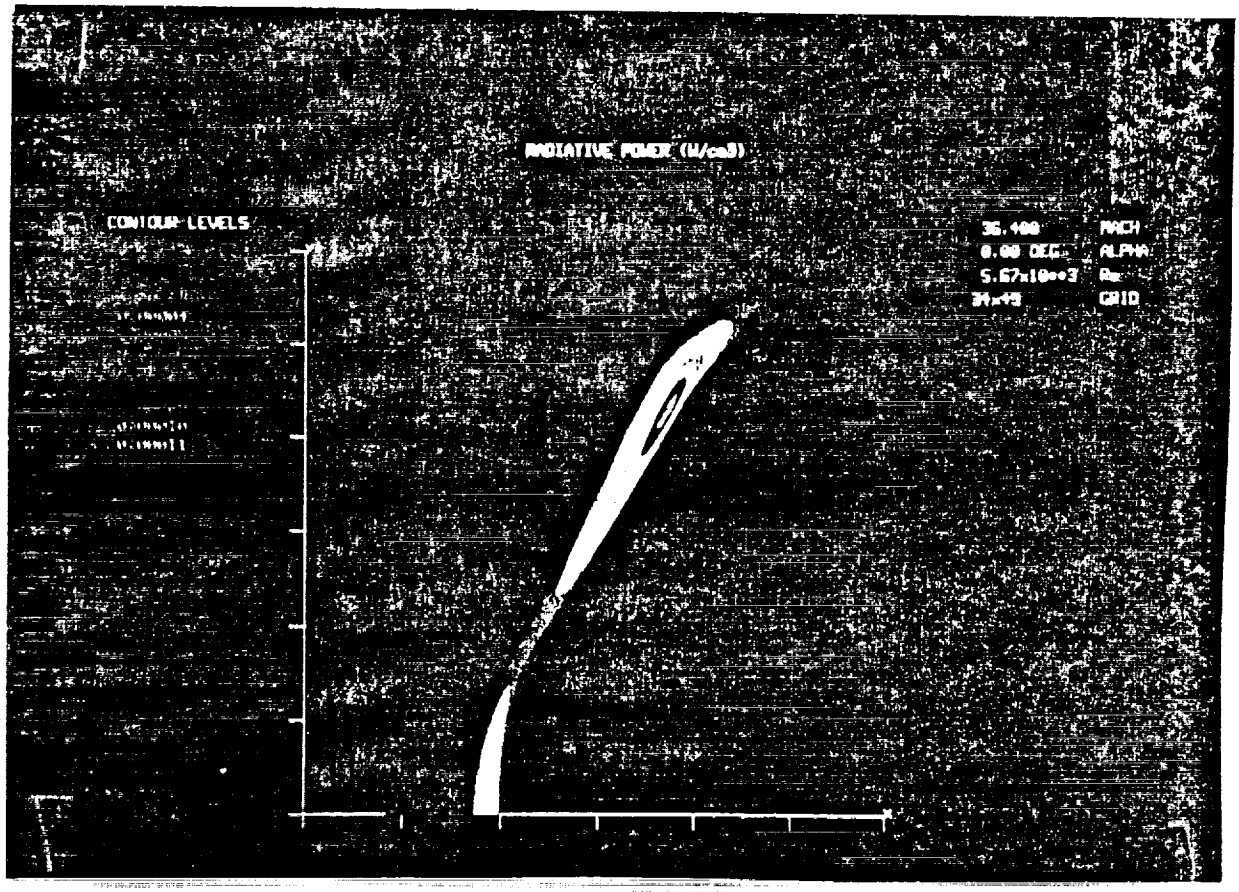
PREDICTED AFE SHOCK LAYER SPECTRA

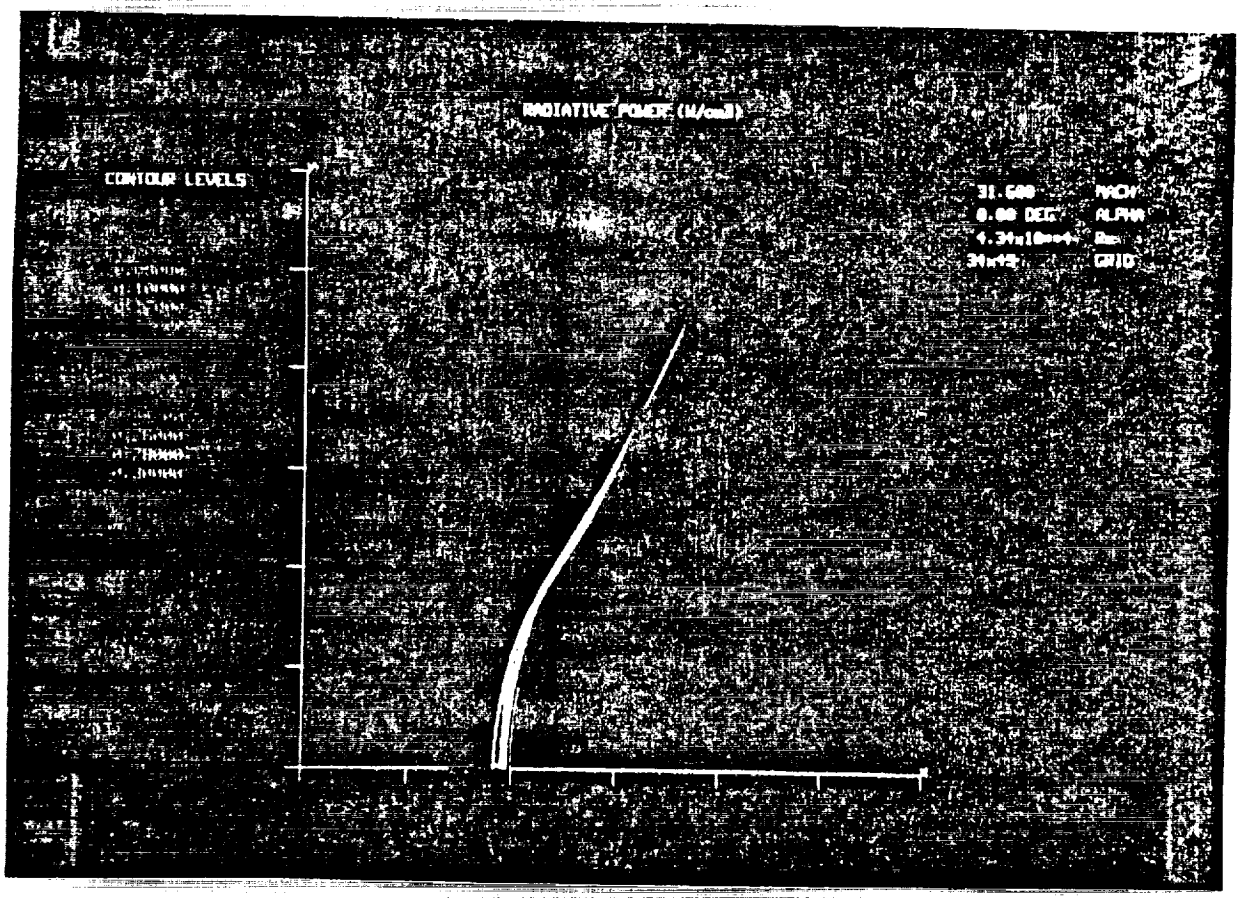
V_∞ = 10 km/sec h = 80 km








RADIATIVE POWER (W/cm3)
CONTOUR LEVELS
35.400 MACH
0.00 DEG. ALPHA
5.67x10e+3 Re
34x49 GRID


RADIATIVE POWER (W/cm3)
CONTOUR LEVELS
31.600 MACH
0.00 DEG. ALPHA
4.34x10e+4 Re
34x49 GRID

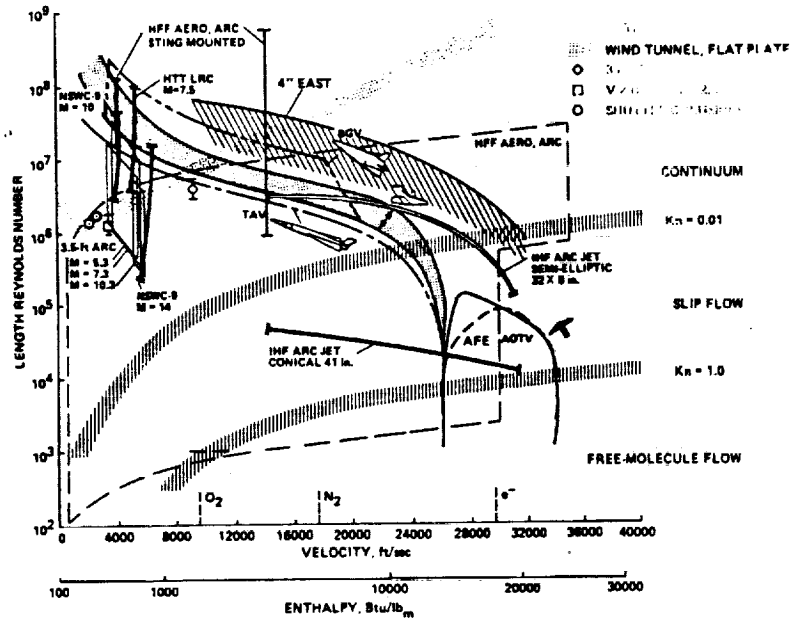


Fig. 1 Flight Simulation Capability

THERMOCHEMICAL NONEQUILIBRIUM

(MULTI-TEMPERATURE NONEQUILIBRIUM NAVIER-STOKES CODES)

- SHOCK TUBE DATA

FACILITY:	E.A.S.T. (ELECTRIC ARC DRIVEN SHOCK TUBE)
FLOW CONDITIONS:	$5 < U_s < 13$ km/sec, $.05 < p_1 < 1$ torr
DATA TAKEN:	SPECTRAL DATA, SPECIES, VIBRATIONAL ENERGY (LIF, CARS)

- SHOCK LAYER DATA

FACILITY:	HFFAF
FLOW CONDITIONS:	$15 < M < 30$, $1 < p < 15$ torr
DATA TAKEN:	HOLOGRAMS, SHADOWGRAPHS (DENSITY, SHOCKS)
FACILITY:	60 MW ARCJET
FLOW CONDITIONS:	$M = 8$, $p_0 = .012$ atm, $H_0 = 46$ MJ/kg
DATA TAKEN:	SPECTRAL DATA (SPECIES DISTRIBUTIONS)

- AFE, FLIGHT EXPERIMENT FOR AOTV

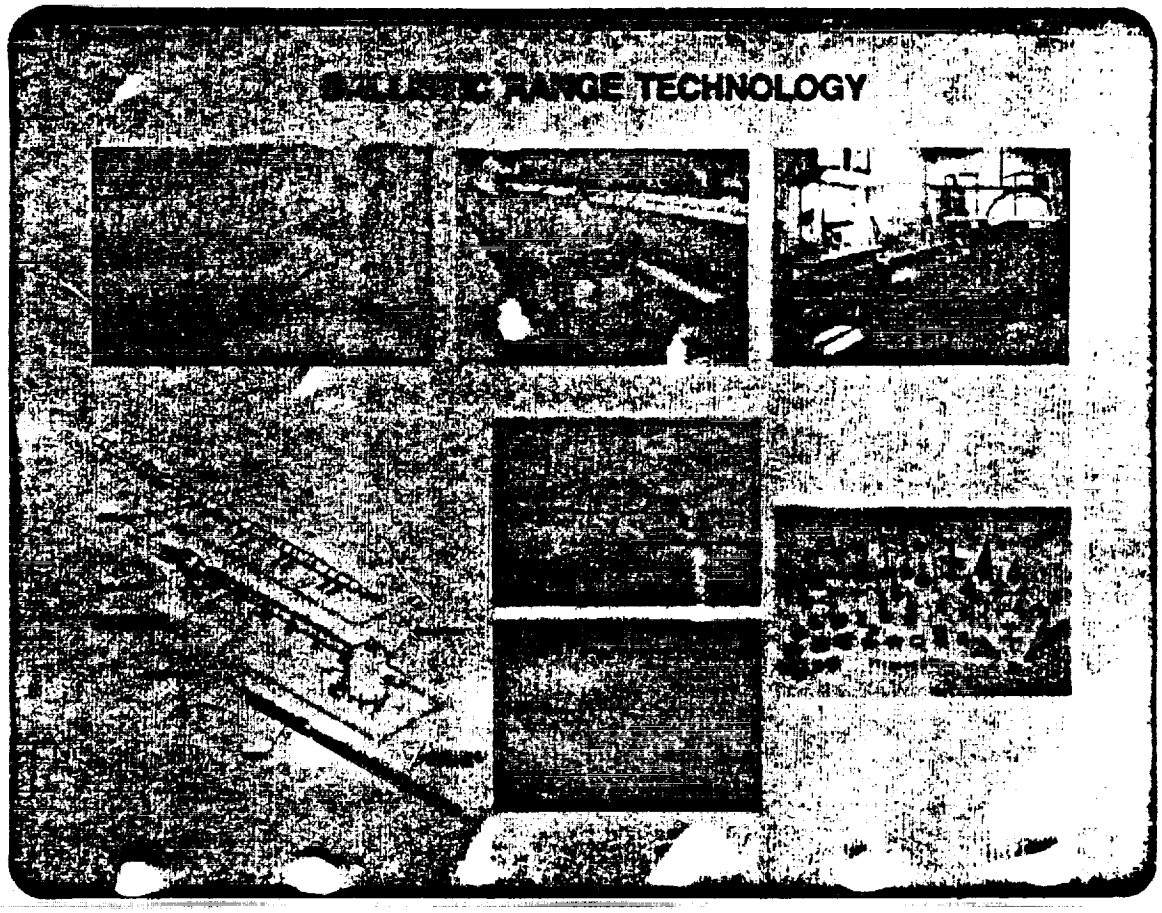
FLOW CONDITIONS:	$8 < V < 10$ km/sec, $70 < h < 120$ km
DATA TAKEN:	RADIATION SPECTRA, SPECIES DISTRIBUTION, SURFACE p & q

BALLISTIC RANGE EXPERIMENTS

MODELS:
- SLENDER SHARP & BLUNT CONES
  - w/o & with Shock Generators
  - w/o & with Flares
- BI-CONIC SHAPES
- AOTV SHAPE

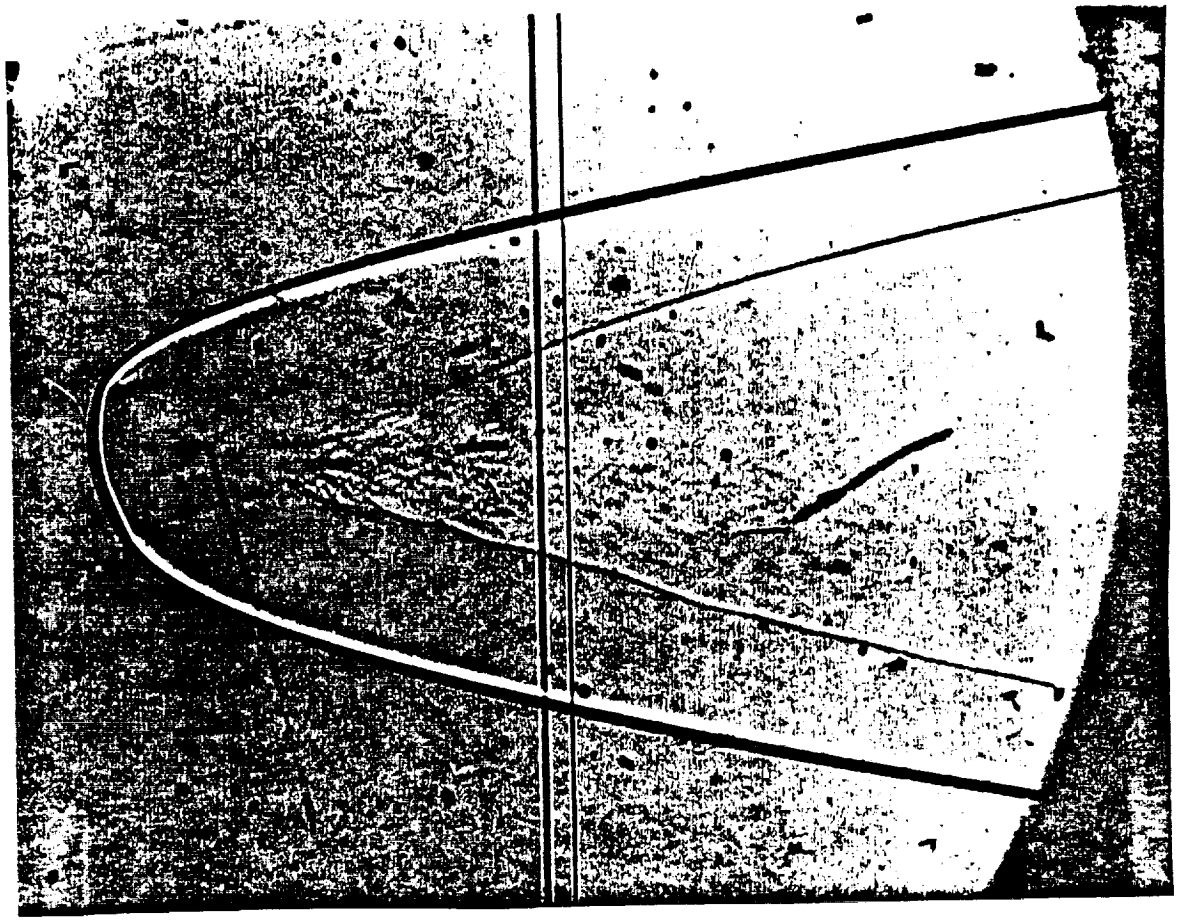
TEST CONDITIONS:
- Model Velocity = 5 & 6 km/s
- M = 14 to 18
- $Re_L = 10^5$ to 10^6

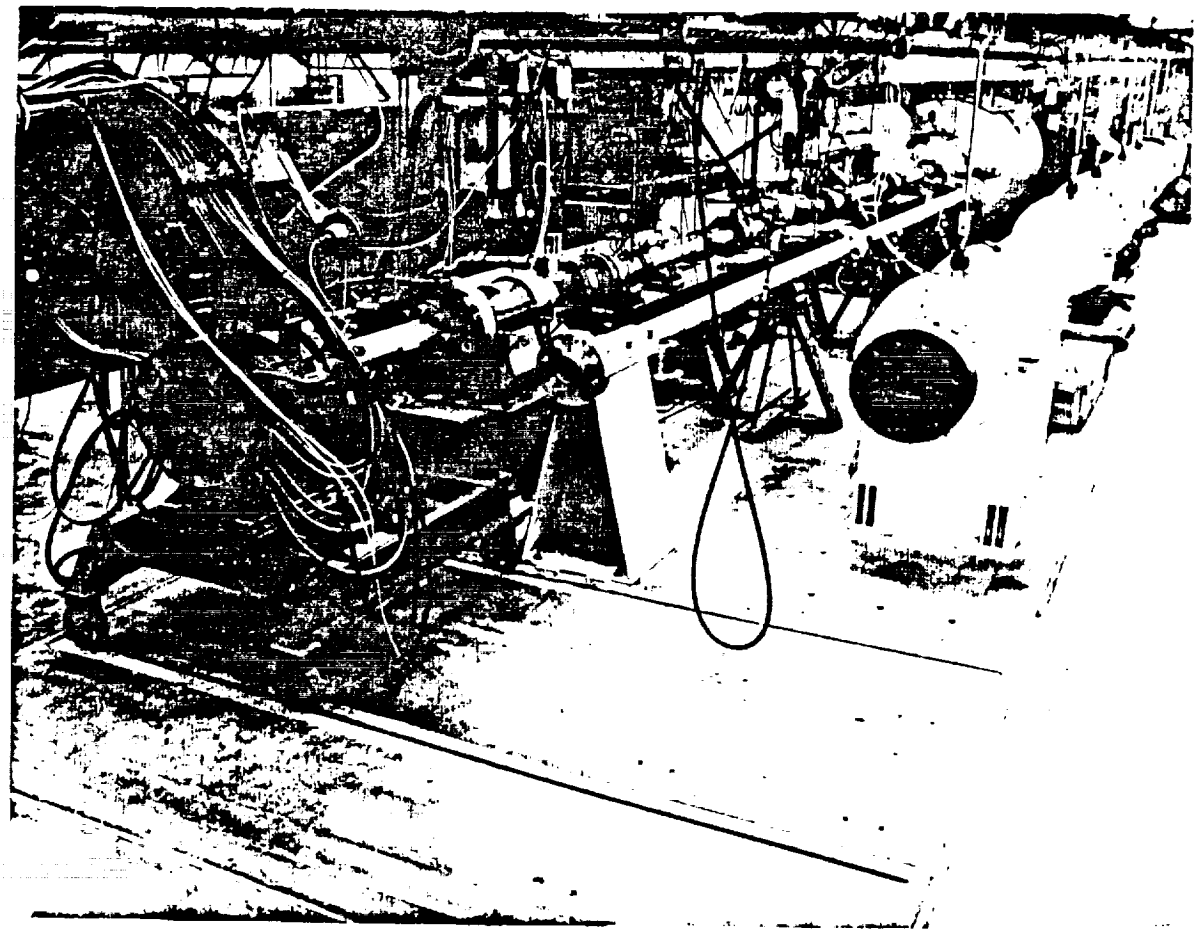
MEASUREMENTS:
- DRAG COEFFICIENT
- SHOCK SHAPE (Shadowgraph)
  - Forebody Shock
  - Embedded Shocks from Shock Generators or Flares
- BASE FLOW-FIELD VISUALIZATION (Shadowgraph)



AMES RESEARCH CENTER HYPERSONIC FACILITIES
HYPERSONIC FREE FLIGHT FACILITY TEST CONDITIONS

• STREAM	
– MACH NUMBER	7 (OR STILL AIR)
– STATIC PRESSURE	0.005 TO 2 atm
– ENTHALPY, max.	3000 Btu/lb
• REYNOLDS NUMBER	50,000,000 ft^{-1}
• MODEL	
– VELOCITY, max.	30,000 ft/sec
– ACCELERATION, max.	1,500,000 g
– SIZE, max.	37 mm diam
– WEIGHT, max.	45 g
• INSTRUMENTED RANGE SECTION	
– DIAMETER	2.5 ft
– LENGTH	75 ft
– NUMBER OF STATIONS	10





RAREFIED FLOW TEST PROGRAM FOR CFD CODE VALIDATION (Particle-Kinetic Simulation)

OBJECTIVE:

- DEVELOP AND DEMONSTRATE CAPABILITY TO STUDY ROTATIONAL SPECTRA IN DIATOMIC GASES UNDER LOW DENSITY RAREFIED CONDITIONS

APPROACH:

- MEASURE RAREFIED GAS FLOW AT HIGH MACH NUMBERS FOR SIMPLE AERODYNAMIC SHAPES IN THE LOW PRESSURE WIND TUNNEL AT U.C. BERKELEY

FUTURE DIRECTIONS:

- INTERACTION OF FAST MOVING OXYGEN ATOMS WITH SOLID SURFACES
- EXPERIMENTAL VALIDATION OF ALGORITHMS BASED ON PARTICLE COLLISION TECHNIQUES

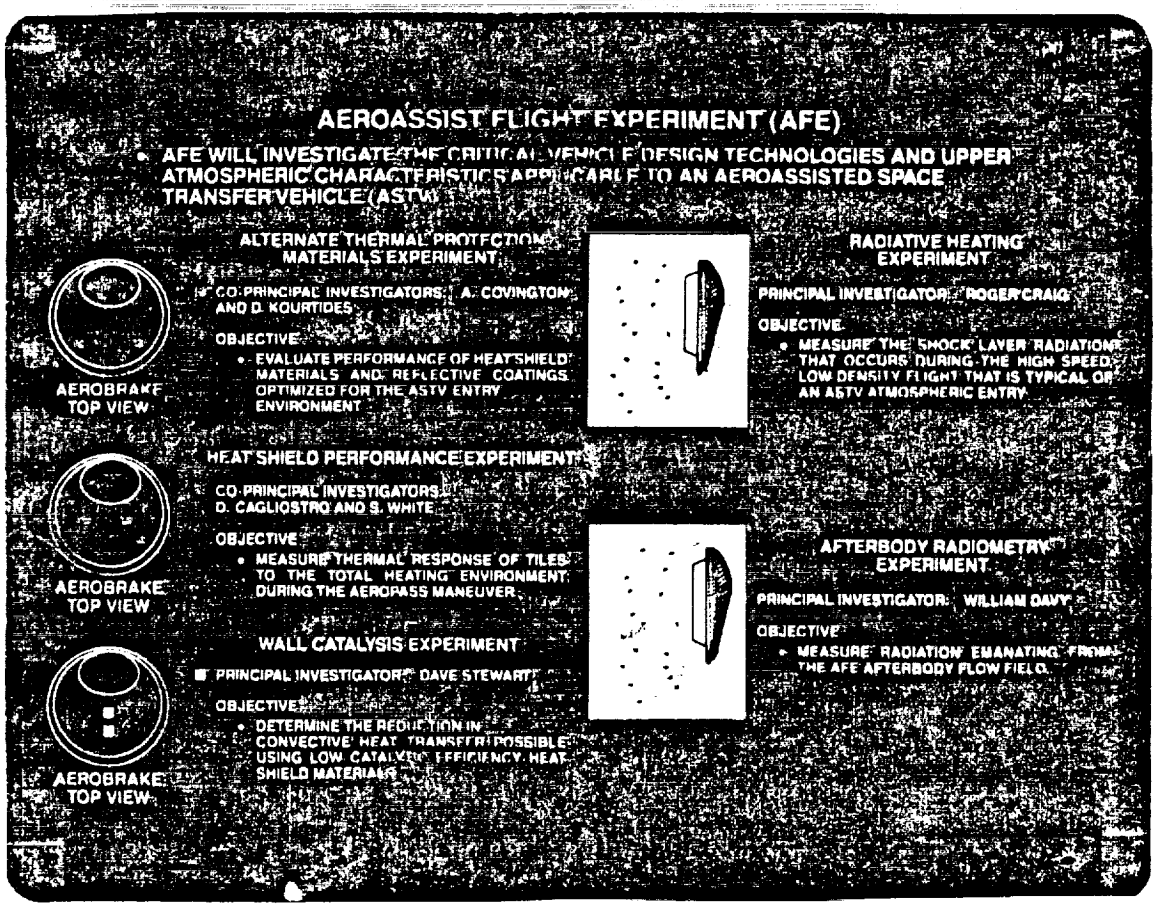
SIGNIFICANCE:

- THIS MEASUREMENT CAPABILITY CAN BE USED TO VALIDATE PARTICLE-KINETIC SIMULATION CODES FOR RAREFIED GASES THAT USE HEURISTIC MOLECULAR EXCHANGE MODELS
- THESE VALIDATED CODES WILL THEN BE USED TO SIMULATE THE FLOW FIELD FOR NASA'S AERO-ASSISTED FLIGHT EXPERIMENT (AFE)

RAREFIED
(PARTICLE - KINETIC SIMULATION)

o LOW DENSITY FLOWFIELD DATA

FACILITY:	U.C. BERKELEY LOW PRESSURE WIND TUNNEL
FLOW CONDITIONS:	50 km < H , 250 km, M , 20, Nitrogen, Oxygen
DATA TAKEN:	DENSITY, VELOCITY & TEMPERATURE FIELDS FLOWFIELD STRUCTURE; SIMPLE CONFIGURATIONS
INSTRUMENTATION	ELECTRON BEAM PROBE FABRY-PEROT INTERFEROMETER QUADRUPOLE MASS ANALYZER



UNIVERSITY GRANTS / CONSORTIUMS

UNIVERSITY	INVESTIGATOR	ACTIVITY
Stanford	MacCormack	Thermo-Chemical Noneq
"	Chapman	Continuum Extension
"	Baganoff	Particle Kinetics
"	Hansen	Instrumentation
Penn. State	Dulikravich	Thermo-Chemical Noneq.
U.C. Irvine	Edwards	Nonequilibrium Radiation
S. J. State	Desutel	AFE Flow Fields (exp.)
U.C. Berkeley	Hurlburt	Rarefied Flows (exp.)
U. Maryland	Anderson	Low Density Separation

AMES' COMPUTATIONAL CHEMISTRY ACTIVITY AND APPLICATIONS TO DETERMINE PROPERTIES OF SHOCK-HEATED AIR AND MARS ATMOSPHERIC GASES

HIGH ENERGY AEROBRAKING WORKSHOP

DAVID M. COOPER

COMPUTATIONAL CHEMISTRY BRANCH

AMES RESEARCH CENTER

February 1, 1989

PRESENTATION OUTLINE

- INTRODUCTION
- RADIATIVE PROPERTIES OF GASES
- EXAMPLE APPLICATIONS
- REACTION RATE CONSTANTS
- HIGH-TEMPERATURE TRANSPORT PROPERTIES
- COLLISION AND EXCITATION CROSS-SECTIONS

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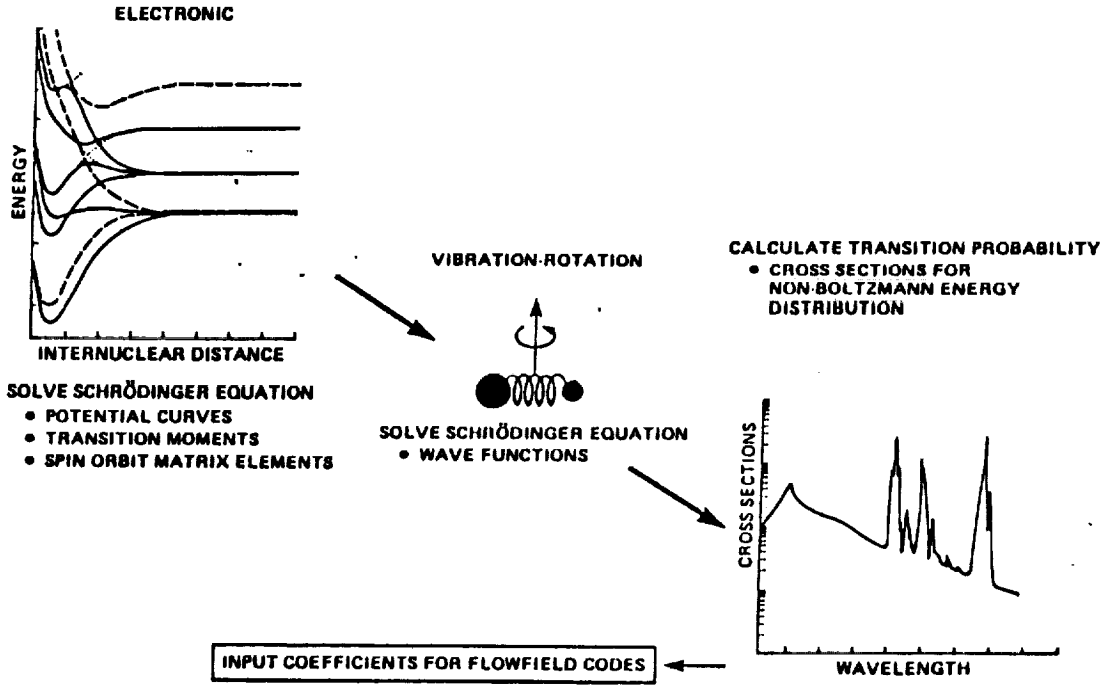
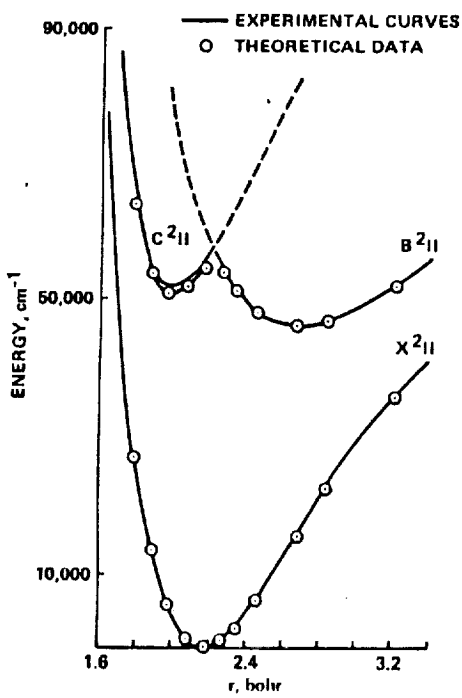
CALCULATION OF MOLECULAR PROPERTIES FROM FIRST PRINCIPLES

DIATOMIC MOLECULES

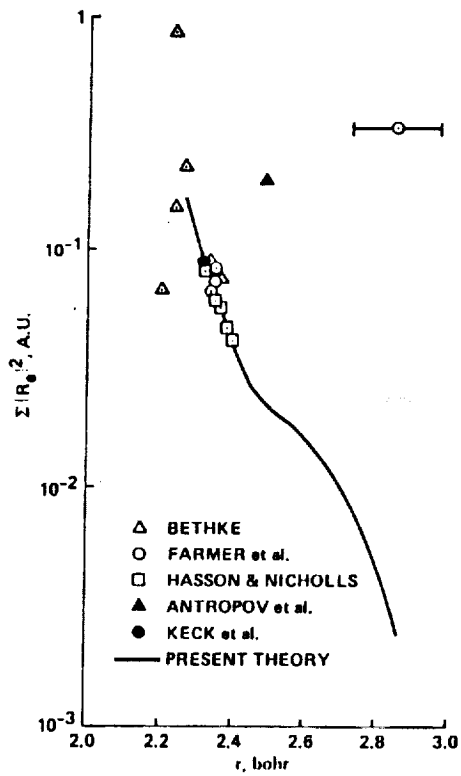


VALIDATION OF QUANTUM CALCULATIONS

NO POTENTIAL ENERGY CURVES



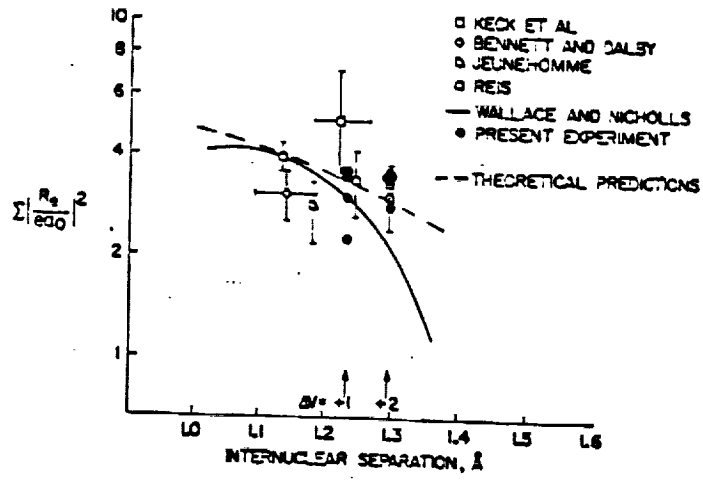
NO BETA ELECTRONIC TRANSITION MOMENT



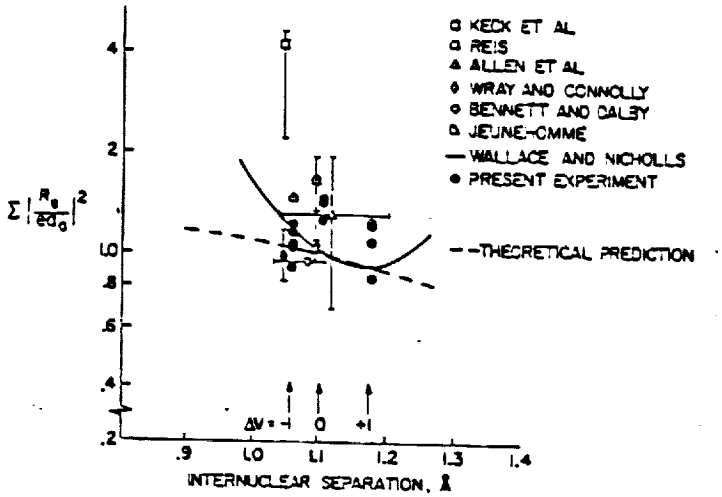
ELECTRONIC TRANSITION MOMENTS

N_2 2 POS. SYS.

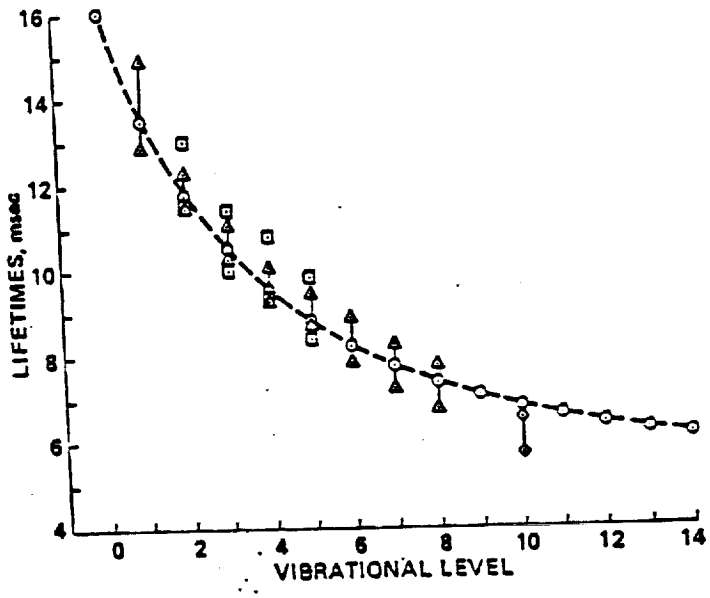
$C\,^3\Pi_u - B\,^3\Pi_g$



N_2^+ First Negative System



N_2^+ MEINEL SYSTEM LIFETIMES



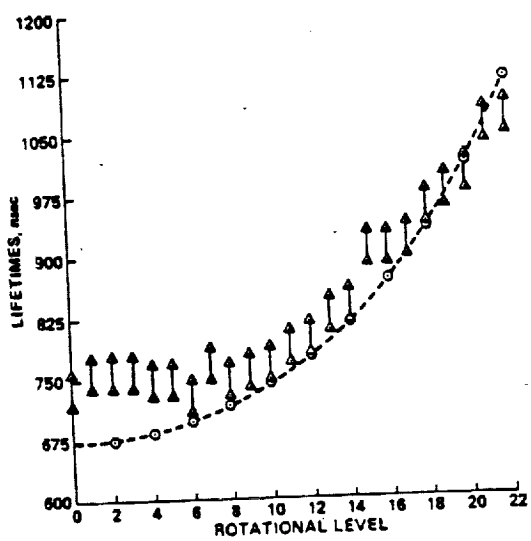
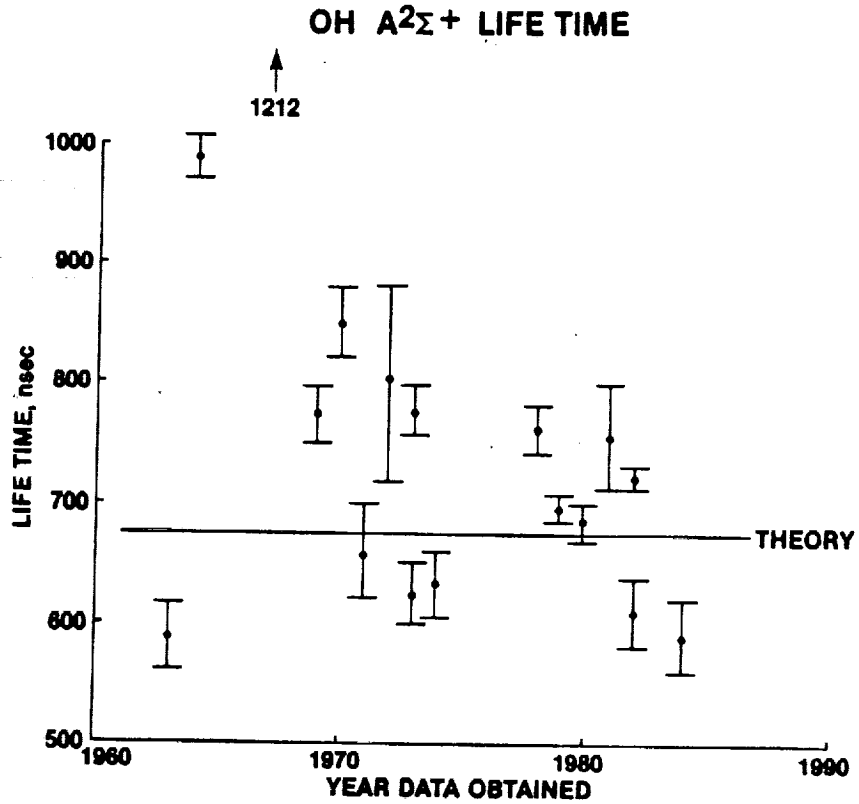


Figure 10. Lifetimes of the OH $A^2\Sigma^+$ state.



RADIATION INTENSITY FACTORS

- **SYSTEMS CALCULATED OR VERIFIED**

N_2

First Positive — Second Positive
Birge-Hopfield — Wu-Benesch
Lyman-Birge-Hopfield

N_2^+

First Negative — Second Negative
Meinel

O_2^+

First Negative — Second Negative

NO

Beta — Delta — Gamma

OH

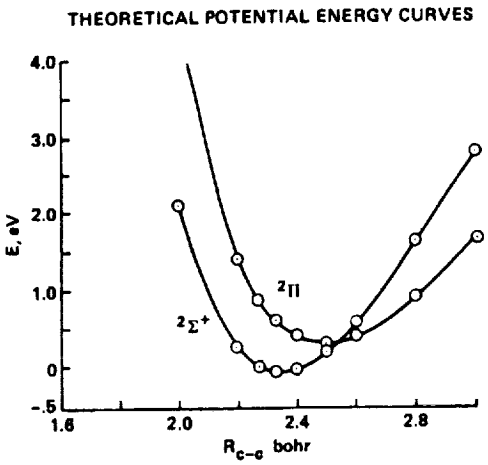
Ultraviolet

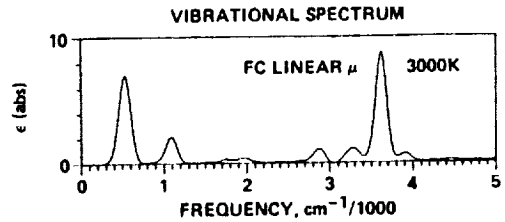
- **SYSTEMS IN PROGRESS**

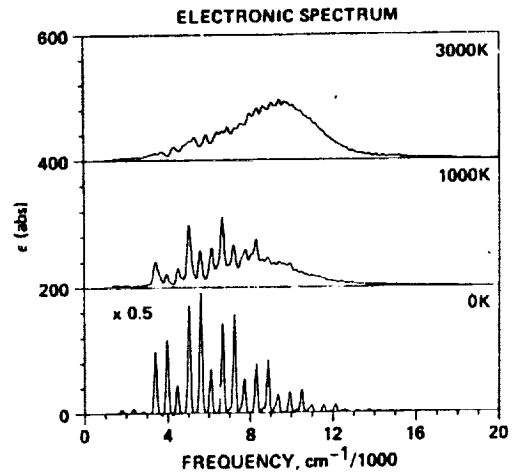
O_2

Schumann-Runge — Herzberg I

THEORETICAL C_2H SPECTRA: DESIGN OF A NEW COMBUSTION PROBE

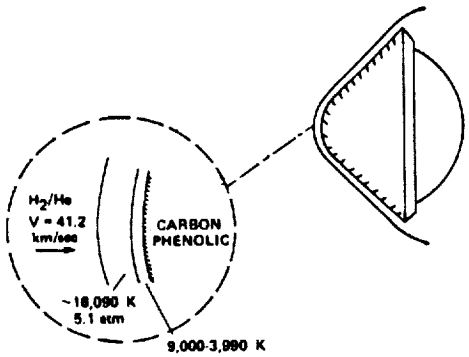






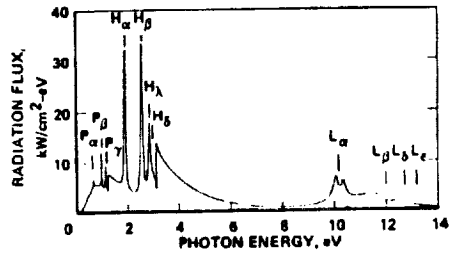
JUPITER ENTRY PROBE

GALILEO

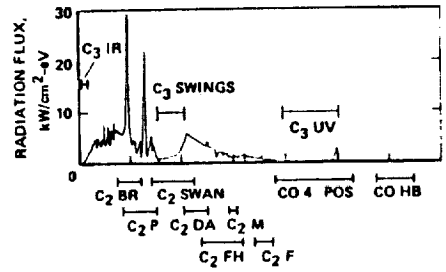


RADIATIVE FLUX

q = 56.4 KW/CM^2 – Interface

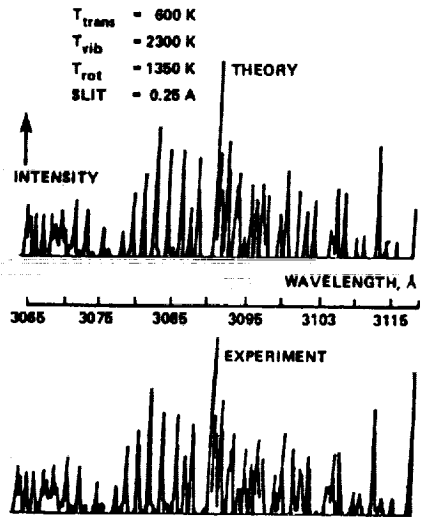


q = 26.1 KW/CM^2 – Wall

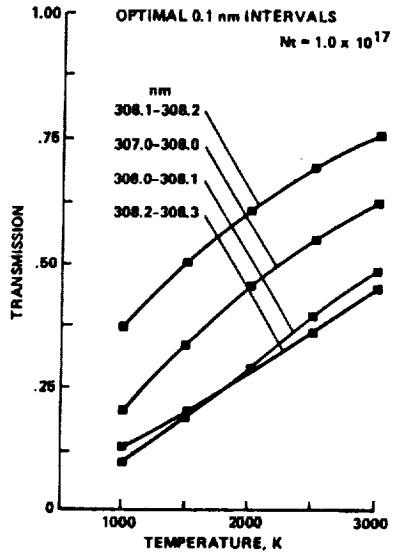


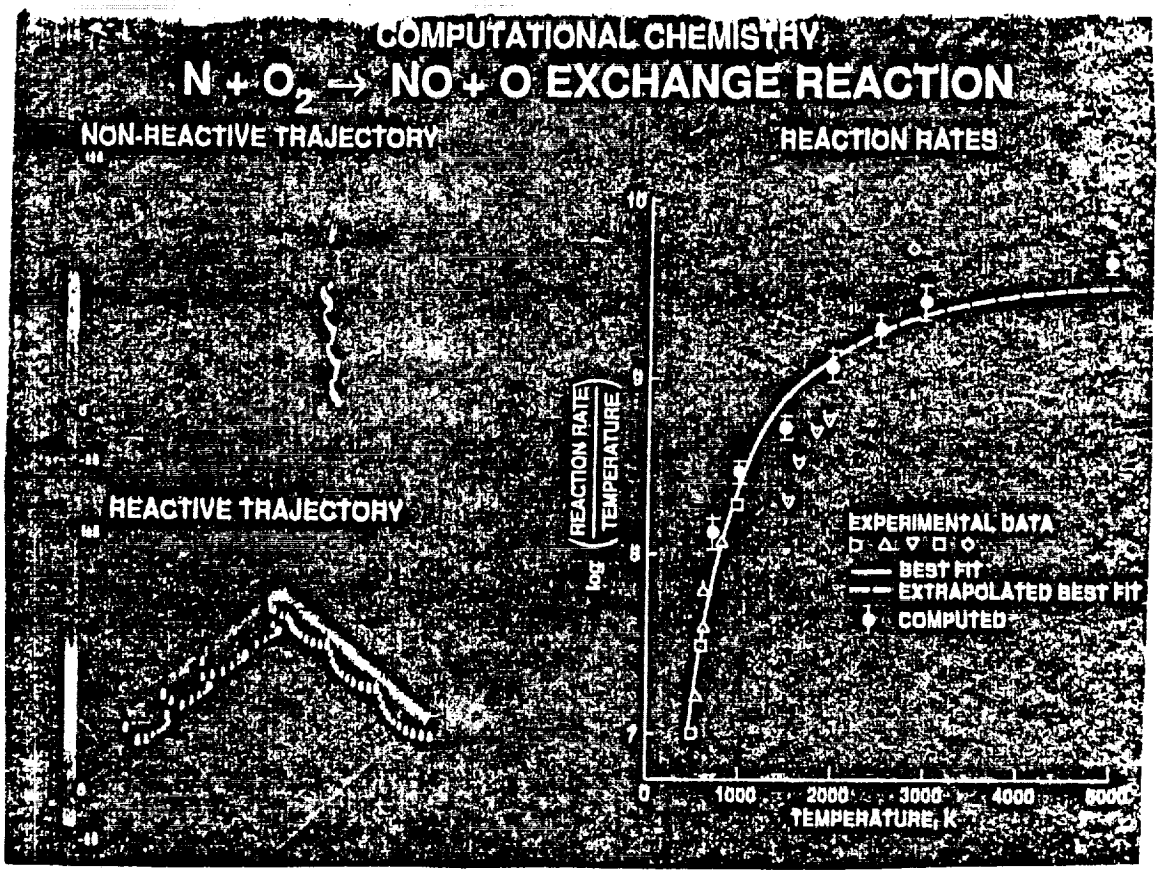
LaRC SCRAMJET DIAGNOSTIC PROBE

INPUT: OH *A-X* LAMP



OUTPUT: CALIBRATION CURVES FOR OH TRANSMISSION



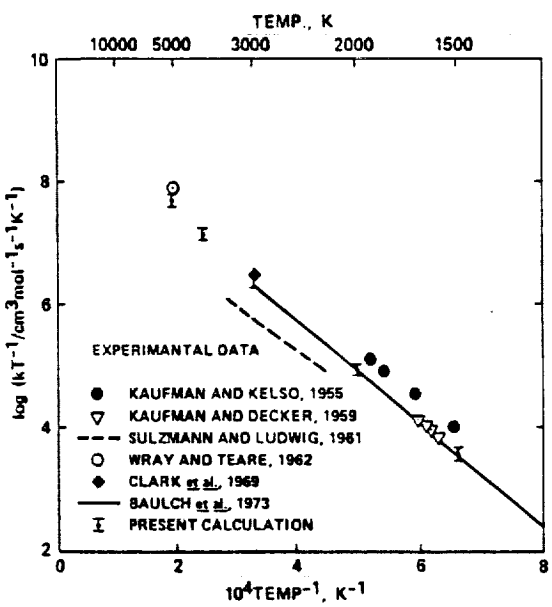


RESULTS OF *ARC* STUDY

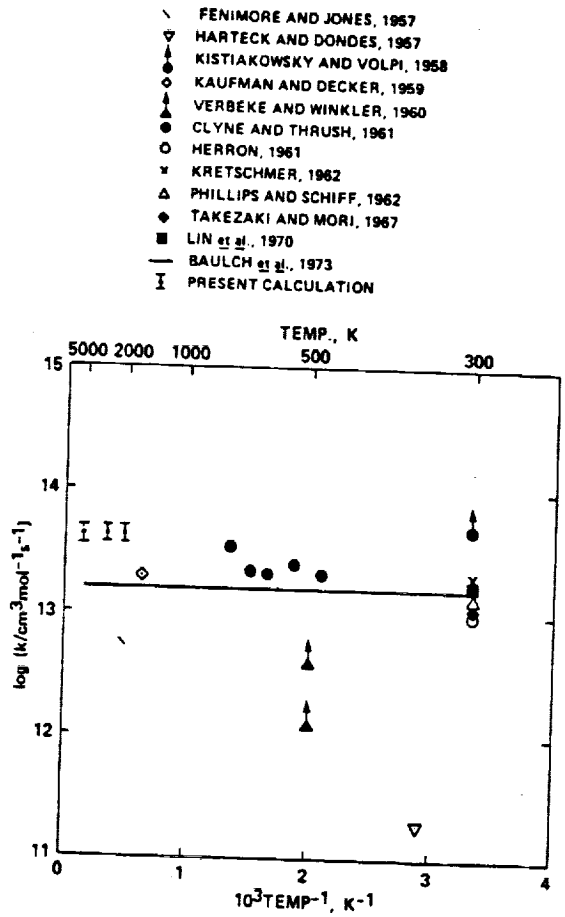
- THE *OH* LAMP SPECTRUM IS WELL-CHARACTERIZED
- THE ORIGINAL *LaRC* EXPERIMENTAL CONFIGURATION CAN PROVIDE TEMPERATURE MEASUREMENTS TO ±60 K *IF PROPERLY CALIBRATED*
- THE USE OF NARROWER DETECTOR CHANNELS (0.4 *nm*) PROVIDES TWO TIMES BETTER SENSITIVITY (±30 K)
- BETTER REPRODUCIBILITY IS OBTAINED BY AVOIDING *OH HOT BANDS* MAJOR (1–1) BAND CONTRIBUTION FOR $\lambda > 313$ *nm*

RECOMMENDED INTERVALS:
307-309, 309-311, AND 311-313 nm

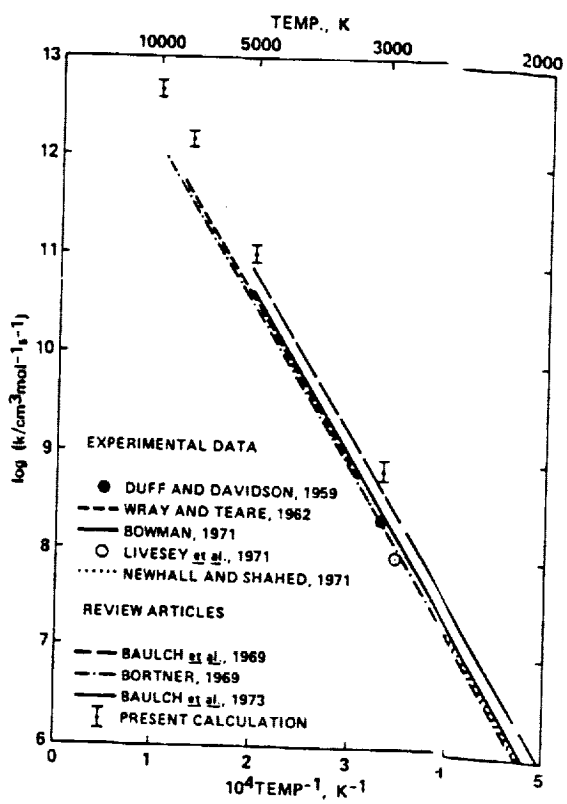
$$NO + O \rightarrow O_2 + N$$



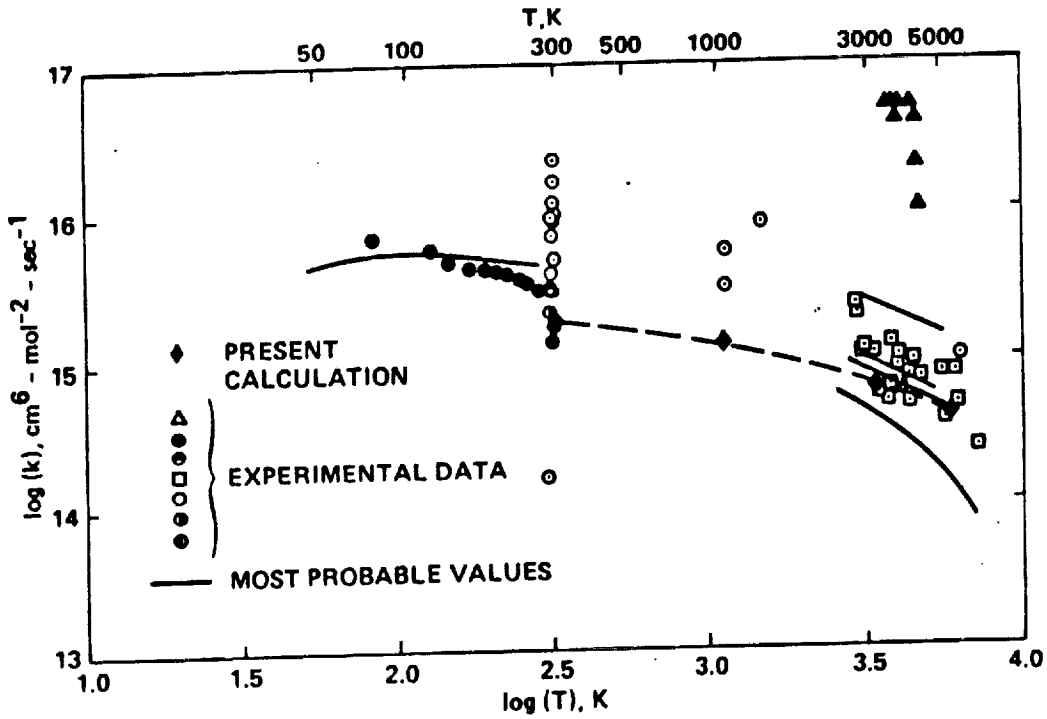
$NO + N \rightarrow N_2 + O$



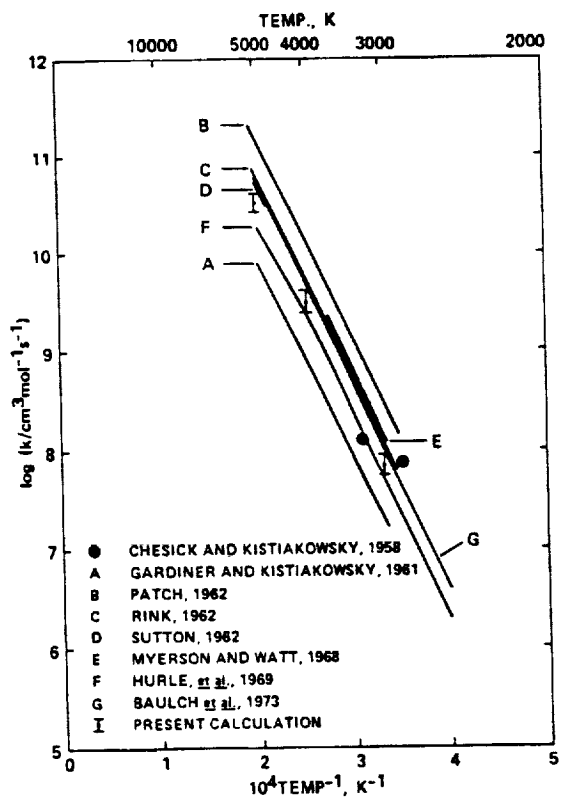
$N_2 + O \rightarrow NO + N$

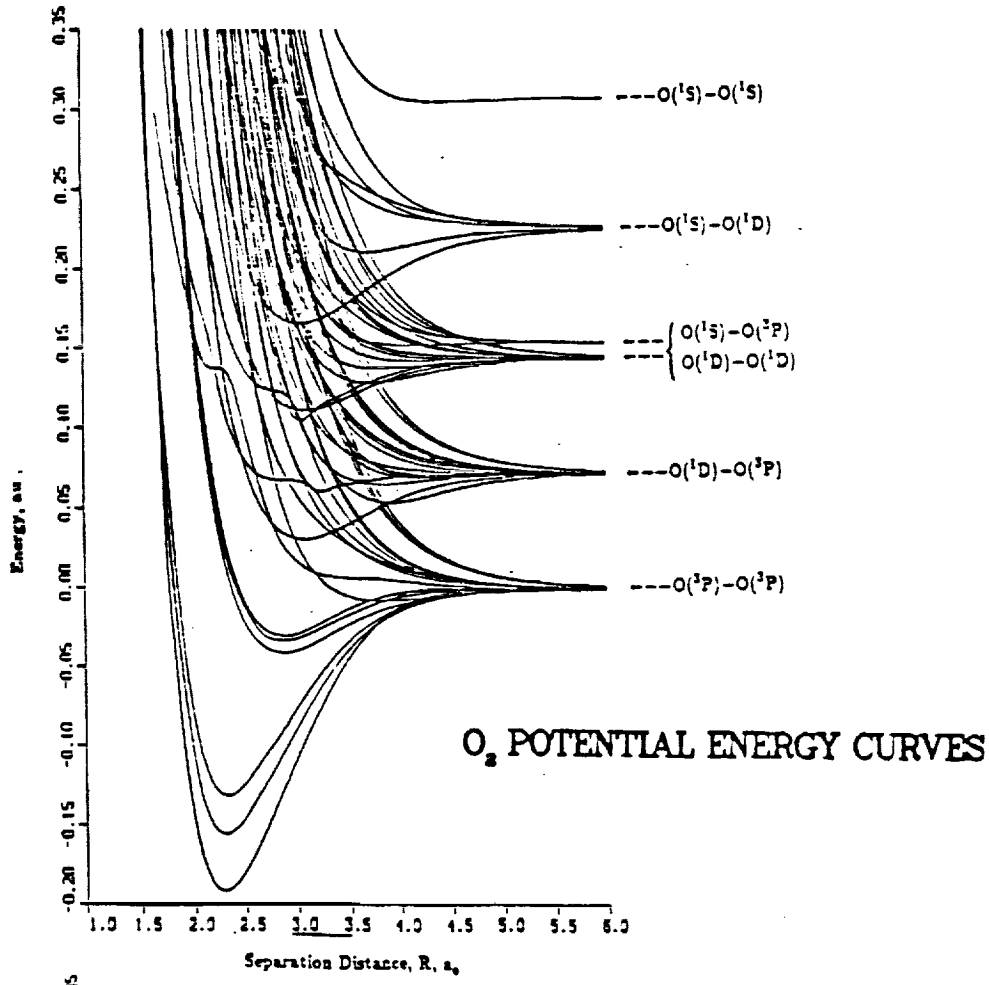


$$H + H + H_2 \longrightarrow H_2 + H_2$$

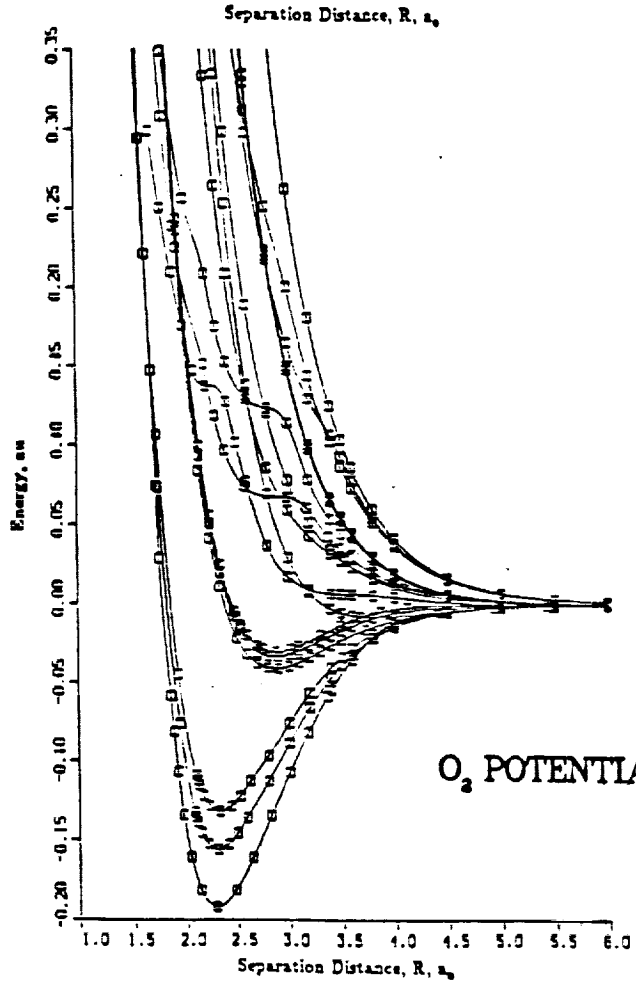


$$H_2 + H_2 \rightarrow H + H + H_2$$



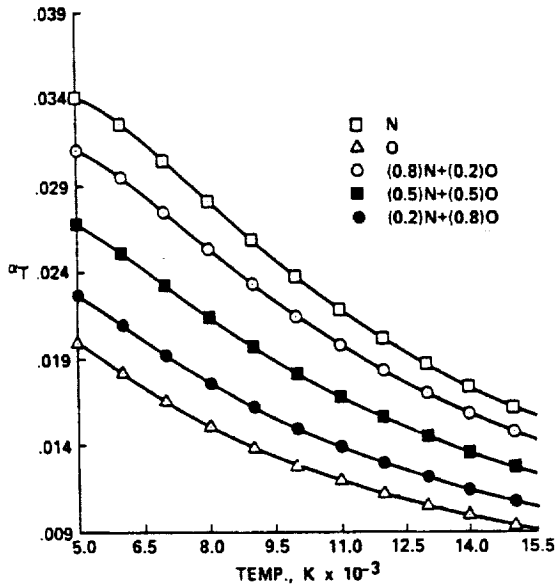


O_2 POTENTIAL ENERGY CURVES

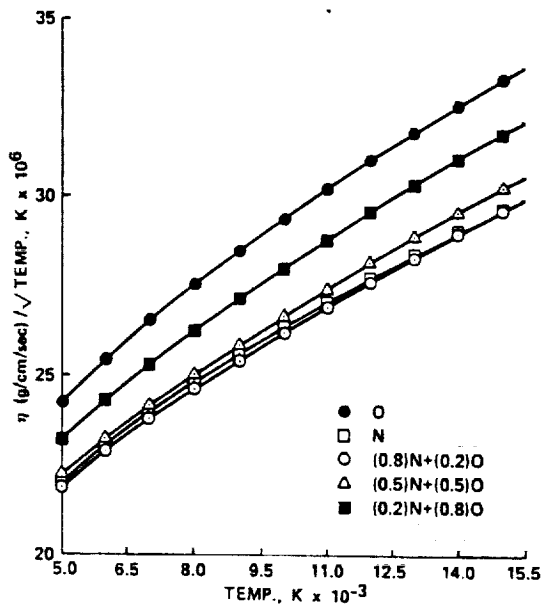


O_2 POTENTIAL ENERGY CURVES

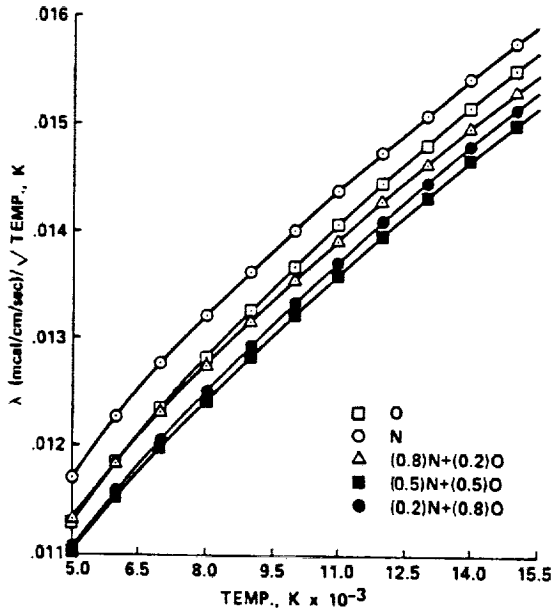
THERMAL DIFFUSION FACTOR



VISCOSITY

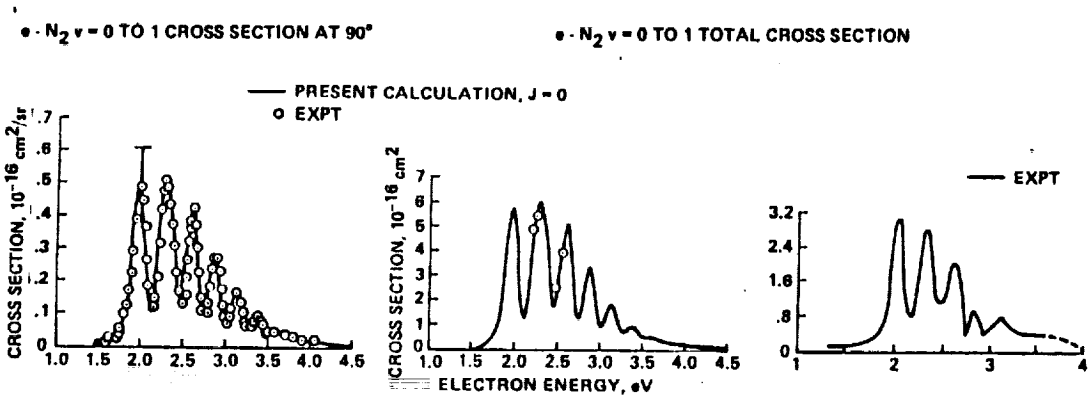


THERMAL CONDUCTIVITY



CALCULATED AND EXPERIMENTAL CROSS SECTIONS

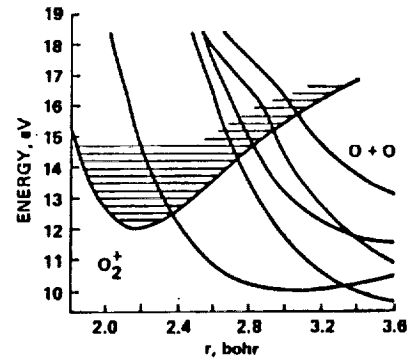
- CRITICAL EFFECT OF ELECTRON-MOLECULE COLLISIONS IN GOVERNING EXCITATION, DISSOCIATION AND IONIZATION OF THE SHOCK LAYER GASES HAS BEEN RECOGNIZED. THIS HAS LED TO A CONSIDERABLE IMPROVEMENT IN THE NONEQUILIBRIUM MODEL.



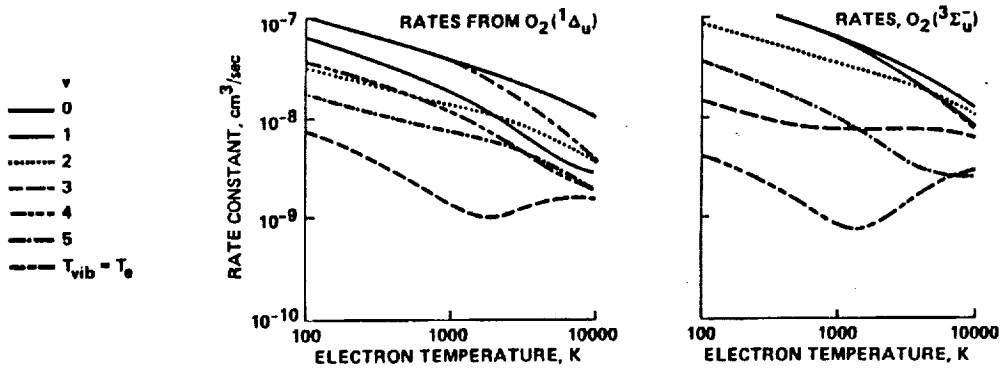
DISSOCIATIVE RECOMBINATION — ASSOCIATIVE IONIZATION

$O_2^+ + e^- \rightarrow O + O$

POTENTIAL ENERGY CURVES:
- ION BOUND STATE
- MANY NEUTRAL
- REPULSIVE STATES



RATE CONSTANTS



FUTURE PLANS

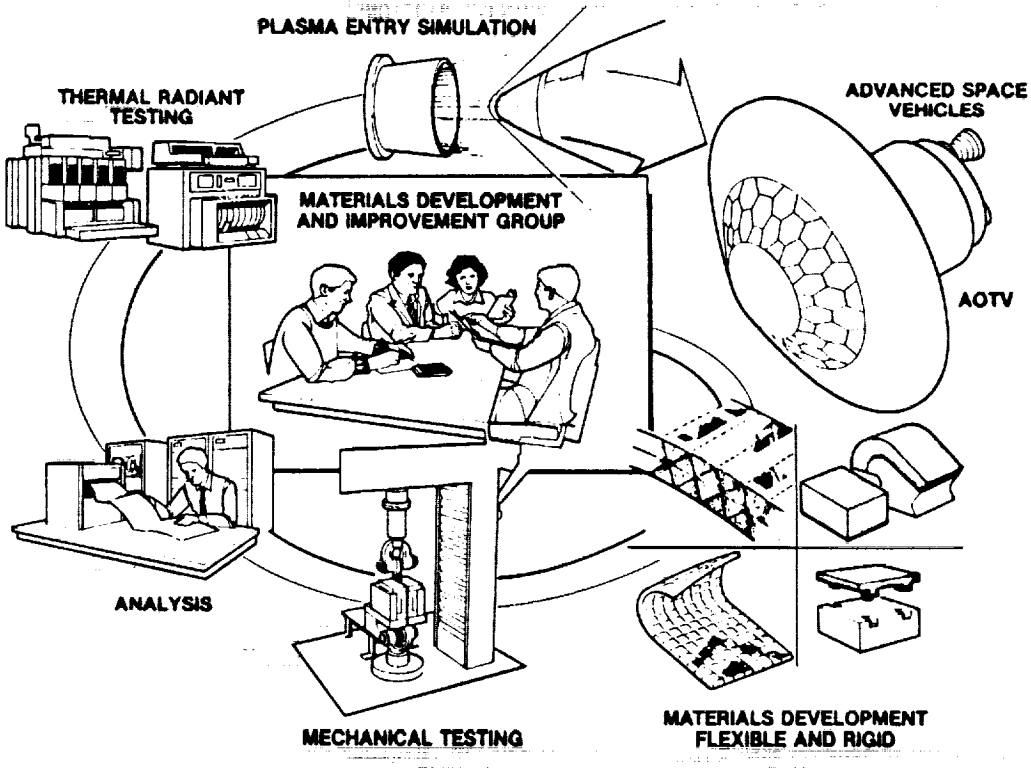
- REACTION RATE CONSTANTS
  - $2CO_2 \rightarrow 2CO + O_2$
  - $CO_2 \rightarrow CO + O$
  - $O_2 \rightarrow O + O$
  - $CO \rightarrow C + O$
  - $N_2 \rightarrow N + N$
  - $O \rightarrow O^+ + e^-$
  - $C \rightarrow C^+ + e^-$
- TRANSPORT PROPERTIES
  - Individual Species (Neutrals and Ions)
  - Mixtures
- RADIATION INTENSITY FACTORS
  - Ablation Product Species
  - Planetary Atmospheric Species
- SURFACE CATALYSIS
  - Surface Reaction Rates
  - Assess Material Efficiency

THERMAL PROTECTION FOR HIGH ENERGY AEROBRAKING VEHICLES

HOWARD GOLDSTEIN
NASA AMES RESEARCH CENTER
THERMAL PROTECTION MATERIALS BRANCH

FEBRUARY 1, 1989

THERMAL PROTECTION SYSTEM DEVELOPMENT PROCESS



LONG RANGE OBJECTIVE

TO PROVIDE THERMAL PROTECTION CONCEPTS AND MATERIALS FOR HEAT SHIELDS OF ENTRY AND HYPERSONIC CRUISE VEHICLES AND PLANETARY PROBES.

PATHFINDER PROGRAM

- GOAL
  - DEVELOP THE THERMAL PROTECTION TECHNOLOGY REQUIRED FOR AEROBRAKING AT MARS AND EARTH RETURN FOR MANNED AND UNMANNED MISSIONS.
- STATE-OF-THE-ART FOR MARS MISSIONS
  - FLEXIBLE (AFRSI) AND RIGID (FRCI, LI-20200, LI-900) SURFACE INSULATION ARE DEVELOPED AND BEING USED IN CURRENT STUDIES WHERE INSULATORS ARE REQUIRED.
  - CONVENTIONAL ABLATORS (AVCOAT 5026, CARBON PHENOLIC) USED IN HIGH HEATING AREAS.
- RESEARCH IN PROGRESS
  - STUDIES OF CATALYCITY IN CO_2.
  - ANALYSIS OF ADVANCED ABLATORS FOR EARTH RETURN.
  - DEVELOPMENT OF ADVANCED FLEXIBLE INSULATORS (TABI, MULTILAYER).
  - DEVELOPMENT OF ADVANCED RIGID INSULATORS (AETB, METB).
- RESEARCH BEING INITIATED
  - DEVELOPMENT OF ADVANCED ABLATORS: NONCATALYTIC, REFLECTIVE.
  - TPS REUSABLE AT MARS, ABLATIVE FOR EARTH RETURN: BUILDING ON RSI TECHNOLOGY.
- FLIGHT EXPERIMENTS
  - AEROASSIST FLIGHT EXPERIMENT
  - ORBITER EXPERIMENTS

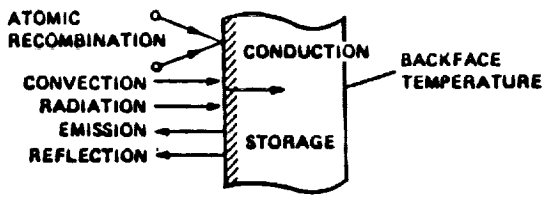
APPROACH

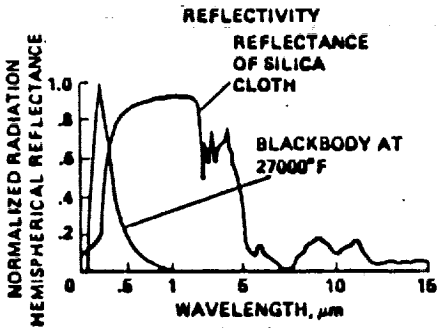
- DEVELOP FAMILIES OF THERMAL PROTECTION MATERIALS AND CONCEPTS APPLICABLE TO CLASSES OF MISSIONS.

- MISSIONS
  - MANNED AND UNMANNED (REUSABLE) LIFTING ENTRY
    - NASP, HGV, AOTV/AFE, HYPERSONIC AIRCRAFT, ASTS, ALS, CERV, MARS SAMPLE AND MANNED RETURN
  - BALLISTIC ENTRY
    - PLANETARY PROBES, DOD VEHICLES

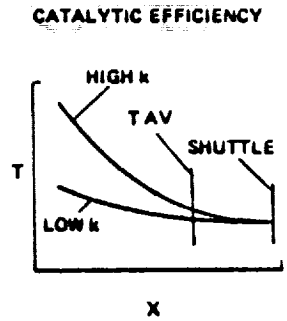
- MATERIALS
  - FLEXIBLE CERAMIC/CERAMIC
    - FELTS, QUILTS, 3-D WOVEN STRUCTURES, MLI COMPONENTS
  - RIGID CERAMIC
    - LOW DENSITY FIBROUS CERAMIC COMPOSITES
    - HIGH STRENGTH CERAMIC/CERAMIC COMPOSITES
  - ABLATIVE
    - CARBON/CARBON, CARBON PHENOLIC, SILICONES, REFLECTIVE AND NON CATALYTIC ABLATORS.

MATERIAL CHARACTERISTICS IMPORTANT FOR FUTURE TRANSATMOSPHERIC VEHICLES

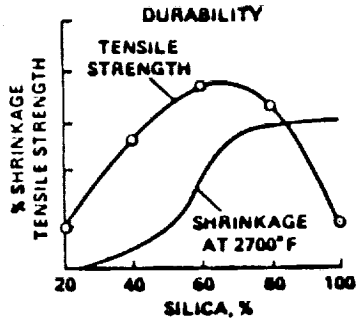




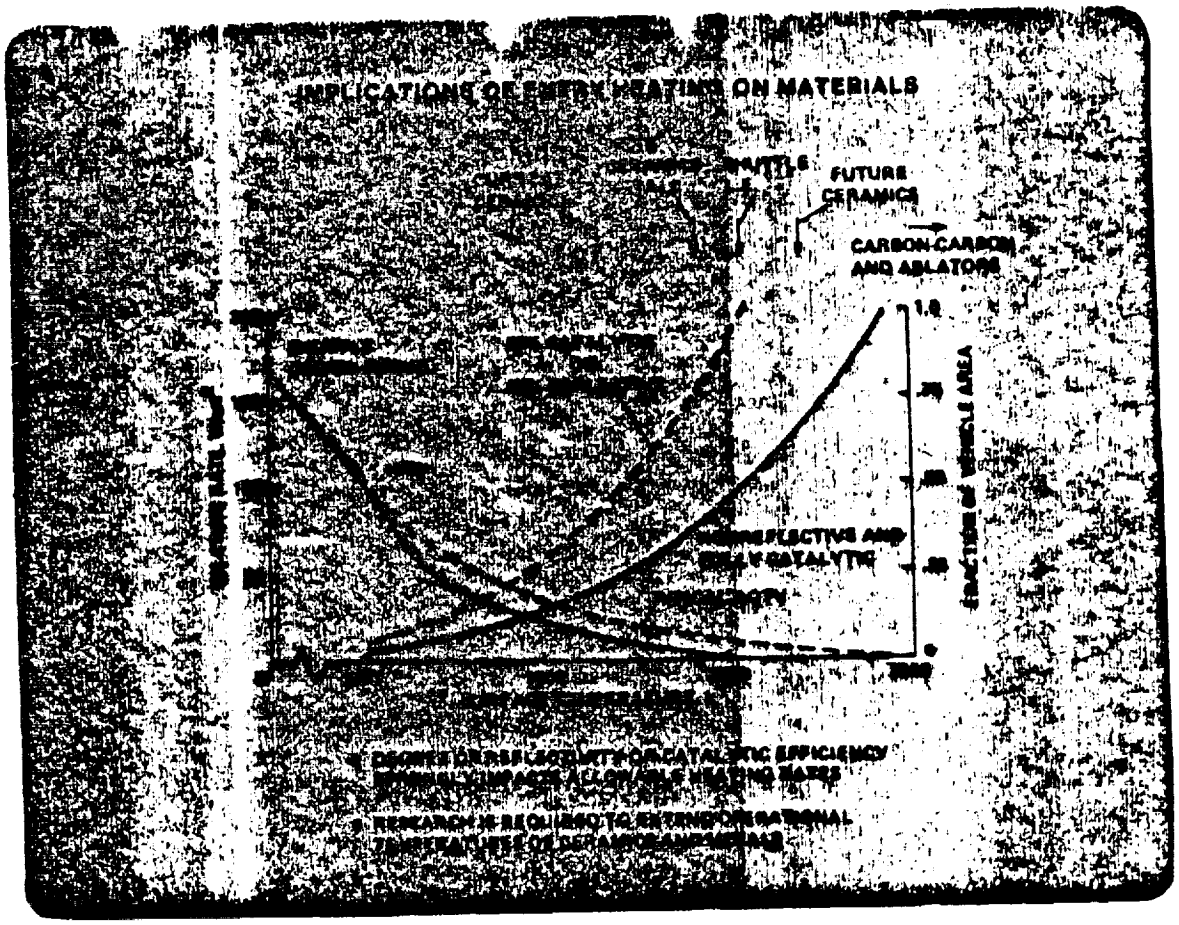
- HOW MUCH RADIATION CAN BE REFLECTED



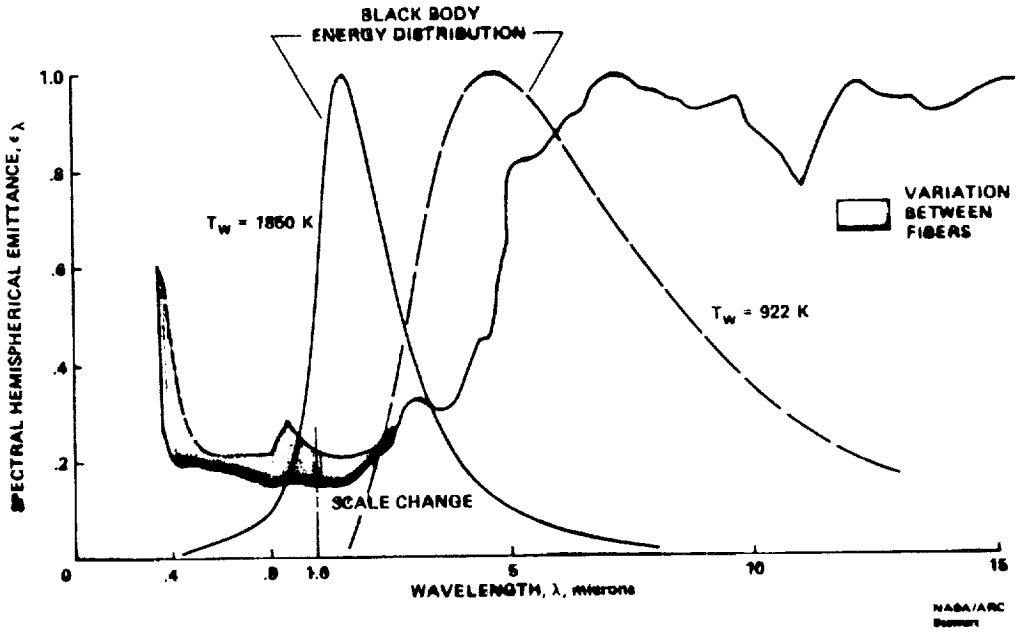
- CAN LOW CATALYTIC EFFICIENCY BE EXTENDED TO TEMPERATURES ABOVE 3000°F?
- CAN NONCATALYTIC COATINGS BE DEVELOPED FOR HIGH TEMPERATURE THERMAL CONTROL?



- WHAT IS OPTIMUM COMBINATION OF THERMOPHYSICAL AND THERMOCHEMICAL PROPERTIES?



RELATIONSHIP BETWEEN EMISSIVE FLUX AND EMISSIVITY OF THE RIGIDIZED FIBROUS CERAMIC COMPOSITES



POTENTIAL MISSIONS

POSSIBLE ENTRY CONFIGURATIONS

	AEROBRAKE	DIRECT ENTRY	ENTRY FROM ORBIT
MARS			
LANDER	X	X	X
ORBITER	X		
SAMPLE RETURN	X	X	X
MANNED RETURN	X	X	X
OTHERS			
PHOBOS	X		
VENUS	X	X	X

REQUIREMENTS FOR MARS MISSIONS THERMAL PROTECTION

- RELIABLE
  - FAIL OPERATIONAL
  - SIMPLE
- LIGHT WEIGHT
  - HIGHLY EFFICIENT
  - UTILIZE ON BOARD RESOURCES: I.E., WATER, WASTE
  - MULTIPLE USE OF STRUCTURAL COMPONENTS

    TPS <---> STRUCTURE <---> RADIATION SHIELDING

NEW THERMAL PROTECTION MATERIALS DESIRED

- REUSABLE FOR LUNAR RETURN
- REUSABLE AR MARS-ABLATIVE OR REUSABLE FOR EARTH RETURN.
- ABLATORS AND INSULATORS
  - NONCATALYTIC, REFLECTIVE
  - UTILIZE ON BOARD RESOURCES
  - UTILIZE LUNAR/MARTIAN RESOURCES
- INSULATORS
  - HIGH TEMPERATURE (HEAT FLUX) CAPABILITY
  - MORE EFFICIENT INSULATION

POSSIBLE THERMAL PROTECTION APPROACHES

MARS LANDER OR AEROBRAKE

	% AREA	PEAK HEAT FLUX BTU/FT^2-SEC	TYPE OF TPS
HIGH L/D			
LEADING EDGES	<5%	100-1000	ABLATOR
FOREBODY	<30%	~10-100	INSULATOR/REFLECTOR/PASSIVELY COOLED
AFTERBODY	>50%	<10	INSULATOR
LOW L/D			
FOREBODY	<30%	20-1500	ABLATOR/REFLECTIVE ABLATOR/INSULATOR
AFTERBODY	>60%	1-20	INSULATOR

EARTH RETURN VEHICLE

DIRECT ENTRY LOW L/D			
FOREBODY	<30%	100-2000	ABLATOR/REFLECTIVE ABLATOR
AFTERBODY	>50%	1-100	INSULATOR
AEROBRAKE PROBABLY LOW L/D			
FOREBODY	<40%	100-2000	ABLATOR/REFLECTIVE ABLATOR/PASSIVELY COOLED
AFTERBODY	>50%	1-100	INSULATOR

HEAT SHIELD MATERIAL THERMAL LIMITS

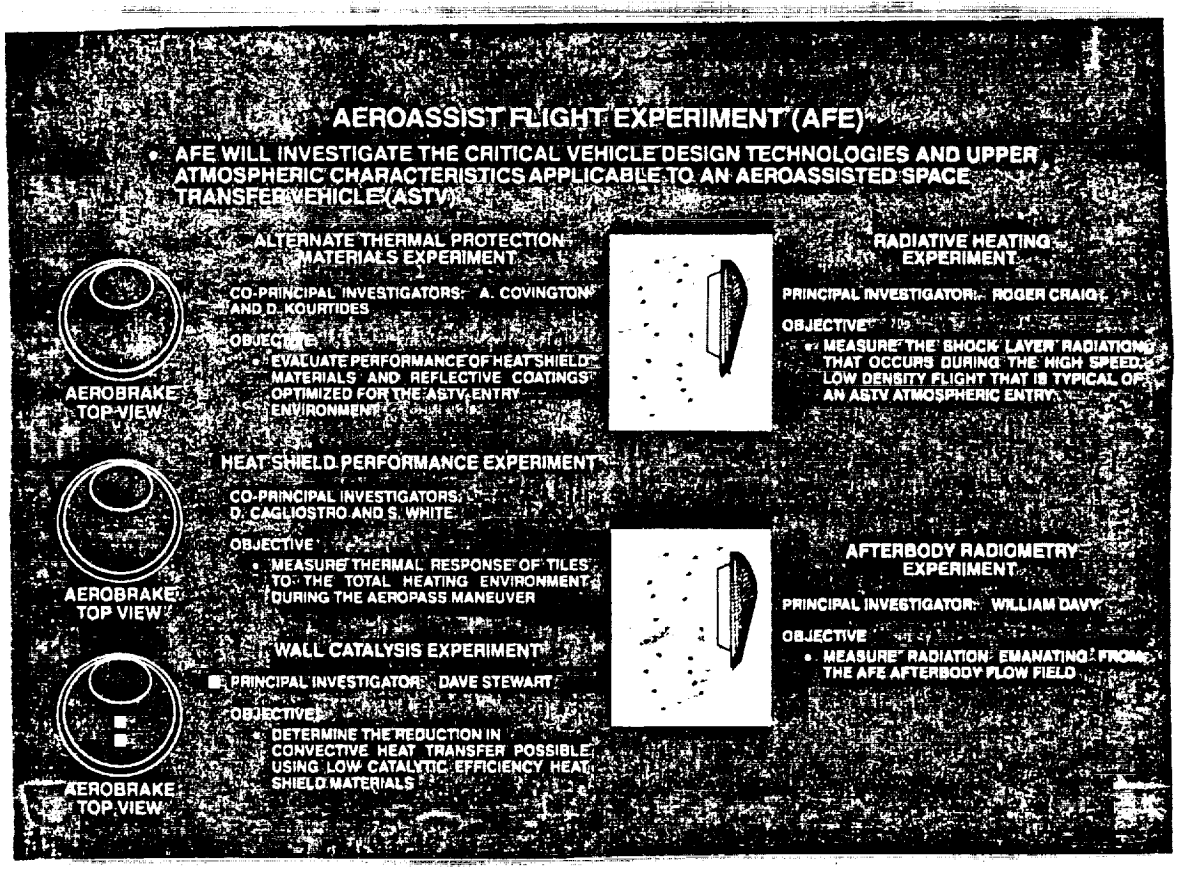
MATERIAL	MAXIMUM USE TEMPERATURE, °F		MAXIMUM HEAT FLUX CAPABILITY BTU/FT²-SEC	EQUIVALENT USE TEMPERATURE, °F
	MULTIPLE FLIGHT	SINGLE FLIGHT		
FLEXIBLE ORGANIC				
FRSI (ε =.9)	700	800	1.4	885
PBI (ε =.9)	900+	1100	2.7	1125
FLEXIBLE CERAMIC				
AFRSI (CURRENT)	1200	2000	4.4	1480
NEXTEL (ε =.65)	>1500	2000	>7.6	1660
NICALON (ε =.58)	1500		10	
RIGID CERAMIC INSULATION				
LI 900	2500	2700	60	2980
FRCI-12	2800	2800	70	3115
ADVANCED	2700		80	3256
METAL (ε =.8)				
TITANIUM	1000		1.7	1000
RENE'41	1600		6.0	1600
INCONEL 617	2000		30	2000
RCC/HCC	3000		55 (F.C.)	3000
			100 M.C.	3560

UTILIZATION OF VEHICLE ON BOARD RESOURCES
FOR THERMAL PROTECTION

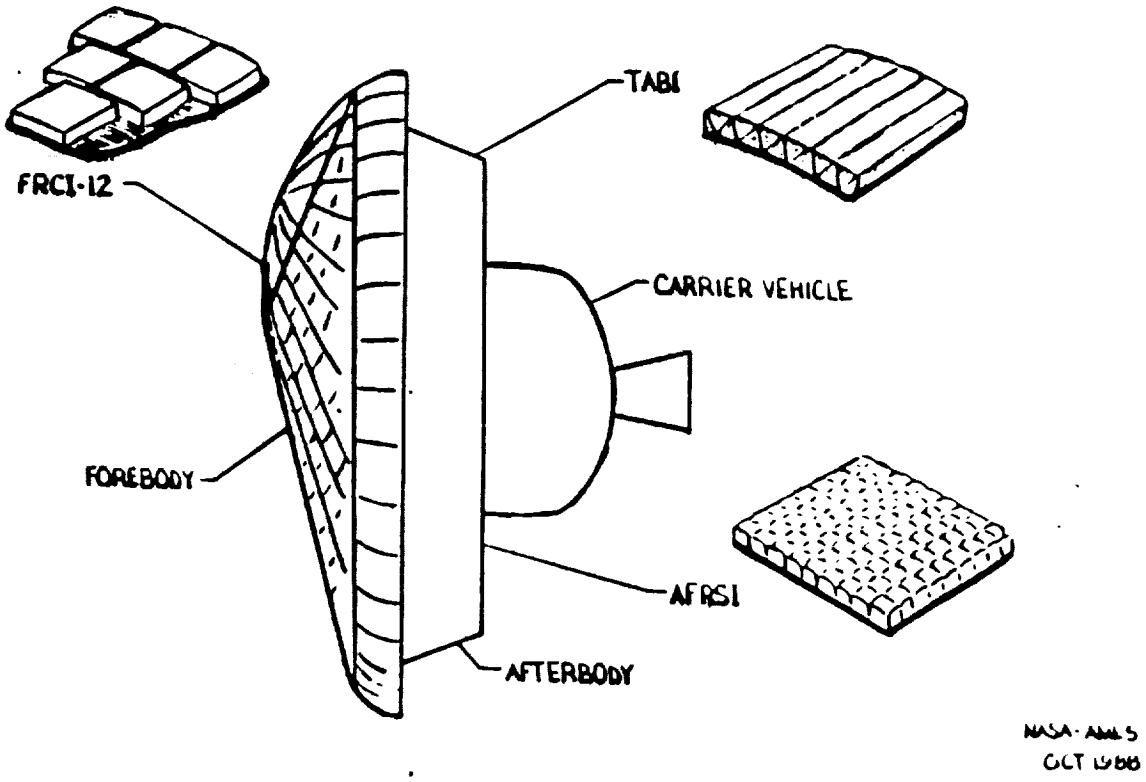
- WATER
  - BIOLOGICAL RECYCLED
  - H_2/LOX ULLAGE
  - FUEL CELLS
- FLUID PUMPS
  - RECONFIGURE FOR AEROPASS
- HEAT SINK
  - RADIATION SHIELDS
  - BIOLOGICAL WASTES
- STRUCTURE
  - RECONFIGURE FOR AEROPASS

UTILIZATION OF PLANETARY RESOURCES
FOR THERMAL PROTECTION

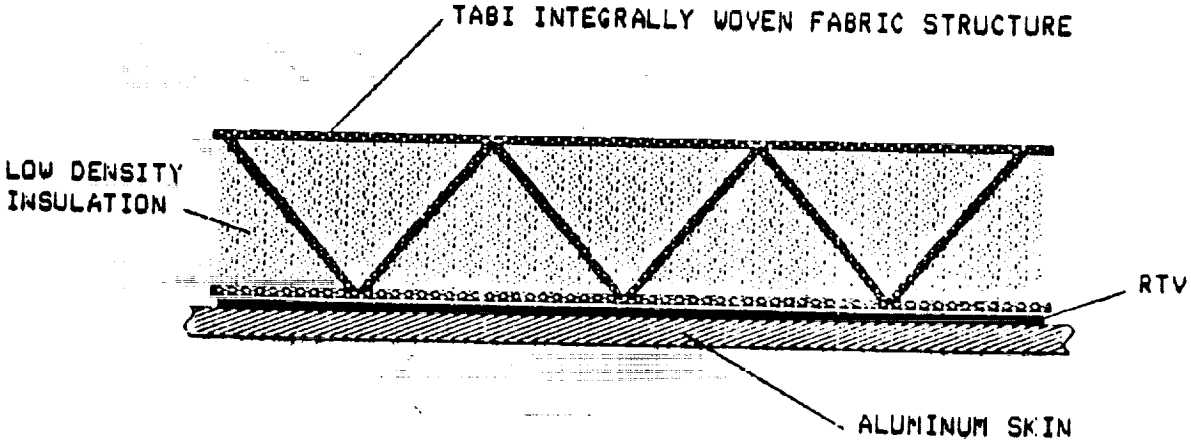
- SAME PROCESSES USED TO PRODUCE OTHER MATERIALS
  - FIBERGLAS
  - CERAMIC FOAM
  - METALS
  - WATER
- FABRICATION METHODS SIMILAR TO THOSE USED FOR HABITAT STRUCTURES
- POTENTIAL HIGH PAYOFF FOR LUNAR OUTPOST STAGING OF MANNED MARS MISSION.



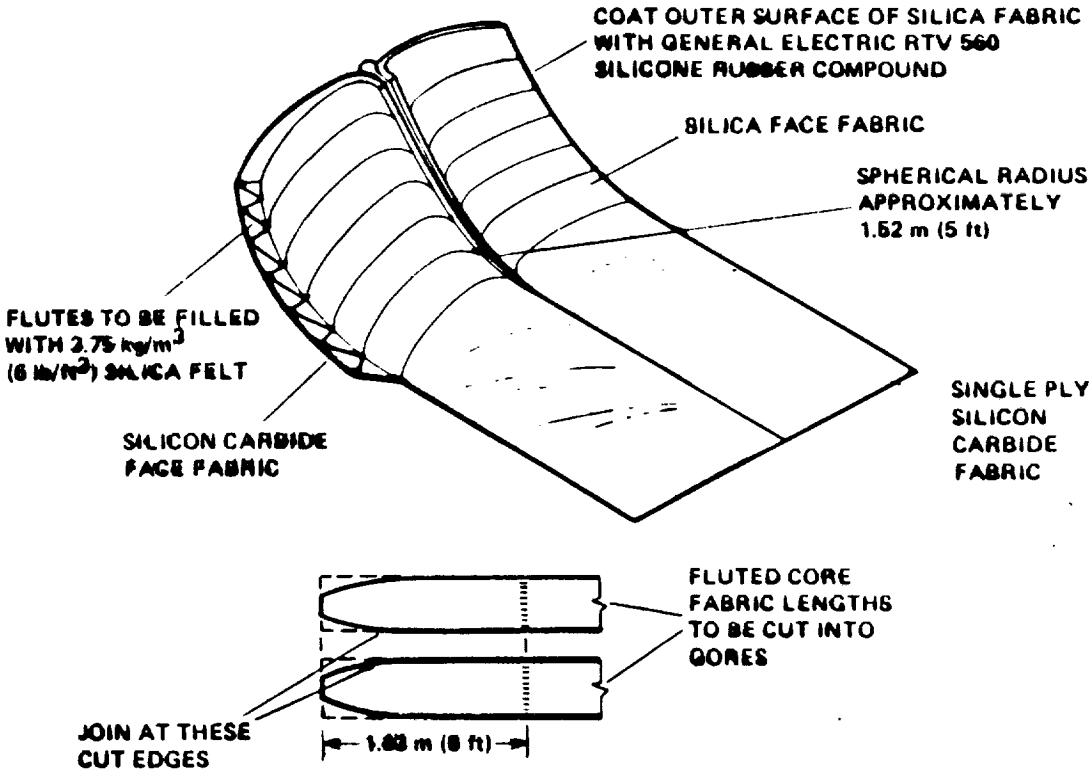
THERMAL PROTECTION SYSTEM FOR AEROASSIST FLIGHT EXPERIMENT (AFE)



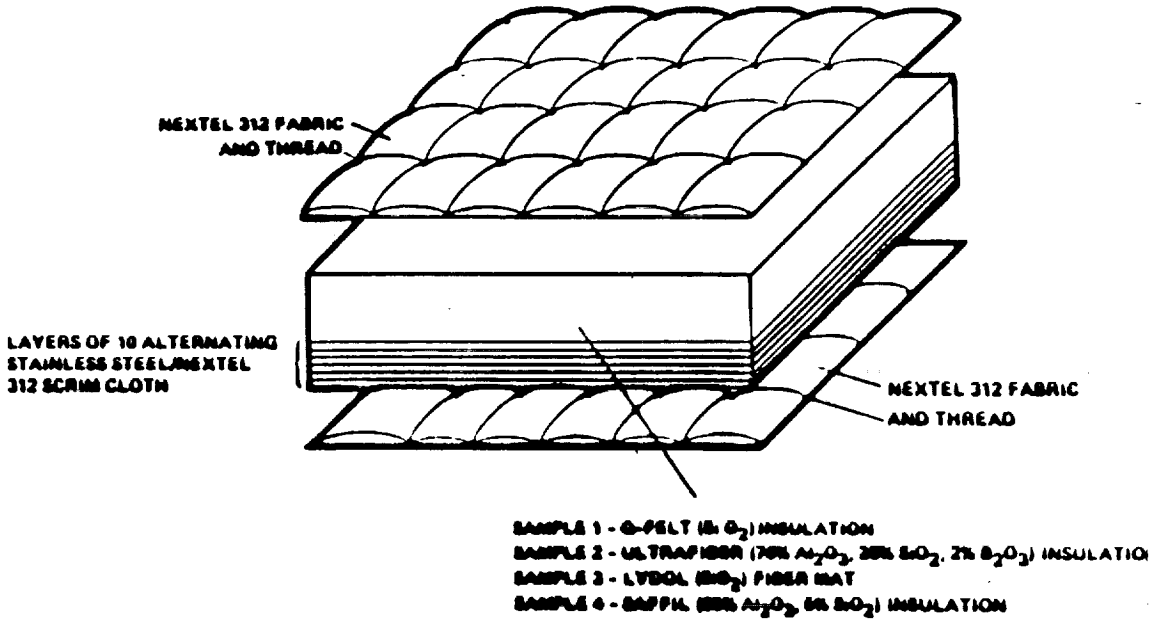
FLEXIBLE TABI TPS CONSTRUCTION



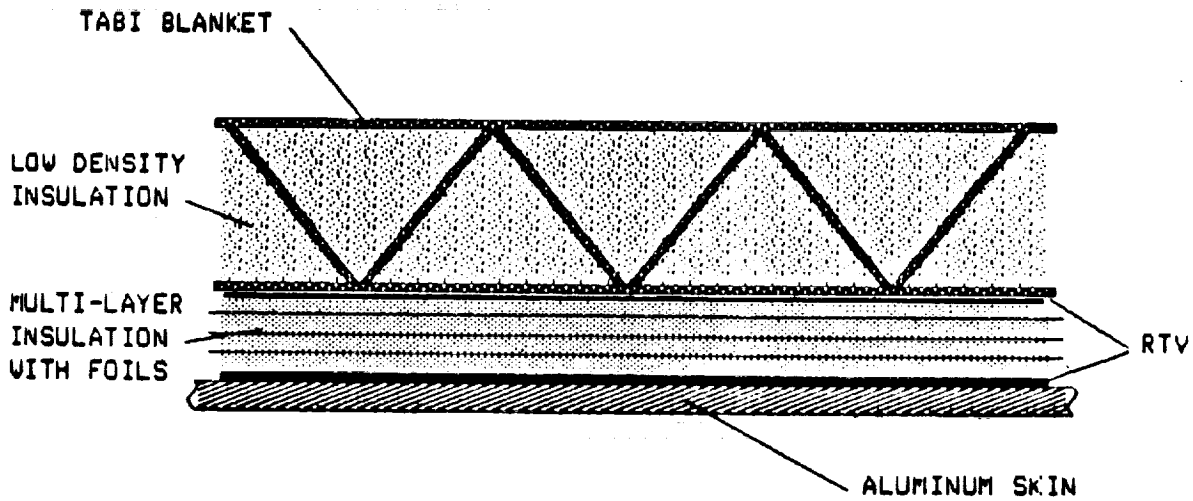
CONSTRUCTING A TWO-GORE TABI BALLUTE STRUCTURE



CERAMIC-METAL FOIL INSULATION

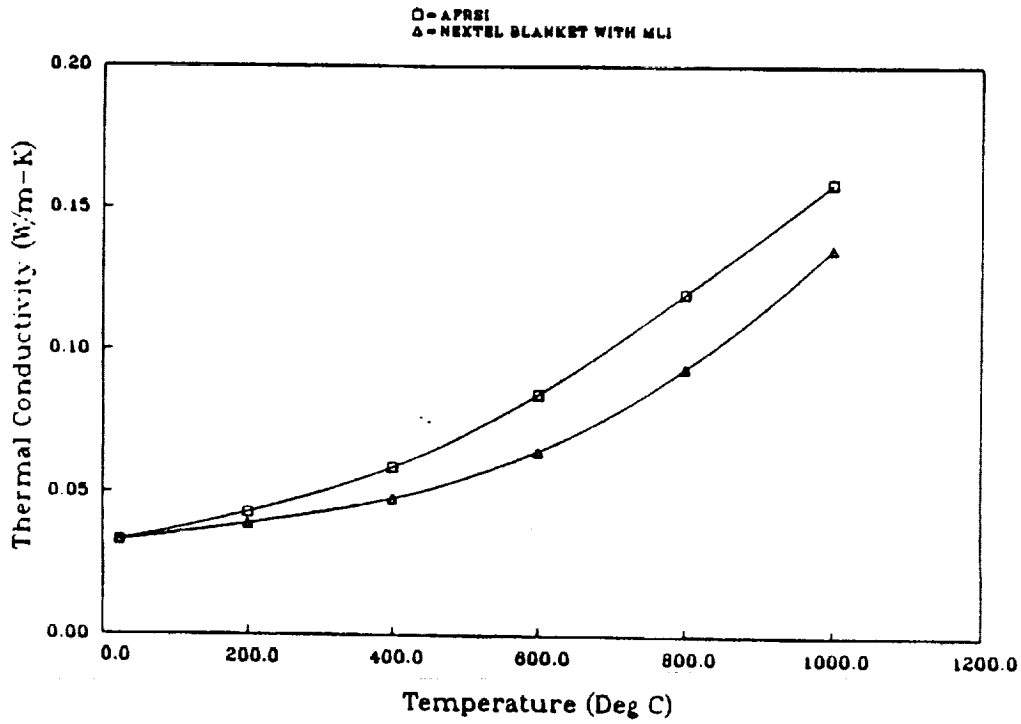


FLEXIBLE TPS CONSTRUCTION



APPARENT THERMAL CONDUCTIVITY OF FLEXIBLE COMPOSITE INSULATION

0.1 Atm Pressure



PERFORMANCE OF CERAMIC FABRICS IN A CONVECTIVE HEATING ENVIRONMENT

FABRIC MATERIAL	CONDITION AFTER EXPOSURE TO INDICATED HEATING RATE, Btu/ft^2-sec		
	LITTLE CHANGE	STIFF	BRITTLE
SILICA	4*	6*	9*
ABS	8**	12**	15**
SILICON CARBIDE	34**	–	–

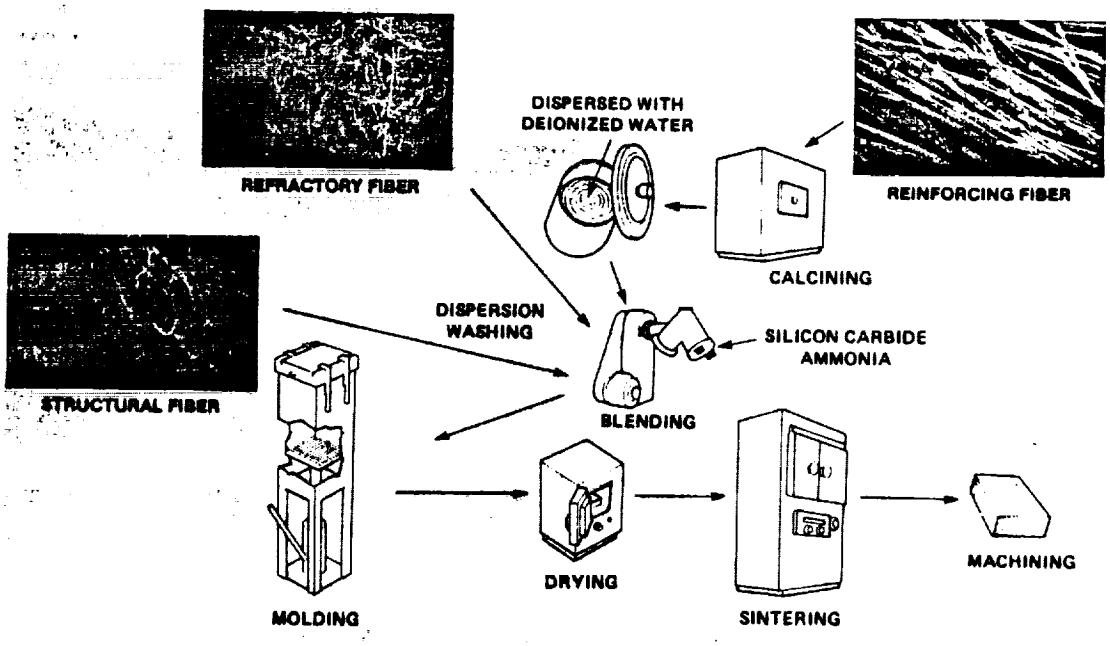
*CALCULATED BASED ON OBSERVED TEMPERATURE PERFORMANCE

**MEASURED RE-RADIATION

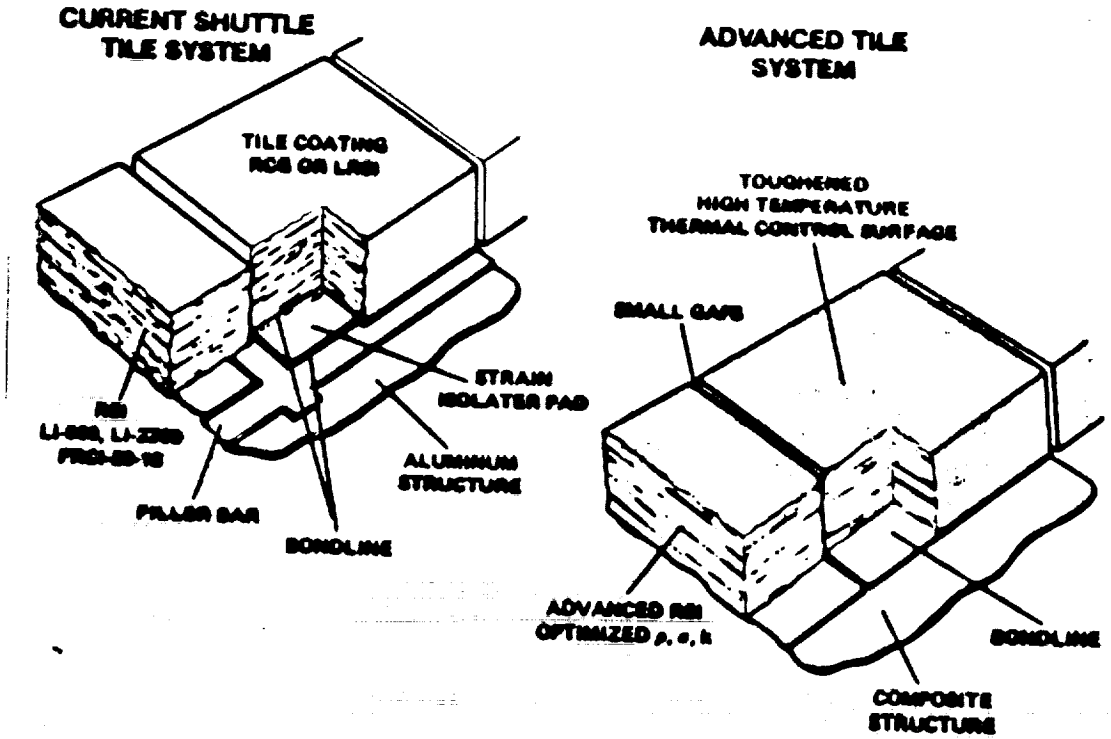
RIGID RSI PROPERTY COMPARISON

PROPERTIES	RIGID RSI MATERIALS			
	LI-900	LI-2200	FRCI-12	AETB-12
TENSILE STRENGTH				
IP (PSI)	68	181	256	157
TTT (PSI)	24	73	81	120
MODULUS				
IP (KSI)	25	80	50	32
TTT (KSI)	7	27	10	16
TEMPERATURE CAPABILITY (ISOTHERMAL SHRINK.)				
2700^{0}F - 1 HR (%)	91		77	42
2500^{0}F - 1 HR (%)	53		44	12
THERMAL CONDUCTIVITY				
PRESSURE = 10^{-3}ATM				
T = 1000^{0}F $\frac{\text{BTU-IN}}{\text{FT}^2\text{-HR}^0\text{F}}$	0.021	0.030	0.027	0.024

MULTIFIBER RIGID RSI PROCESS

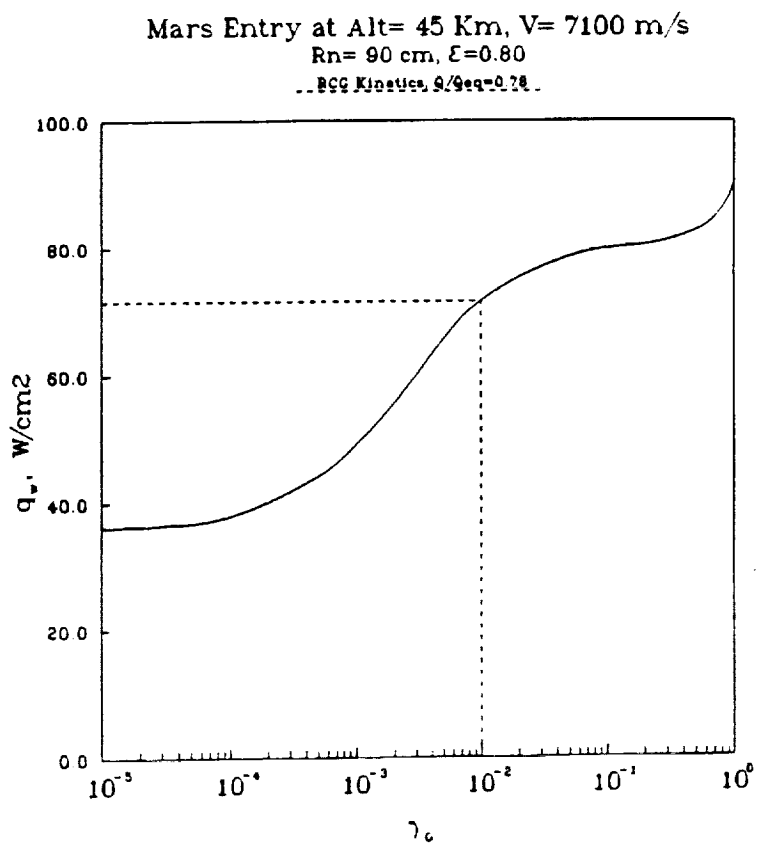


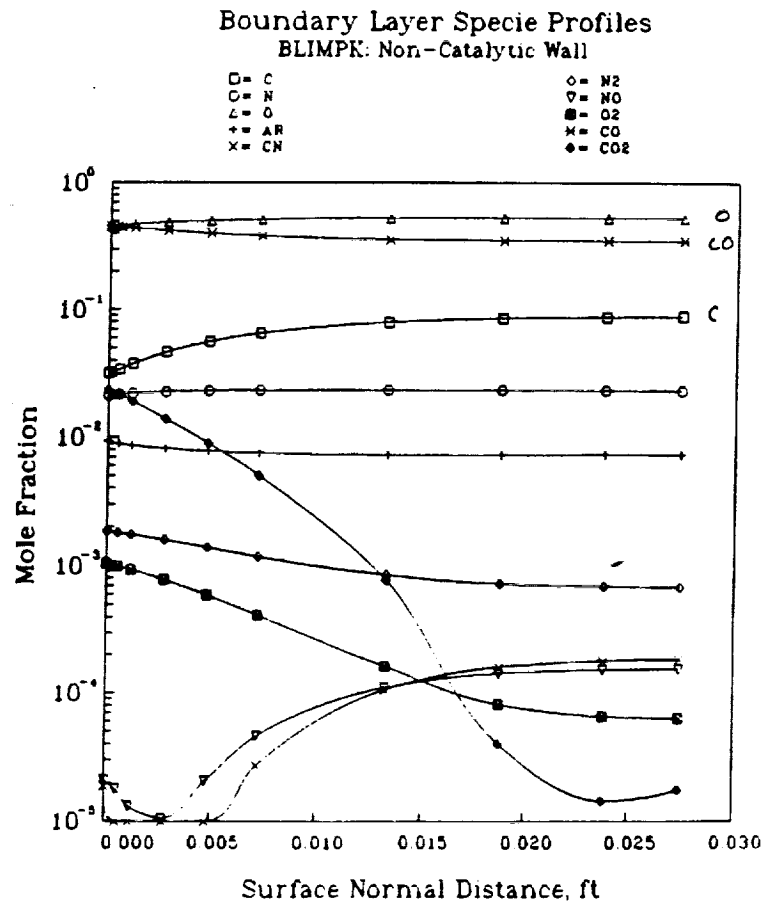
ADVANCED RSI THERMAL PROTECTION SYSTEMS

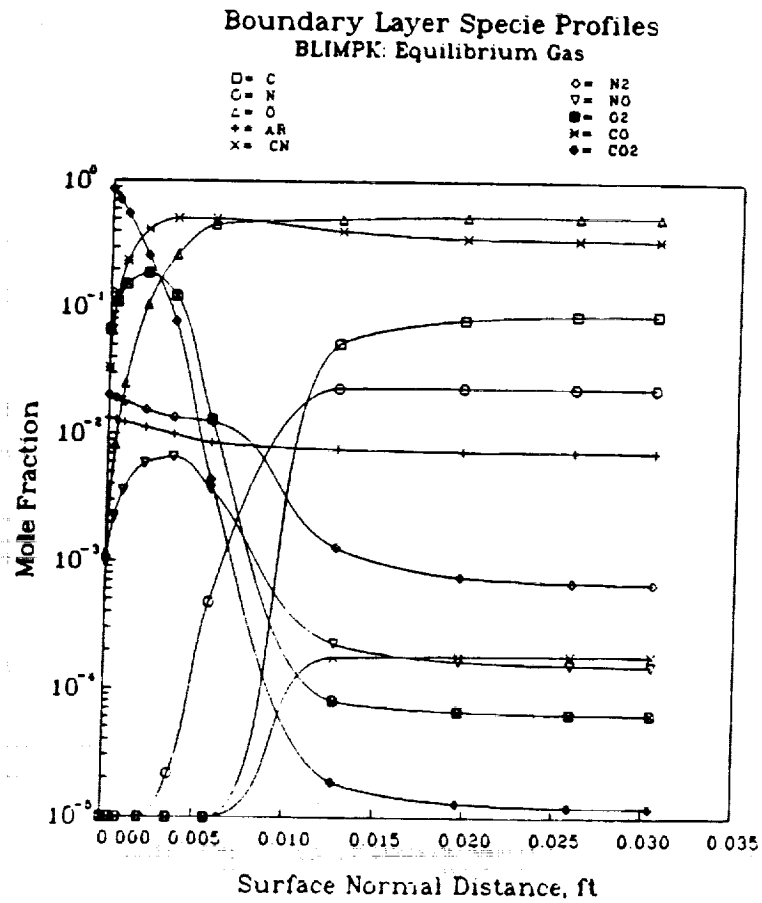


MARS ENTRY MODEL

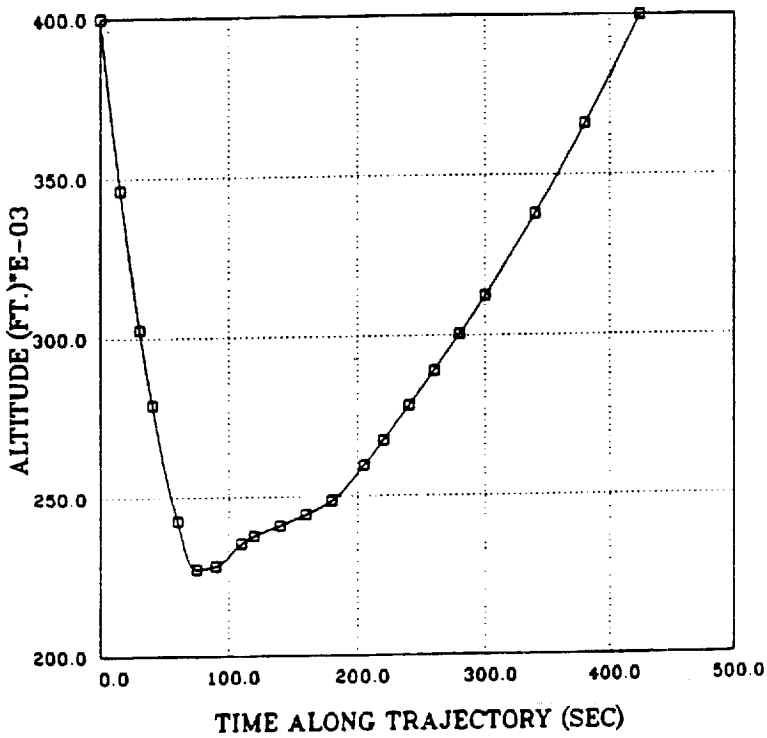
- ATMOSPHERE: 96% CO_2
- GEOMETRY: TAUBER'S SHUTTLE, Rn = 90 cm.
- PEAK HEATING: V = 7100 m/s, ALT = 44 km



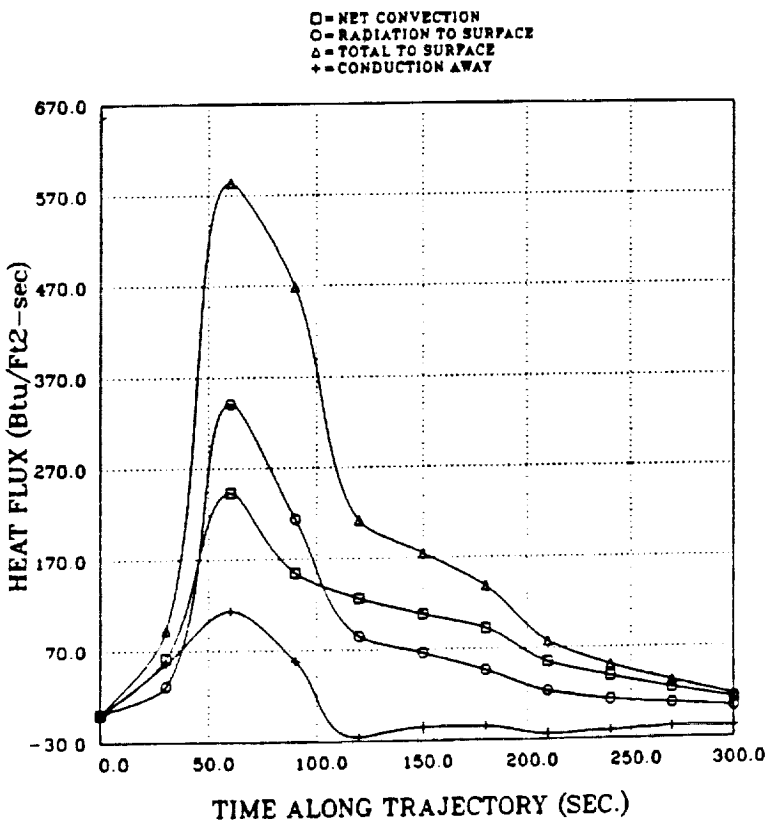

Boundary Layer Specie Profiles
BLIMPK: Non-Catalytic Wall
□= C
○= N
△= O
+= AR
×= CN
◇= N2
▽= NO
■= O2
✱= CO
◆= CO2
O
CO
C
Mole Fraction
Surface Normal Distance, ft


Boundary Layer Specie Profiles
BLIMPK: Equilibrium Gas
□= C
○= N
△= O
+= AR
×= CN
◇= N2
▽= NO
■= O2
✱= CO
◆= CO2
Mole Fraction
Surface Normal Distance, ft

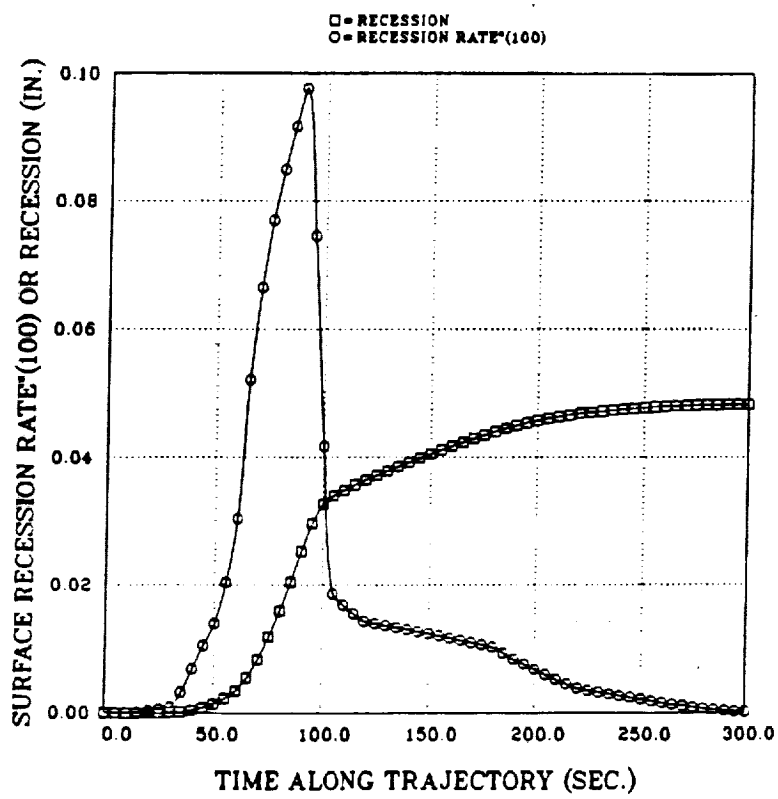
JSC/MARS SAMPLE RETURN PHASE A TRAJECTORY



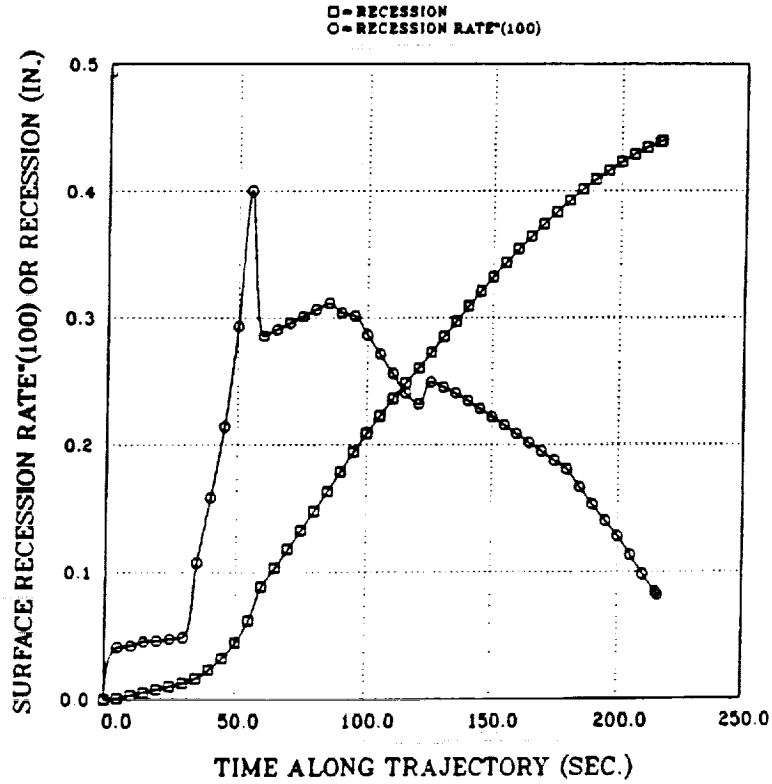
MARS RETURN GRAPHITE ABLATION/HEAT LOADS



MARS RETURN GRAPHITE ABLATION/SURFACE RECESSION
SCALA SLOW KINETICS



MARS RETURN AVCOAT ABLATION/SURFACE RECESSION



STATUS OF DEVELOPMENT

- RIGID LOW DENSITY CERAMIC
  - SHUTTLE TPS FLIGHT PROVEN
    - LI-900, LI-22000, FRCI-20-12
  - IMPROVED MATERIALS DEVELOPED
    - FRCI, AETB, METB
    - TOUGHENED COATING
  - OPTIMIZED MATERIALS TO BE DEFINED
- RIGID HIGH DENSITY CERAMIC
  - CERAMIC MATRIX COMPOSITES IN EARLY STATE OF DEVELOPMENT
- FLEXIBLE
  - SHUTTLE TPS FLIGHT PROVEN
    - FRCI, AFRSI
  - IMPROVED MATERIALS UNDER DEVELOPMENT
    - TABI, ORGANIC CERAMIC COMPOSITES, MLI CERAMIC COMPOSITES
- ABLATORS
  - MARS RETURN MISSION REQUIREMENTS DEFINED
  - NON CATALYTIC REFLECTIVE ABLATOR DEVELOPMENT STARTING

TECHNOLOGY NEEDS

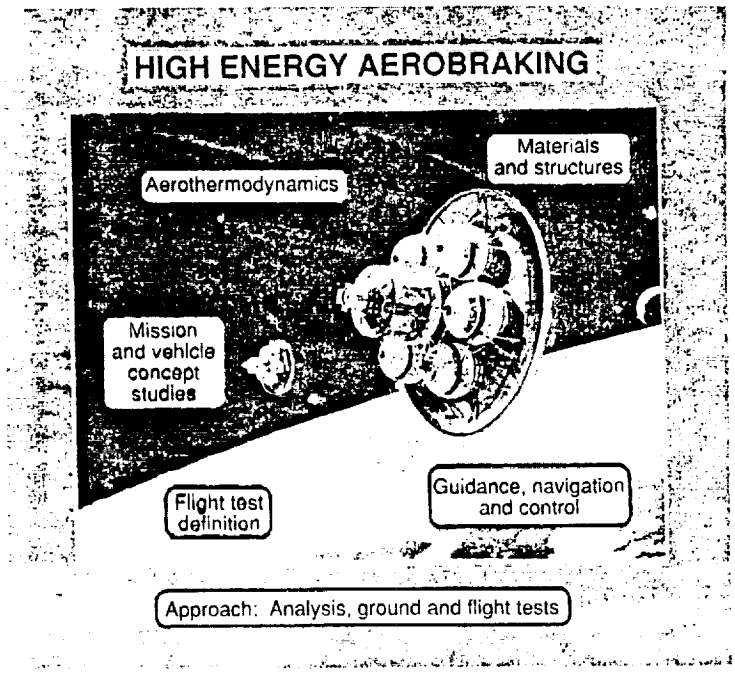
- ADVANCED INSULATORS AND ABLATORS: OPTIMIZED FOR MISSIONS
  - REFLECTIVE
  - NONCATALYTIC
  - OPTIMUM DENSITY
  - HIGHER TEMPERATURE (INSULATORS)
  - REUSABLE (ABLATORS)
- NEW CONCEPTS TO MINIMIZE WEIGHT AND COST
  - UTILIZE ONBOARD RESOURCES
  - UTILIZE PLANETARY RESOURCES

SPECIFICS OF LANGLEY'S AEROBRAKING EFFORTS: PAST, PRESENT AND PLANNED

TECHNICAL OVERVIEW OF OAST HIGH ENERGY AEROBRAKING PROGRAM

GERALD WALBERG

PRESENTED AT THE
HIGH ENERGY AEROBRAKING WORKSHOP
JANUARY 31-FEBRUARY 2, 1989
AMES RESEARCH CENTER



STATE OF THE ART
OVERALL

- Only partial ground-based simulation possible
- Vehicle design must be based on computational techniques
- Computational techniques now being developed
  - Lunar mission vehicle analyses nearing completion
  - Mars mission vehicle analyses require major advances
- Validation by ground and flight tests required
  - AFE provides validation for lunar vehicle analyses
  - Additional ground and flight tests required to validate Mars vehicle analyses

OAST/OFFICE OF EXPLORATION WORKSHOP

AEROBRAKING ISSUES AND DISCONNECTS

- TECHNOLOGY READINESS DATES
  - MARS AEROBRAKING: CONFIGURATION ISSUE, STRUCTURES ISSUE (120" DIA.?), MODERATE HEATING
    - NO FLIGHT TEST BEYOND AFE REQUIRED
    - ON ORBIT ASSEMBLY DEMO?
    - TECHNOLOGY READINESS 1996
  - EARTH AEROBRAKING: HEATING ISSUE
    - HIGH SPEED FLIGHT TEST REQUIRED
    - TECHNOLOGY READINESS 2000
  - FUNDING: REDUCTIONS IN PATHFINDER WILL SLIP TECHNOLOGY READINESS
- AEROBRAKE REUSABILITY - SAME AEROSHELL USED FOR:
  - (A) MARS AEROBRAKING AND ENTRY - MAYBE
  - (B) MARS AEROBRAKING AND SUBSEQUENT EARTH AEROBRAKING (ONCE) - MAYBE
  - (C) MARS AND EARTH AEROBRAKING (MULTIPLE TIMES) - PROBABLY NOT

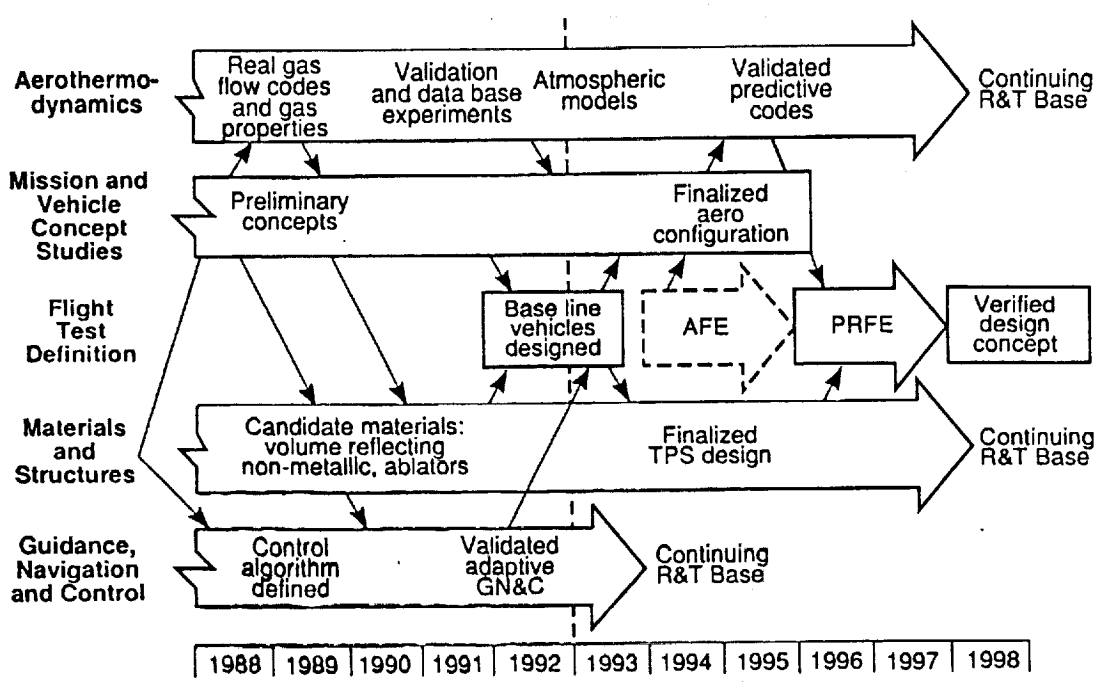
AEROBRAKING ISSUES AND DISCONNECTS (CONT'D)

- STRUCTURAL WEIGHT OF AEROBRAKE
  10% AND 15% ASSUMPTIONS NEED VERIFICATION
  - VERY LARGE MARS VEHICLES (120' DIA.?)
  - HIGH EARTH ENTRY HEATING (RADIATIVE AND CONVECTIVE)
- VEHICLE CONFIGURATIONS

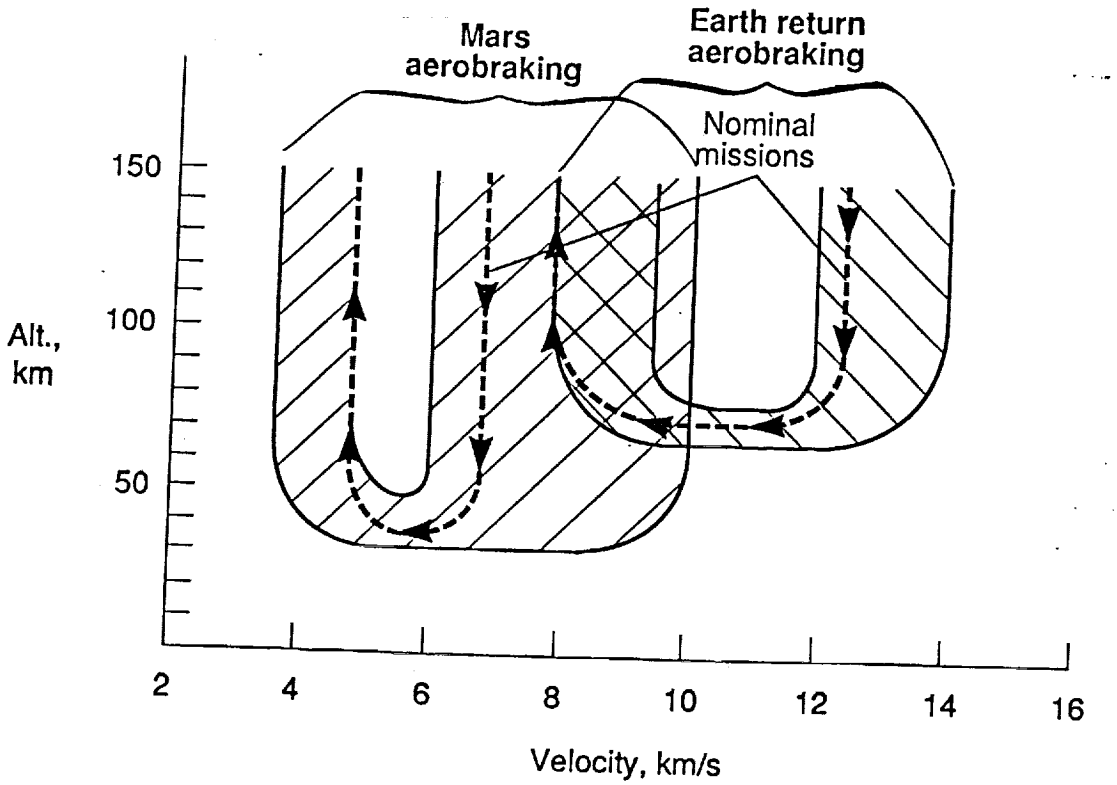
  MARS - NAVIGATION INACCURACIES; ATMOSPHERIC UNCERTAINTIES; MAX G's; PACKAGING
  - HIGHER L/D's (.5-.8)?

  EARTH - HEATING (RADIATIVE AND CONVECTIVE); MAX G's; ATMOSPHERIC UNCERTAINTIES
  - LESS BLUNT?
  - BLUNTED RAKED CONE?
- AEROBRAKING AND SOME ADVANCED PROPULSION SYSTEMS MAY BE SYNERGETIC

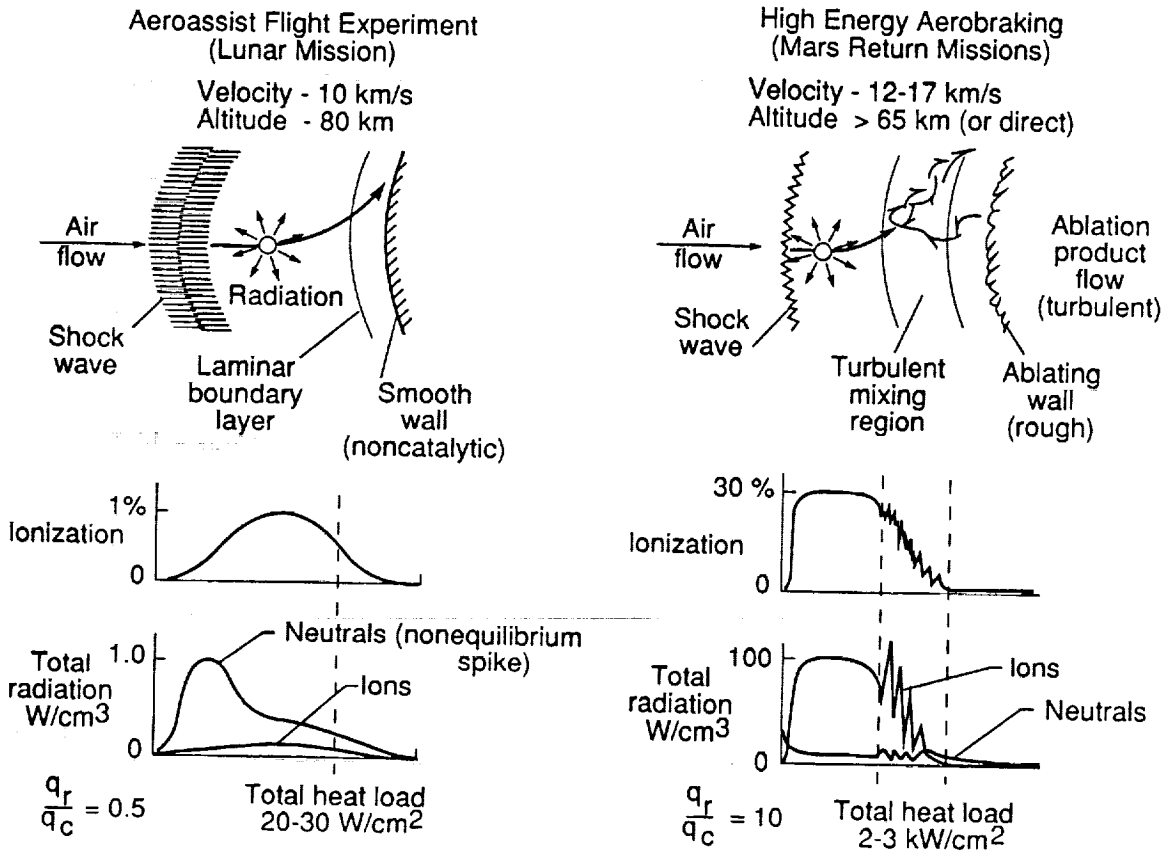
HIGH ENERGY AEROBRAKING MILESTONES AND DELIVERABLES



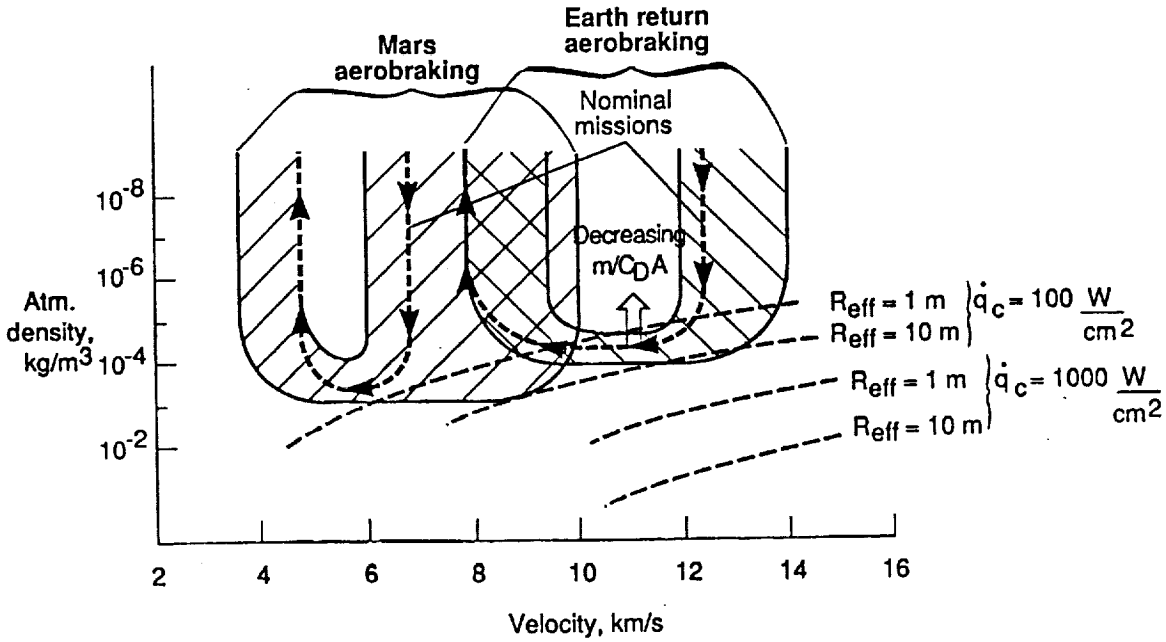
FLIGHT DOMAINS FOR CURRENT MARS MISSION STUDIES



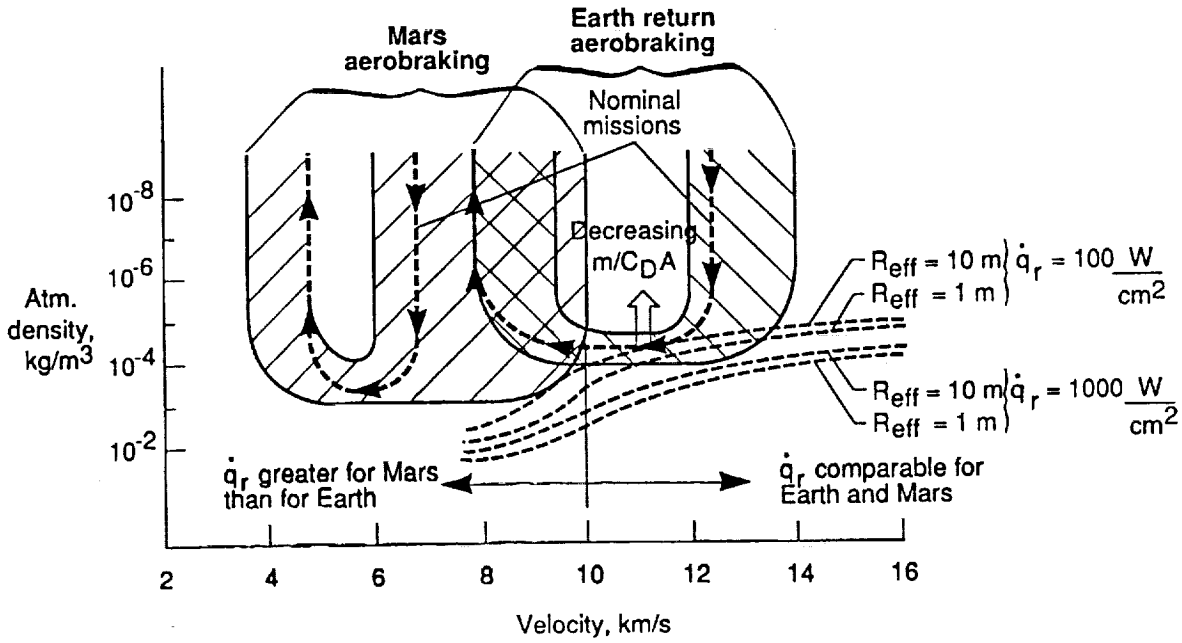
SHOCK LAYER PHYSICS COMPARISON



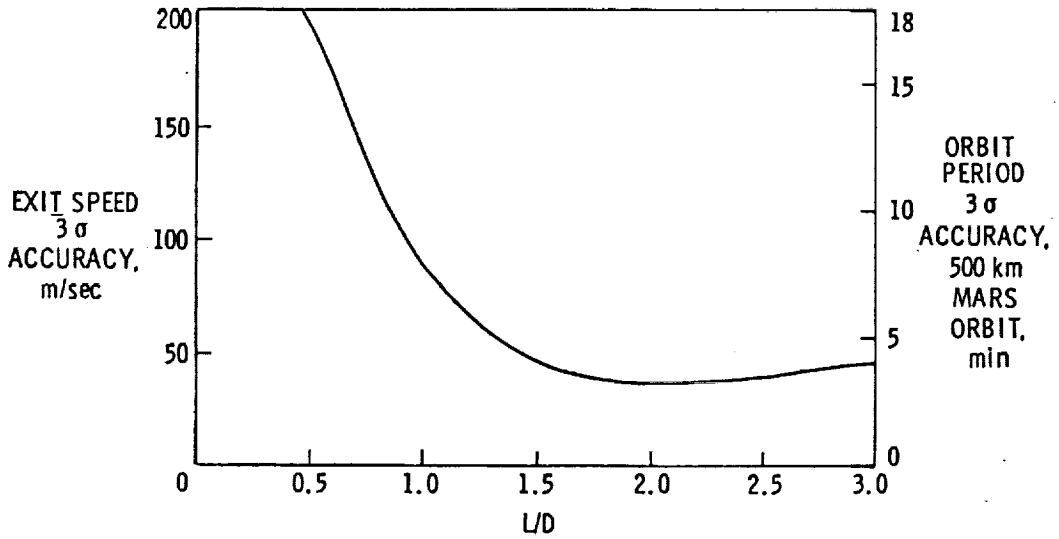
CONVECTION HEATING RATES FOR MARS AND EARTH AEROBRAKING



RADIATIVE HEATING RATES FOR EARTH AEROBRAKING

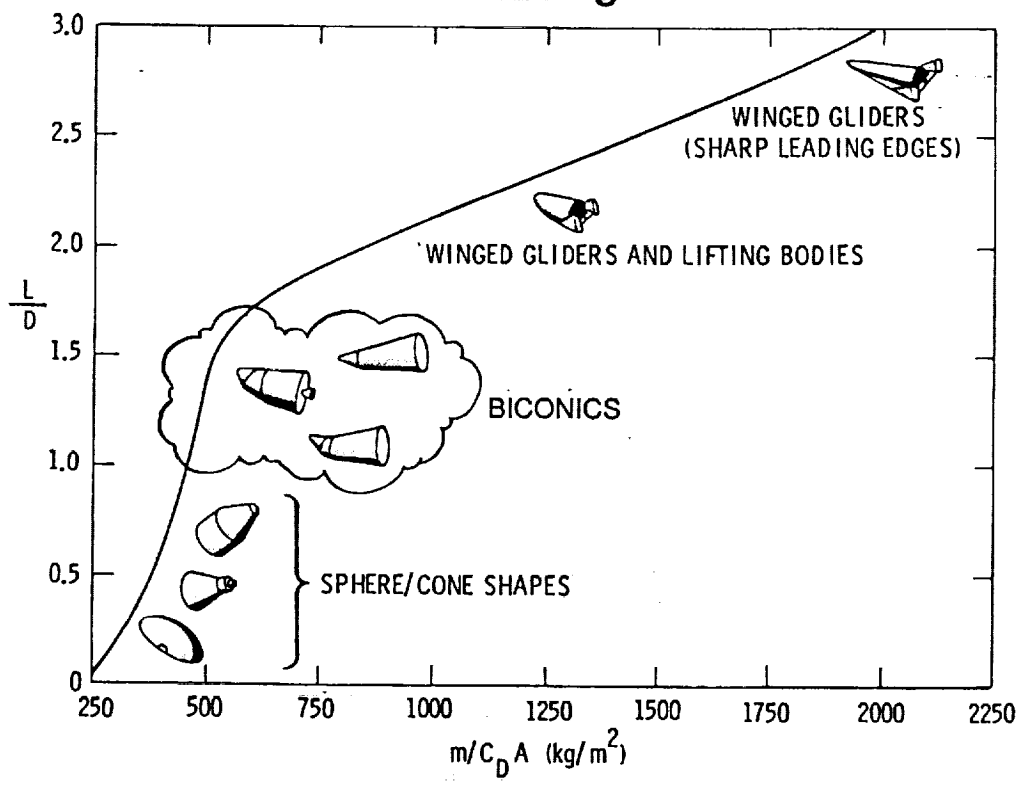


EFFECT OF L/D ON MARS AEROBRAKING ACCURACY



NASA L-5694-19 J. WALBERG 8/9-11/82

L/D AND m/C_DA FOR TYPICAL CONFIGURATIONS
m = 5000 kg



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STATUS OF LaRC HEAB MISSION ANALYSIS AND GUIDANCE STUDIES

by

Dick Powell
Space Systems Division

February 1, 1989

INTRODUCTION

LaRC past involvement with AOTV has included:

1. Systems analysis
2. Trajectory optimization
3. Guidance and control systems designs
4. Aerodynamic characteristics determination
5. Modelling of atmospheric uncertainties
6. 6 DOF simulations
7. Heating/flow field analysis

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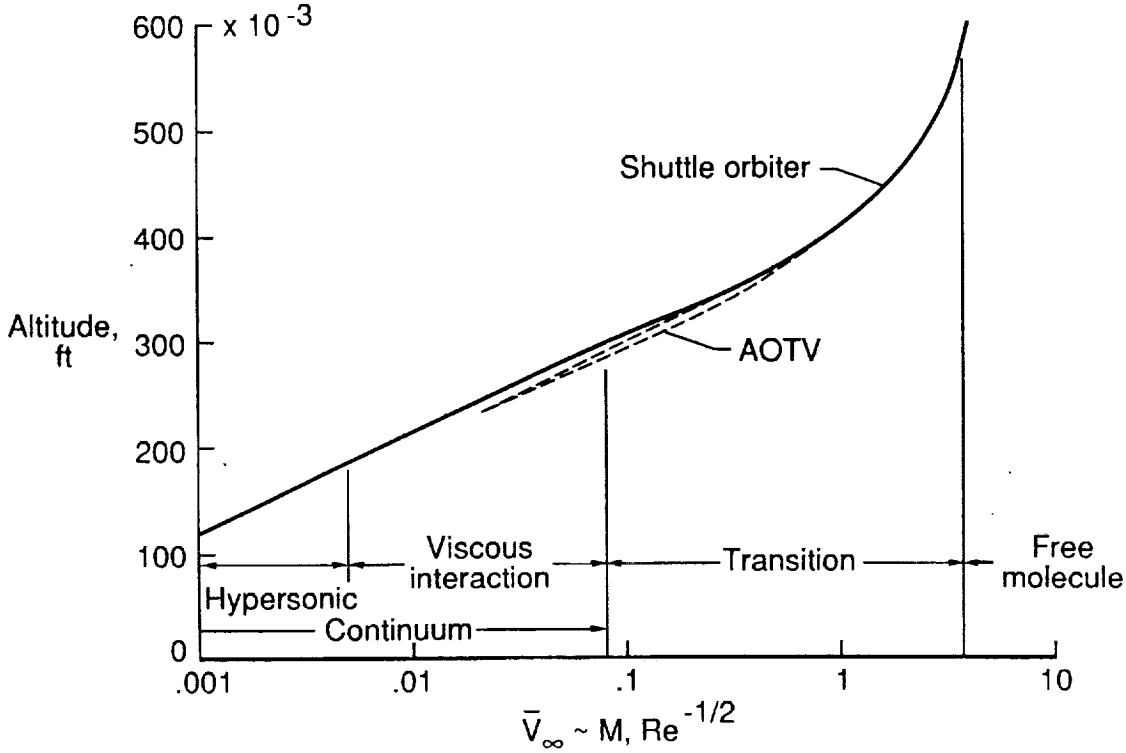
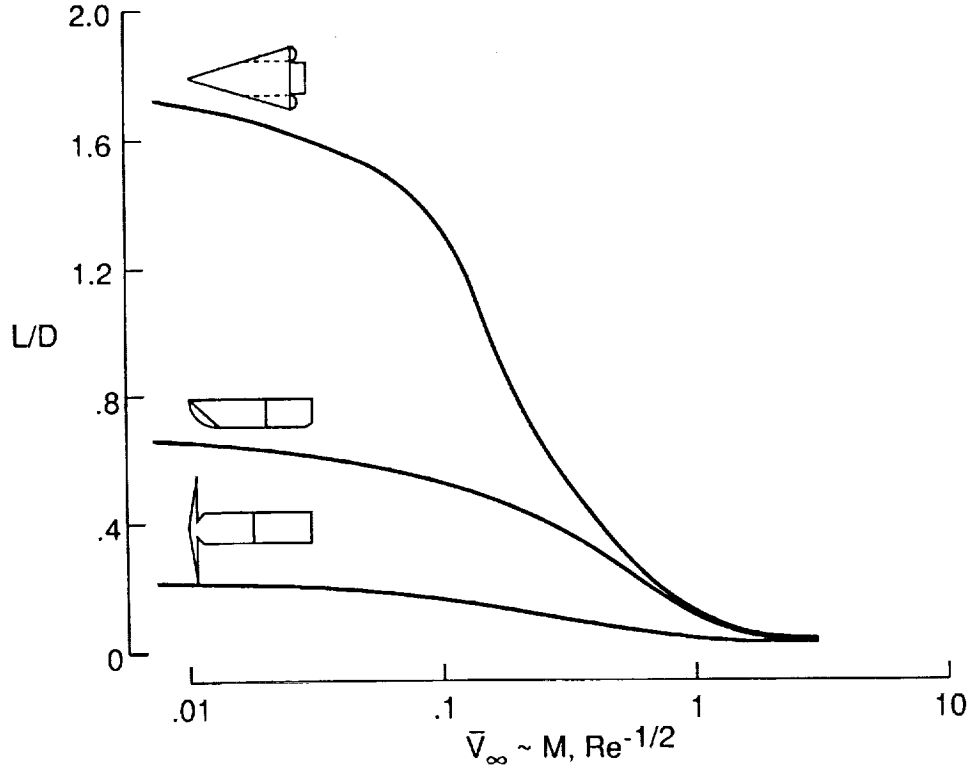
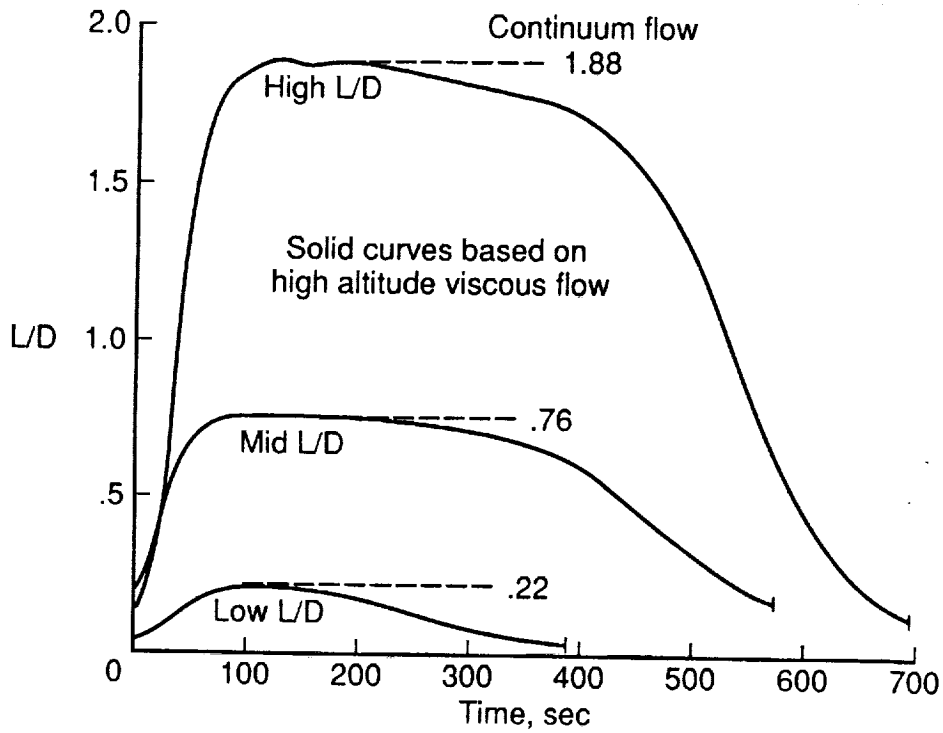
FLIGHT REGIMES OF THE SPACE SHUTTLE ORBITER AND AOTV



AOTV L/D PERFORMANCE COMPARISON



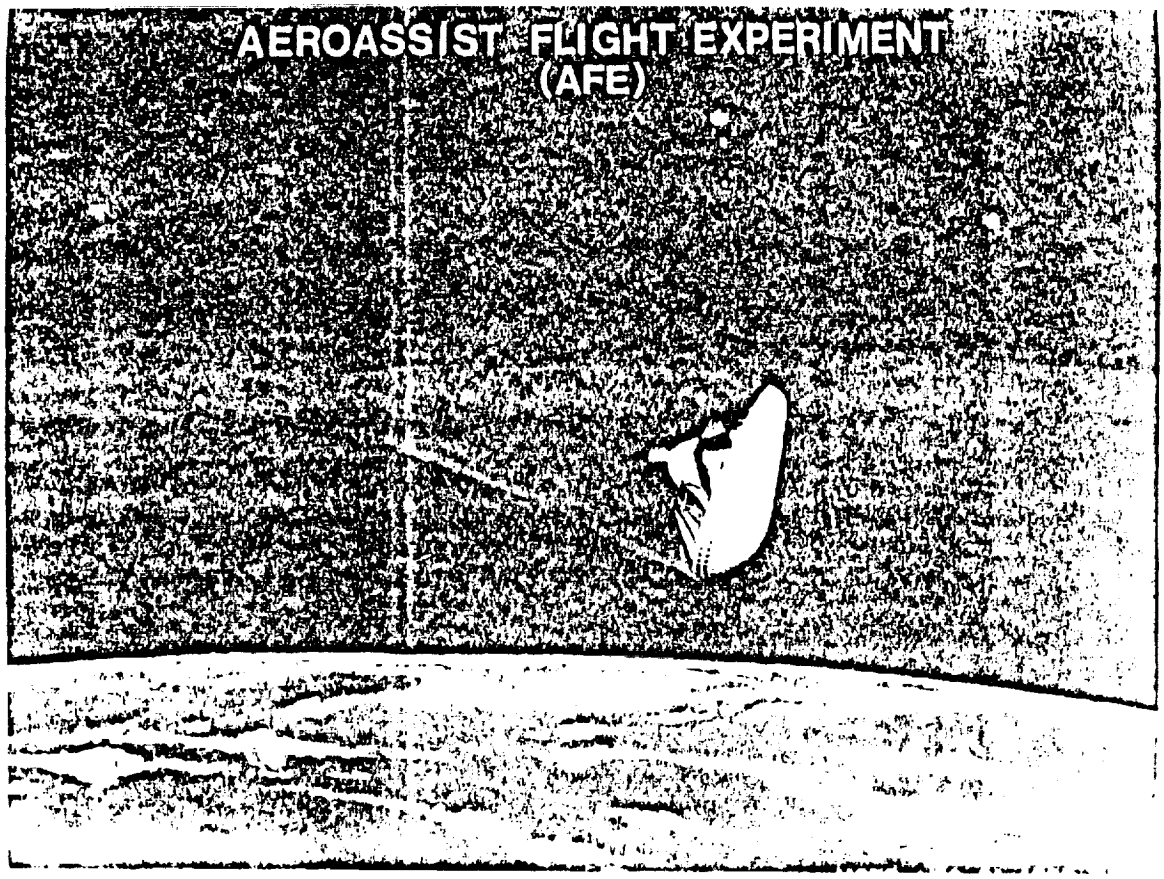
AOTV LIFT/DRAG HISTORIES

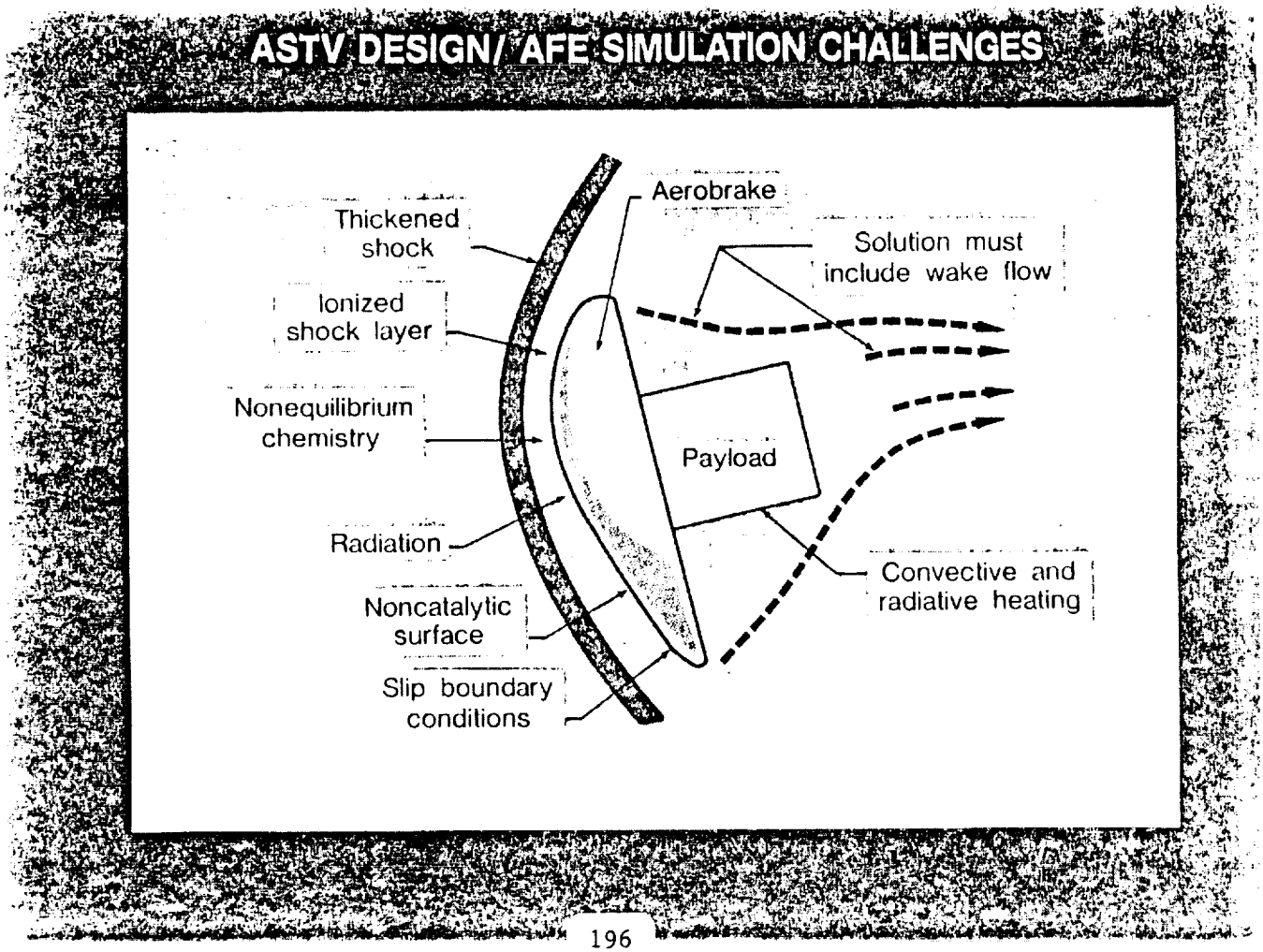


AEROASSIST FLIGHT EXPERIMENT

Objective

To investigate critical vehicle design and environmental technologies applicable to the design of aeroassisted space transfer vehicles


AEROASSIST FLIGHT EXPERIMENT
(AFE)


ASTV DESIGN/ AFE SIMULATION CHALLENGES
Aerobrake
Thickened shock
Solution must include wake flow
Ionized shock layer
Nonequilibrium chemistry
Payload
Radiation
Convective and radiative heating
Noncatalytic surface
Slip boundary conditions

AFE MISSION APPROACH

Accomplish the flight of an instrumented subscaled ASTV to obtain nonequilibrium flow-field data to:

- Resolve radiative heating issue
- Determine wall catalysis effects
- Develop/demonstrate TPS materials
- Define wake flow, base heating
- Assess aerodynamics and control
- Provide CFD code verification data

VEHICLE AND INTERPLANETERY TRAJECTORY ASSESSMENT

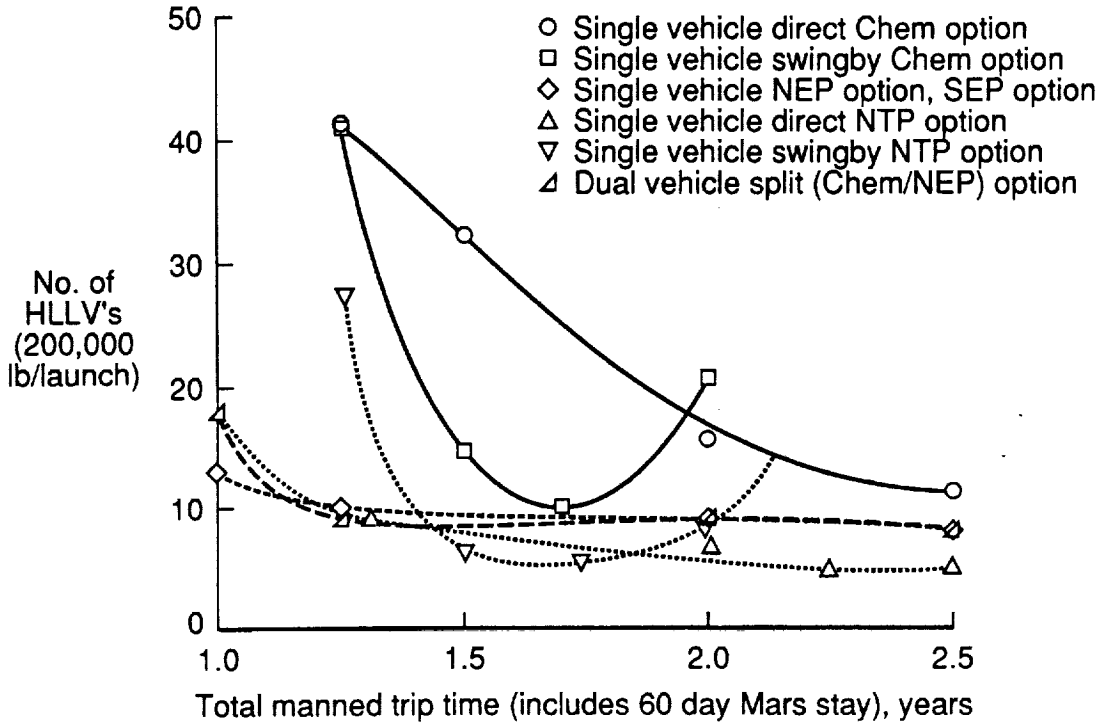
Vehicle Classes Studied

- Single vehicle chemical option (CHEM)*
- Single vehicle nuclear thermal option (NTP)*
- Single vehicle nuclear electric option (NEP)
- Single vehicle solar electric option (SEP)
- Dual vehicle split option (CHEM/NEP)*

Interplanetary Trajectory Modes Studies

- Opposition class mission
- Direct transfer
- Use of Venus swingby*

LEO WEIGHT REQUIRED FOR VARIOUS ALL PROPULSIVE MISSIONS



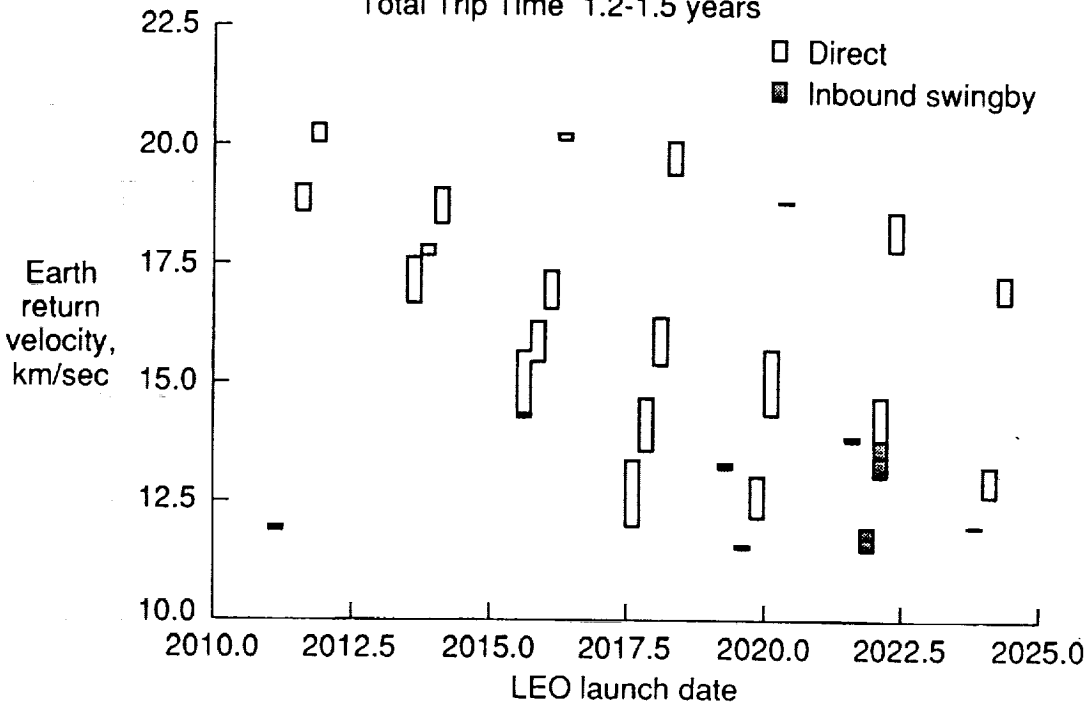
MANNED MARS MISSION STUDY

Present Investigations

- Focus on a single chemically propelled vehicle
  - 1-2 year roundtrip
  - 60 day Mars stopover
  - Trajectory includes Venus swingby
- Feasibility of high energy aerobraking at both Earth and Mars
- Venus swingby analysis investigating the effect of a propulsive maneuver at closest point of approach

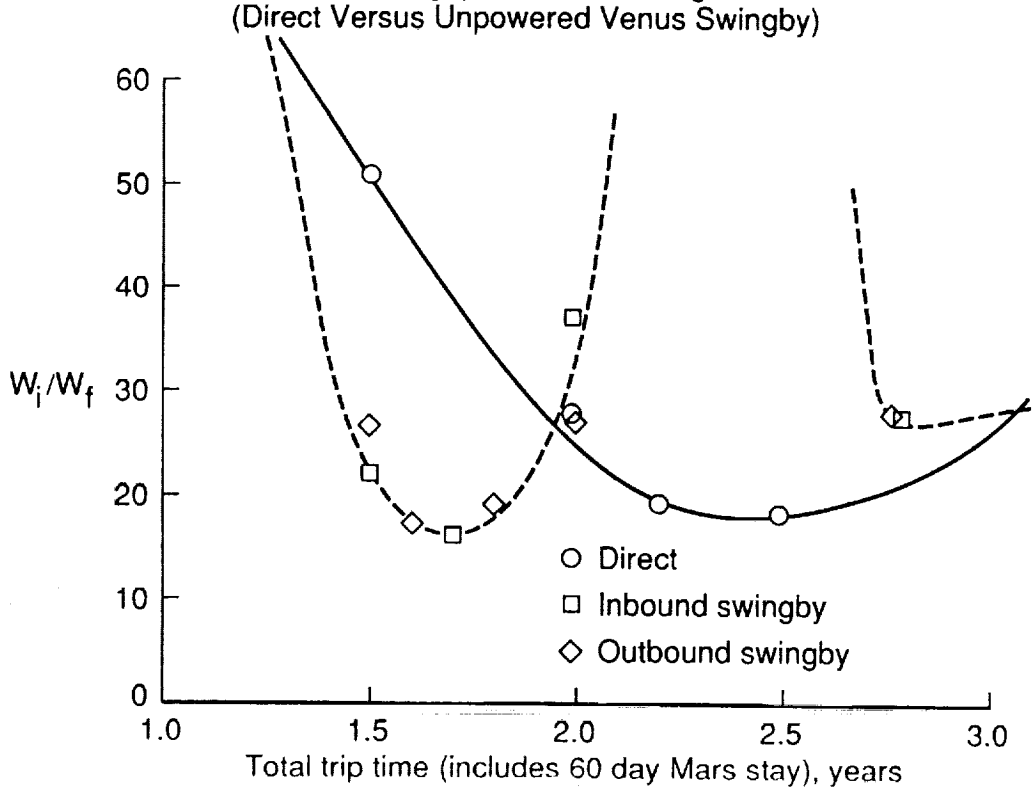
SINGLE VEHICLE CHEM OPTION

Effect of Swingby on Earth Entry Velocity
(Direct Versus Unpowered Venus Swingby)
Total Trip Time 1.2-1.5 years

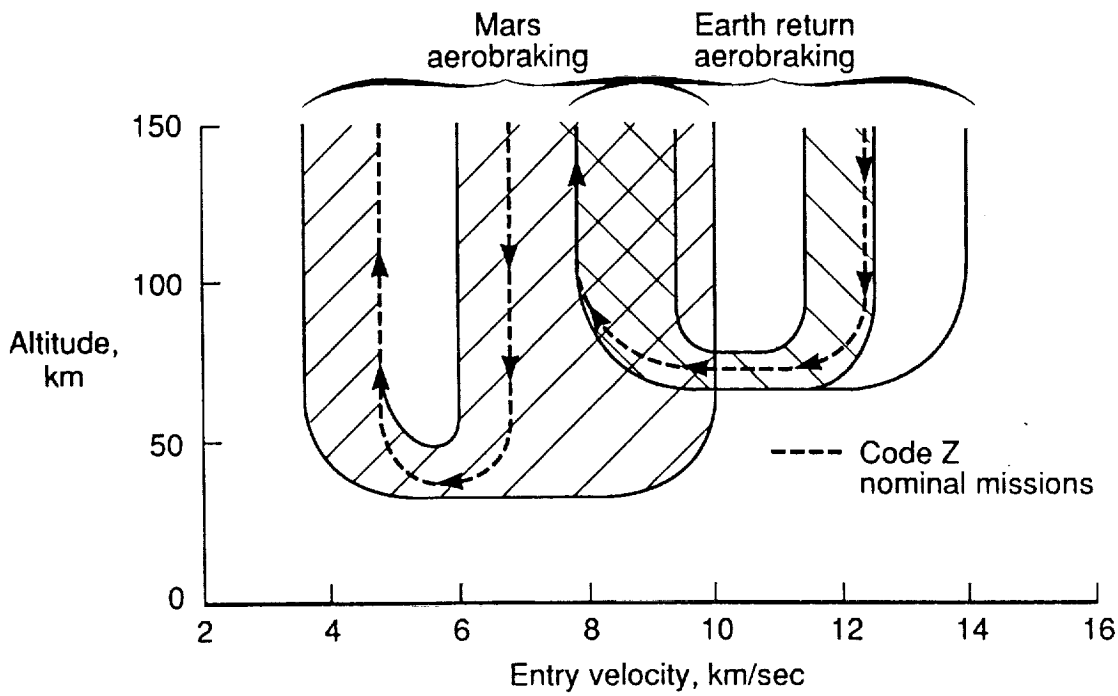


SINGLE VEHICLE CHEM OPTION

Effect of Swingby on Vehicle Weight Ratio
(Direct Versus Unpowered Venus Swingby)



FLIGHT DOMAINS UNDER CONSIDERATION IN AEROBRAKING STUDY



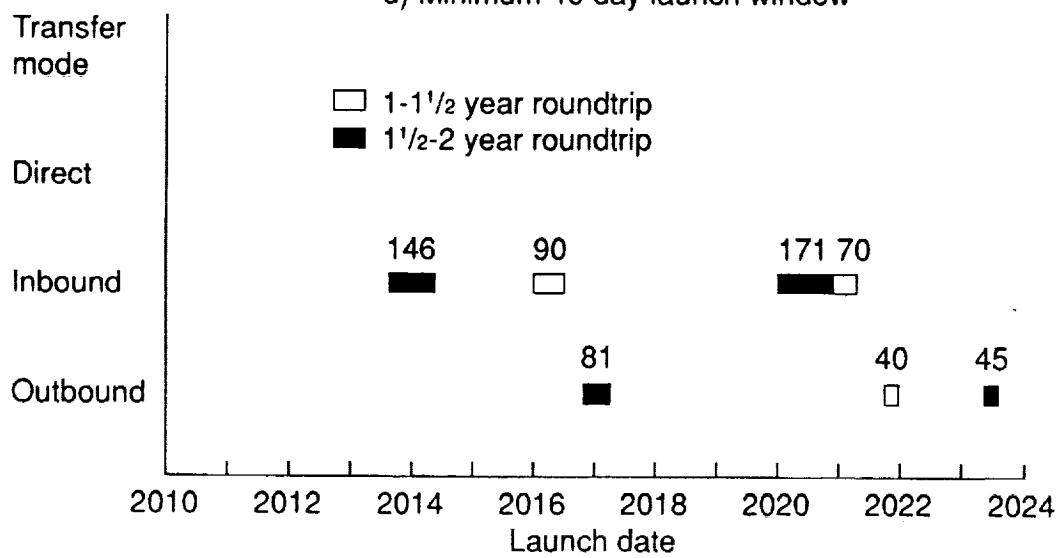
LAUNCH OPPORTUNITY DEFINITION

Constraints

- Earth entry velocity limited to 12.5 km/sec
- No restriction on Mars entry velocity
- Efficient missions from a weight standpoint
- Minimum 40 day launch opportunity
- 7 windows over 15 year period were found

LAUNCH OPPORTUNITIES

Constraints: a) Triptime 1-2 years
b) $W_i/W_f < 50$
c) Earth reentry velocity < 12.5 km/sec
d) Minimum 40 day launch window



HIGH ENERGY AEROBRAKE CONFIGURATION STUDY

- Use interplanetary data to generate conditions at atmospheric interface
- 4 configurations under study
  - Modified AFE shape, L/D = 0.28
  - Slant-nose cylinder, L/D = 0.60
  - Symmetric biconic, L/D = 1.0
  - Bent biconic, L/D = 1.5
- Include viscous aerodynamic effects
- Preliminary stagnation point heating (convective and radiative) analysis

LaRC GUIDANCE ACTIVITIES PROVIDE SYNERGISM WITH HIGH-ENERGY AEROGBRAKING PROGRAM

HEAB Objective:

Onboard autonomous optimal guidance technology to support high-energy aerobraking missions

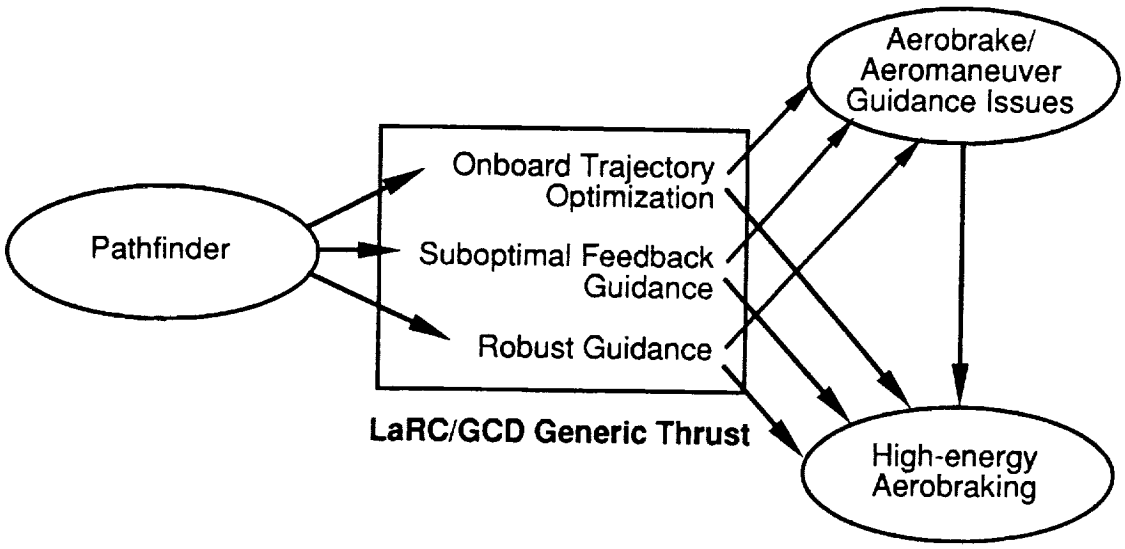
LaRC/GCD Generic Guidance Thrust:

Onboard autonomous optimal guidance technology for aeromaneuvering spacecraft

Benefits:

- Generic activities support aeromaneuver guidance technology
- Pathfinder program funds enable high-energy aerobraking focus

HIGH-ENERGY AEROBRAKING PROGRAMMATIC SYNERGISM



HIGH-ENERGY AEROBRAKING

Out of House: Two Grants

- Robust suboptimal aerobraking guidance via singular perturbation theory
- Parallel sequential quadratic programming for online optimal control of aerobraking trajectories

In-House:

- GN&C system studies for manned Mars mission; preliminary bank angle control for entry
- Aerobraking applications primary focus for in-house guidance research

HIGH ENERGY AEROBRAKING – CURRENT STATUS

- Two grants have been initiated:
  1. Robust suboptimal guidance with Georgia Tech is underway
  2. Parallel sequential quadratic programming for optimal trajectories with Cornell will begin about February 1989
- Preliminary system studies of Mars entries for vehicles typical of 6 to 10 person manned mission have shown:
  1. Variable bank angles implying an active guidance/control system are required for capture
  2. A capture entry flight path angle window of greater then 1 degree is possible for a typical manned Mars mission vehicle when bank angle is variable

EXPECTED RESULTS FROM HEAB STUDIES

Systems Studies

- Identify areas of manned Mars missions critical to GN&C design
- Establish error bounds to be used as targets for GN&C design

Grant Studies

- Develop techniques for real-time, adaptive GN&C
- Apply study results to develop near optimal HEAB GN&C techniques that can operate autonomously in real-time

SUMMARY

- LaRC has experience in design of aerobraking vehicles
- Interplanetary trajectory analysis complete for various propulsion systems
- Configuration analysis initiated for candidate vehicles (L/D range from 0.3 ot 1.5)
- Guidance algorithm design initiated

CURRENT STATUS/PLANS

- Improved LaRC analysis capability of planetary vehicles
- Completed initial assessment of planetary mission options
- Defined range of conditions for Earth and Mars entry interface
- Initiated high energy aerobrake concept definition activity

LANGLEY COMPUTATIONAL AND EXPERIMENTAL PROGRAMS

Kenneth Sutton
Space Systems Division
Langley Research Center

Presented To

High Energy Aerobraking Workshop
Ames Research Center
January 31 - February 2, 1989

PAST AND CURRENT RESEARCH APPLICABLE TO HIGH ENERGY AEROBRAKING

- o Apollo, Fire, 50 K Entry
- o Viking
- o Pioneer Venus Probes
- o Galileo Probe
- o SO2P - Titan Aerobrake, Bent Biconic Configuration
- o Shuttle Flight Data
- o AOTV, AFE
  Air Radiation Revisited

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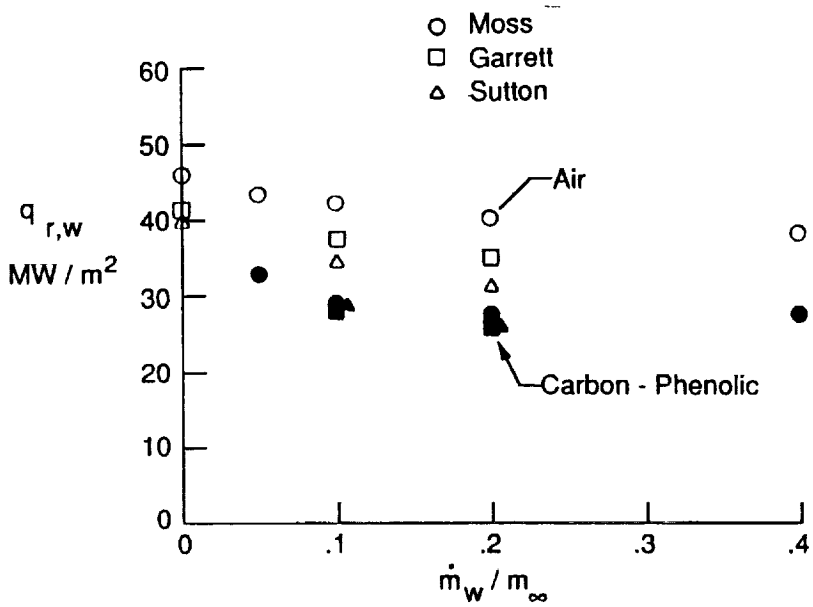
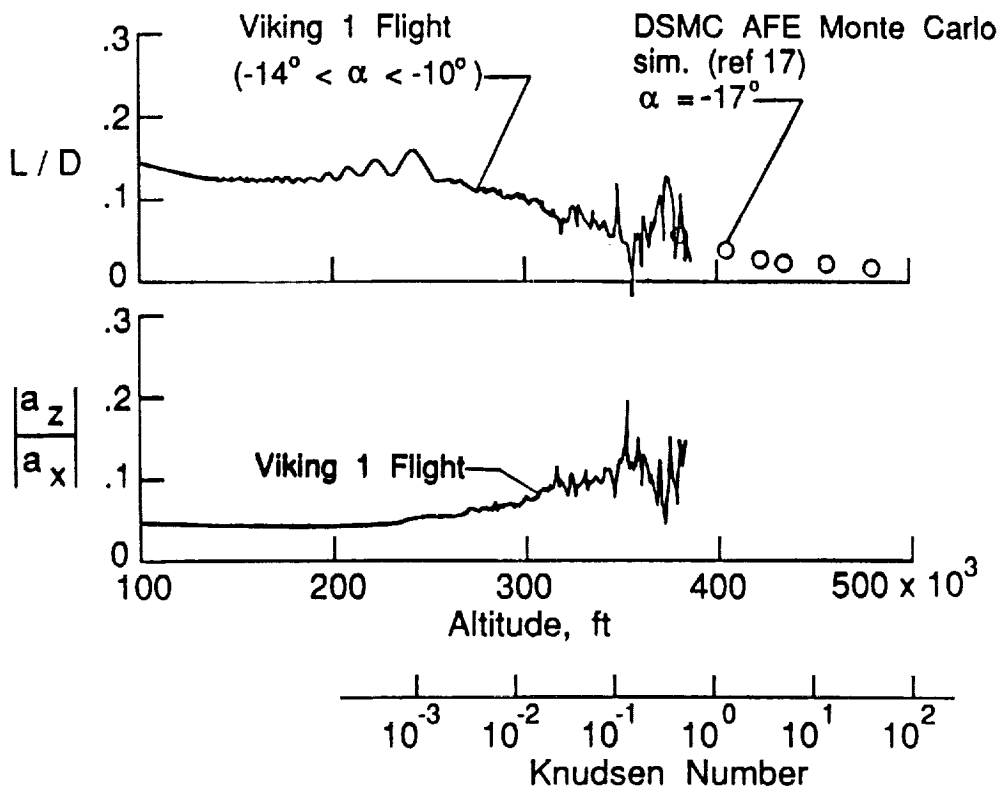
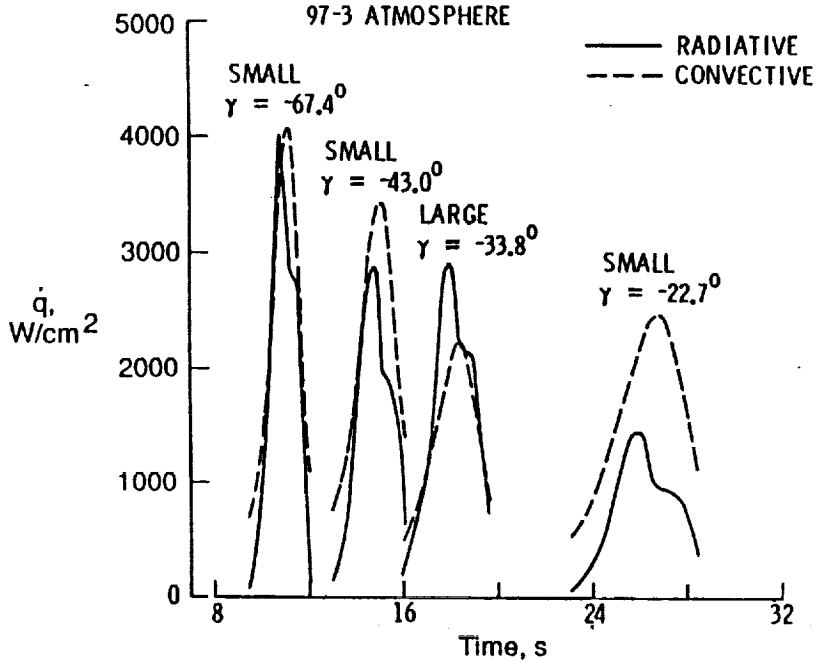
AIR STAGNATION - POINT RADIATION WITH MASS INJECTION

V_∞ = 15.25 km / s R_n = 3.05 m Z = 61 km

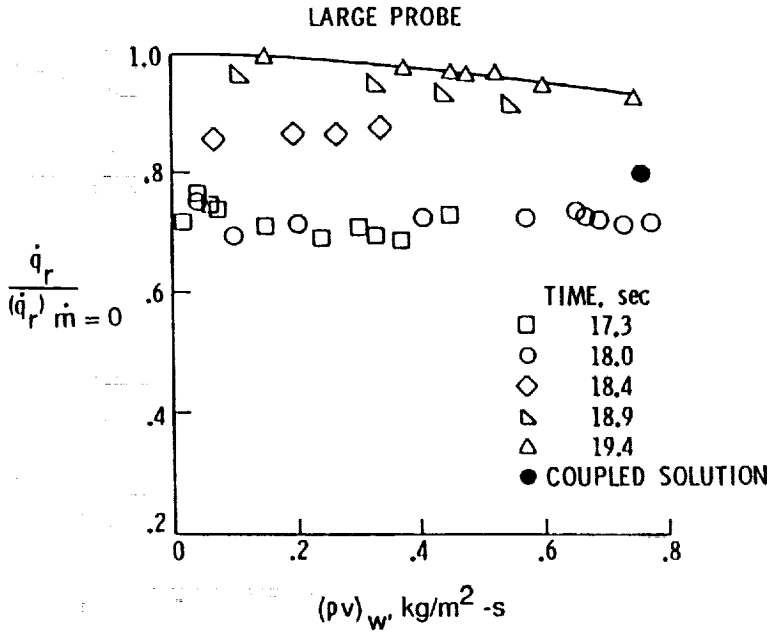




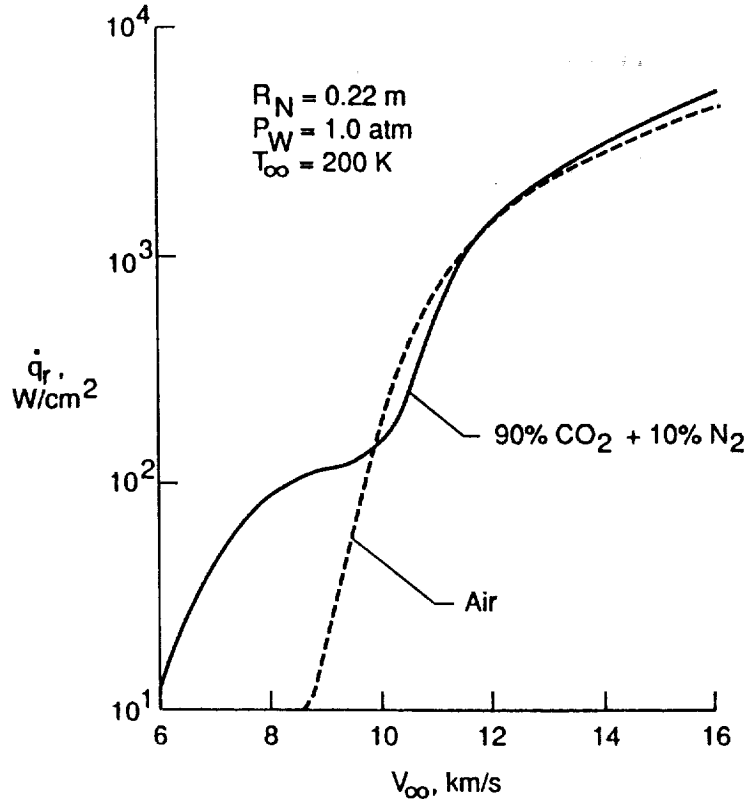
HEATING RATES FOR PIONEER VENUS PROBES



RADIATIVE BLOCKAGE BY ABLATION PRODUCTS PIONEER VENUS

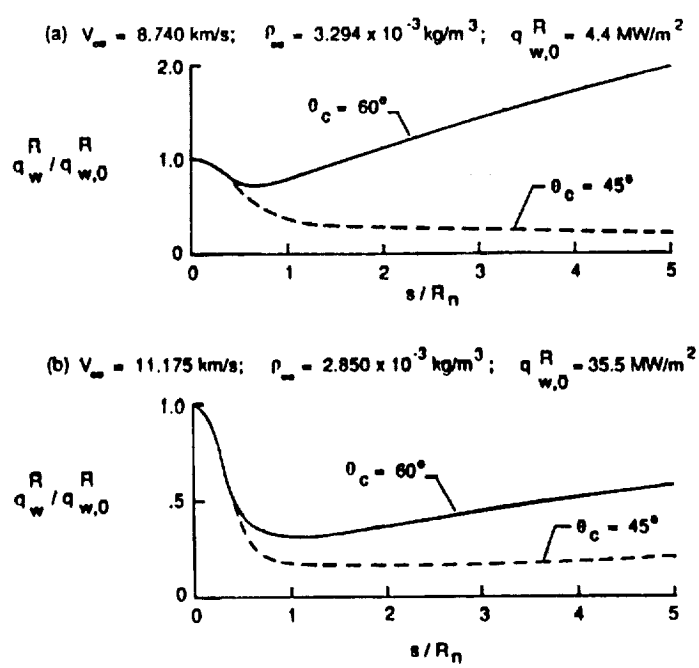


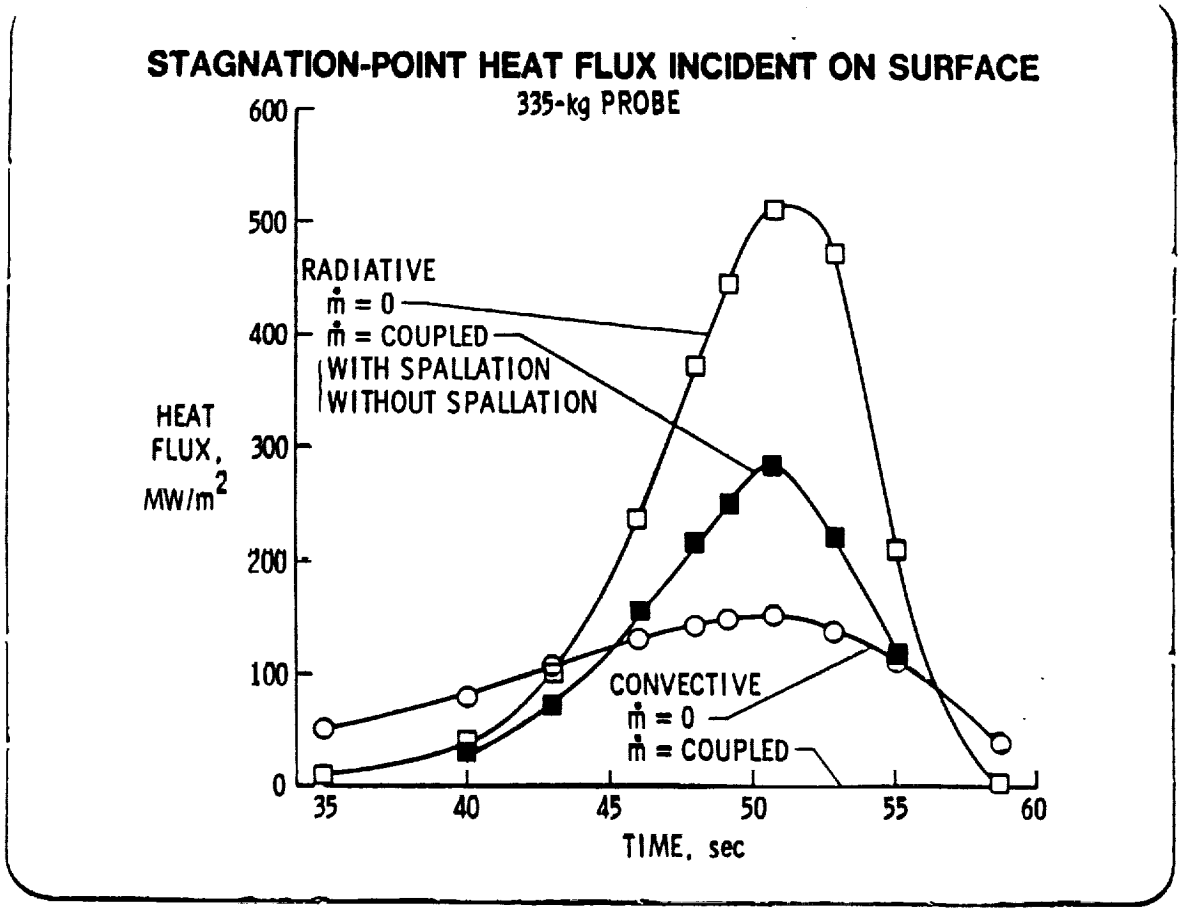
STAGNATION-POINT RADIATIVE HEATING RATES IN $CO_2 + N_2$ AND AIR

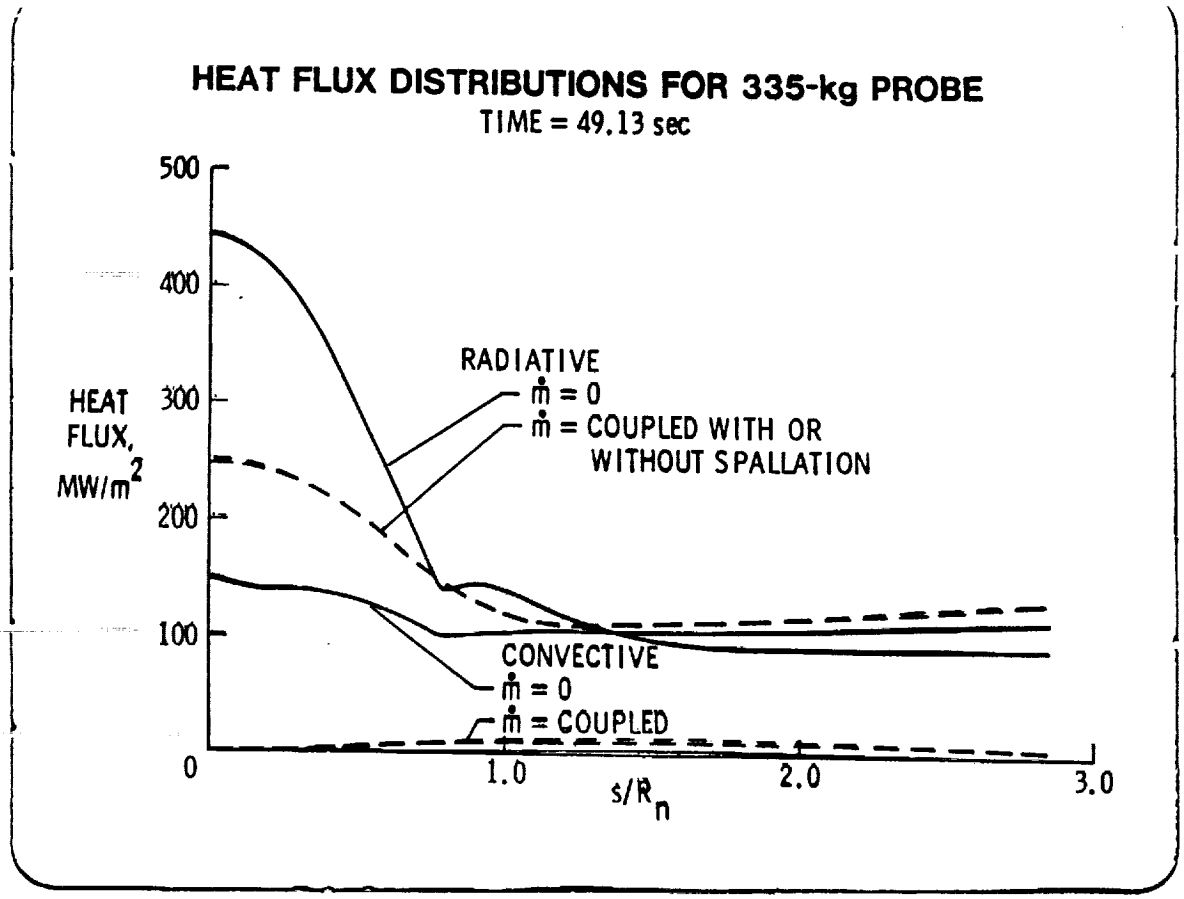


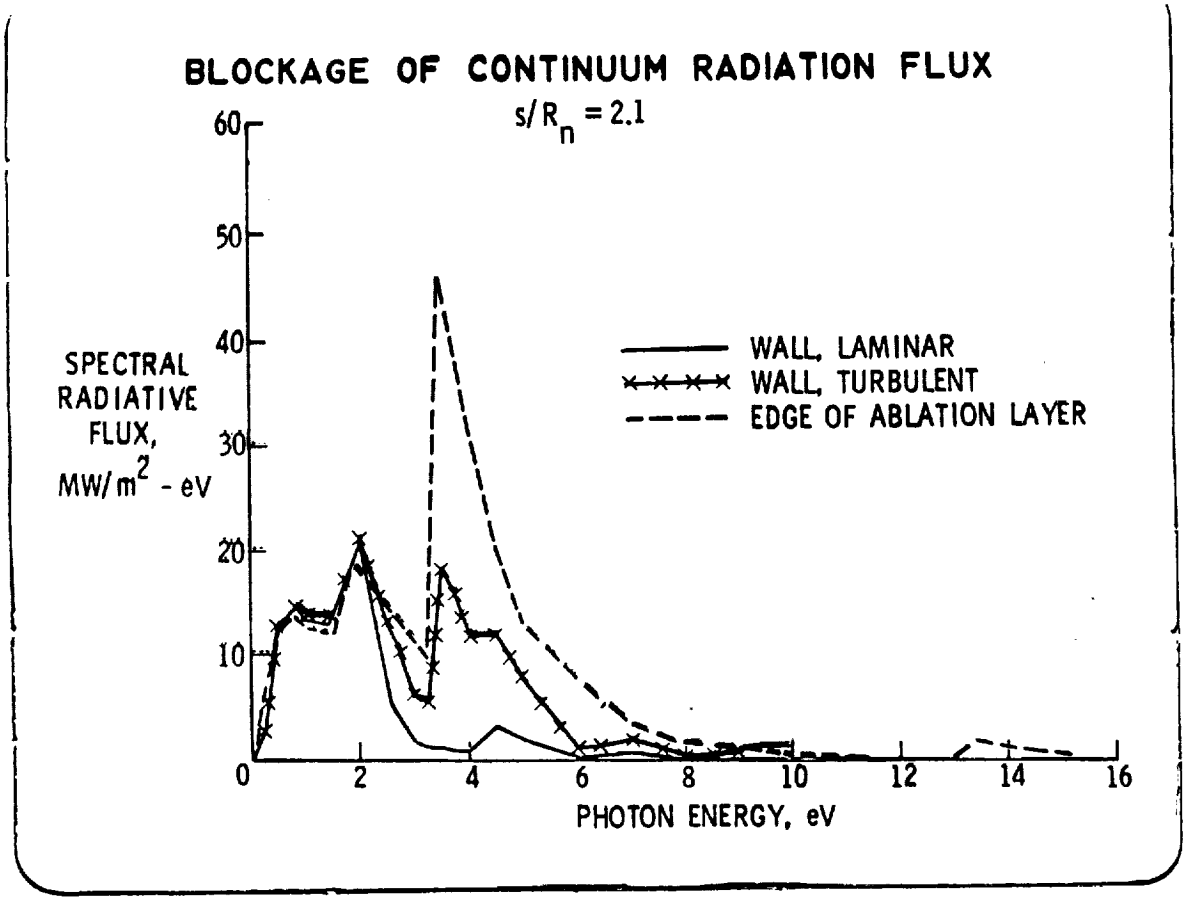
VENUS ENTRY

RADIATION OVER SPHERE - CONES, R_n = 30 CM

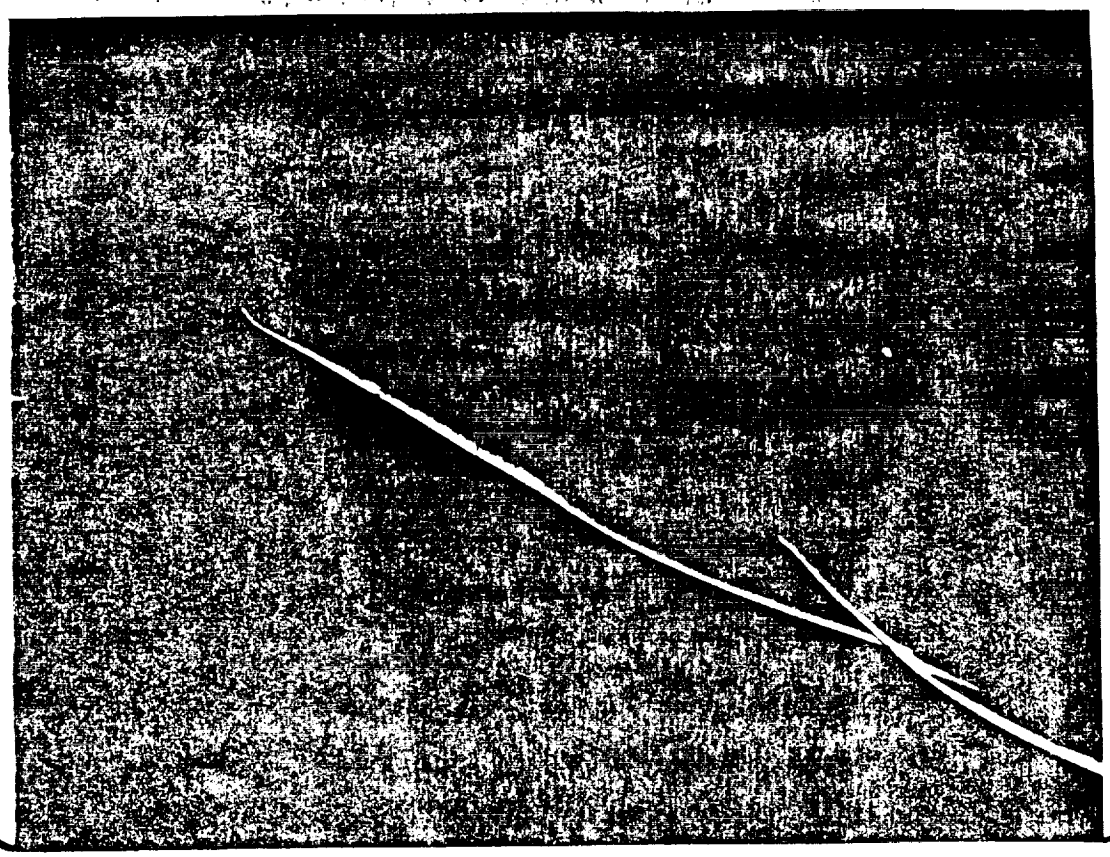



STAGNATION-POINT HEAT FLUX INCIDENT ON SURFACE
335-kg PROBE
HEAT FLUX, MW/m2
600
500
400
300
200
100
0
RADIATIVE
ṁ = 0
ṁ = COUPLED
WITH SPALLATION
WITHOUT SPALLATION
CONVECTIVE
ṁ = 0
ṁ = COUPLED
35
40
45
50
55
60
TIME, sec


HEAT FLUX DISTRIBUTIONS FOR 335-kg PROBE
TIME = 49.13 sec
HEAT FLUX, MW/m2
500
400
300
200
100
0
RADIATIVE
ṁ = 0
ṁ = COUPLED WITH OR WITHOUT SPALLATION
CONVECTIVE
ṁ = 0
ṁ = COUPLED
1.0
2.0
3.0
s/Rn

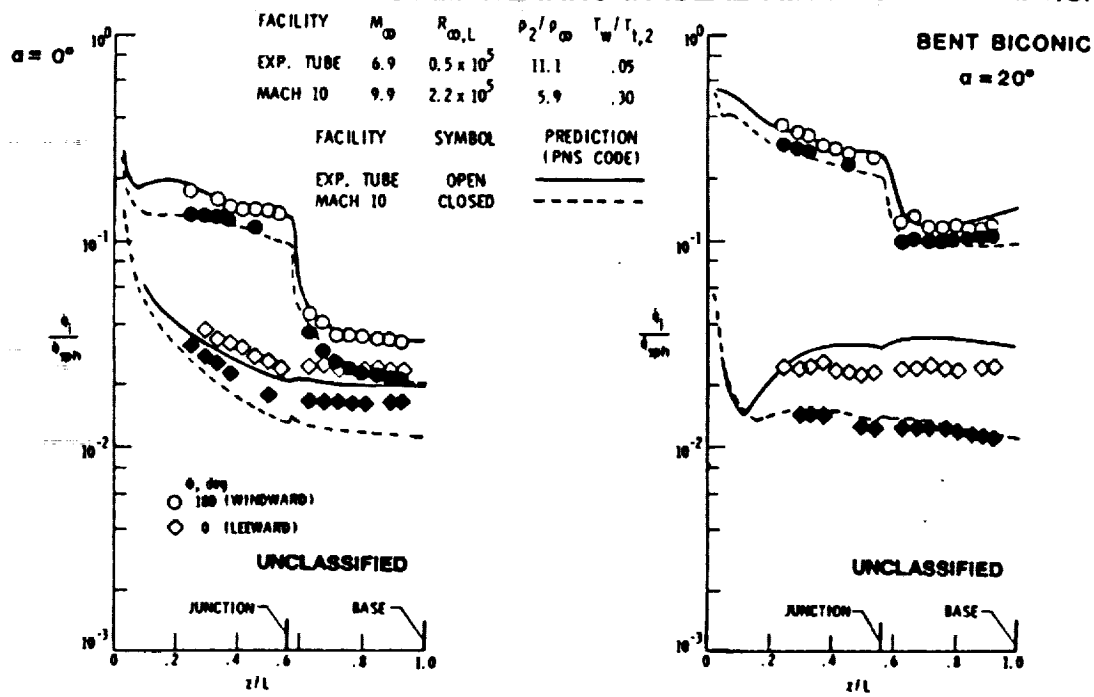


SCHLIEREN OF BENT BICONIC AT MACH 6 IN AIR



UNCLASSIFIED

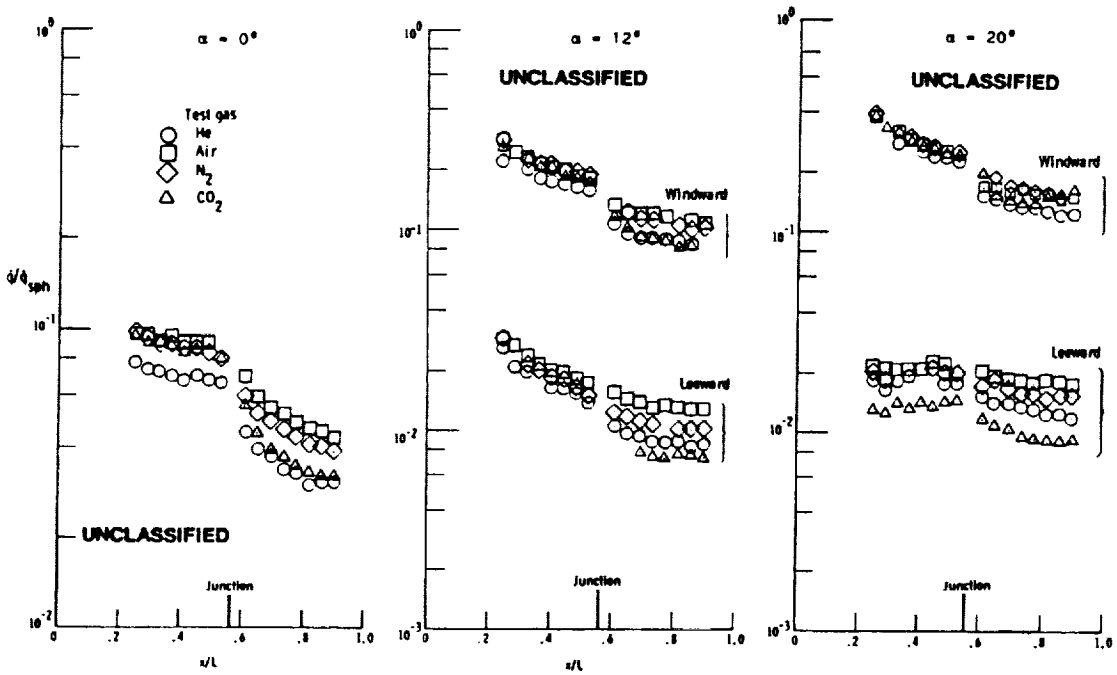
MEASURED AND PREDICTED HEATING IN IDEAL AIR AND REAL AIR(U)



UNCLASSIFIED

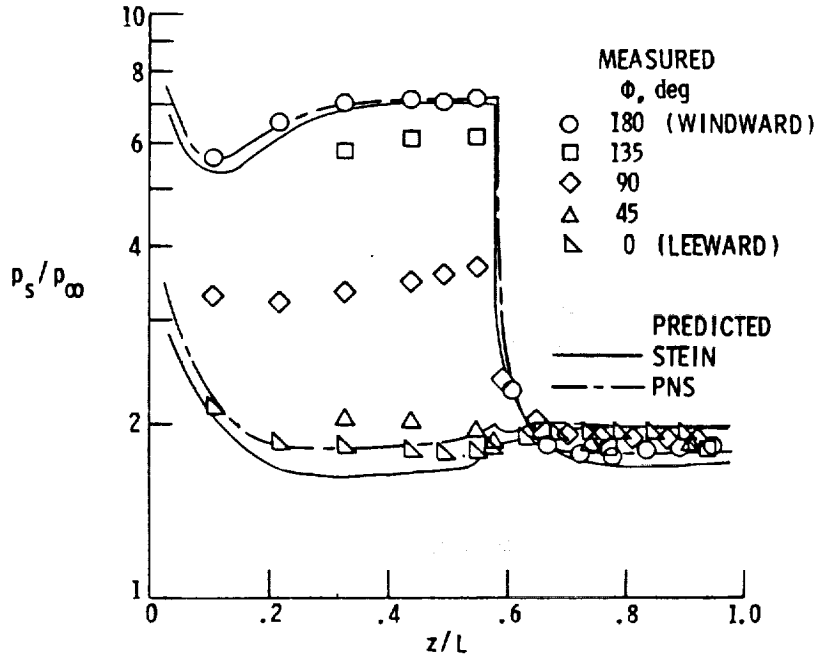
UNCLASSIFIED

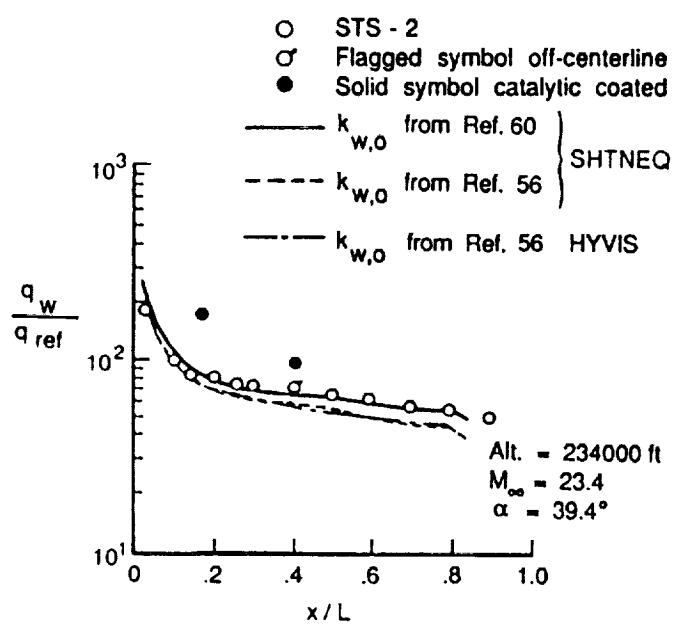
HEATING DISTRIBUTIONS FOR STRAIGHT BICONIC IN PRESENT TEST GASES(U)



UNCLASSIFIED

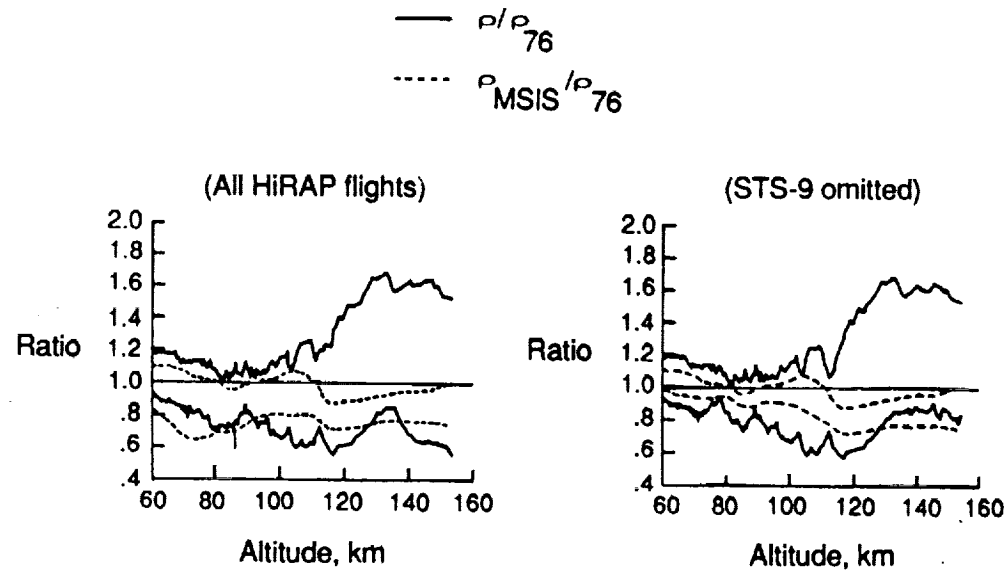
LONGITUDINAL PRESSURE DISTRIBUTION FOR BENT BICONIC; $\alpha = 0°$





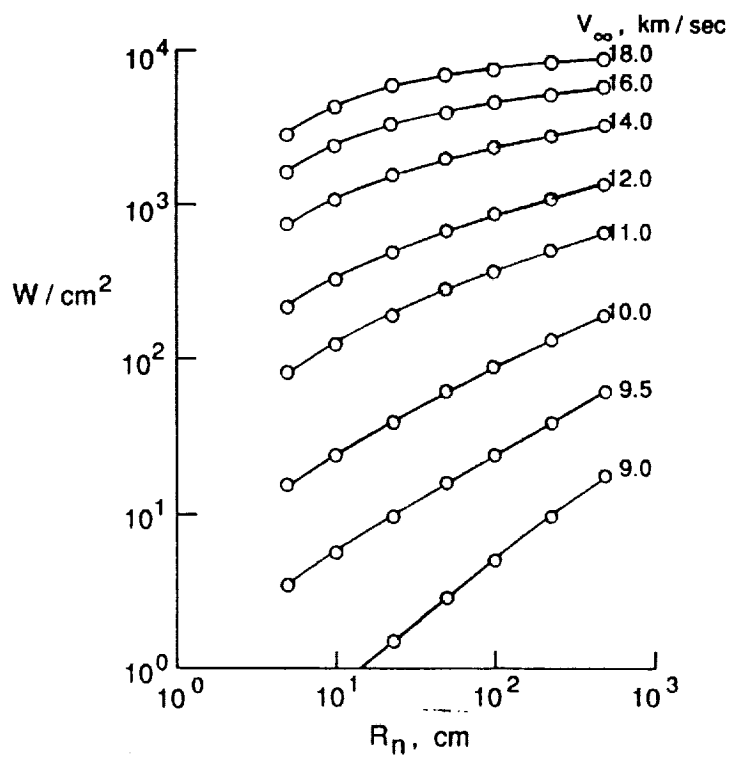
NONEQUILIBRIUM CENTERLINE HEATING

ENVELOPE OF MAXIMUM AND MINIMUM DENSITY RATIOS



AIR RADIATIVE HEATING RATES

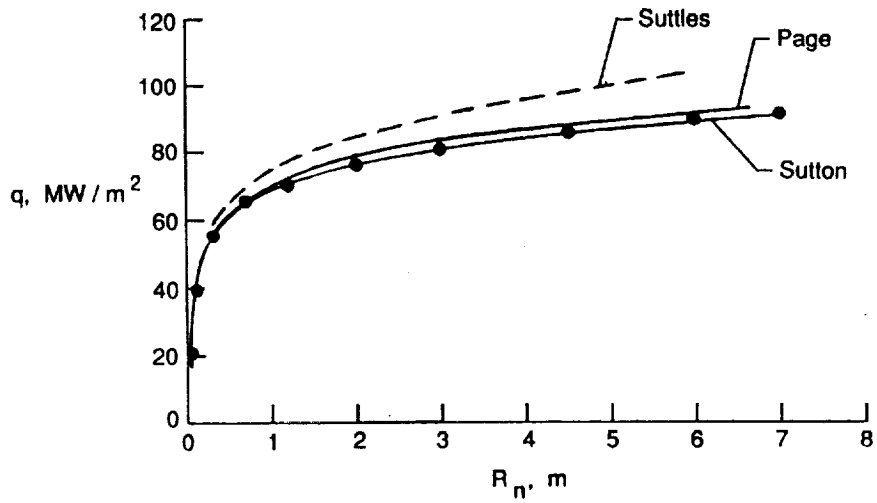
Z = 61 km $\rho_\infty = 3.06 \times 10^{-4}$ kg / m^3



AIR RADIATION

V_∞ = 16 km / s

ρ_∞ = 4.224 x 10^{-4} kg / m^3

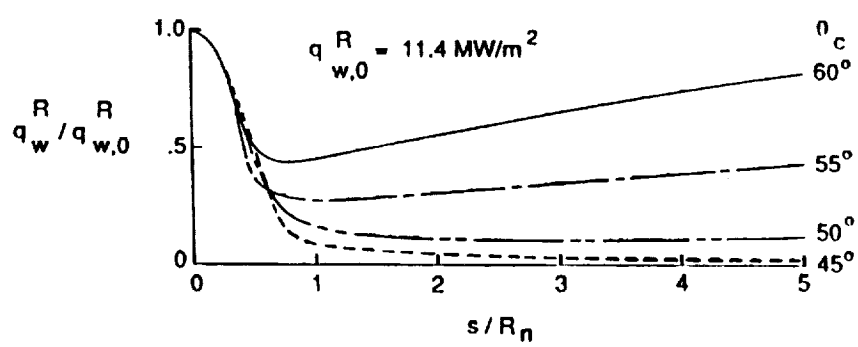


AIR RADIATION OVER SPHERE - CONES

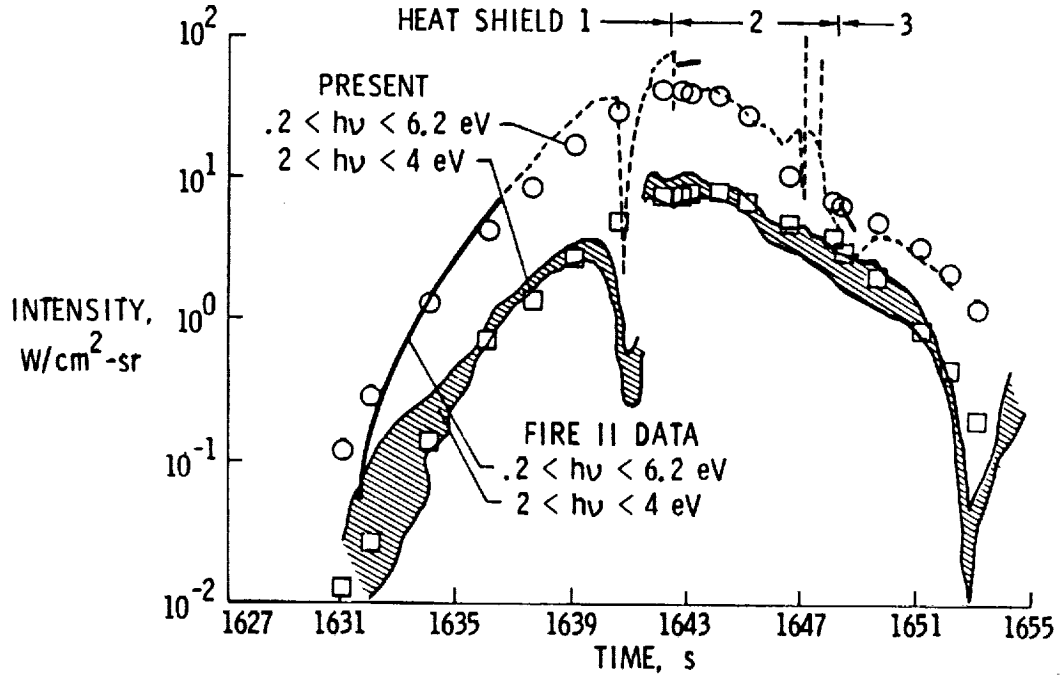
V_∞ = 12.20 km/s

ρ_∞ = 2.744 x 10^{-4} kg/m^3

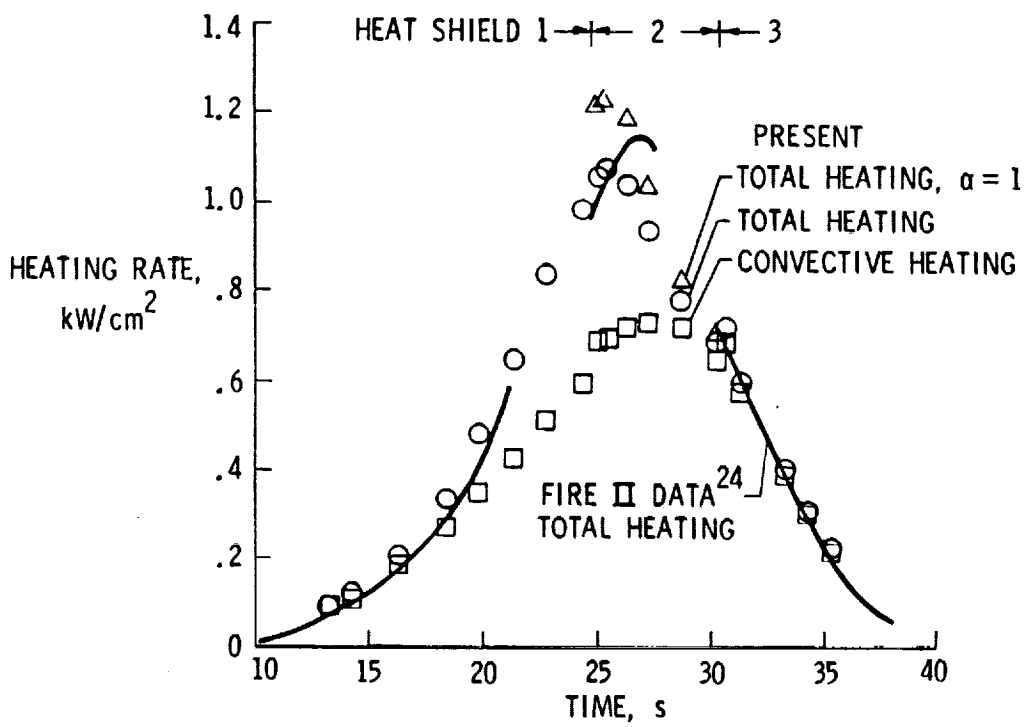
R_n = 2.00 m



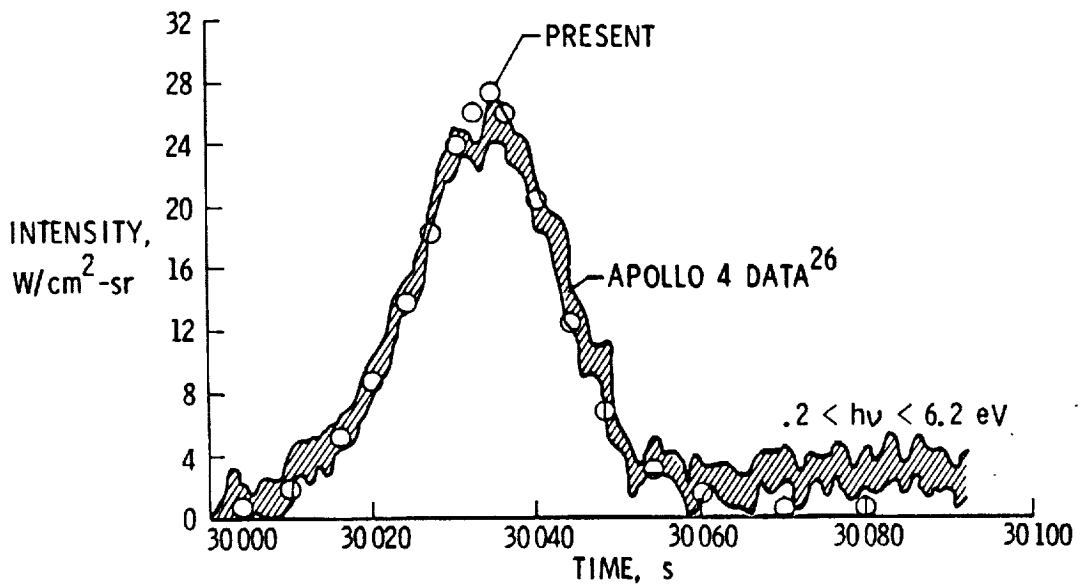
RADIATION DATA FROM FIRE II



TOTAL HEATING DATA FROM FIRE II



RADIATION DATA FROM APOLLO 4



PROGRAM LAURA
LANGLEY AEROTHERMODYNAMIC UPWIND RELAXATION ALGORITHM

- PHYSICS

  3 - Dimensional Navier - Stokes Equations

  Steady Or Unsteady Flow

  Laminar (Turbulent Boundary Layer)

  Chemical Nonequilibrium (11 Species, 2 Chemical Kinetic Models, Air)

  Thermal Nonequilibrium (Two - Temperature Model)

  Documented In NASA TP 2867

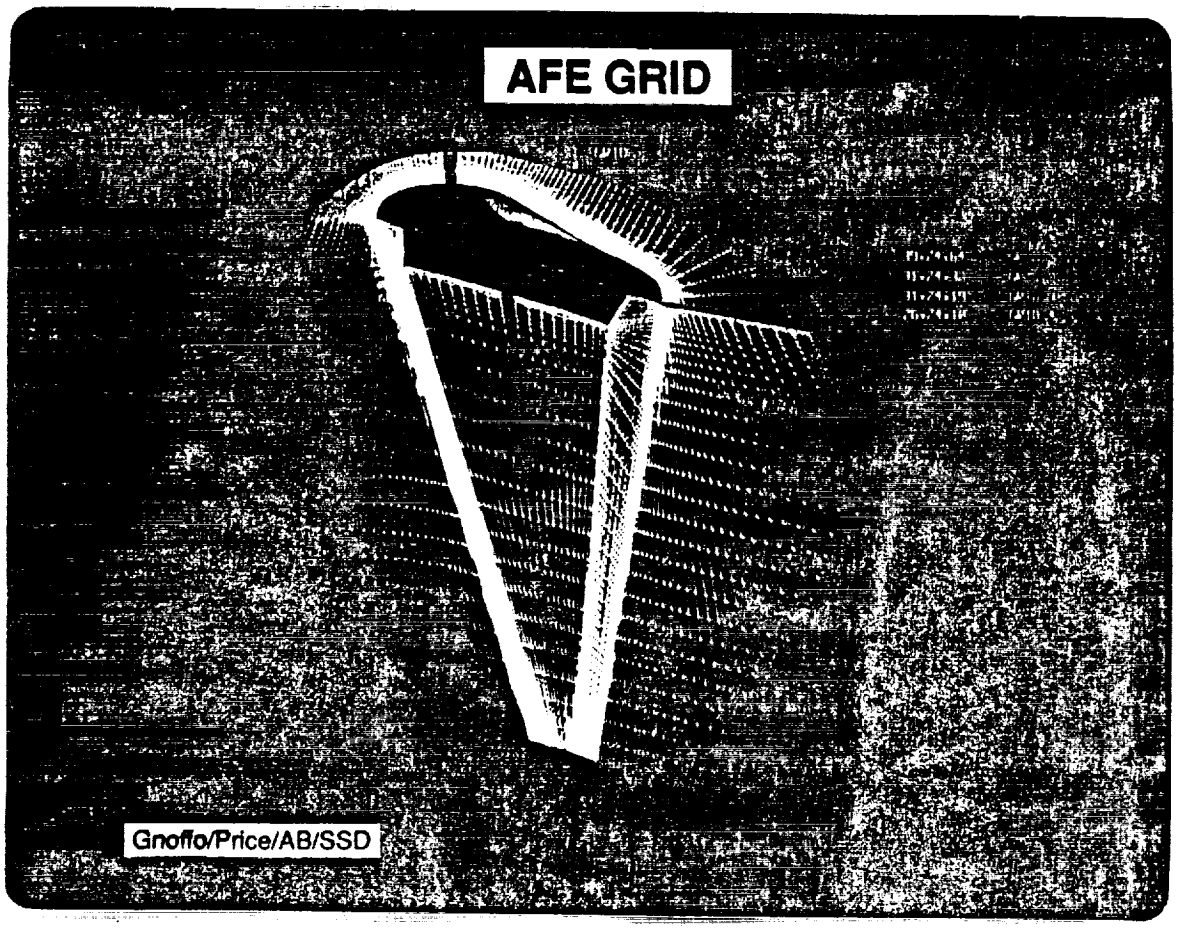
- NUMERICS

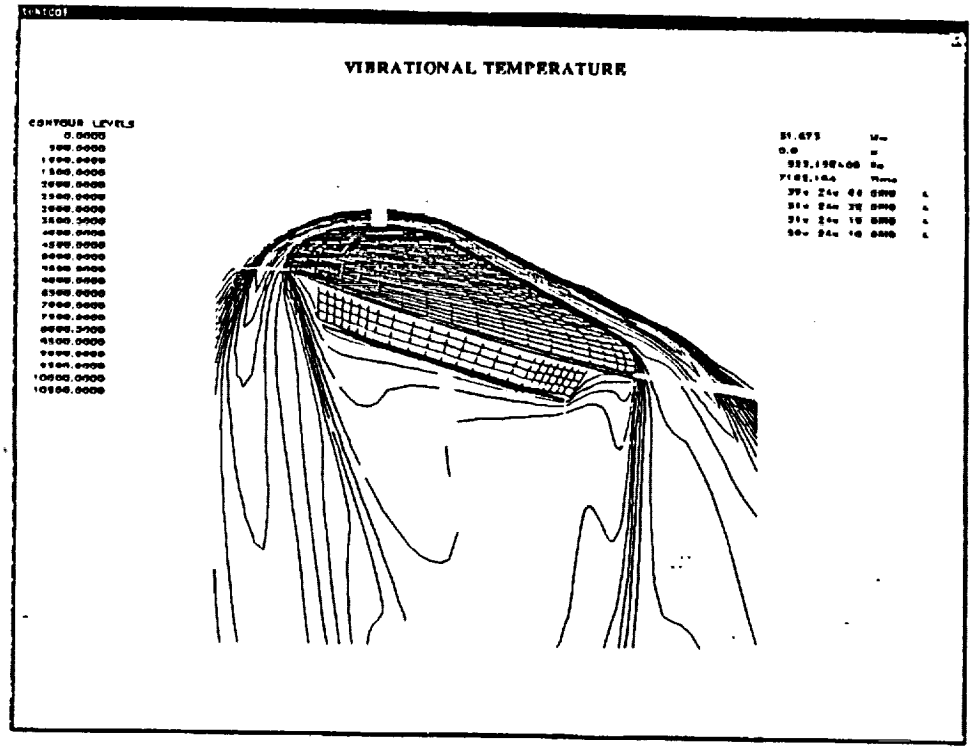
  Finite Volume, Roe's Averaging, STVD Limiters

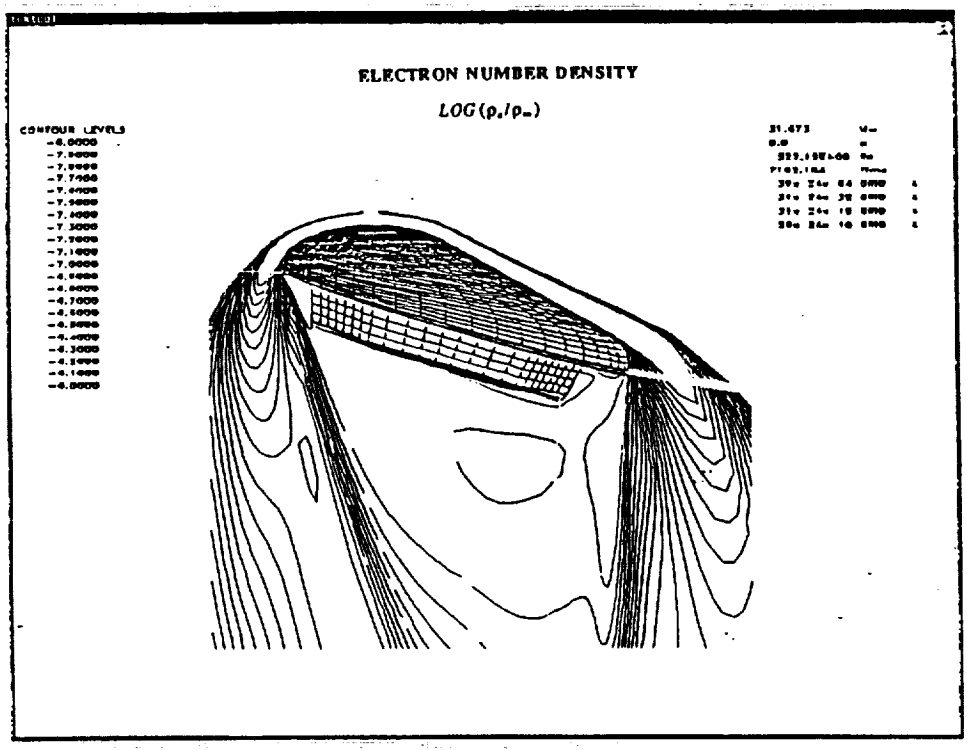
  Fluid Mechanics And Chemistry Strongly Coupled

  Point Implicit Relaxation, Freeze Inverse Jacobian

  Ideally Suited For Parrallel, Asynchronous Iteration Using Unstructured Grids


AFE GRID
Gnoffo/Price/AB/SSD

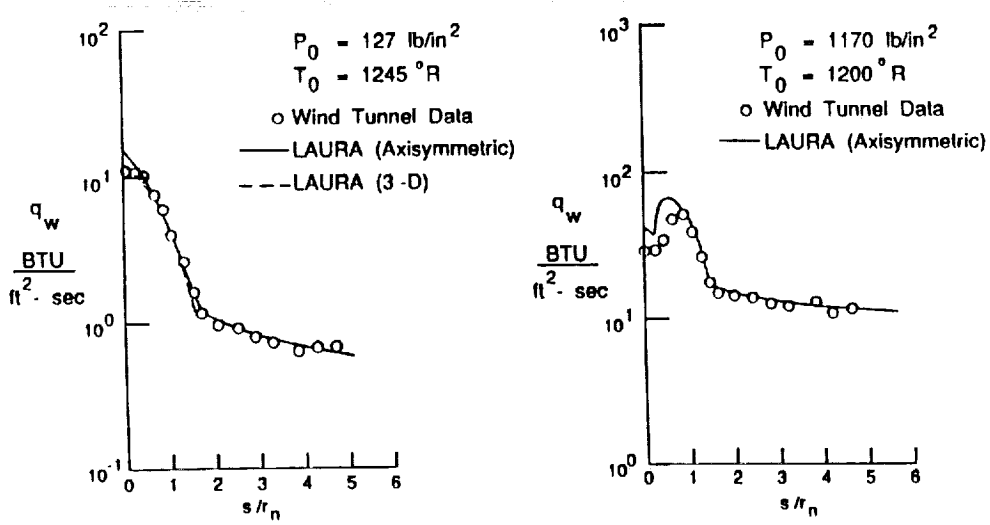

VIBRATIONAL TEMPERATURE
CONTOUR LEVELS



HEAT TRANSFER PREDICTIONS WITH THE LAURA CODE

8° Sphere - Cone

r_n = 2.5 in. M = 5 α = 0°

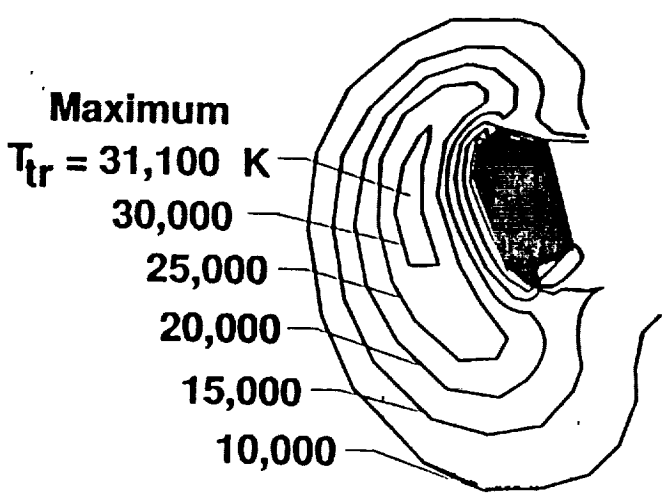


DIRECT SIMULATION MONTE CARLO (DSMC) METHOD

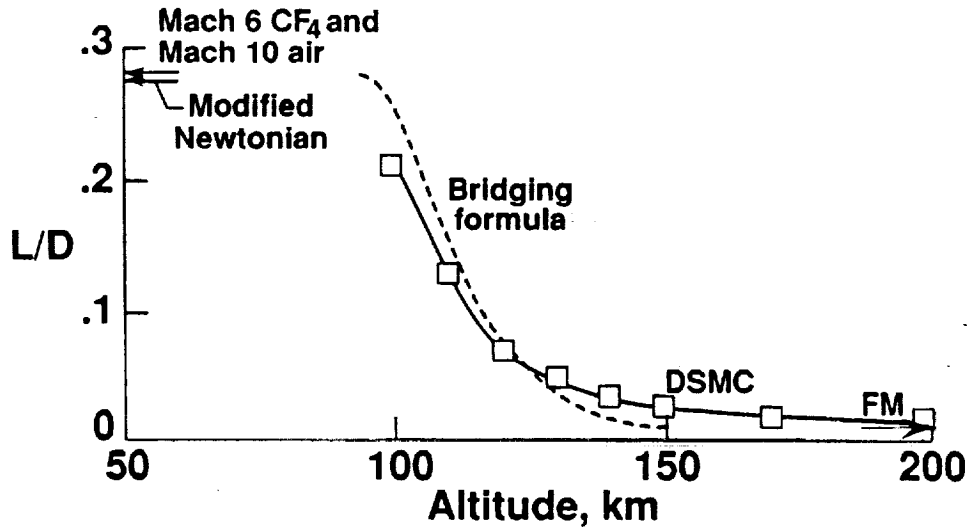
- Each Simulated Molecule Represents A Large Number Of Real Molecules
- Position Coordinates And Velocity Components Stored In The Computer
- Molecules Followed Simultaneously Through Representative Intermolecular Collisions And Boundary Interactions
- Multicomponent Flow
- 3 - Dimensional Flow
- Thermodynamic And Chemical Nonequilibrium
- Radiation
- Steady Or Unsteady Flow
- Arbitrary Boundary Conditions Easily Implemented

TRANSLATIONAL TEMPERATURE CONTOURS FOR AFE FLOWFIELD

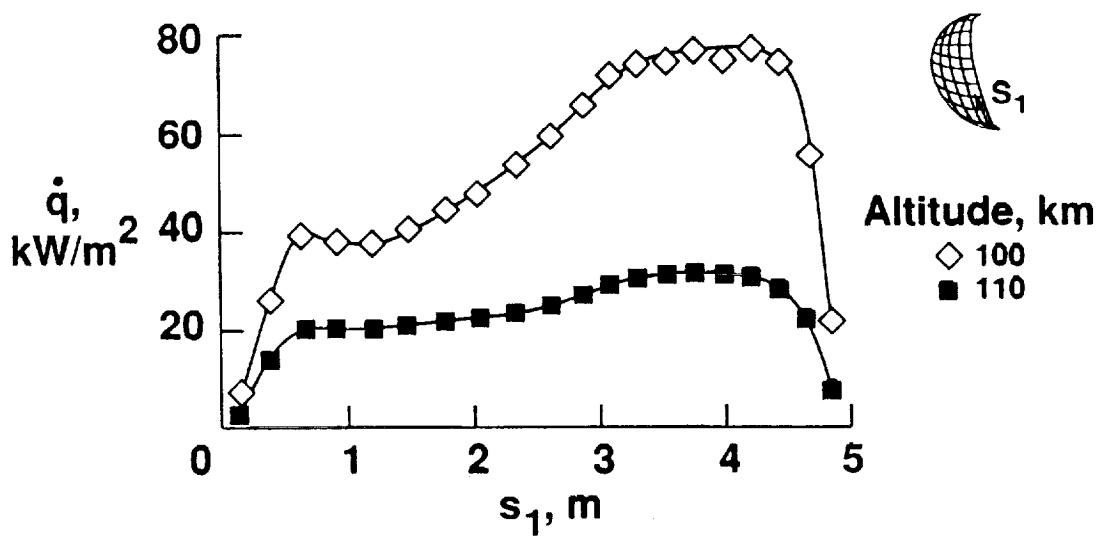
Alt = 120 km



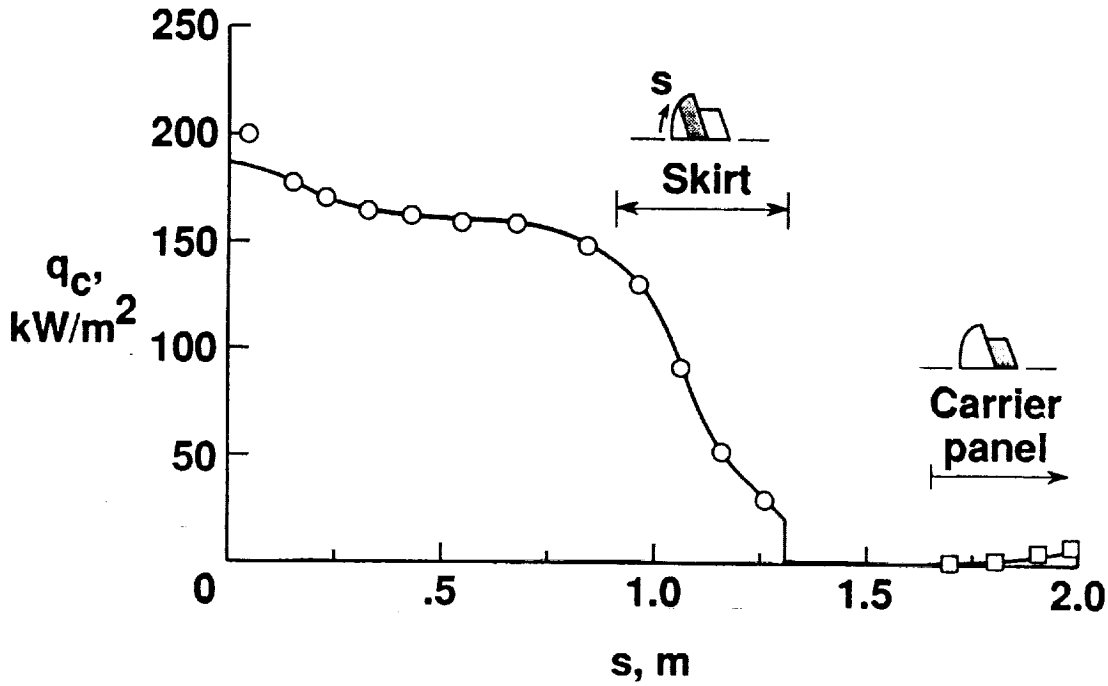
L/D VARIATION



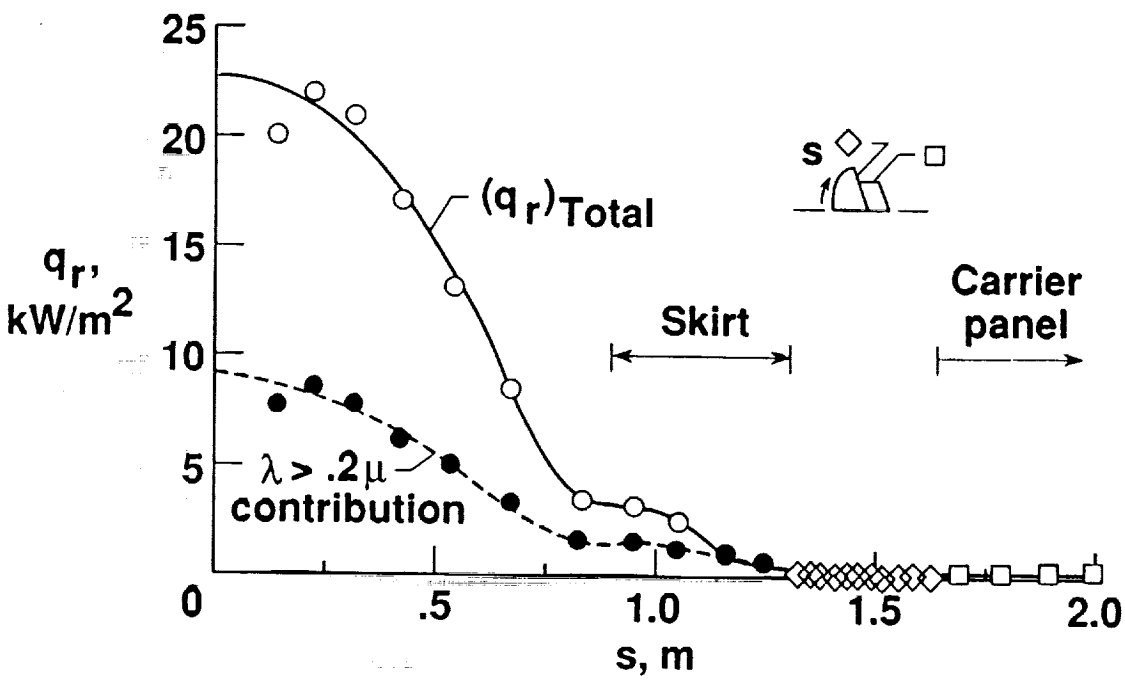
SURFACE HEAT TRANSFER RATE DISTRIBUTIONS



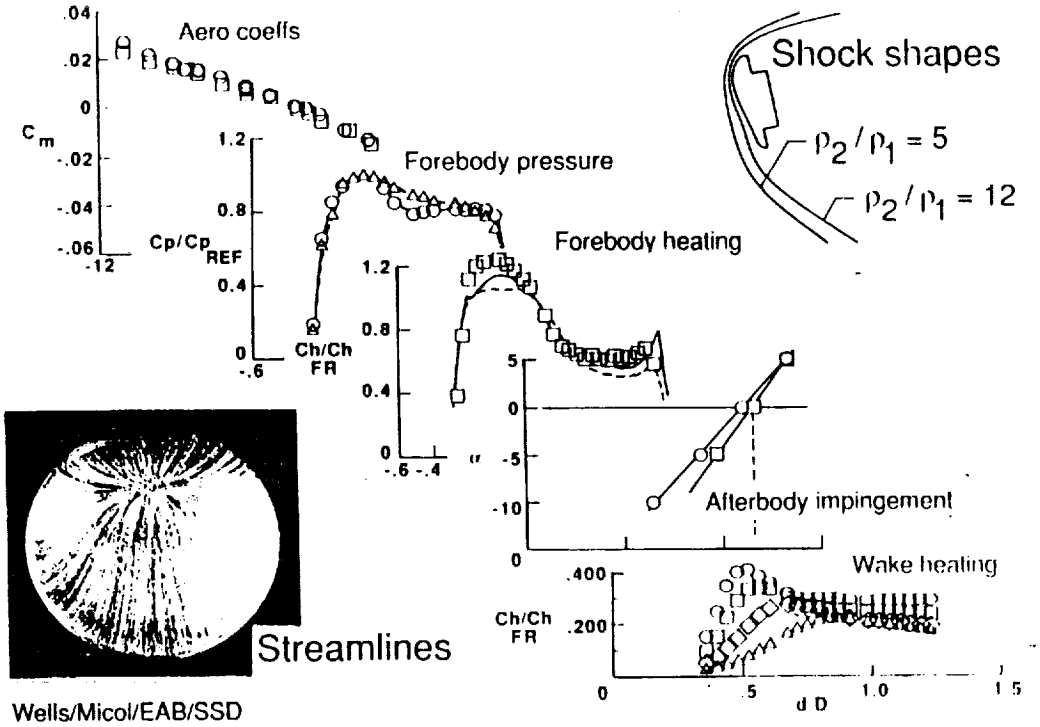
CONVECTIVE HEATING DISTRIBUTION
AFE Aerobrake and carrier panel



RADIATIVE HEATING DISTRIBUTION

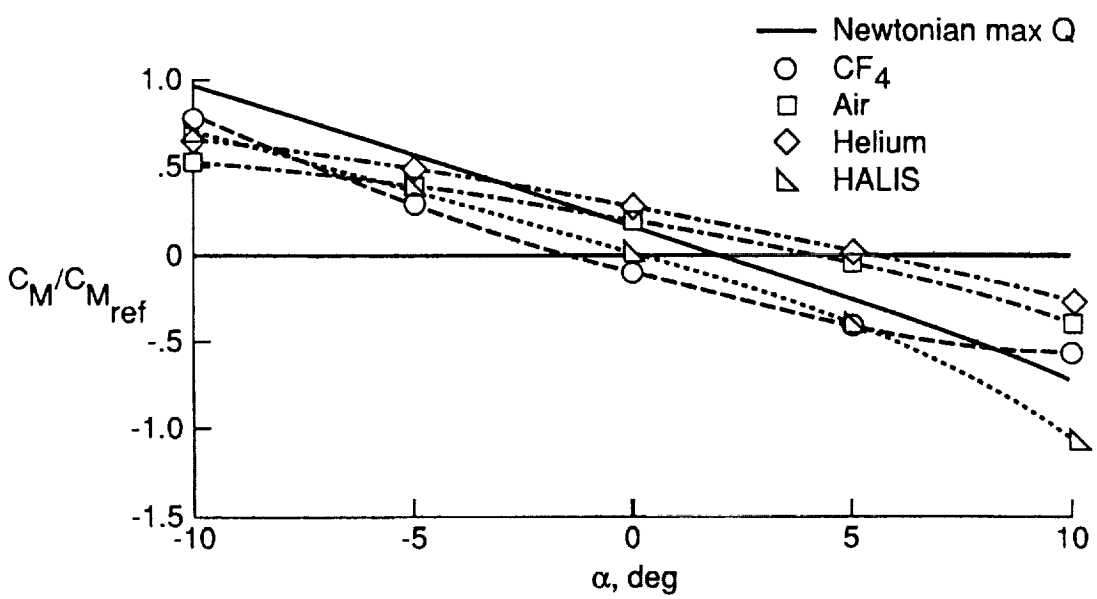


AFE EXPERIMENTAL DATA BASE



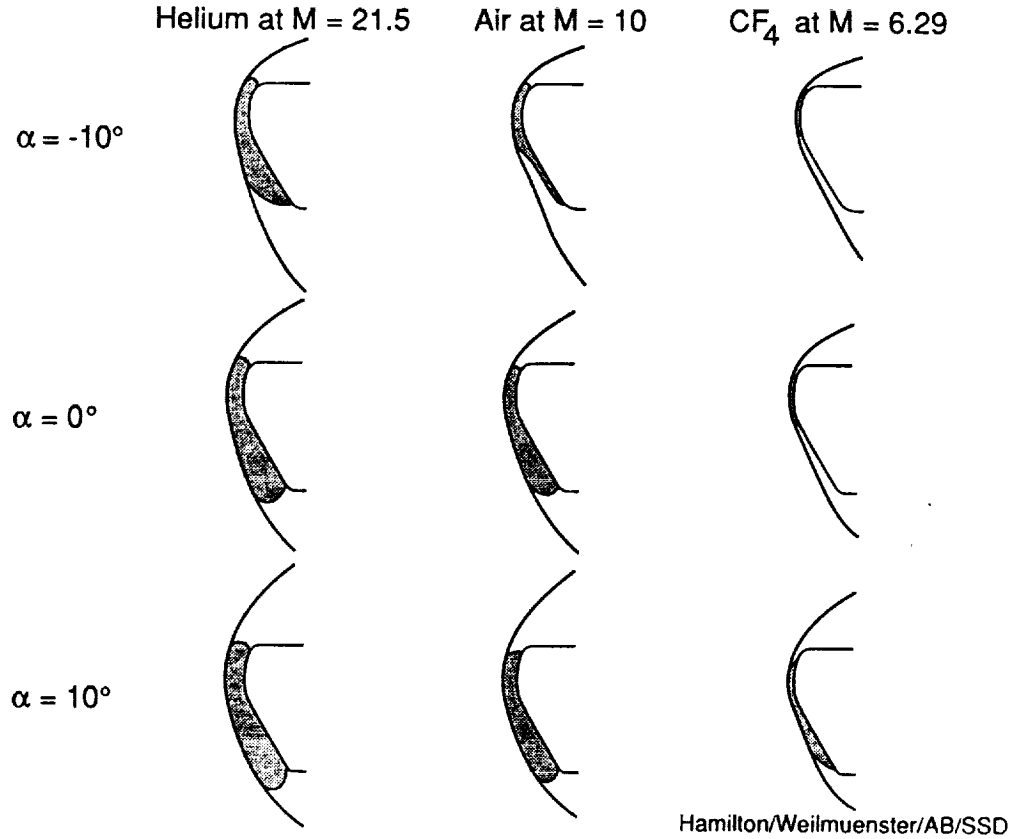
Wells/Micol/EAB/SSD

COMPARISON OF COMPUTED FLIGHT POINT PITCHING MOMENT WITH COMPUTED TUNNEL RESULTS



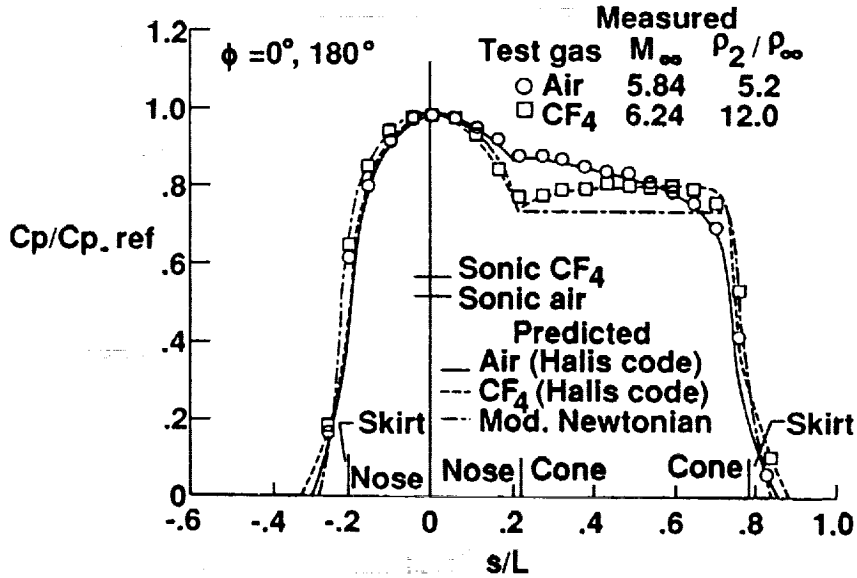
Hamilton/Weilmuenster/AB/SSD

SHOCK SHAPES AND SHOCK LAYER SONIC REGION IN THE AFE SYMMETRY PLANE



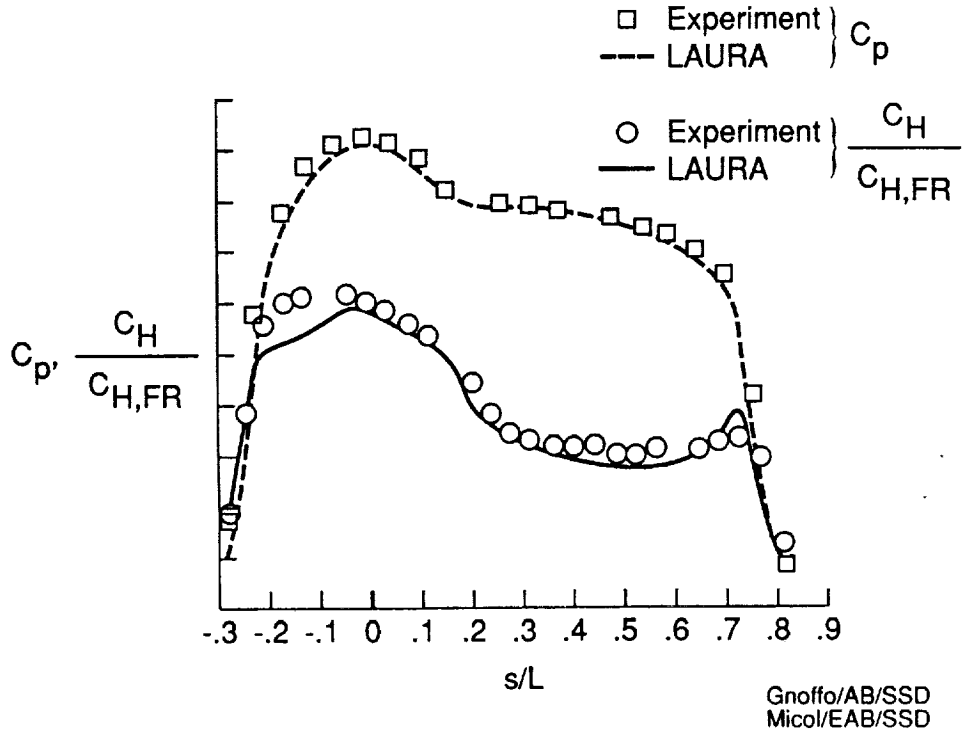
EFFECT OF DENSITY RATIO ON PRESSURE DISTRIBUTIONS

Mach = 6 $\alpha=0°$ $Re_\infty = 0.5\times10^6$/ft



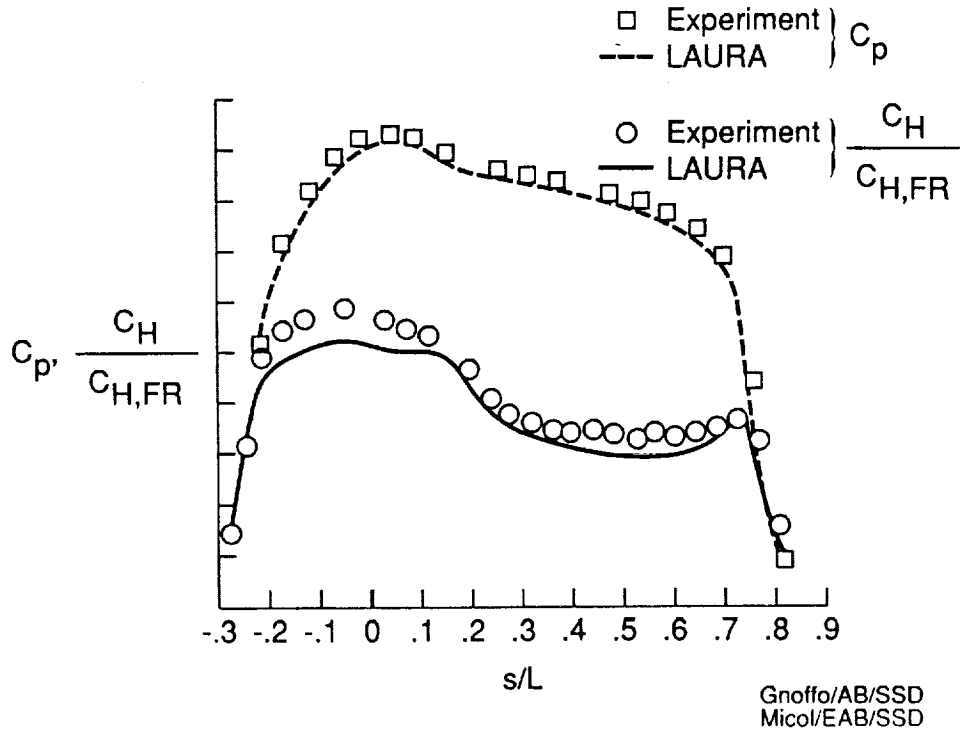
PRESSURE AND HEATING DISTRIBUTION FOR AFE

Mach 10 $\alpha = 0°$



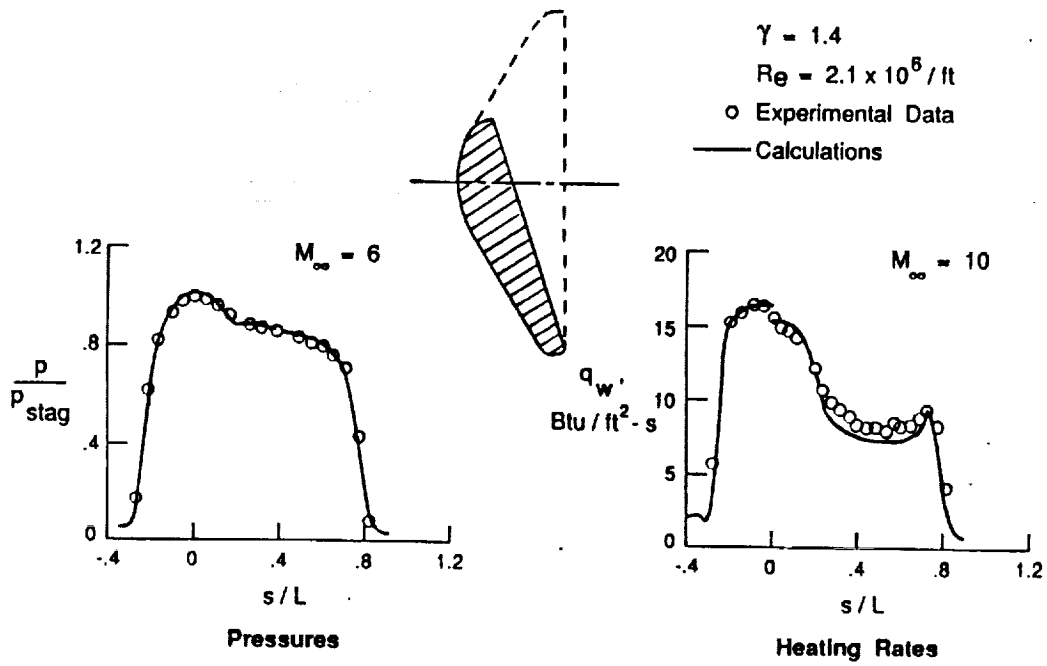
PRESSURE AND HEATING DISTRIBUTION FOR AFE

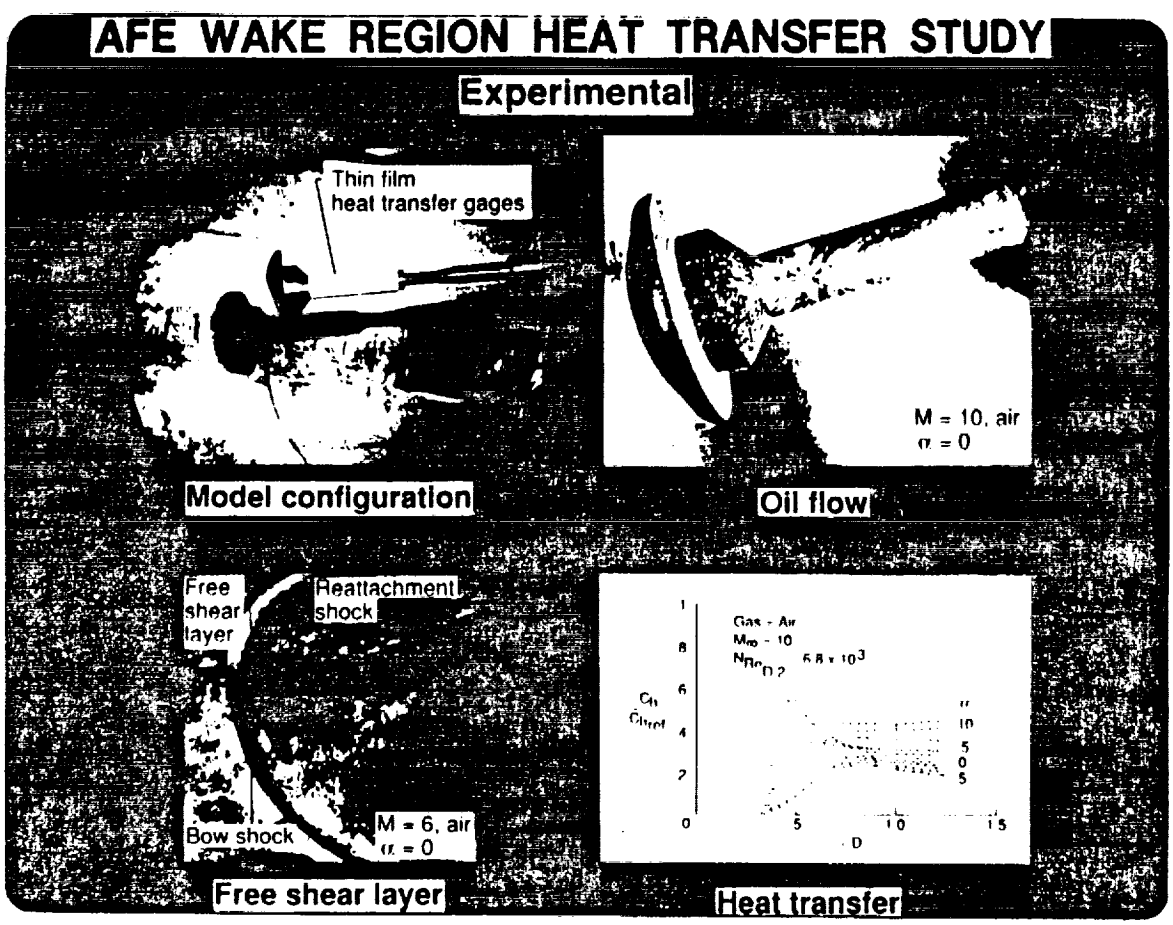
Mach 10 $\alpha = 5°$



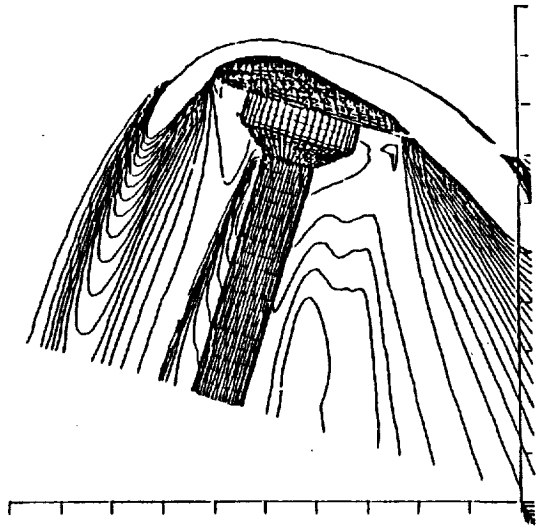
COMPARISON OF CALCULATIONS OVER AN "EQUIVALENT AXISYMMETRIC" AFE WITH WIND TUNNEL DATA

$\alpha = 0°$





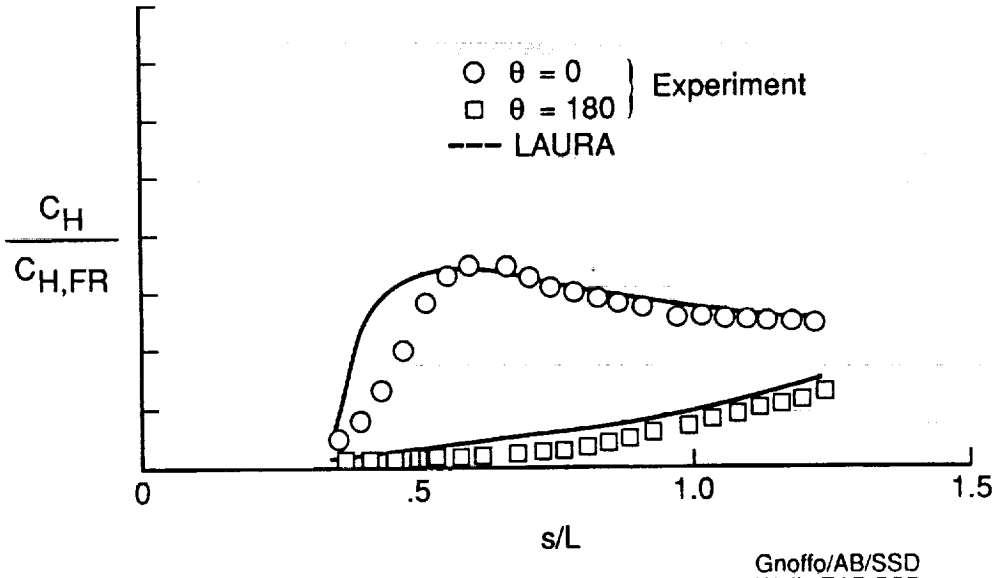
PRESSURE



Gnoffo/AB/SSD

HEATING DISTRIBUTIONS FOR AFE STING

Mach 10 $\alpha = 0°$



Gnoffo/AB/SSD
Wells/EAB/SSD

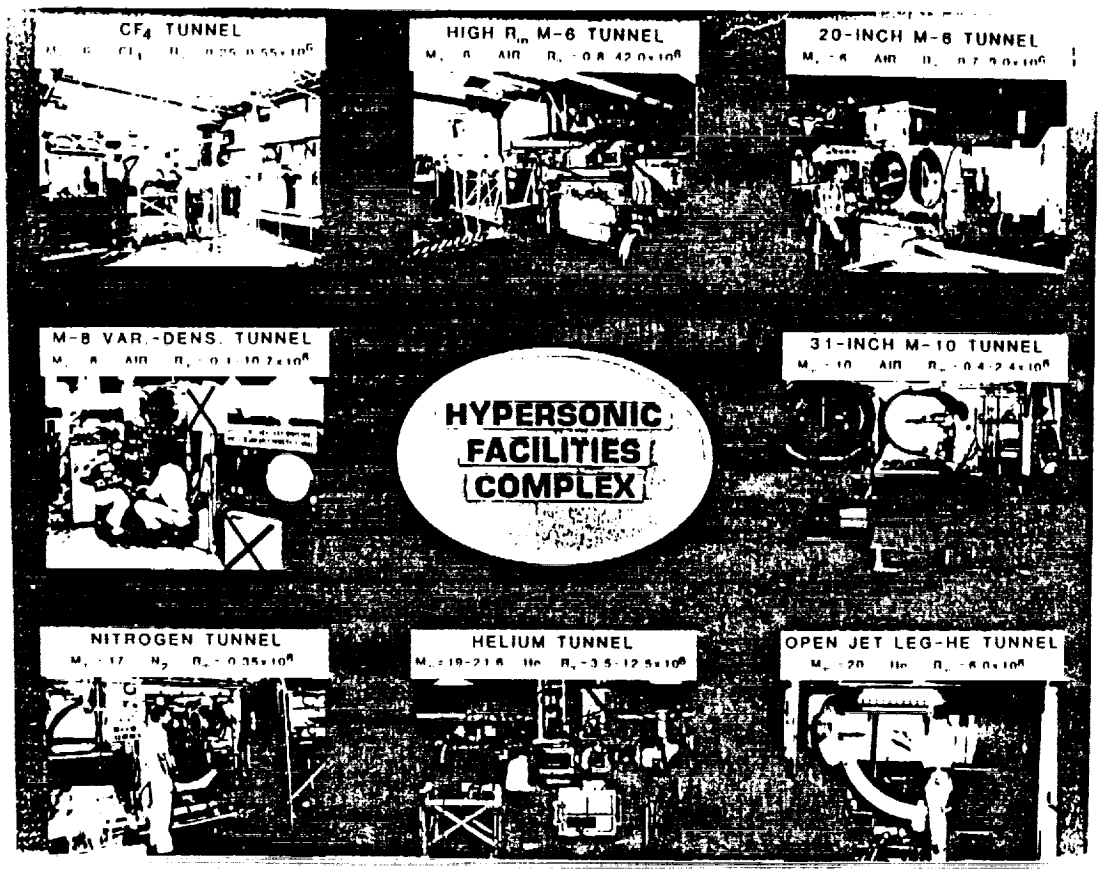
EXPERIMENTAL AERODYNAMIC/AEROTHERMODYNAMIC DATA BASE FOR HIGH ENERGY AEROBRAKING (HEAB) CONCEPTS

CAPABILITIES

- PERSONNEL - EXPERIMENTALISTS OF EAB (INCLUDES PRESENT MANAGER/PRINCIPAL INVESTIGATOR FOR AFE GROUND-BASED DATA BASE; PRINCIPAL INVESTIGATOR FOR MARS SAMPLE RETURN MISSION CONCEPT STUDY):
- FACILITIES
  - LaRC UNITARY PLAN WIND TUNNEL (M=2 - 4.6, AIR)
  - LaRC 20-INCH MACH 6 AIR TUNNEL
  - LaRC 20-INCH MACH 6 CF4 TUNNEL
  - LaRC 31-INCH MACH 10 AIR TUNNEL
  - LaRC 20-INCH MACH 13.5/17 NITROGEN TUNNEL
  - LaRC 22-INCH MACH 20 HELIUM TUNNEL
  - GASL EXPANSION TUBE (HE, AIR, CO2 TEST GASES, 16<U<23 KFT/S)
  - ANU T3 PISTON DRIVEN SHOCK TUNNEL
  - UNIVERSITY OF QUEENSLAND T4 PISTON DRIVEN SHOCK TUNNEL

NOTE: EFFECT OF HIGH NORMAL SHOCK DENSITY RATIO ASPECT OF REAL GAS STUDIED VIA TESTS AT M=6 IN AIR AND CF4

REAL GAS EFFECTS, INCLUDING SURFACE CATALYCITY, STUDIED WITH HIGHLY INSTRUMENTED MODELS VIA TESTS IN GASL ET, ANU T3 AND UQ T4



LaRC HYPERSONIC FACILITIES COMPLEX

AGGREGATE OF CONVENTIONAL (NON-IMPULSE) HYPERSONIC TUNNELS PROVIDING A WIDE RANGE OF MACH AND REYNOLDS NO.'S AND DENSITY RATIOS (RATIOS OF SPECIFIC HEATS).

O RELATIVELY SMALL, ECONOMICAL, BLOWDOWN RESEARCH ORIENTED FACILITIES

FACILITY CHARACTERISTICS (LISTED FROM LEFT CORNER, MOVING CLOCKWISE)

FACILITY	TEST GAS	MACH NO.	R_N /FT x 10^{-6}	DENSITY RATIO	NOZZLE TYPE	NOZZLE SIZE, IN.	TEST CORE, IN.
HYP. CF4	FREON 14	6	.02 TO .7	12	ASC*	20 DIA.	14
HIGH RN M=6	AIR	6	2 TO 45	5.3	ASC	12 DIA.	4-8
20 IN. M=6	AIR	6	.5 TO 9	5.3	2-D	20x20	14x14
31-IN. M=10	AIR	10	.2 TO 2	5.9	3-D	31x31	12x12
OPEN JET He.**	He.	17	3	4	CONICAL	20 DIA.	8-10
HYP. He.	He.	18 TO 22	2 TO 20	4	ASC	22 DIA.	8-10
HYP. N_2	N_2	17	.2 TO .8	6.6	ASC	20 DIA.	8-10
M=8 VAR. DENS.	AIR	8	.1 TO 10	5.6	ASC	18 DIA.	7-16

* AXIS SYMMETRIC CONTOUR

** PILOT HYPERSONIC QUIET TUNNEL

GENERAL PLANS
HIGH - ENERGY AEROBRAKING

- COMPUTATIONAL DATA BASE
  - Re - establish And Excercise Radiation Flowfield Codes Used in Prior Planetary Entry Missions
  - Transfer And Expand Knowledge From AFE Studies
  - Modify Existing Codes And / Or Develop New Codes
- EXPERIMENTAL DATA BASE
  - Parametric Studies Of Preliminary Concepts
  - Optimize / Refine Characteristics For Most Promising Concepts
  - Establish Data Base For Baseline Concepts
  - CFD Code Calibration
- INTERACT WITH AND SUPPLY RESULTS TO SYSTEM STUDIES

SPECIFICS OF JSC'S AEROBRAKING EFFORTS: PAST, PRESENT AND PLANNED

JSC AEROBRAKING EFFORTS:

PAST, PRESENT AND FUTURE

JDG-1, 2/1/89

PRESENTATION OVERVIEW

- INTRODUCTION - J. GAMBLE
- AFE - D. CURRY
- MRSR - J. GAMBLE
- GN&C - G. MCSWAIN
- CFD - C. LI
- AEROTHERMODYNAMICS/TPS - D. CURRY
- CONCLUDING REMARKS - J. GAMBLE

JDG-2, 2/1/89

PAST EFFORTS
APPLICABLE TO AEROBRAKING

- APOLLO
  - GN&C
    - BASIC CONCEPTS EVOLVED INTO SHUTTLE AND AFE
      - Definition of entry corridor using skip out boundary, g limits and heating constraints
      - Use bank about velocity vector for trajectory control
      - Early part of entry trajectory very similar to aerocapture trajectory
  - AEROTHERMODYNAMICS AND THERMAL PROTECTION SYSTEMS
    - METHODOLOGY DEVELOPED FOR PREDICTING ABLATIVE AEROTHERMAL ENVIRONMENT
    - EXPERIMENTAL DATA BASE FOR ABLATIVE TPS AT LUNAR RETURN VELOCITIES

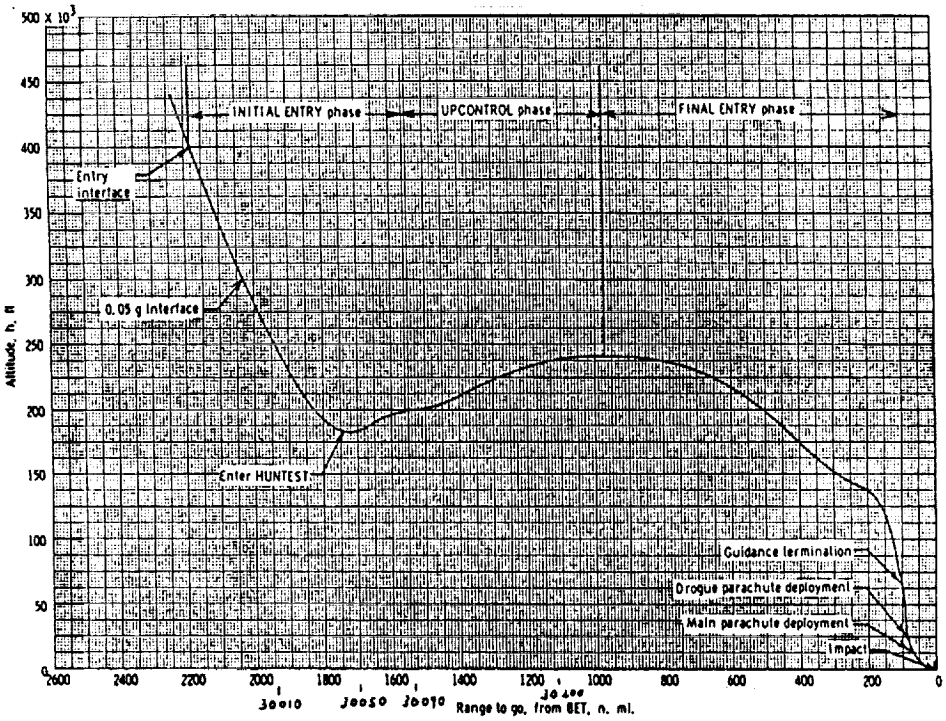
JDG-3, 2/1/89

PAST EFFORTS CONT'D

- SHUTTLE
  - GN&C
    - SIMILAR TO APOLLO
    - HEATING CONSTRAINSTS SIGNIFICANT DRIVER
  - AEROTHERMODYNAMICS AND THERMAL PROTECTION SYSTEM
    - LARGEST AEROTHERMODYNAMICS TEST PROGRAM IN HISTORY
    - EXTENSIVE PREFLIGHT TO FLIGHT DATA COMPARISONS IN ALTITUDE REGION OF INTEREST TO AEROBRAKING
    - METHODOLOGY DEVELOPED FOR ANALYSIS OF REUSABLE TPS AEROTHERMAL ENVIRONMENT

JDG-4, 2/1/89

Apollo guidance computer entry control.

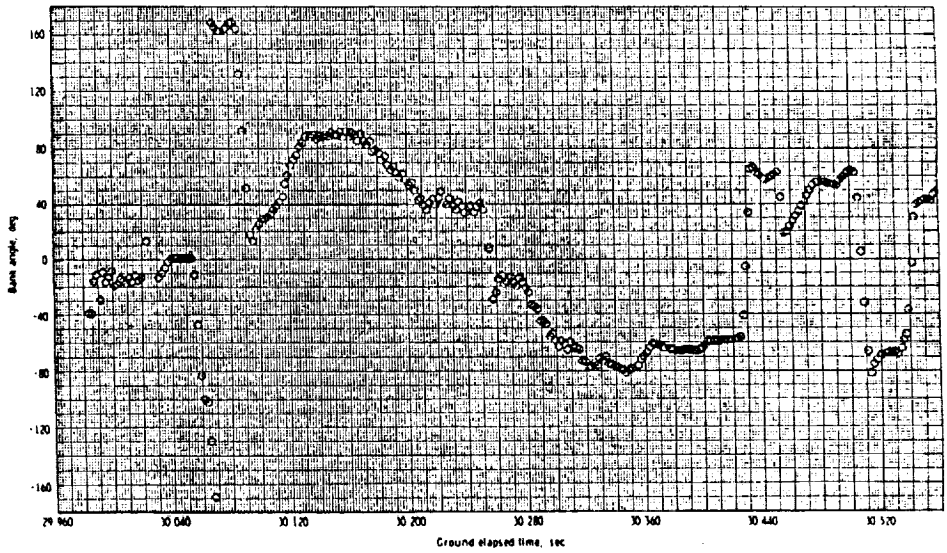


APOLLO 4 ENTRY TRAJECTORY
SIMULATED LUNAR RETURN

ALTITUDE VERSUS RANGE TO GO

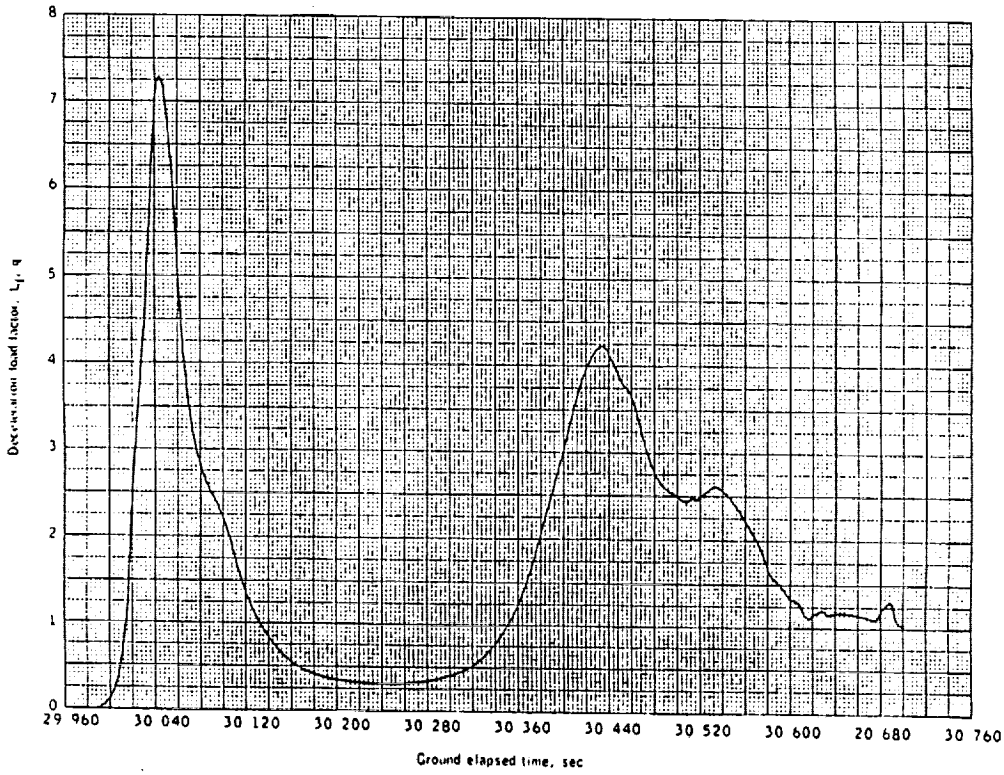
JDG-5, 2/1/89

Bank-angle time history.



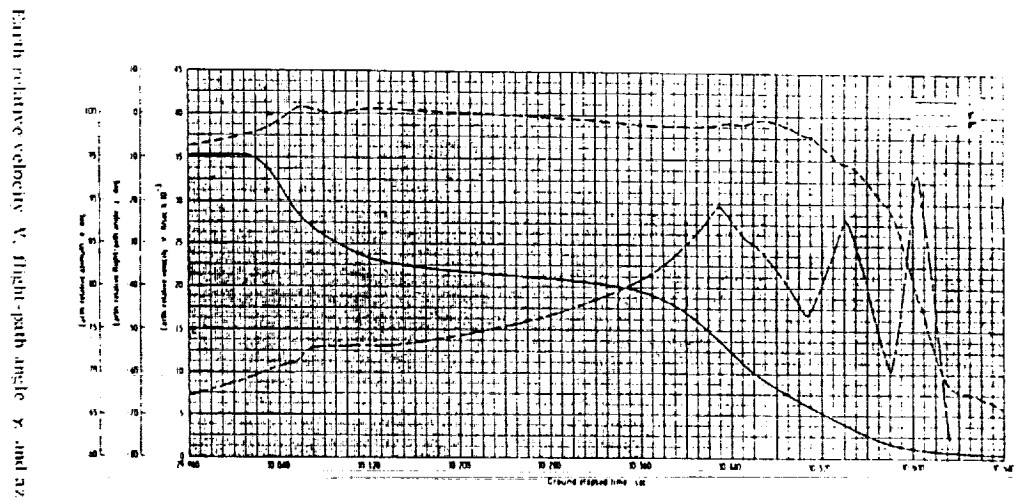
APOLLO 4 BANK ANGLE TIME HISTORY

JDG-6, 2/1/89



APOLLO 4 LOAD FACTOR TIME HISTORY

JDG-7, 2/1/89



APOLLO 4 ENTRY TIME HISTORY

JDG-8, 2/1/89

CONCLUDING REMARKS

- JSC HAS CONSIDERABLE EXPERIENCE IN ENTRY AND AEROCAPTURE PROGRAMS (APOLLO, SHUTTLE, AFE).
  - GN&C
  - AERODYNAMICS
  - AEROTHERMODYNAMICS
  - TPS
- CONSIDERABLE RESOURCES ARE CURRENTLY BEING DEVOTED TO AEROCAPTURE ACTIVITIES.
  - AFE - 23 MYE
  - MRSR - 7 MYE
  - PATHFINDER
    - GN&C (AUTONOMOUS LANDING) - 2.5 MYE, $200K FY89
    - CFD/AEROTHERMO - 1 MYE, $68K FY89
    - TPS - 1 MYE, $85K FY89
- STRONG INTEREST IN SUPPORT OF HEA IN ALL DISCIPLINE AREAS

JDG-66, 2/1/89

ADVANCED PROGRAMS OFFICE PERSONNEL WORKING PATHFINDER

JOE GAMBLE — MRSR COORDINATION FOR AEROSCIENCE BRANCH

CHRIS CERIMELE — AERODYNAMICS AND FLIGHT MECHANICS
ROBERT ESS — AERODYNAMICS AND FLIGHT MECHANICS
MATT ONDLER — AERODYNAMICS AND FLIGHT MECHANICS

CHIEN LI — COMPUTATIONAL FLUID DYNAMICS CODE DEVELOPMENT
PHIL STUART — BICONIC BODY AND MARS ATMOSPHERE CFD
*JOHN MCGARY — AFE AERODYNAMICS
*LUEN TAM — AFE THERMAL NONEQUILIBRIUM

CARL SCOTT — NONEQUILIBRIUM CHEMISTRY AND CATALYSIS
EFFECTS ON HEATING, ARC JET DIAGNOSTICS
STEVE FITZGERALD — ARC JET CFD
*SIVARAM AREPALLI — ARC JET LASER DIAGNOSTICS
*BILL ROCHELLE — RADIATIVE HEATING
CONVECTIVE HEATING IN MARS ATMOSPHERE
*PAUL TING - CONVECTIVE HEATING IN MARS ATMOSPHERE
*STEVE MUELLER — CONVECTIVE HEATING IN MARS ATMOSPHERE

* = LOCKHEED ENGINEERING AND SCIENCE CO.

CDS 1/24/89

N900088X

High Energy Aerobraking Workshop

NASA Ames Research Center

January 31 - February 2, 1989

AFE AEROBRAKE TECHNOLOGY

Donald M. Curry
NASA Johnson Space Center

N900089X

AEROASSIST FLIGHT EXPERIMENT (AFE)

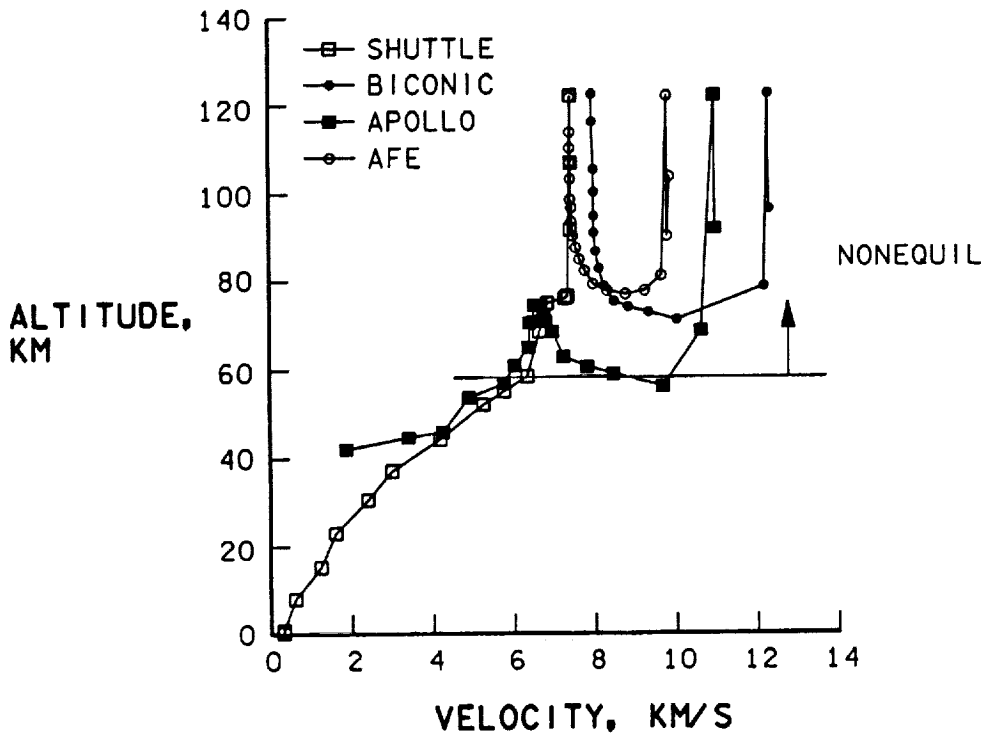
BACKGROUND

- AEROASSIST BRAKING SIGNIFICANTLY ENHANCES SPACE TRANSFER VEHICLE (STV) PERFORMANCE AS OPPOSED TO ALL-PROPULSIVE STV
- ALL NEW INITIATIVES (GEO, LUNAR, AND MARS) UTILIZE AEROBRAKING STV AS A NECESSARY PART OF THEIR MISSION PLAN
- UNDERSTANDING AEROTHERMODYNAMIC ENVIRONMENT IS CRITICAL TO DESIGN OF LIGHTWEIGHT HEATSHIELDS FOR AEROASSIST STV
- BASIC DESIGN QUESTIONS ARE NOW UNANSWERED; AN AEROASSIST STV CANNOT PRESENTLY BE DESIGNED WITH A MINIMUM WEIGHT, REUSEABLE THERMAL PROTECTION SYSTEM WITHOUT AFE RESULTS

AFE OBJECTIVES

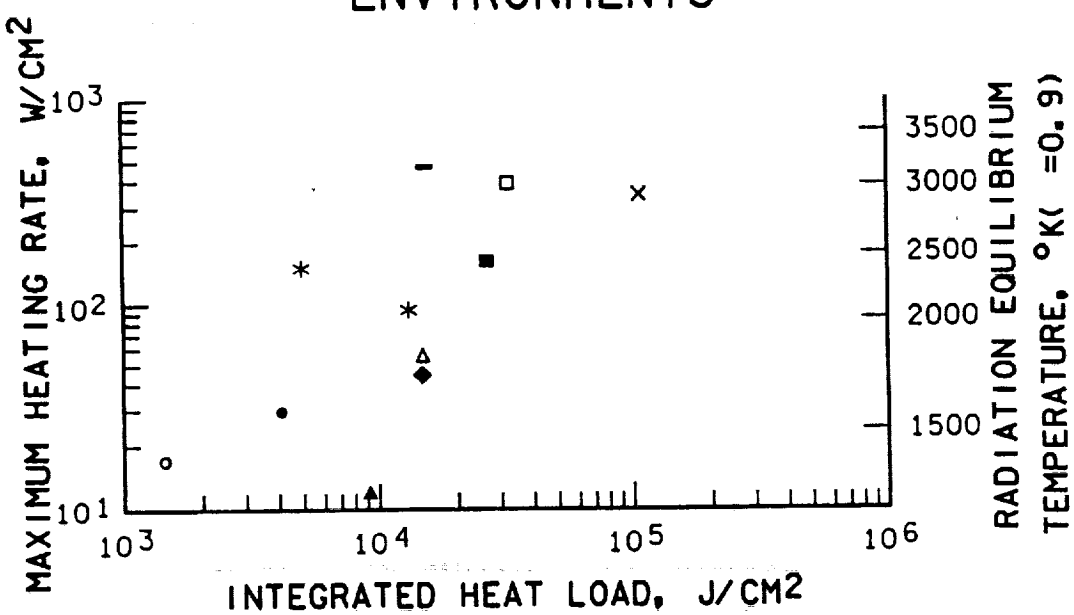
- TO INVESTIGATE CRITICAL VEHICLE DESIGN TECHNOLOGY ISSUES APPLICABLE TO AEROASSIST VEHICLES
- PROVIDE CRITICAL AERODYNAMIC AND AEROTHERMODYNAMIC ENVIRONMENTAL DATA THAT CANNOT BE SIMULATED IN GROUND FACILITIES
- PROVIDE VERIFICATION DATA OF EXPERIMENTAL AND COMPUTATIONAL FLOWFIELD TECHNIQUES IN THE NONEQUILIBRIUM CHEMISTRY FLIGHT REGIME

EARTH TRAJECTORIES



6626.ART, 1

TPS DESIGN AND FLIGHT TEST ENVIRONMENTS



- • AFE
- ◆ SHUTTLE FLIGHT
- ○ VIKING FLIGHT
- ■ AEROCAPTURE MARS
- □ AEROCAPTURE EARTH
- ▲ LANDER MARS
- △ SHUTTLE DESIGN
- × APOLLO DESIGN
- ✳ APOLLO ORBITAL RETURN
- – APOLLO LUNAR RETURN

6627.ART, 1

N900090X

AFE TECHNOLOGY

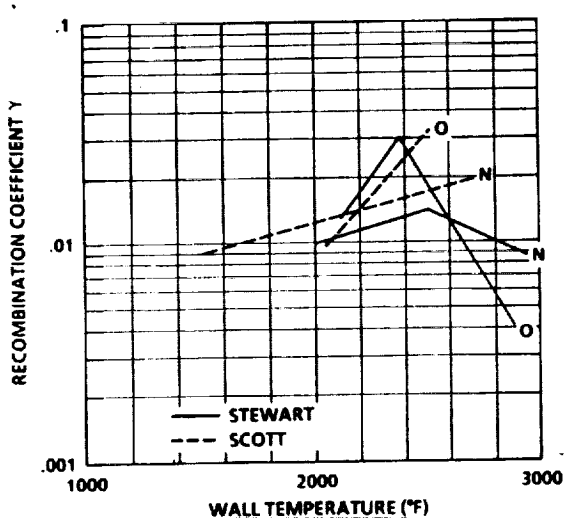
ISSUE	*STATUS*
• WALL CATALYSIS	• UNCERTAINTY IN WALL CATALYSIS HAS BEEN REDUCED BY RECENT STUDY CONTRIBUTIONS FROM LaRC, ARC AND JSC
• AEROPASS WEIGHT	• EFFECT OF WEIGHT INCREASE ON TRAJECTORIES, ENVIRONMENTS, AND TILE TEMPERATURES HAS BEEN STUDIED
• TILE TEMP SENSITIVITY	• EFFECTS OF VARIOUS CHANGES ON TILE RESPONSE BETTER UNDERSTOOD
• TRAJECTORY SYNTHESIS	• EFFECTS OF TRAJECTORY OPTIMIZATION HAS BEEN STUDIED

N900091X

Wall Catalysis

N900092B

MEASURED RECOMBINATION COEFFICIENTS FOR FRCI-12 TILE



SURFACE REACTION RATE COEFFICIENT

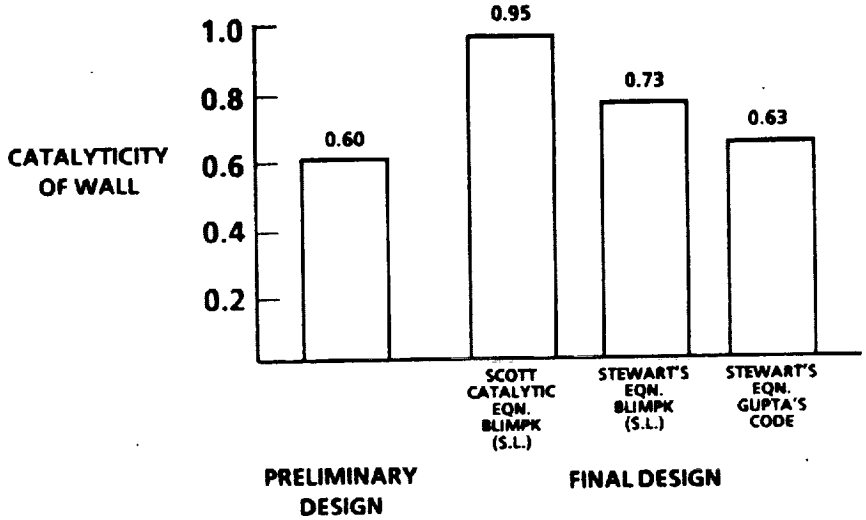
$$K = \sqrt{\frac{B\,T_w}{2\pi m}}\,\gamma$$

B = BOLTZMANN CONSTANT
M = MASS OF ATOM
C = WALL CATALYTIC FACTOR
= $\dot{q}_C/\dot{q}_{FC}$
= f (K, H, FLUID PROPERTIES)
H = HEAT RECOMBINATION

- A FULLY CATALYTIC WALL IS ONE THAT CAUSES ALL DISSOCIATED ATOMS TO RECOMBINE AT THE SURFACE AND RELEASES CHEMICAL ENERGY THAT RESULTS IN HIGHER HEAT TRANSFER

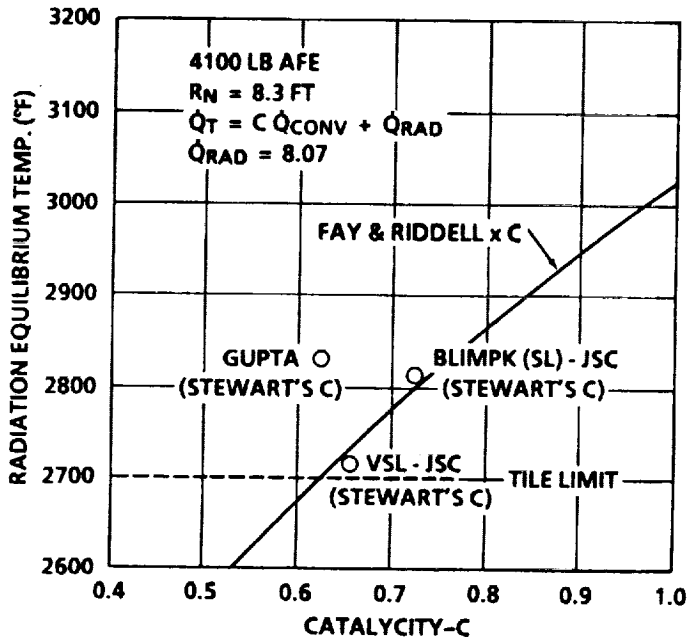
N900093X

HISTORY OF CATALYTIC WALL FACTOR



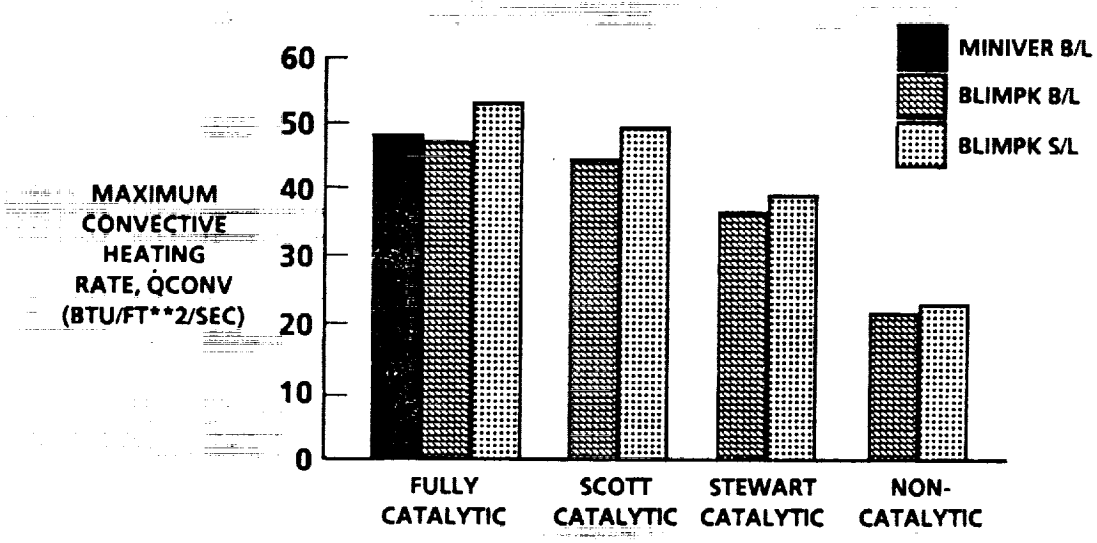
N900094B

EFFECT OF CATALYTICITY ON STAGNATION POINT TILE TEMPERATURES



N900095X

AFE STAGNATION POINT HEATING RATES AT TIME OF MAX. HEATING (110 SEC) IN 4100 LB TRAJECTORY

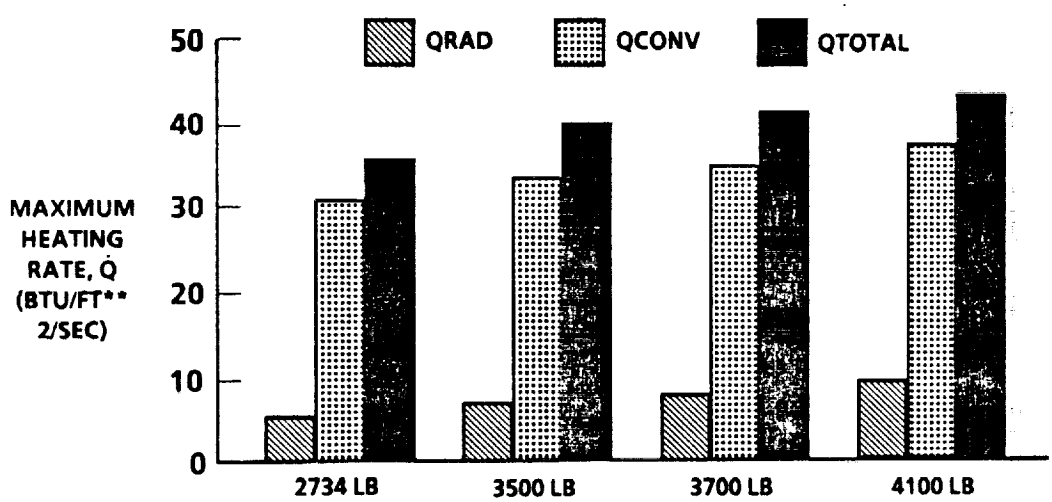


N900096X

Aeropass Weight

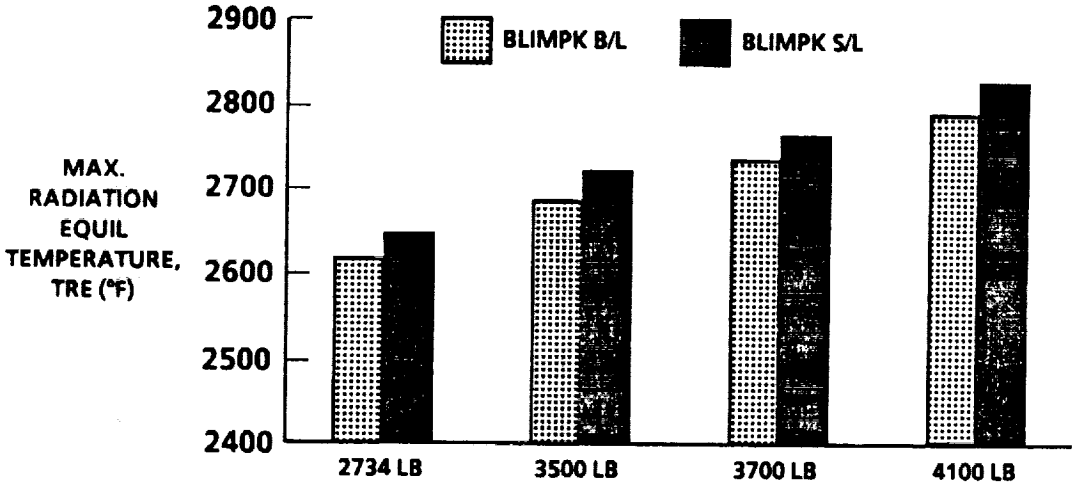
N900097X

AFE MAX HEATING RATE COMPONENTS AT STAGNATION POINT USING STEWART CATALYCITY EQS WITH BLIMPK B/L ANALYSIS



N900098X

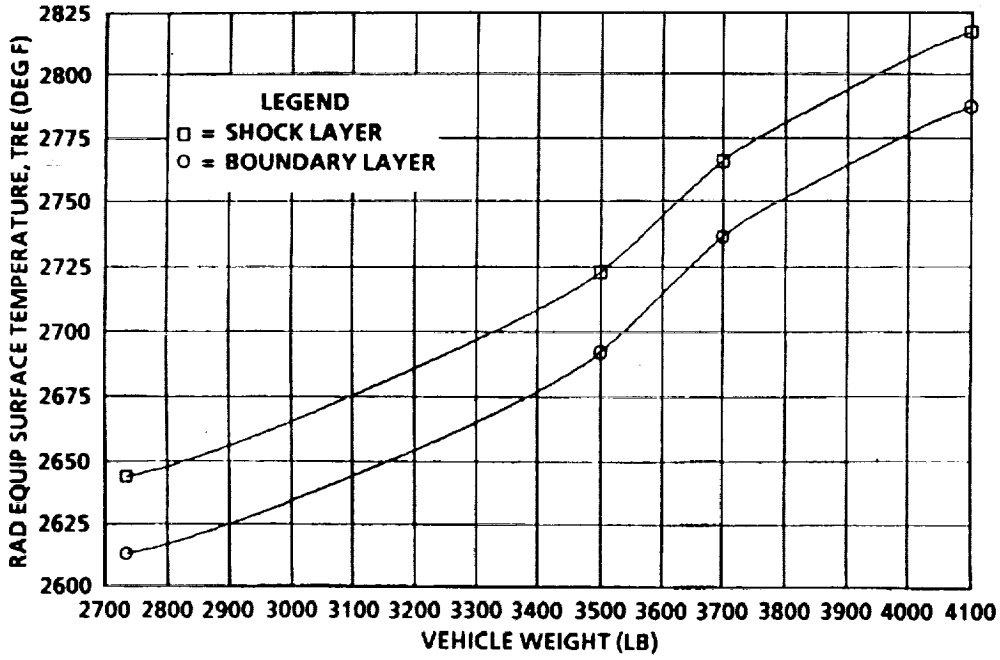
AFE MAX. RADIATION EQUILIBRIUM SURFACE TEMPERATURE AT STAGNATION PT USING STEWART CATALYCITY EQS



N900099B

AFE MAX RADIATION EQUIL SURFACE TEMPERATURES AT STAG PT

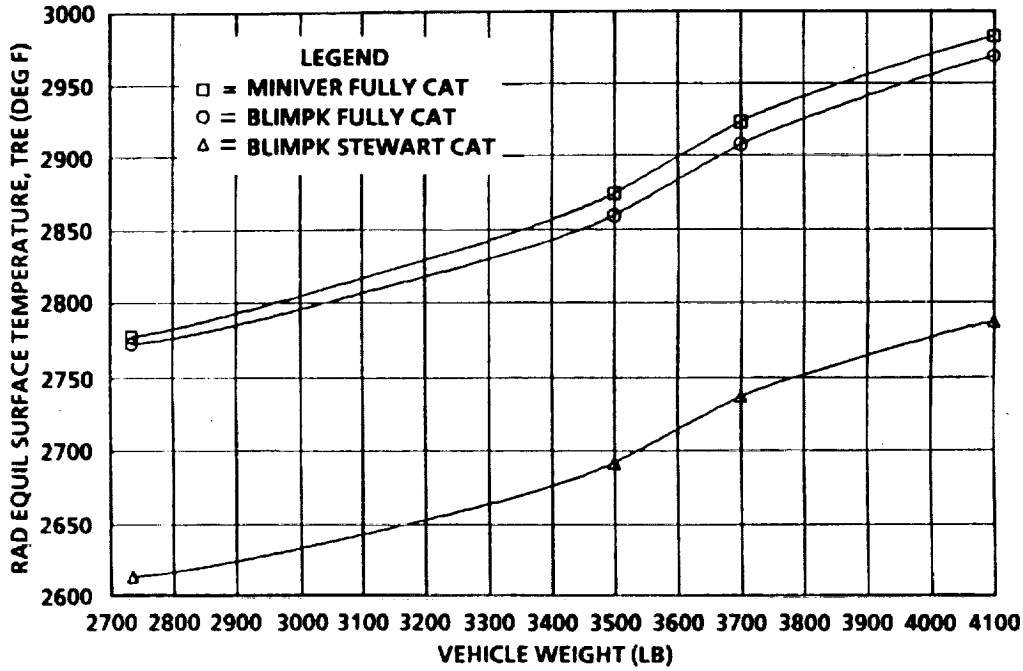
S/L & B/L BLIMPK STEWART CAT WALL, RNOSE = 8.3 FT, EMISS = 0.85



N900100B

AFE MAX RADIATION EQUIL SURFACE TEMPERATURES AT STAG PT

B/L FULLY & PARTIALLY CAT WALL, RNOSE = 8.3 FT, EMISS = 0.85

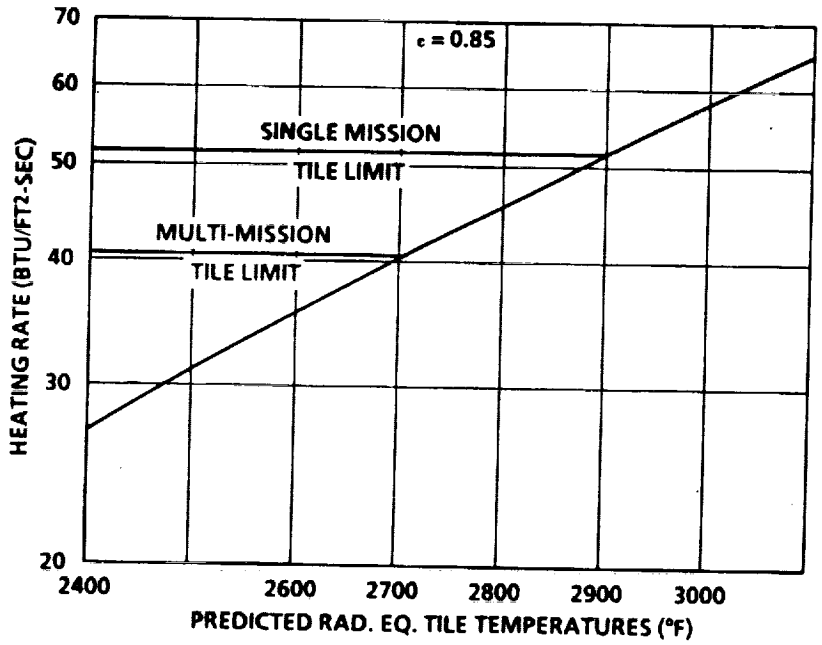


N900101X

Tile Temperature Sensitivity

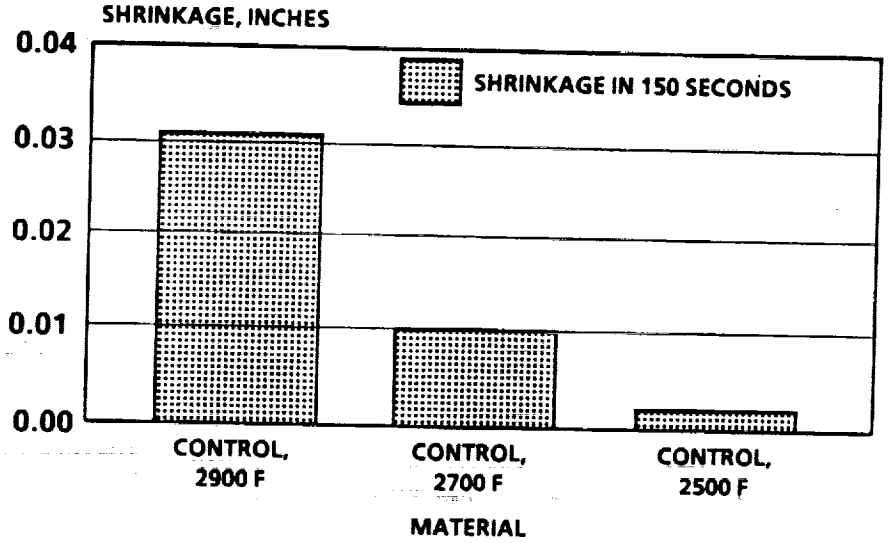
N900102B

RADIATION EQUILIBRIUM TEMPERATURES VS HEATING RATE



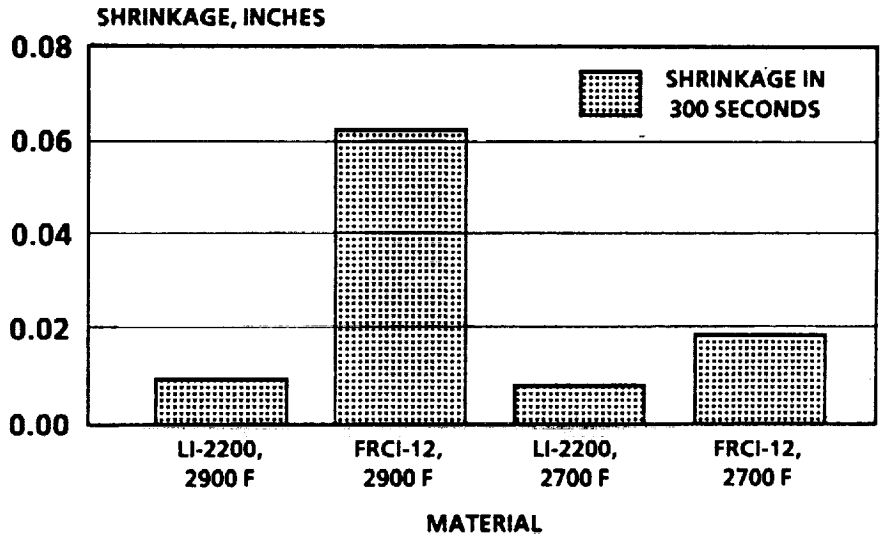
N900103X

AFE OVER TEMPERATURE
FRCI – 12 SHRINKAGE EVALUATION



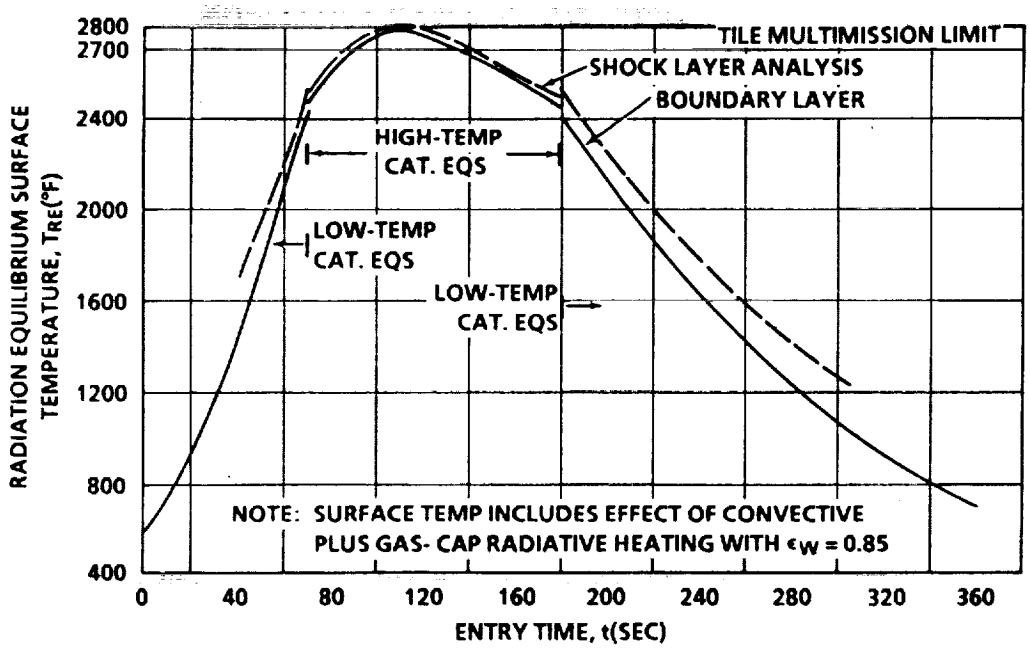
N900104X

AFE OVER TEMPERATURE
RSI SHRINKAGE EVALUATION



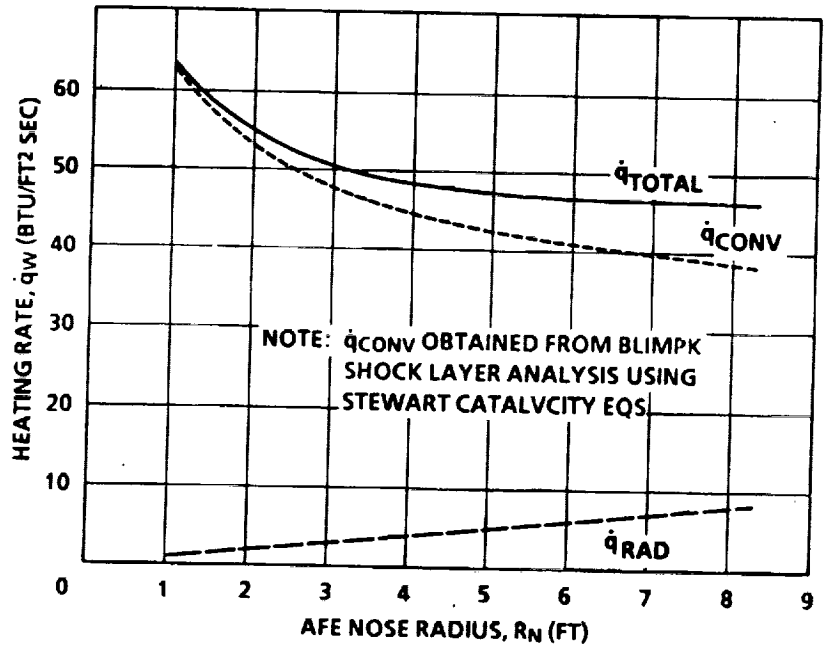
N900105B

4100-LB AFE RAD. EQUIL. SURFACE TEMPERATURES AT STAGNATION PT USING BLIMPK PROG WITH STEWART CATALYCITY EQS FOR R_N = 8.3 FT



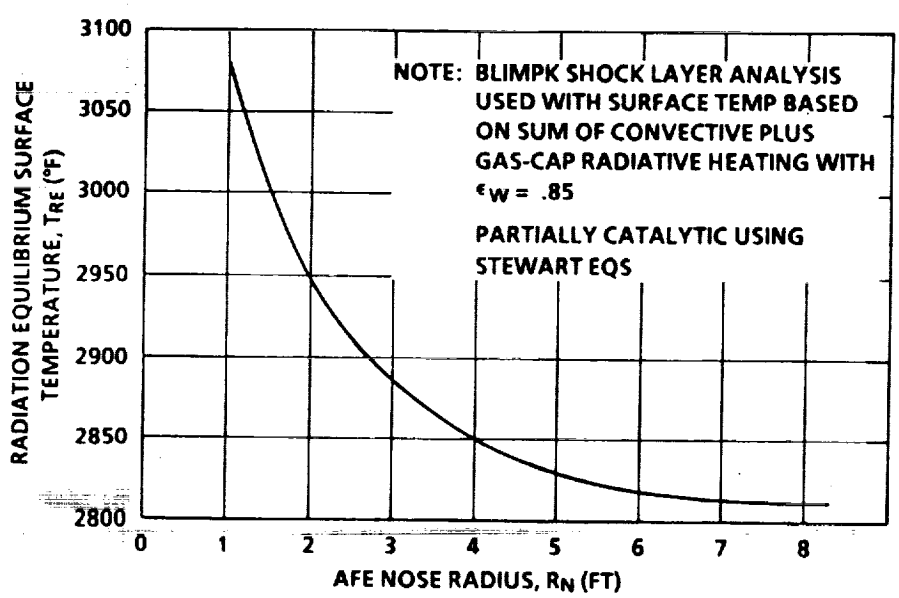
N900106B

TOTAL, CONVECTIVE, AND GAS-CAP RADIATIVE HEATING AT STAG. PT. OF AFE AS A FUNCTION OF NOSE RADIUS FOR 4100-LB VEHICLE AT 110 SEC IN TRAJ



N900107B

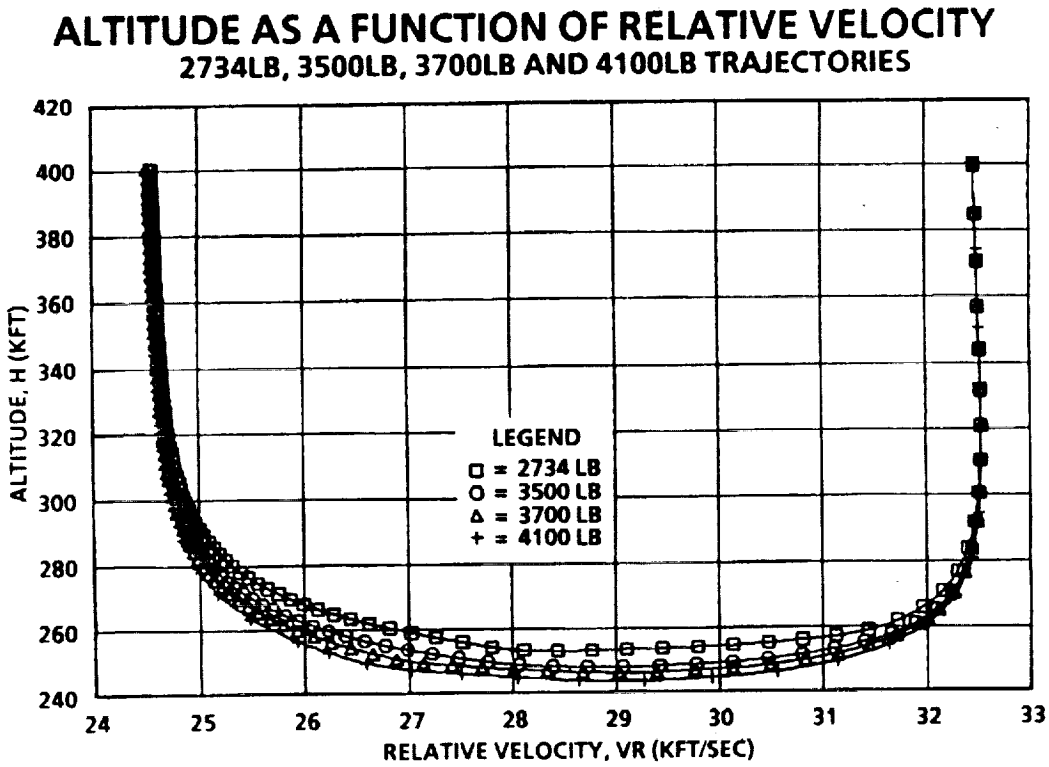
RAD. EQUIL SURFACE TEMPERATURE AT STAG. PT OF AFE AS A FUNCTION OF NOSE RADIUS FOR 4100-LB VEHICLE AT 110 SEC IN TRAJ



N900108X

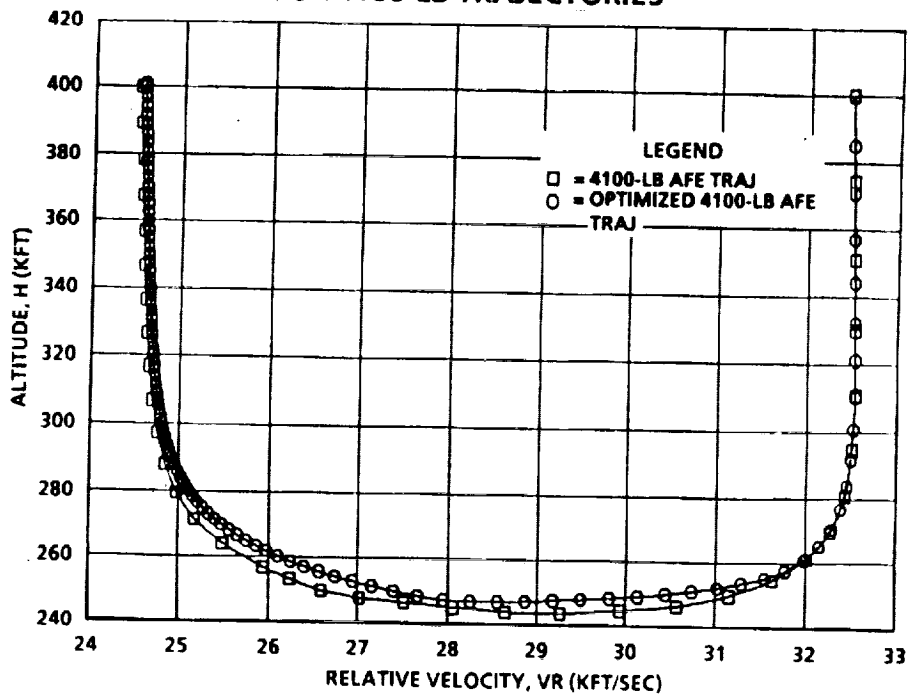
Trajectory Synthesis

N9001098



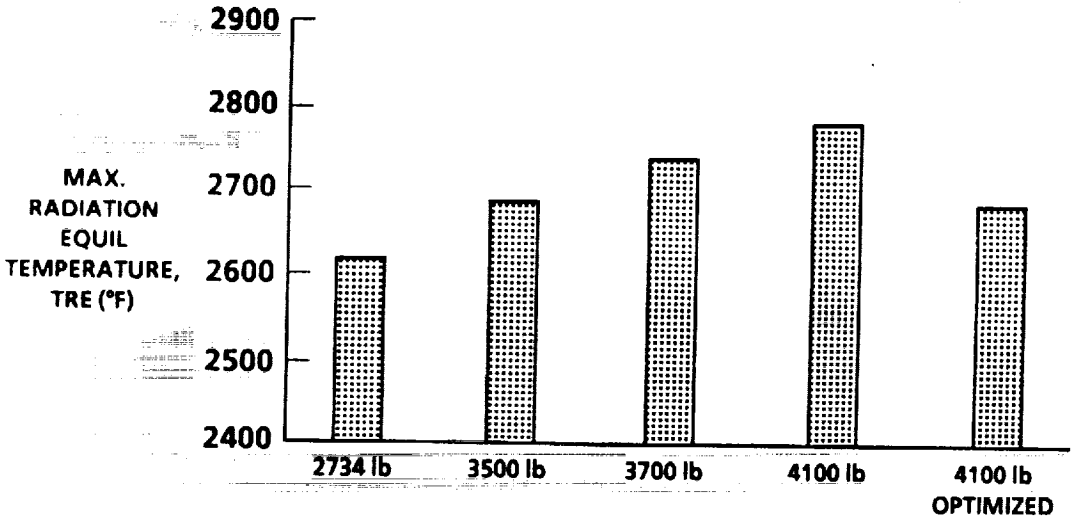
N9001108

ALTITUDE AS A FUNCTION OF RELATIVE VELOCITY
FOR 4100-LB TRAJECTORIES



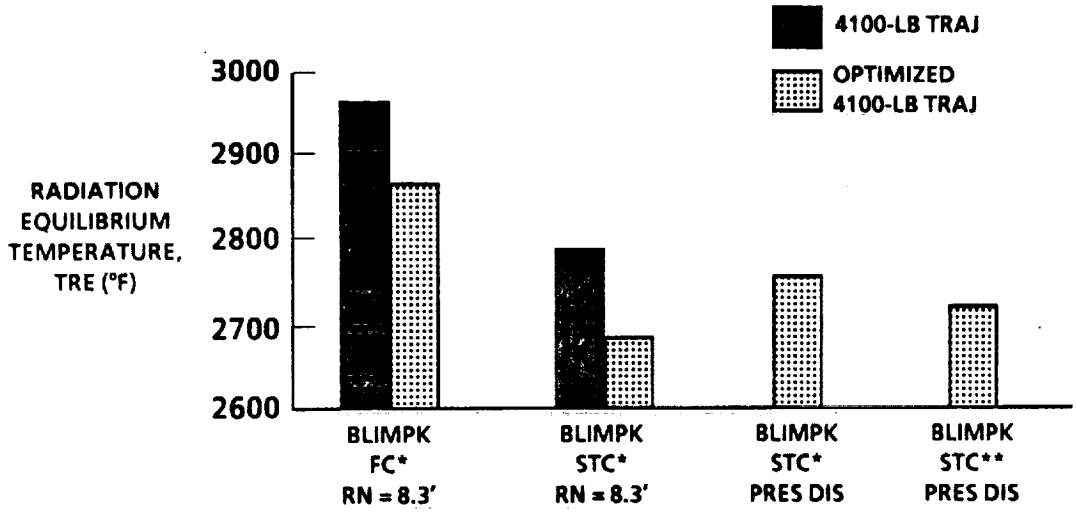
N900111X

AFE MAX. RADIATION EQUILIBRIUM SURFACE TEMPERATURE AT STAG PT USING BLIMPK B/L PROG WITH STEWART CATALYCITY EQS



N900112X

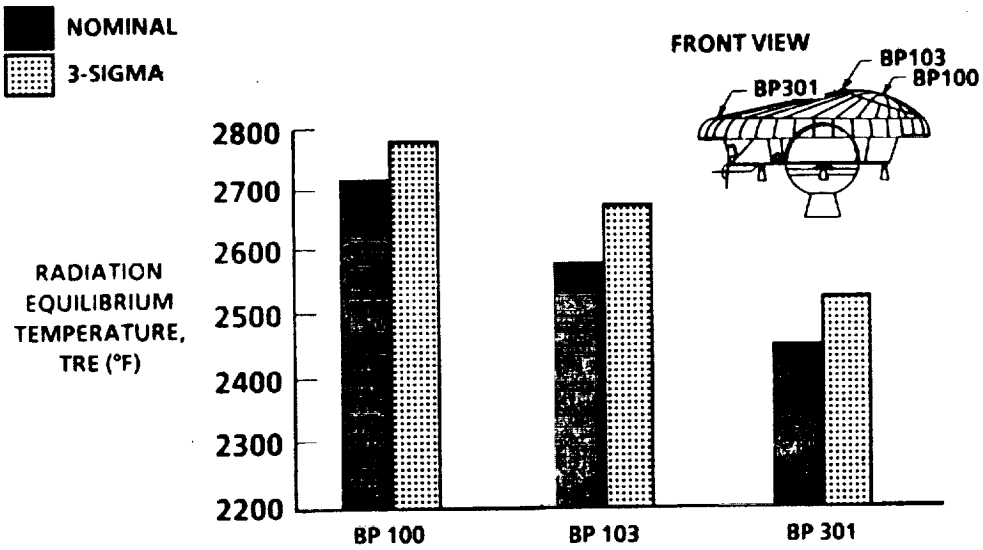
COMPARISON OF MAX. RAD EQUILIB TEMPERATURES FOR 4100-LB AFE TRAJECTORIES



* W/O GAS CAP RADIATION IN ITERATION FOR CONVECTION
**WITH GAS CAP RADIATION IN ITERATION FOR CONVECTION

N900113X

MAXIMUM RADIATION EQUILIBRIUM TEMPERATURES FOR OPTIMIZED 4100-LB AFE TRAJECTORY NOMINAL AND 3-SIGMA CASES



N900114X

AFE Technology Applied to High Energy Aerobraking

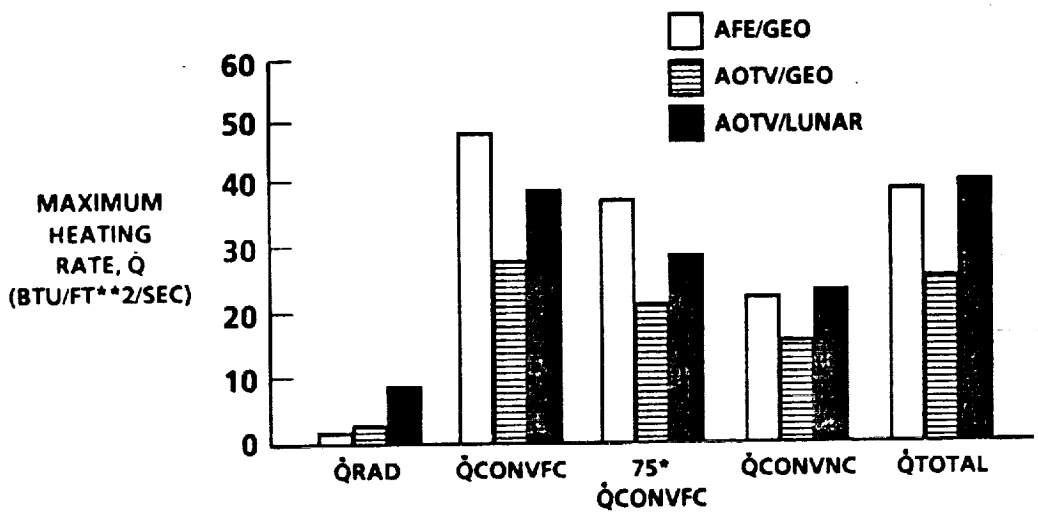
N900115X

AEROASSIST TRAJECTORIES COMPARISON
PHYSICAL PROPERTIES, AERODYNAMICS, AND ENTRY CONDITIONS

	AFE	AOTV GEO RETURN	AOTV LUNAR RETURN
WEIGHT (lbs)	4100	29 000	29 000
DIAMETER (ft)	14	40	40
AREA (ft^2)	154	1257	1257
L/D	0.28	0.28	0.28
W/CDS (psf)	20.3	17.6	17.6
W/CLS (psf)	71.8	62.2	62.2
ALTITUDE (ft)	400 000	400 000	400 000
INERTIAL VELOCITY (fps)	33 830	33 830	36 060
FLT. PATH ANGLE (deg)	-4.50	-4.50	-4.90
ATMOSPHERE	'62 STD.	'76 STD.	'76 STD.

N900113X

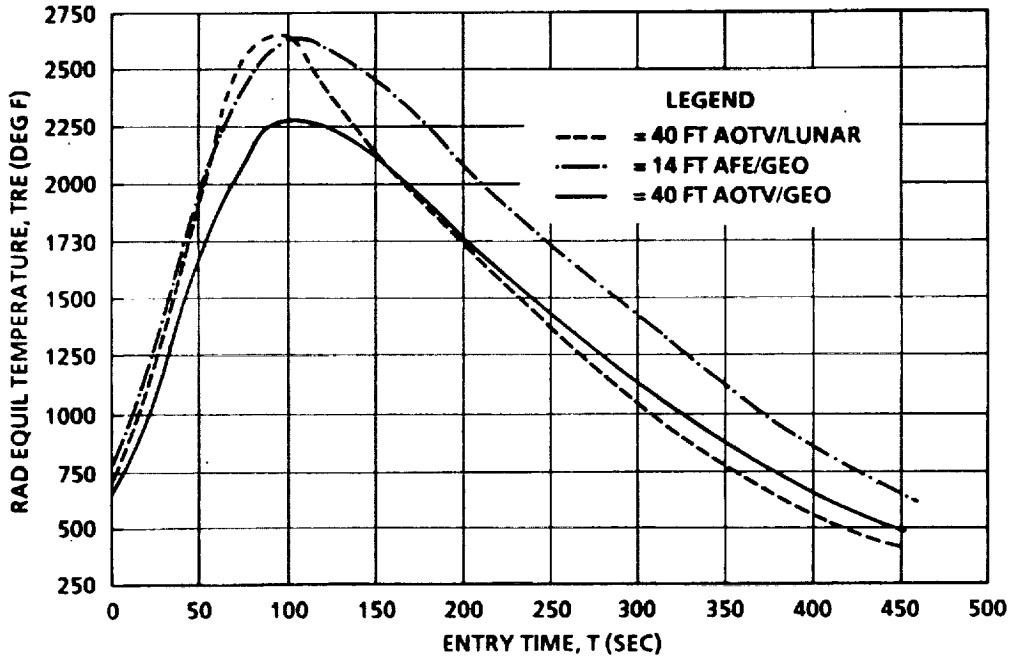
AEROBRAKE MAXIMUM HEATING RATE COMPARISONS USING RIED/ROCHELLE RADIATION PROGRAM



N900117B

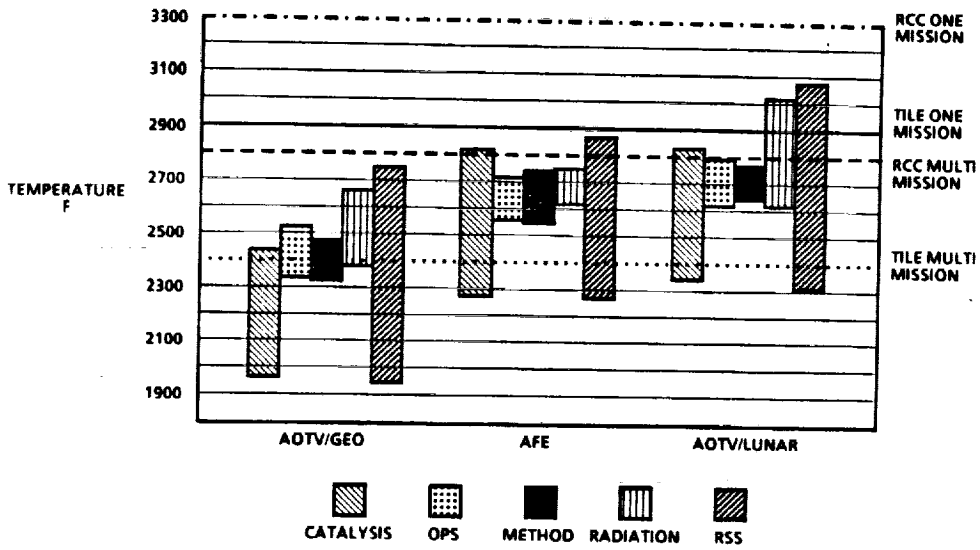
SURFACE RAD EQUIL TEMPERATURES AT STAG PT

BLIMPK B/L & RIED/ROCHELLE GAS CAP RADIATION



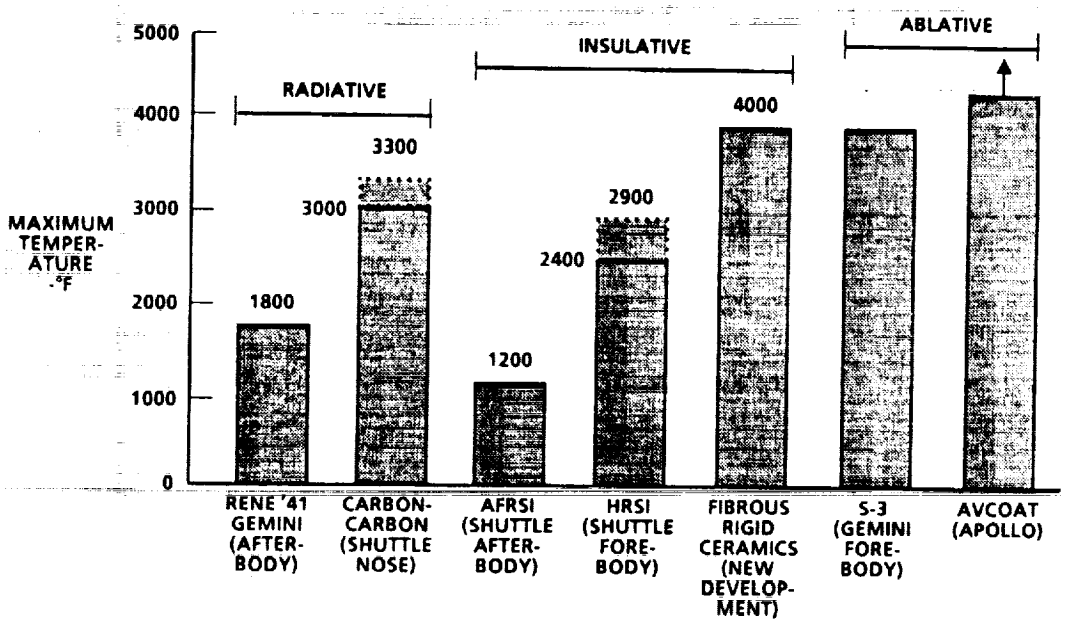
N900118X

RADIATION EQUILIBRIUM TEMPERATURES WITH HEATING UNCERTAINTIES



N900119X

CANDIDATE THERMAL PROTECTION MATERIALS



N900120X

FUTURE CHALLENGES FOR REUSABLE, RIGID, FIBROUS CERAMICS LONG TERM

- STABLE, ADVANCED FIBERS THAT CAN BE USED IN A 3200-4000°F USE TEMPERATURE RFC MATERIAL
  - REQUIRED FIBER CHARACTERISTICS:
    - LOW THERMAL EXPANSION ($3\text{-}8 \times 10^{-7}$ IN/IN °F)
    - SMALL AVERAGE FIBER DIAMETER (1.5-3 MICRONS)
    - HIGH MELTING POINT (4000-4500°F)
    - MODERATE TENSILE STRENGTH ($150\text{-}220 \times 10^3$ LB/IN^2)
    - LOW FIBER POROSITY TO ENHANCE STRENGTH
    - THERMAL STABILITY TO 3200-4000°F
- APPLICATIONS

PROGRAM	*PEAK DESIGN TEMPERATURE*
AOTV RETURNING FROM THE MOON (SCALED UP AFE)	3100-3200°F
MARS AEROCAPTURE BI-CONIC VEHICLE	3000-3400°F
AEROASSIST ORBIT TRANSFER VEHICLE RETURNING FROM MARS (SIMILAR SHAPE AS AFE)	3200-4000°F

N900121X

NON-WEIGHT FACTORS INFLUENCE TPS SELECTION

EVALUATION CRITERIA	ABLATIVE	INSULATIVE		RADIATIVE	
		RSI	RFC	METAL	CARBON-CARBON
MATURITY	HIGH	HIGH	EMERGING	HIGH	HIGH
MAX USE TEMP	5000 °F	2800 °F	4000 °F	1800 °F	3500 °F
OUTGASSING	HIGH	INTERMEDIATE	LOW	NIL	LOW
STRENGTH	LOW	LOW	LOW	HIGH	INTERMEDIATE
DENSITY (PSF)	2.0-3.0	0.6-2.0	1.0-3.0	2.0-3.0	1.0-2.0
OXIDATION RESISTANCE					
• ATOMIC	POOR	GOOD	GOOD	GOOD	REQUIRES COATING
• DIATOMIC	LOW	LOW	HIGH	HIGH	
SIZE LIMITS	NONE	1 FT X 1 FT	2 FT X 6 FT*	NONE	5 FT X 5 FT*
MAN-RATED	YES	YES	NO	YES	YES
DAMAGE TOLERANCE	INTERMEDIATE	LOW	LOW	HIGH	INTERMEDIATE
REPAIRABILITY	POSSIBLE	POSSIBLE	UNDEVELOPED	YES	POSSIBLE
MULTI-USE	NO	YES	YES	YES	YES
REFURBISHMENT	NO	YES	UNDEVELOPED	YES	UNKNOWN
LONG TERM SPACE EXPOSURE	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN

*FURNACE/EQUIPMENT LIMITED

Mars Rover Sample Return
Aerobraking Efforts

JDG-9, 2/1/89

PRESENTATION OUTLINE

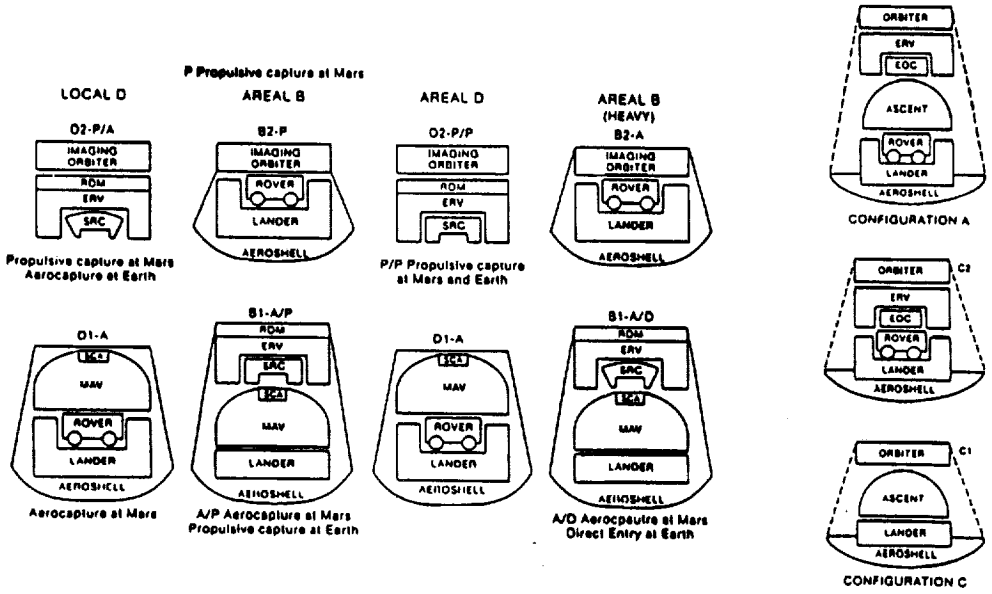
- MRSR BACKGROUND
  - LAUNCH CONFIGURATIONS
  - MISSION DESCRIPTION
- JSC AEROCAPTURE RESULTS
  - L/D AND NAVIGATION REQUIREMENTS
  - PRELIMINARY CONFIGURATION
  - AERO/AEROTHERMO CONSIDERATIONS
  - ATMOSPHERE CONSIDERATIONS
- AEROCAPTURE TECHNOLOGY SUMMARY

JDG-10, 2/1/89

MRSR BACKGROUND

- MRSR PROJECT MANAGED BY JPL WITH JSC PARTICIPATION
  - JSC RESPONSIBLE FOR AEROCAPTURE, ENTRY AND LANDING ELEMENT AND EARTH RETURN ELEMENT
  - PRE PHASE A STUDY COMPLETED IN OCTOBER 1988
  - PHASE A STUDY BEGINS IN MARCH 1989
- BASELINE MISSION FOR PRE PHASE A WAS 1998 LAUNCH OF TWO SEPARATE VEHICLES USING AEROCAPTURE AT MARS
- PHASE A MISSION MAY INCLUDE A 1996 LAUNCH OF MAPPING ORBITER WITH 1998 AND 2001 LAUNCH OF ROVER AND RETURN VEHICLES

JDG-11, 2/1/89

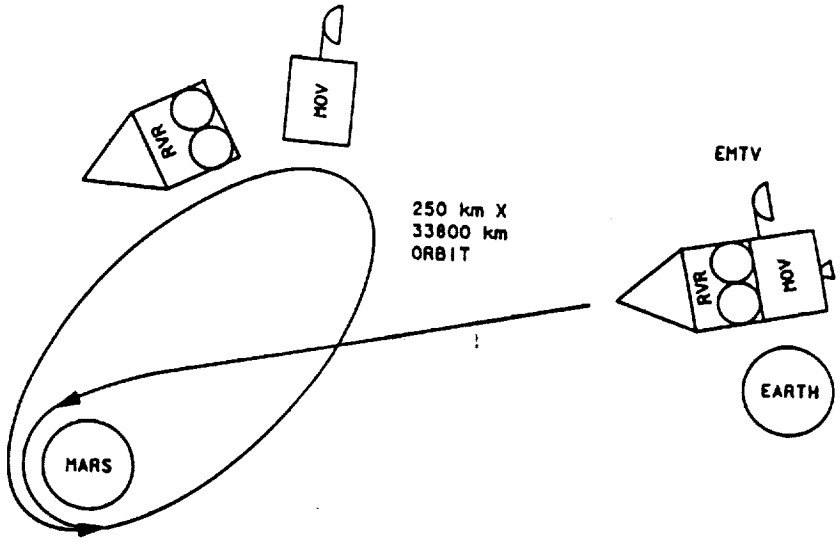


MRSR configuration trade space.

JDG-12, 2/1/89

NASA-S-88-00501

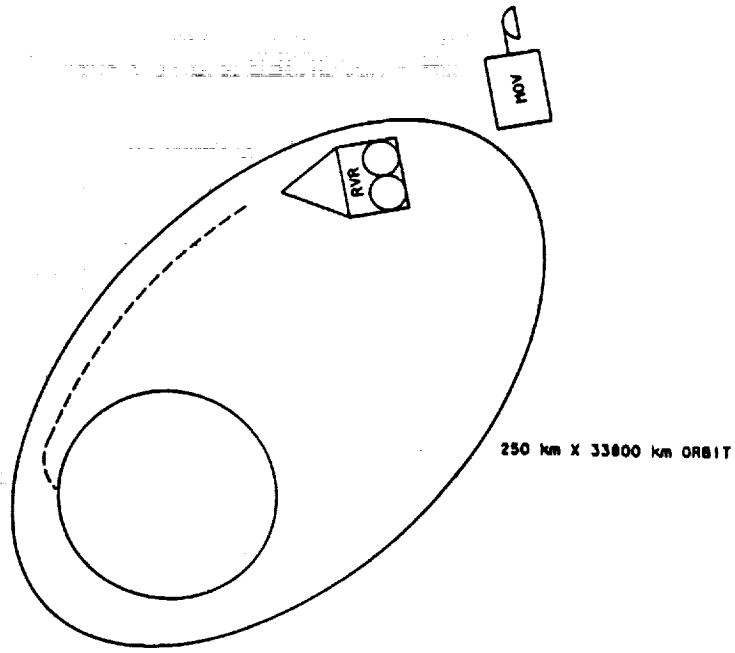
MISSION B2
EARTH TO MARS AND AEROCAPTURE



JDG-13, 2/1/89

NASA-S-88-00502

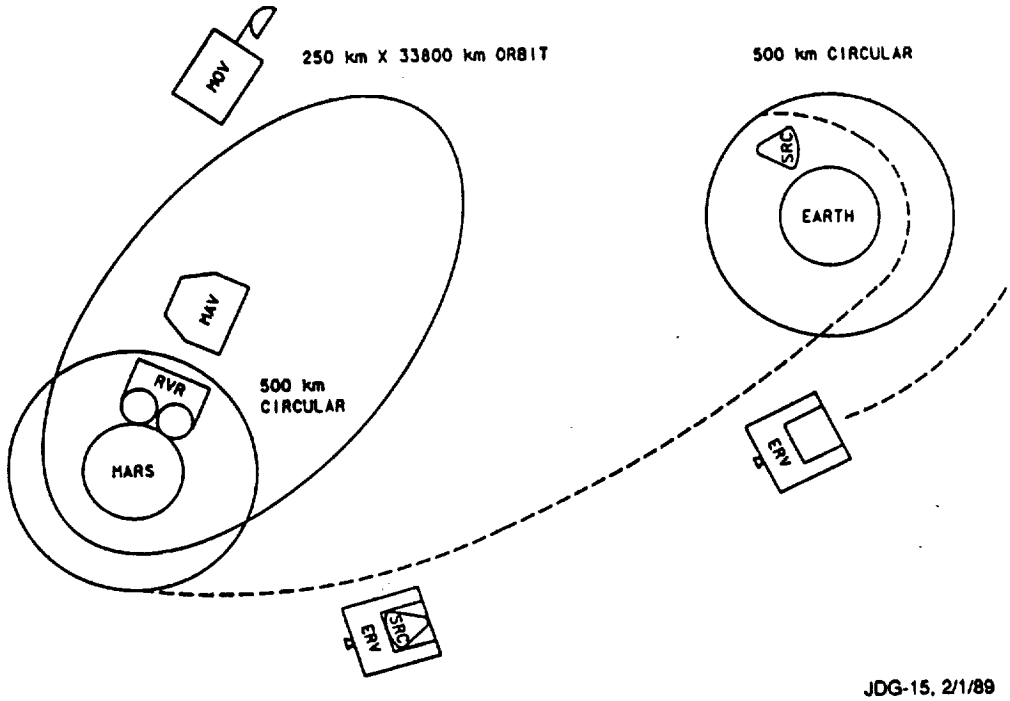
MISSION B2
MARS LANDING AND ORBITAL OPERATIONS



JDG-14, 2/1/89

NASA-S-88-00494

EARTH RETURN AND AEROCAPTURE



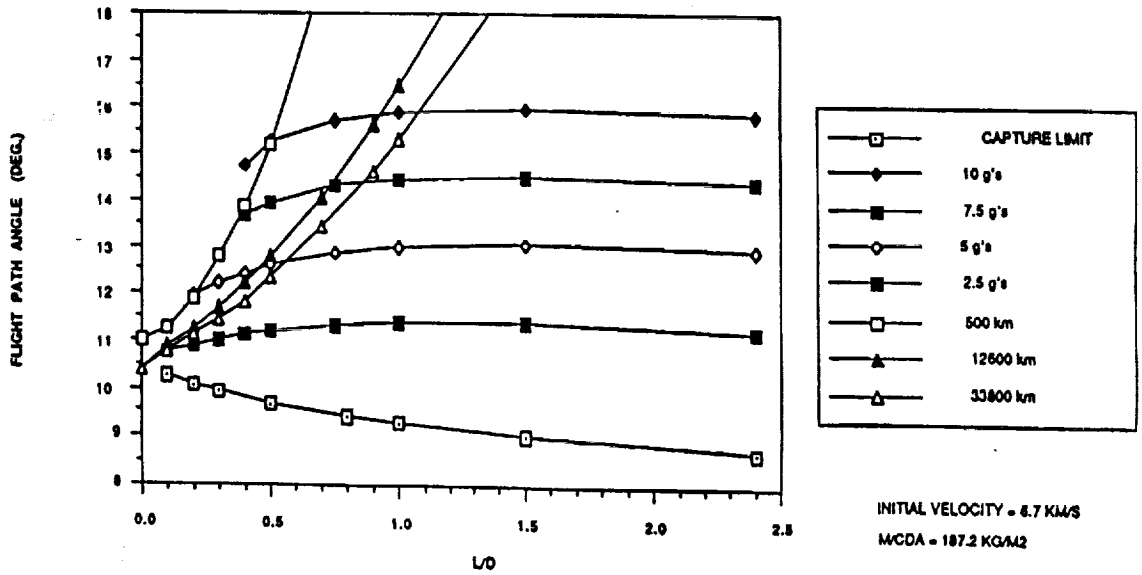
JDG-15, 2/1/89

L/D REQUIREMENTS

- O MARS AEROCAPTURE ENTRY CORRIDORS DEFINED FOR MRSR RANGE OF APPROACH VELOCITIES (6.0 - 6.7 km/s AT 125 km alt).
  - OPEN LOOP CORRIDOR BASED ON SKIP OUT AND MAXIMUM g LOADS.
  - MODIFIED AFE CLOSED LOOP GUIDANCE USED TO VERIFY CORRIDOR CAPABILITY AND TO EVALUATE PERFORMANCE.
    - o USES BANK ABOUT VELOCITY VECTOR FOR CONTROL.
    - o CONCEPT SIMILAR TO APOLLO AND SHUTTLE GUIDANCE.
- O EARTH RETURN AEROCAPTURE VELOCITY SLIGHTLY GREATER THAN APOLLO LUNAR RETURN (APPROXIMATELY 12 km/s AT 125 km alt) .

JDG-16, 2/1/89

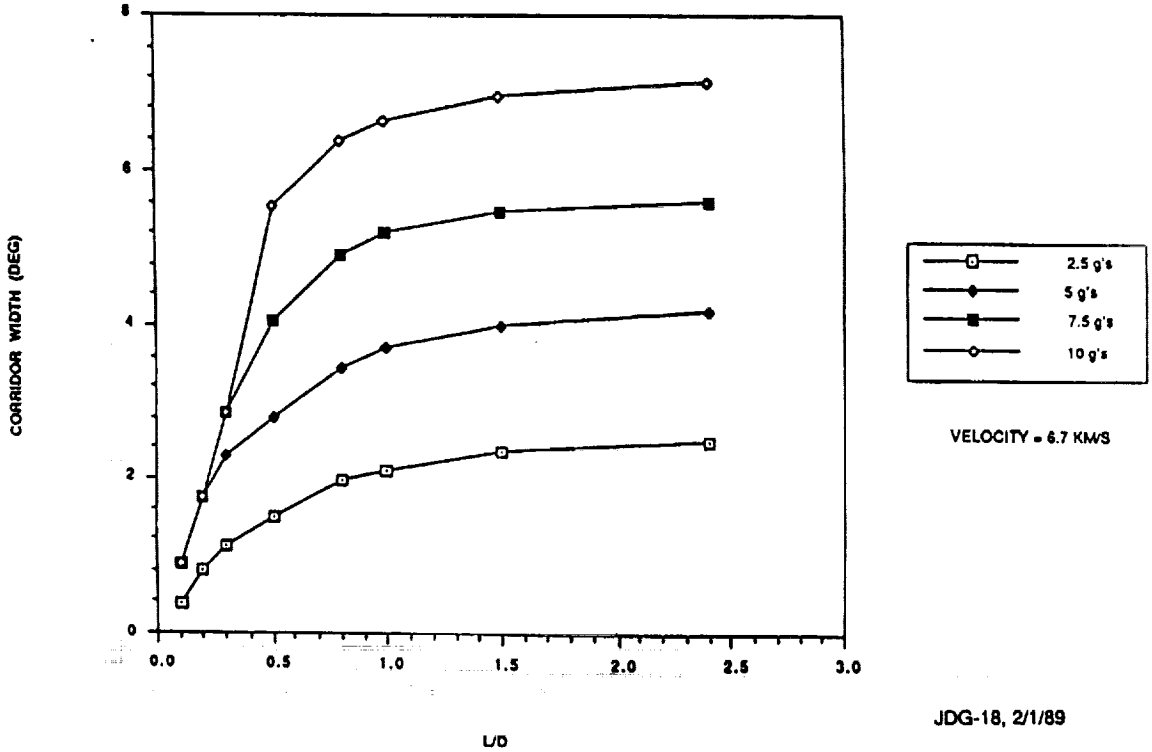
MRSR OPEN LOOP AEROCAPTURE CORRIDOR



INITIAL VELOCITY = 6.7 KM/S
M/CDA = 187.2 KG/M2

JDG-17,2/1/89

AEROCAPTURE CORRIDOR WIDTH
CIRCULAR ORBIT (500 KM)

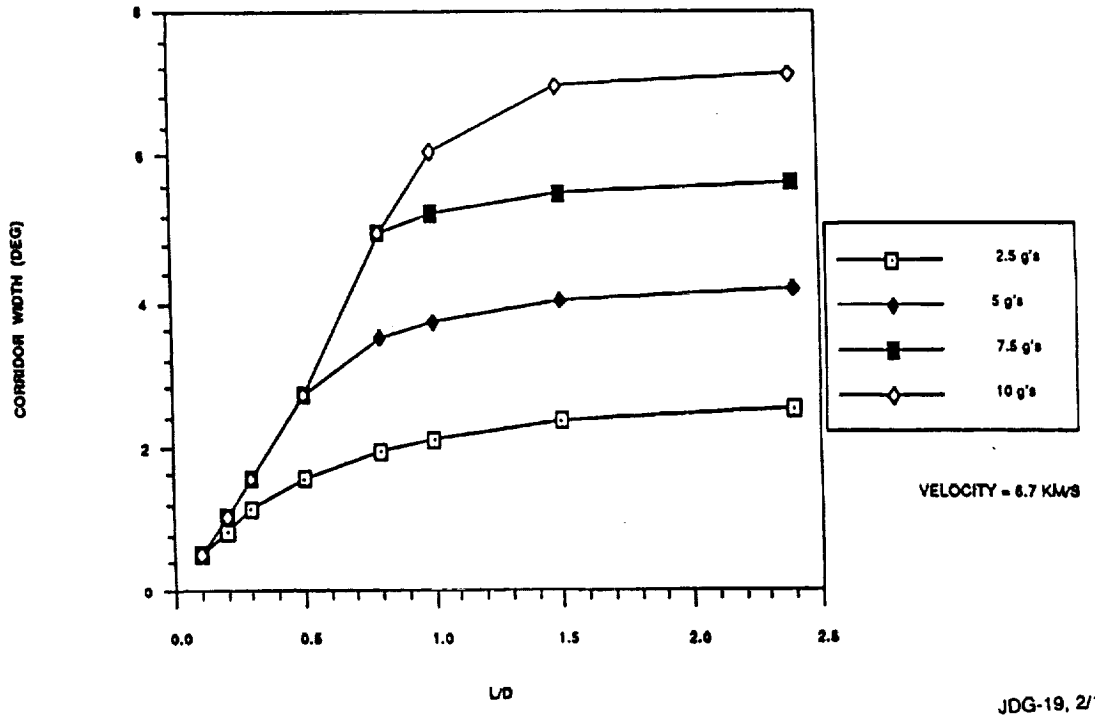


VELOCITY = 6.7 KM/S

JDG-18, 2/1/89

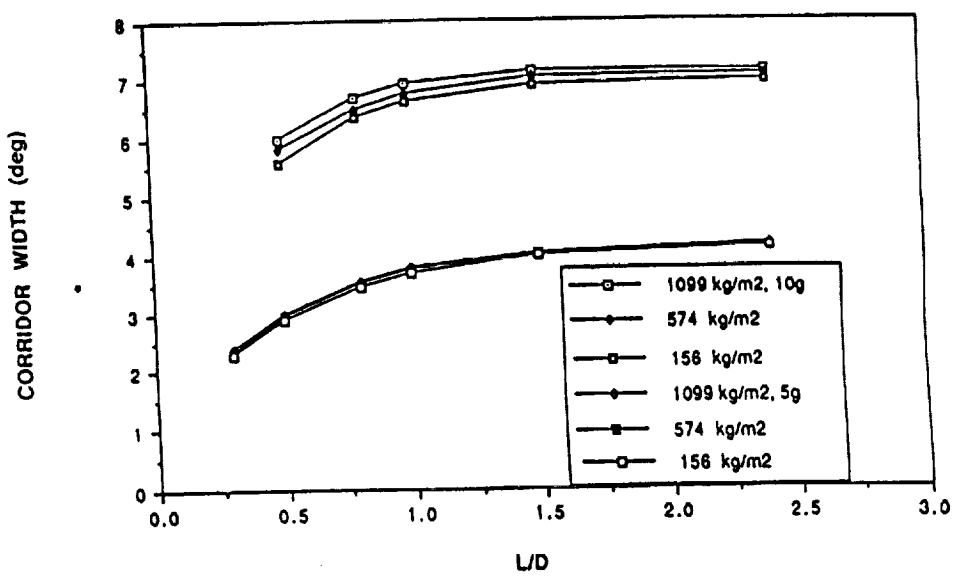
AEROCAPTURE CORRIDOR WIDTH

1 SOL ORBIT (33800 KM)



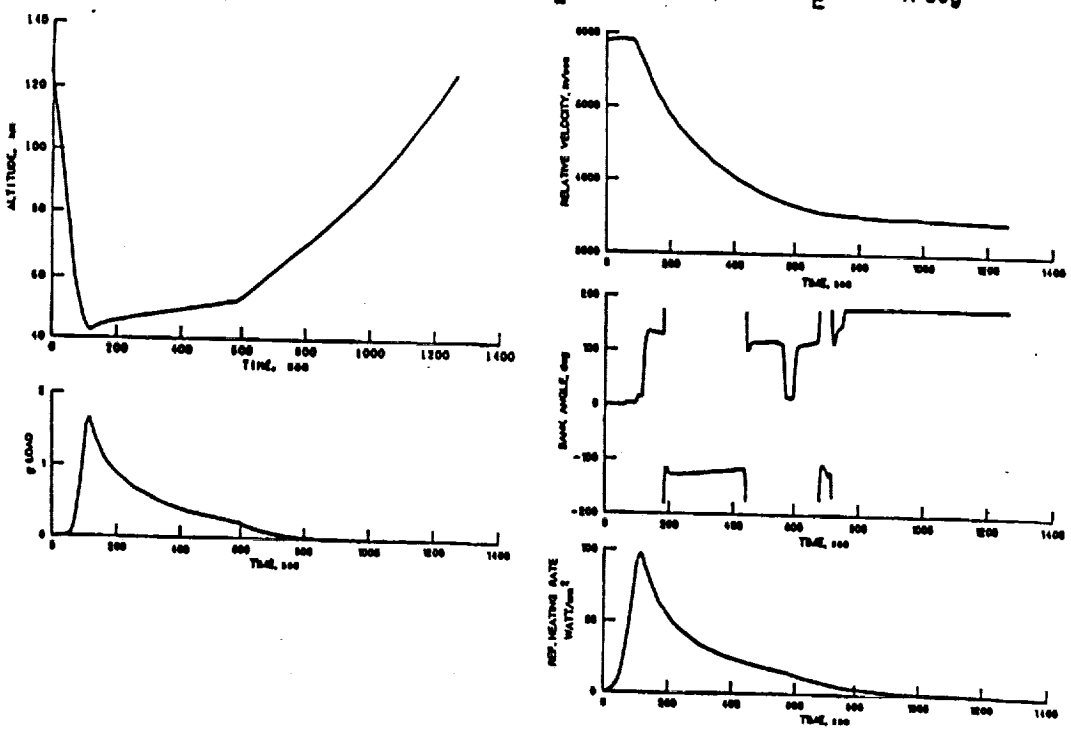
JDG-19, 2/1/89

EFFECT OF BALLISTIC COEFFICIENT ON CORRIDOR WIDTH



JDG-20, 2/1/89

TYPICAL MARS AEROCAPTURE TRAJECTORY FOR L/D = 1.0, M/C_DA = 400 kg/m^2
CAPTURE TO 500 km CIRCULAR ORBIT, V_E = 6 km/sec, $GAMMA_E$ = -11 deg

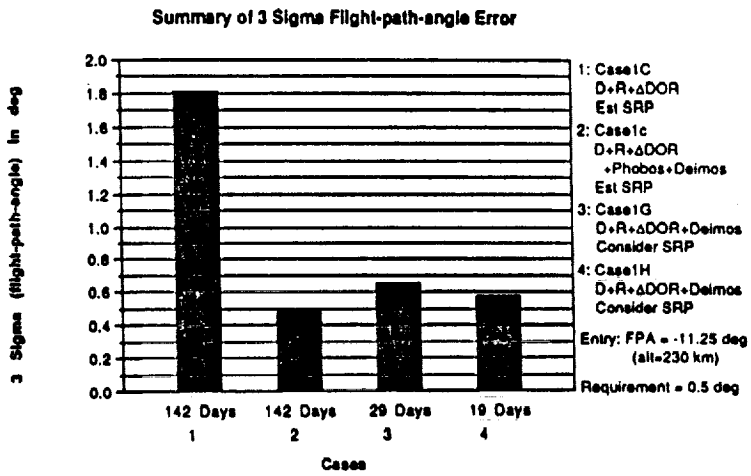


JDG-21, 2/1/89

MARS APPROACH NAVIGATION

- RADIOMETRIC NAVIGATION USING DSN WILL PROVIDE MARS APPROACH ACCURACY IN FLIGHT PATH ANGLE OF APPROXIMATELY +/- 2 DEGREES.
- ADDITION OF OPTICAL NAVIGATION USING SIGHTINGS ON PHOBOS AND DEMOS IMPROVES ACCURACY TO APPROXIMATELY +/- 0.5 DEGREE.

JDG-22, 2/1/89

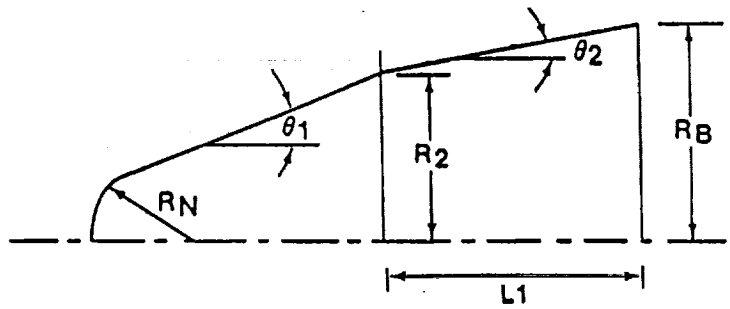


JDG-23, 2/1/89

MRSR AEROCAPTURE CONFIGURATION

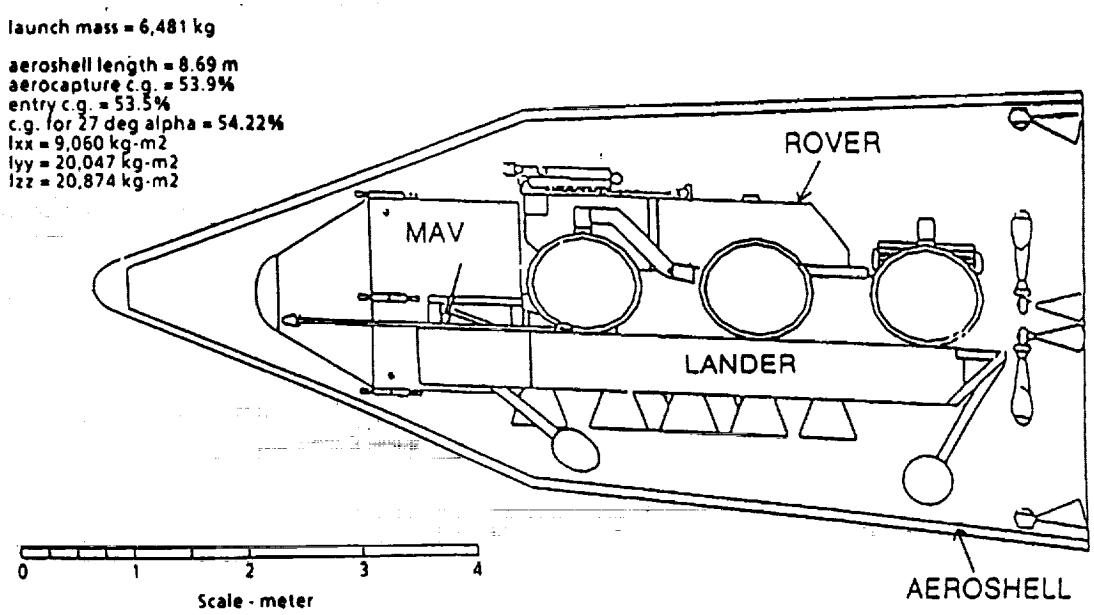
- CONFIGURATIONS WITH L/D OF 0.3 TO 2.4 WERE CONSIDERED DURING THE PRE PHASE A STUDY.
- COMPROMISE BETWEEN L/D REQUIREMENTS AND PACKAGING CONSIDERATIONS LED TO CHOICE OF L/D OF 0.6 TO 1.0.
- A SYMMETRIC BICONIC WAS CHOSEN AS THE BASELINE AEROCAPTURE CONFIGURATION.
  - BASE DIAMETER OF 15 FT BASED ON TITAN IV PAYLOAD FAIRING.
  - CONE ANGLES OF 4 AND 23.9 DEGREES BASED ON FAIRING, L/D AND PACKAGING CONSIDERATIONS.
  - NOSE RADIUS OF 1.0 FT FOR HIGHER L/D. LARGER RADIUS DESIRABLE FOR PACKAGING.

JDG-24, 2/1/89



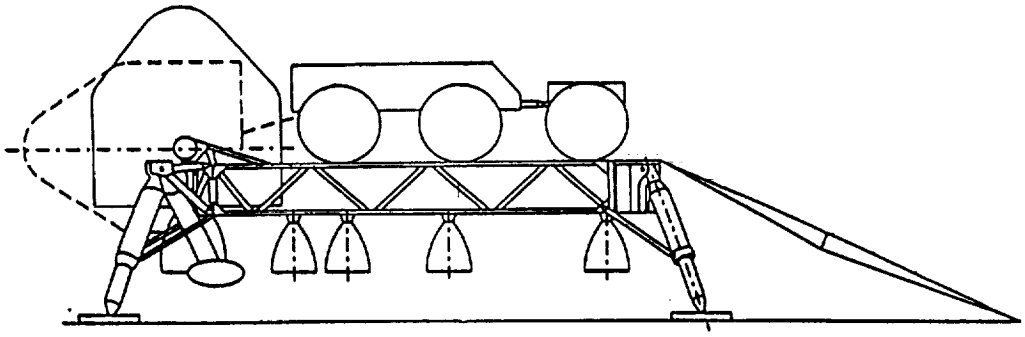
Configuration definition.

JDG-25, 2/1/89



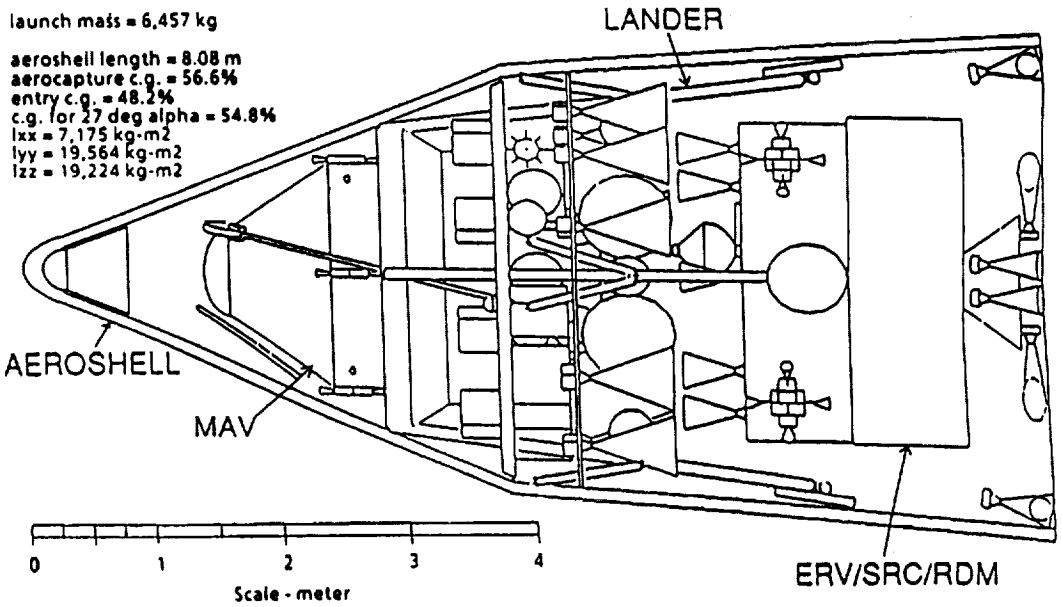
Configuration D1 areal side view.

JDG-26, 2/1/89



Conf. D1 areal deployed lander.

JDG-27, 2/1/89



Configuration B1 A/D side view.

JDG-28, 2/1/89

SEGMENT	MASS, KG					
	D1 LOCAL	B1 A/D	D1 AREAL	B2 HEAVY	B2 AREAL	B1 A/P
LANDED PAYLOAD	2151	1862	2978	1820	1162	1862
LANDED MASS	3002	2519	3829	2760	1978	2519
MASS AT CHUTE DEPLOY	4216	3787	5122	3761	2854	3789
ENTRY MASS	4442	4049	5566	4313	3356	4051
INJECTED MASS	4955	6215	6208	6219	5009	6349
LAUNCH MASS	5173	6457	6481	6467	5207	6595

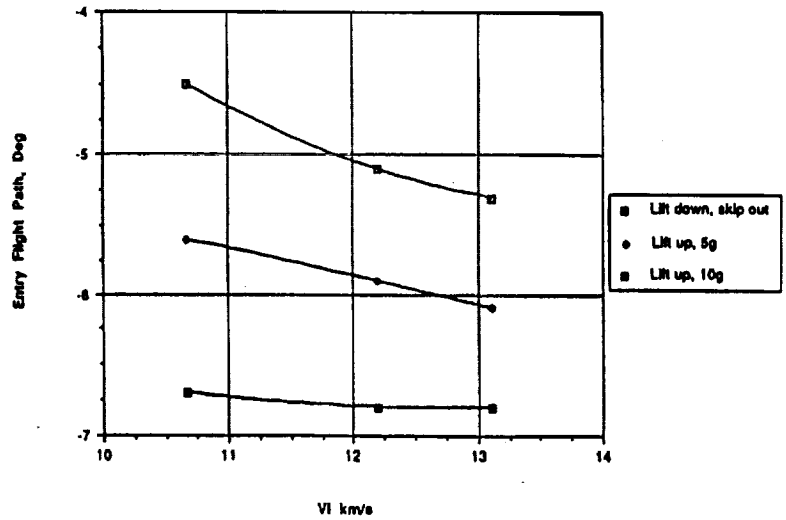
SUMMARY OF CONFIGURATION MASS

JDG-29, 2/1/89

EARTH RETURN CONFIGURATIONS

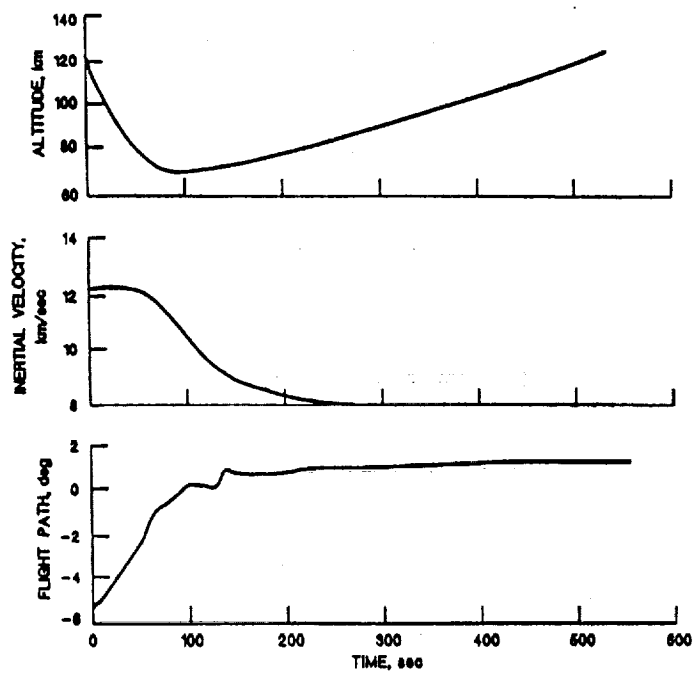
- BOTH AEROCAPTURE AND DIRECT ENTRY ARE BEING CONSIDERED FOR THE SAMPLE RETURN CAPSULE.
- TWO L/D CONFIGURATIONS WERE CONSIDERED FOR THE SAMPLE RETURN CAPSULE.
  - 0.3 L/D SCALED DOWN APOLLO CAPSULE.
  - 1.0 L/D SYMMETRICAL BICONIC.
- APOLLO CONFIGURATION WAS SELECTED AS BASELINE.
  - PERFORMANCE APPEARS ADEQUATE FOR MRSR REQUIREMENTS.
  - MRSR RETURN CONDITIONS SIMILAR TO APOLLO LUNAR RETURN.
  - EARLY PART OF LUNAR RETURN TRAJ SIMILAR TO AEROCAPTURE
  - SUBSTANTIAL AERO AND AEROTHERMO DATA BASE EXISTS.

JDG-30, 2/1/89



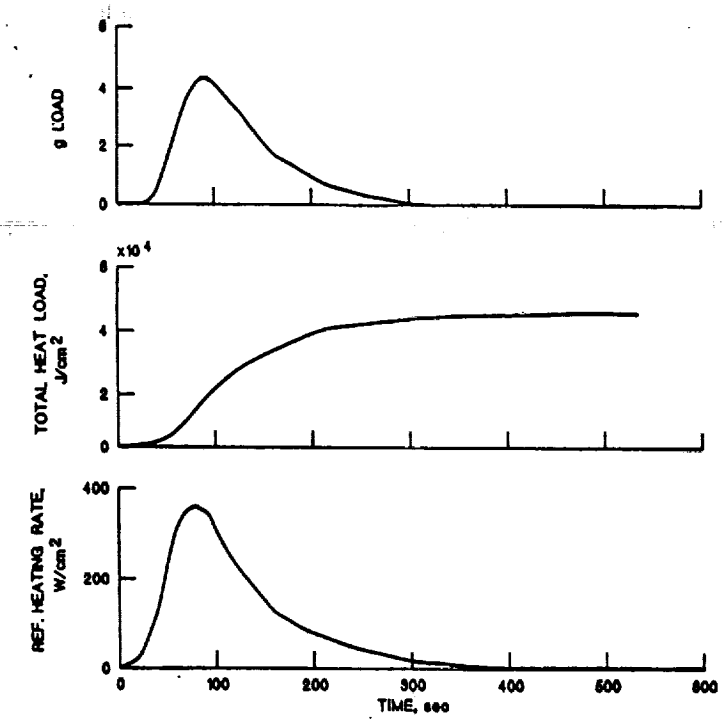
Aerobraking entry corridor, L/D = 0.3.

JDG-31, 2/1/89



Earth return nominal trajectory - aerobraking.

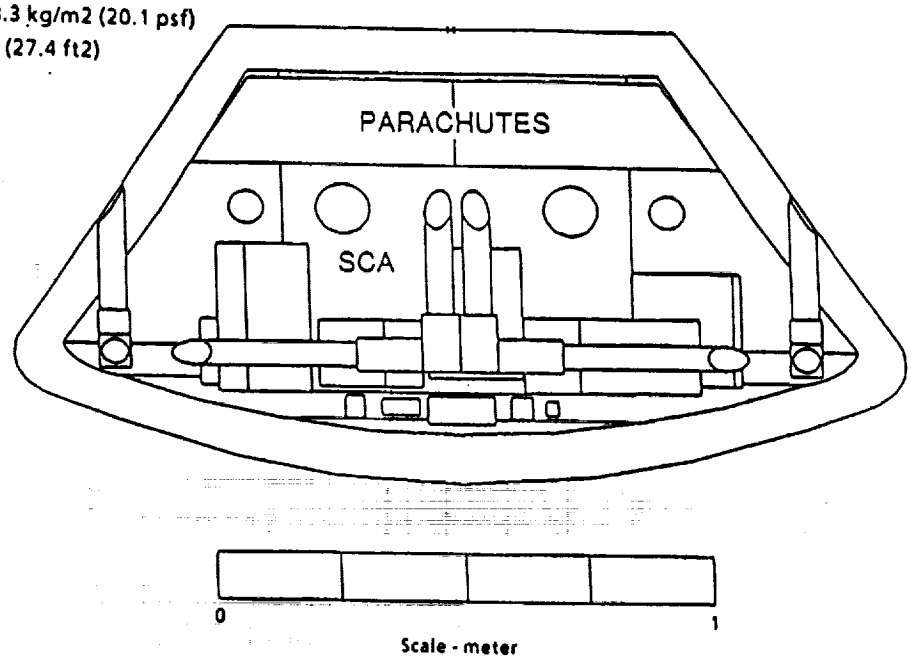
JDG-32, 2/1/89



Earth return nominal trajectory - aerobraking.

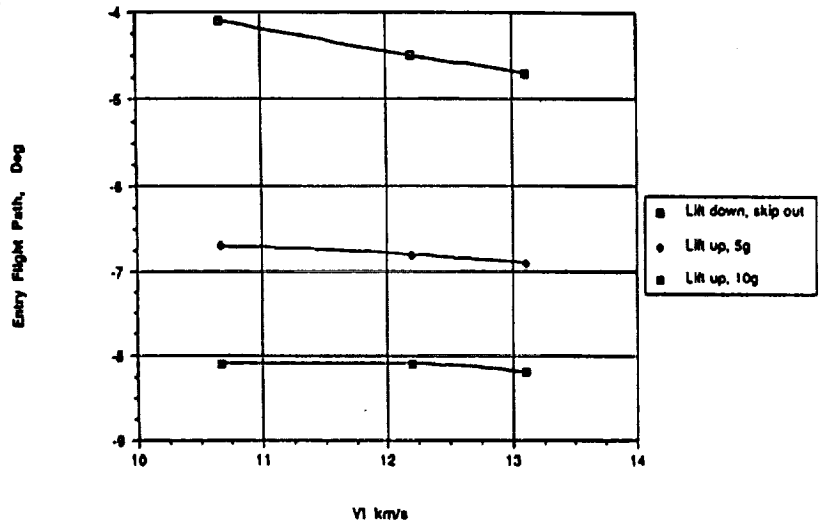
JDG-33, 2/1/89

Weight = 329 kg (725 lbs)
W/CDA = 98.3 kg/m2 (20.1 psf)
A = 2.54 m2 (27.4 ft2)
L/D = 0.3



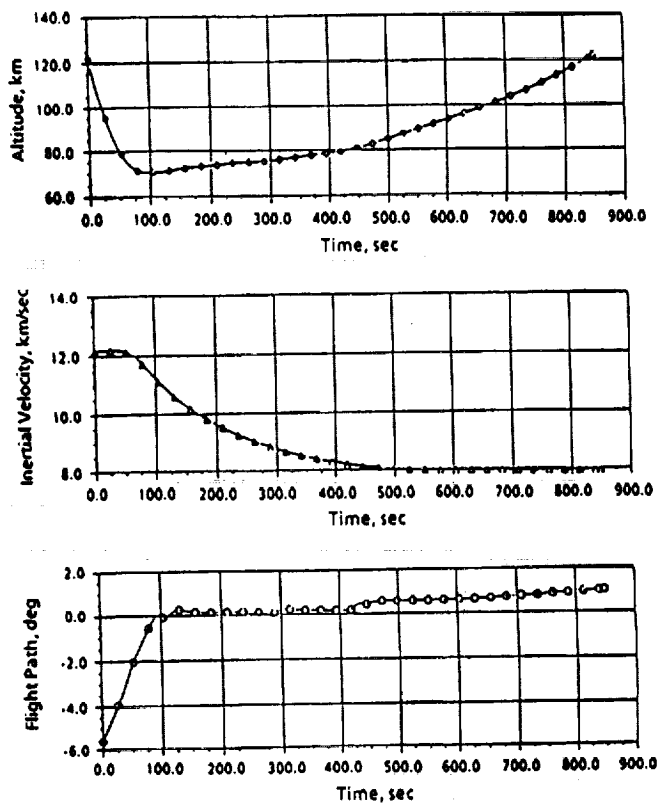
Direct entry SRC side view.

JDG-34, 2/1/89



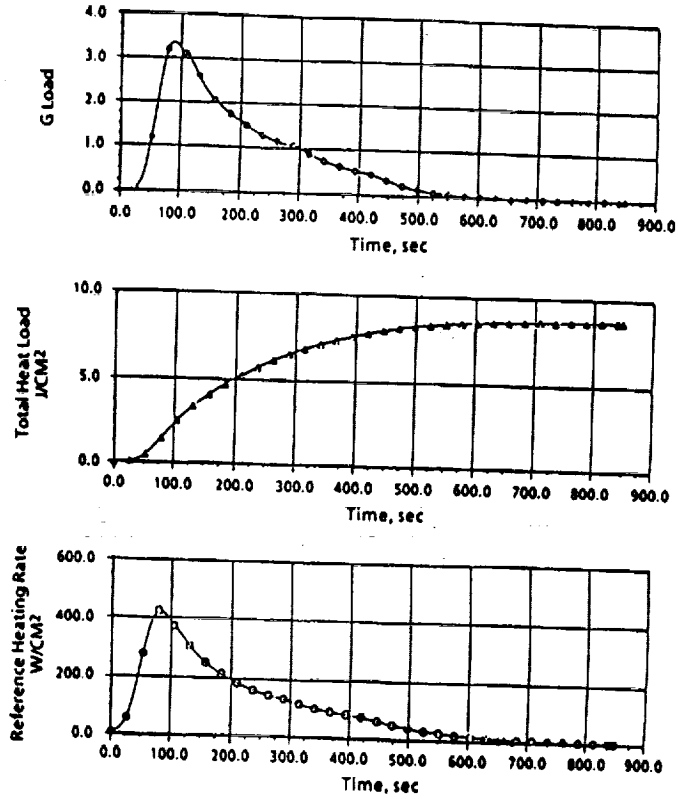
Aerobraking entry corridor, L/D = 1.0.

JDG-35, 2/1/89



Earth return nominal trajectory - aerocapture, L/D = 1.0.

JDG-36, 2/1/89



Earth return nominal trajectory - aerocapture, L/D = 1.0.

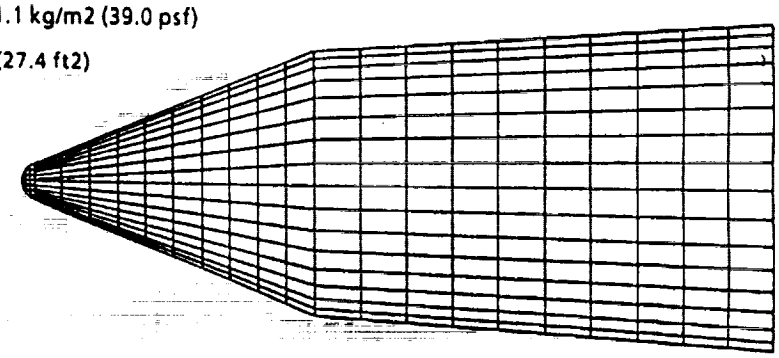
JDG-37, 2/1/89

Weight = 329 kg (725 lbs)

W/CDA = 191.1 kg/m2 (39.0 psf)

A = 2.54 m2 (27.4 ft2)

L/D = 1.0



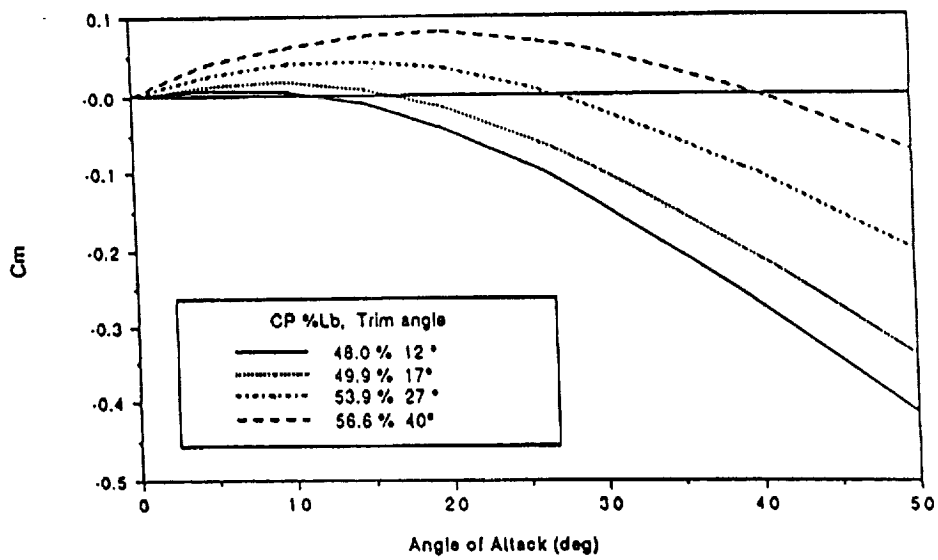
Biconic sample return capsule.

JDG-38, 2/1/89

MRSR AERODYNAMICS CONSIDERATIONS

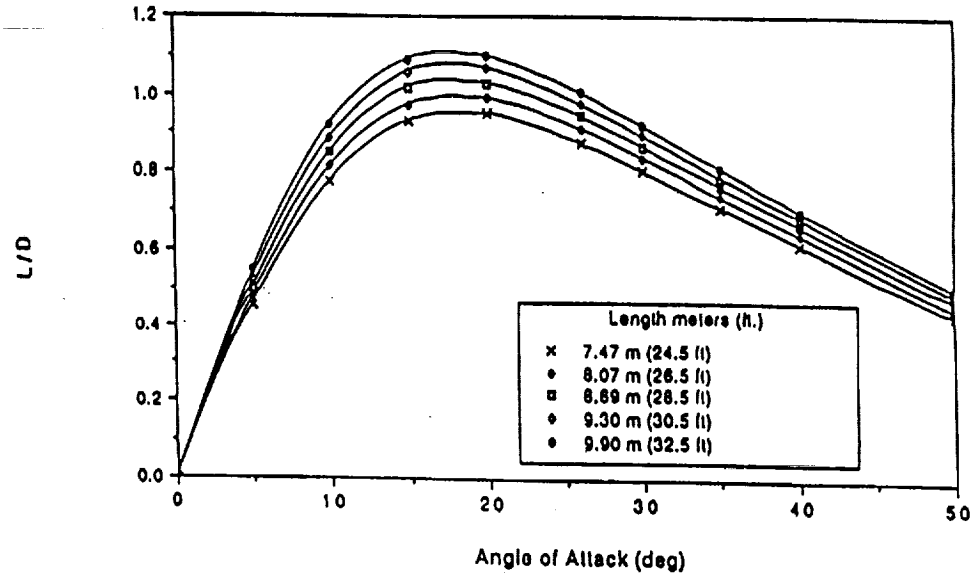
- LONGITUDINAL AND LATERAL DIRECTIONAL STABILITY CHARACTERISTICS FAVOR HIGHER ANGLE OF ATTACK FOR BICONIC AEROCAPTURE CONFIGURATION.
- CG PACKAGING CONSIDERATIONS ALSO FAVOR HIGHER ANGLE OF ATTACK.
- LOWER BALLISTIC COEFFICIENT AT HIGHER ANGLE OF ATTACK RESULTS IN LOWER HEATING RATE, BUT MAY INCREASE TOTAL HEAT LOAD.
- MARS THIN ATMOSPHERE RESULTS IN REQUIREMENT FOR PARACHUTE DEPLOYMENT AT MACH 2-3, SO SUBSONIC AND TRANSONIC AERODYNAMICS ARE NOT A CONCERN FOR MRSR.
  - PRELIMINARY AERODYNAMIC DESIGN HAS BEEN BASED ON NEWTONIAN AERODYNAMICS.
  - BICONIC AERO CHARACTERISTICS IN THE MACH 2-5 RANGE STILL NEED PRELIMINARY ANALYSIS.

JDG-39, 2/1/89



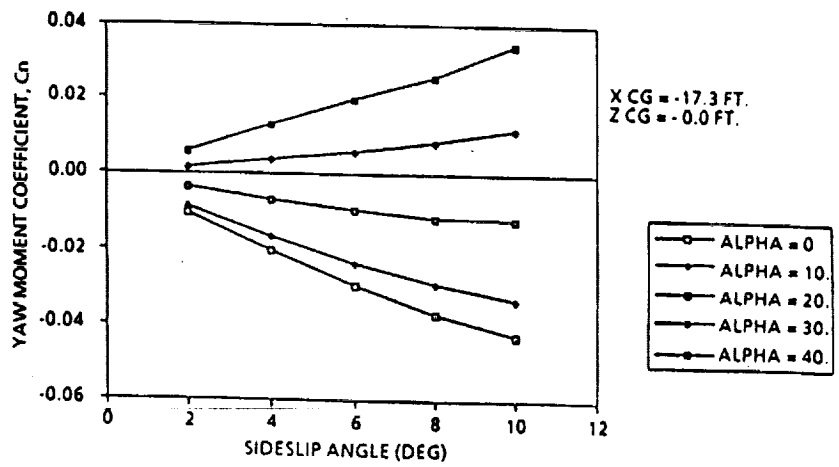
Cm vs. angle of attack
bionic M.

JDG-40, 2/1/89



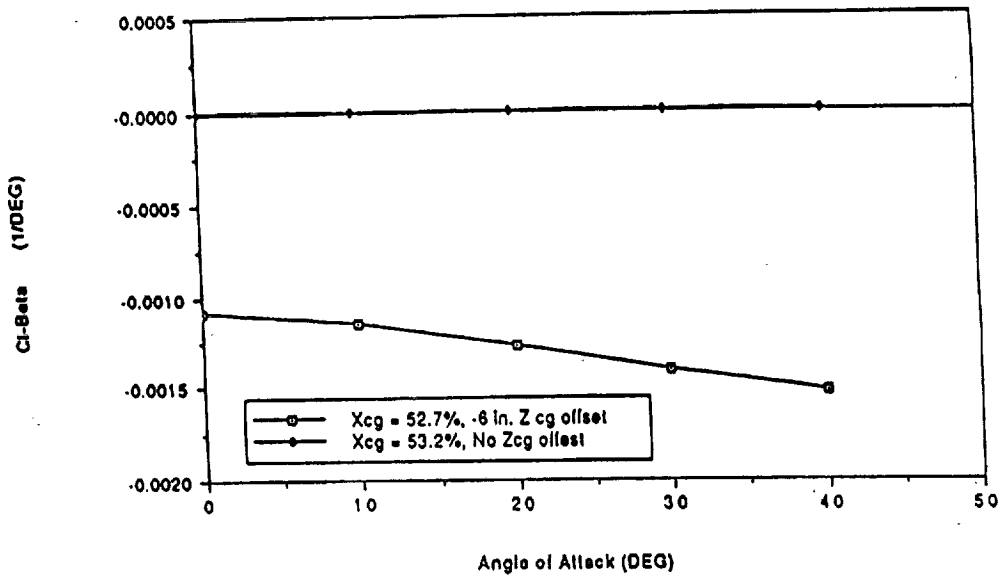
L/D vs. angle of attack
biconic M derivatives.

JDG-41, 2/1/89



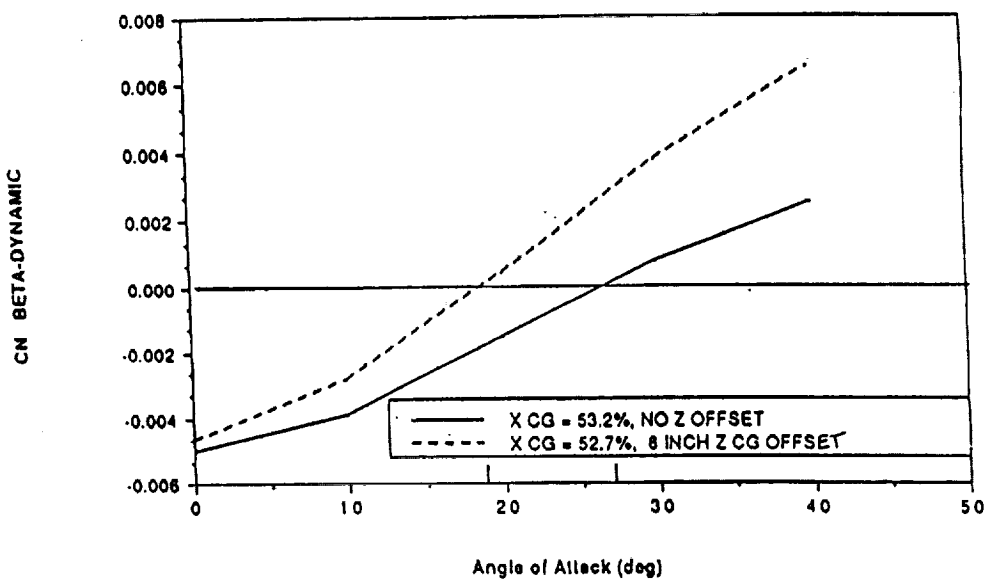
Lateral-directional stability.

JDG-42, 2/1/89



Rolling moment slopes vs. alpha
biconic M.

JDG-43, 2/1/89



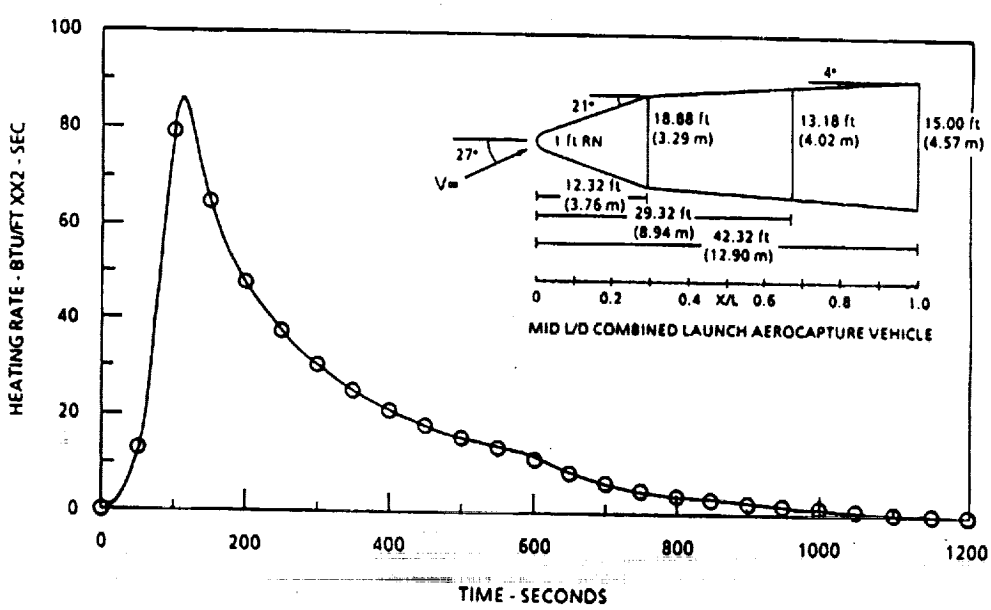
CN beta-dynamic vs. alpha
biconic M.

JDG-44, 2/1/89

AEROTHERMO/TPS CONSIDERATIONS

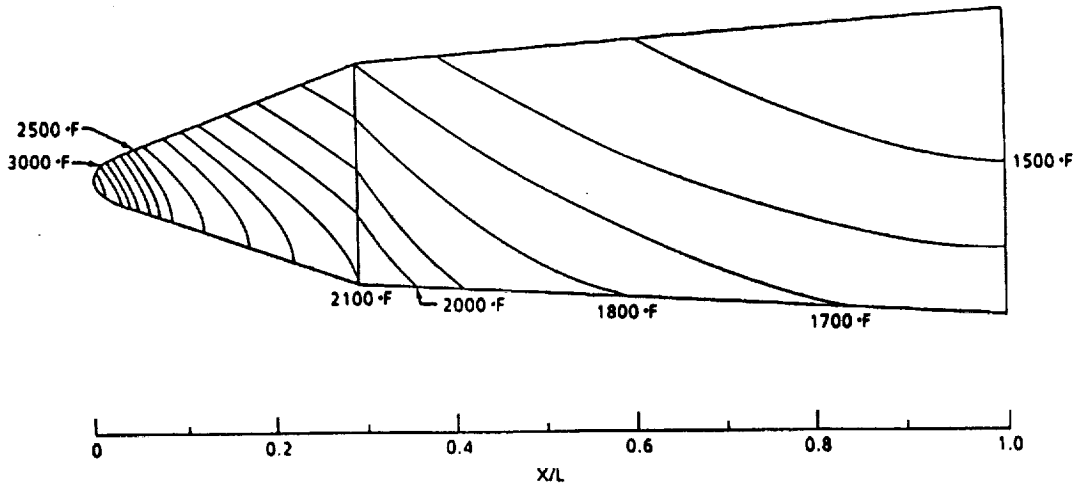
- LOW MARS APPROACH VELOCITY AND RELATIVELY SMALL VEHICLE SIZE RESULT IN FAIRLY BENIGN AEROTHERMAL ENVIRONMENT.
- EFFECT OF CO2 ATMOSPHERE HAS TO BE DETERMINED.
- SMALL MASS MARGINS FOR MRSR EMPHASIZE NEED TO MINIMIZE TPS AND STRUCTURAL MASS.
  - PRELIMINARY RESULTS INDICATE POTENTIAL FOR TAILORING AEROCAPTURE TRAJECTORY TO MAINTAIN LAMINAR BOUNDARY LAYER. TPS MASS SAVINGS OF 200+ kg.
  - USE OF COMPOSITE MATERIALS FOR AEROSHELL STRUCTURE OFFER POTENTIAL FOR 400 kg OR MORE MASS SAVINGS.
- DISSIPATION OF RTG HEAT (10-12 kw) DURING AEROCAPTURE AND ENTRY IS A MAJOR CONCERN. MAINTAINING SAMPLE AT - 40 DEGREES DURING EARTH RETURN AND AEROCAPTURE IS A CONCERN.

JDG-45, 2/1/89



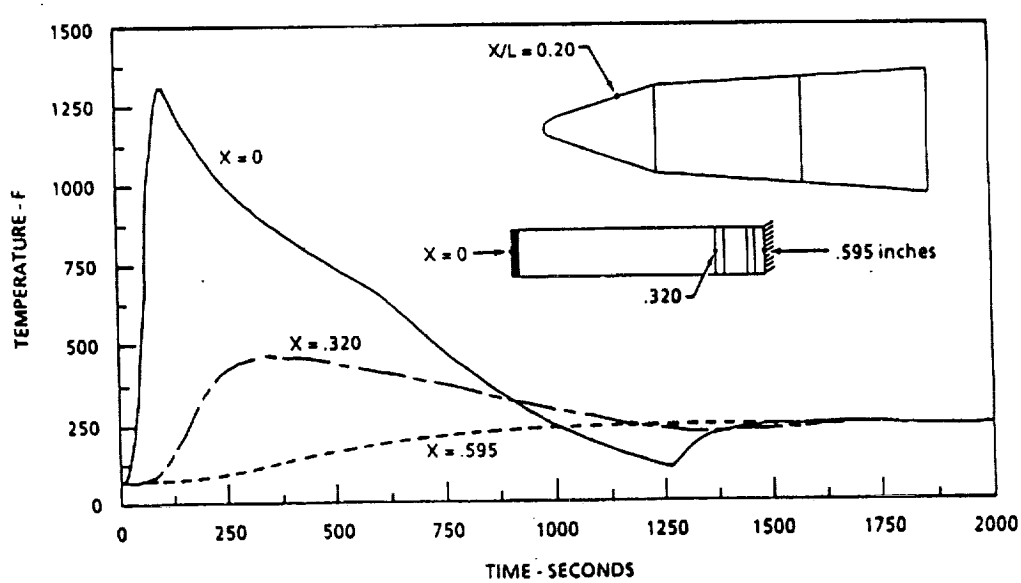
MRSR reference heating - Earth to Mars aerobrake.

JDG-46, 2/1/89



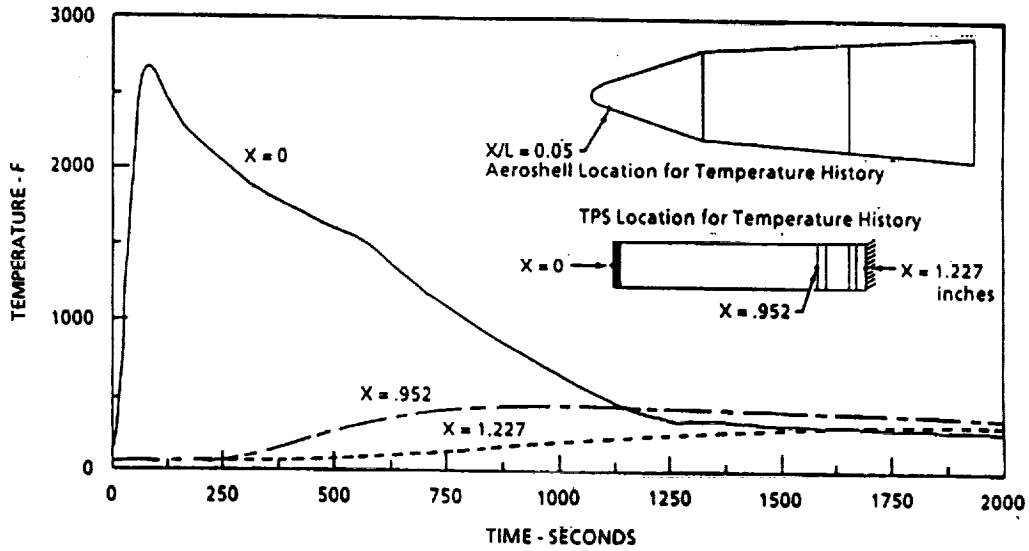
Peak isotherms Mars aerocapture.

JDG-47, 2/1/89



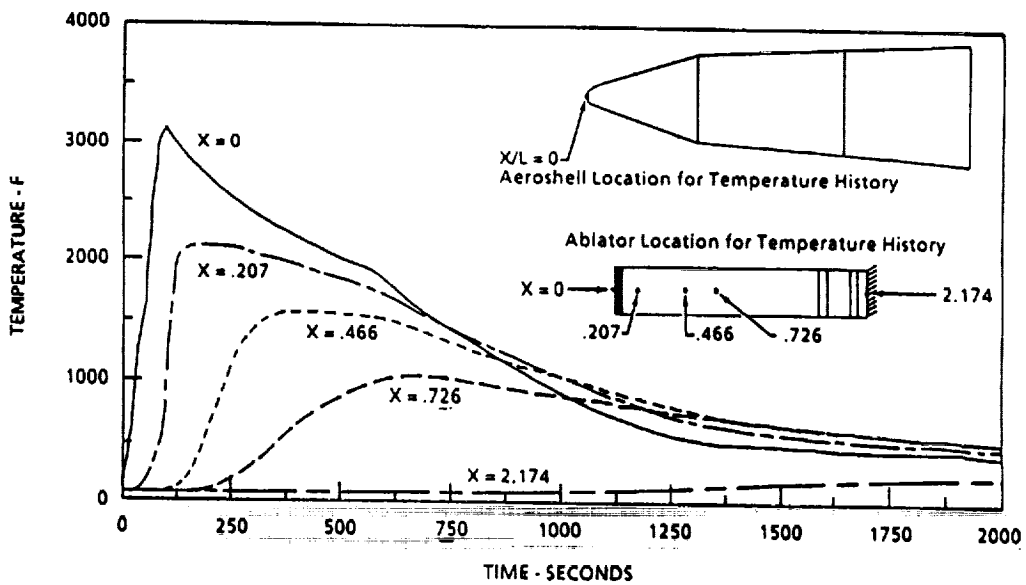
MRSR - Earth to Mars aerobrake - upper surface X/L = 0.20 - temperature time history of HRSI surface, HRSI/SIP interface, and aluminum backwall for 2,000 seconds.

JDG-50, 2/1/89



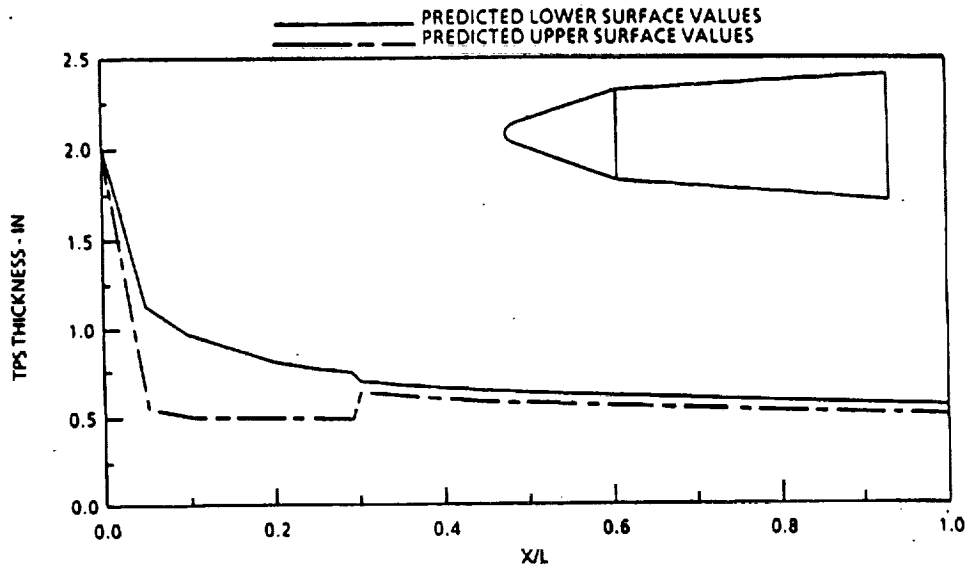
MRSR - Earth to Mars aerobrake - lower surface X/L = 0.05 - temperature time history of HRSI surface, HRSI/SIP interface, and aluminum backwall for 2,000 seconds.

JDG-49, 2/1/89



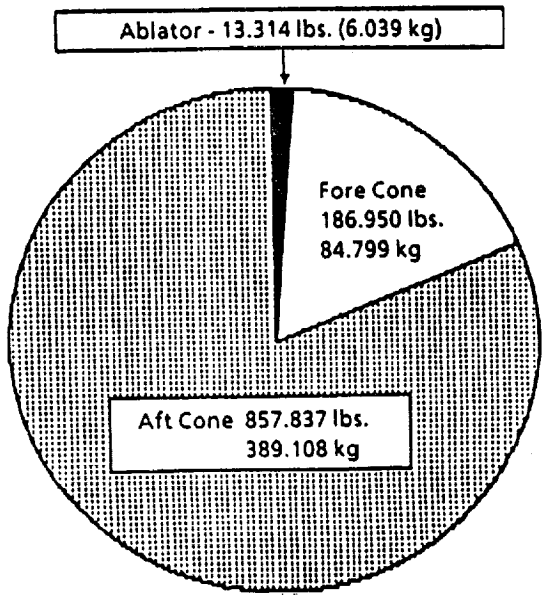
MRSR - Earth to Mars aerobrake - ablator temperature time history at the surface, three interior nodes, and aluminum carrier plate backwall.

JDG-48, 2/1/89



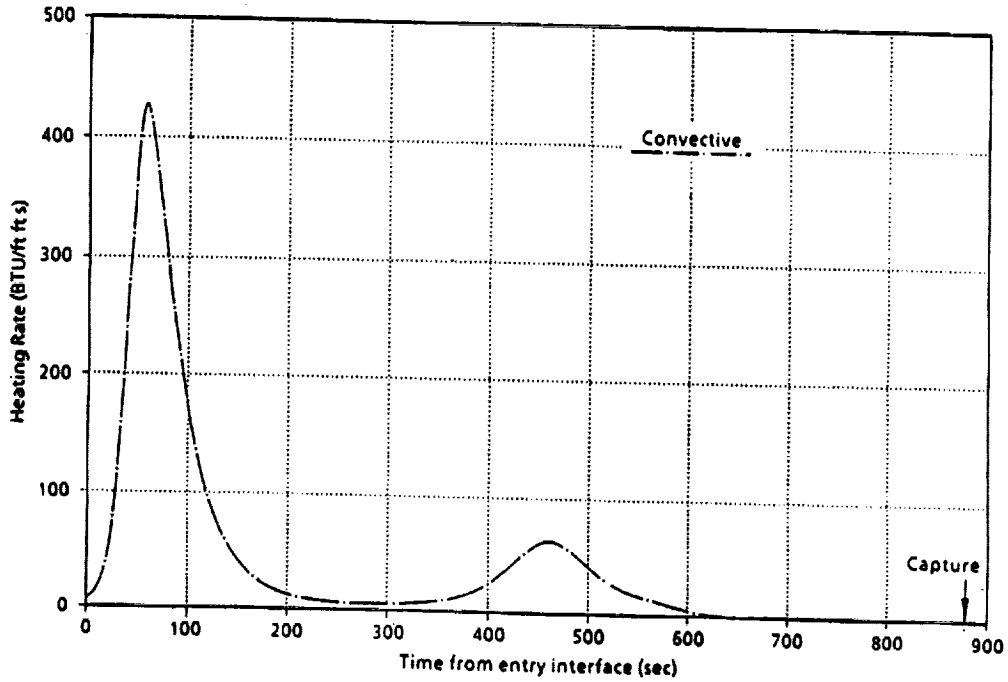
MRSR - Earth to Mars aerobrake - upper and lower centerline TPS thickness versus X/L.

JDG-51, 2/1/89



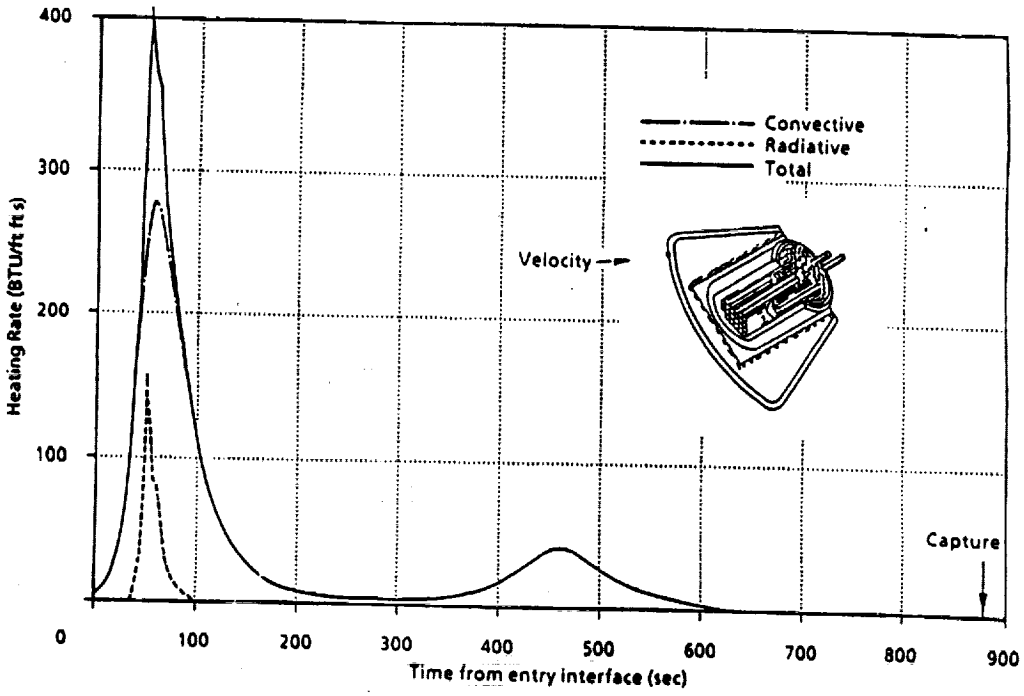
MRSR - TPS weight distribution - Mars aerocapture, preliminary design.

JDG-52, 2/1/89



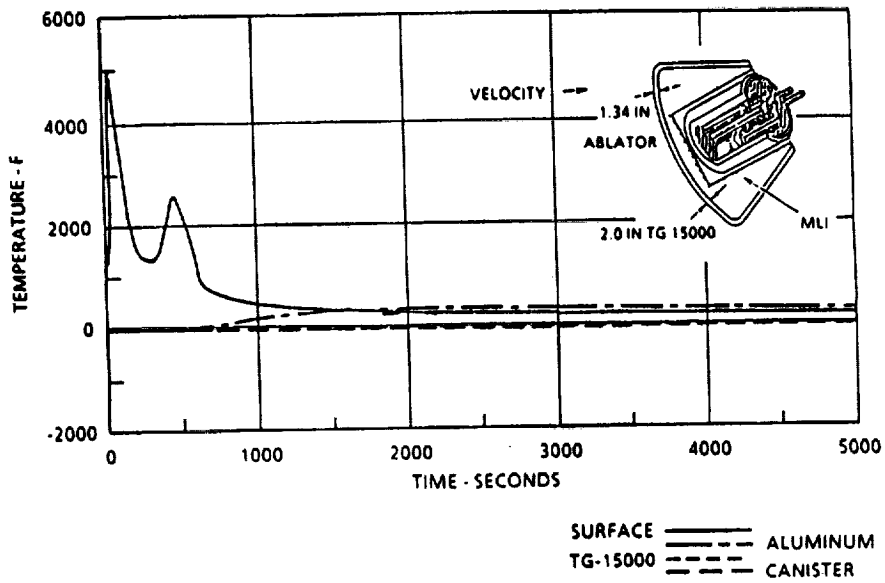
- Reference heating rate on a 1-ft sphere for SRC direct entry.

JDG-53, 2/1/89



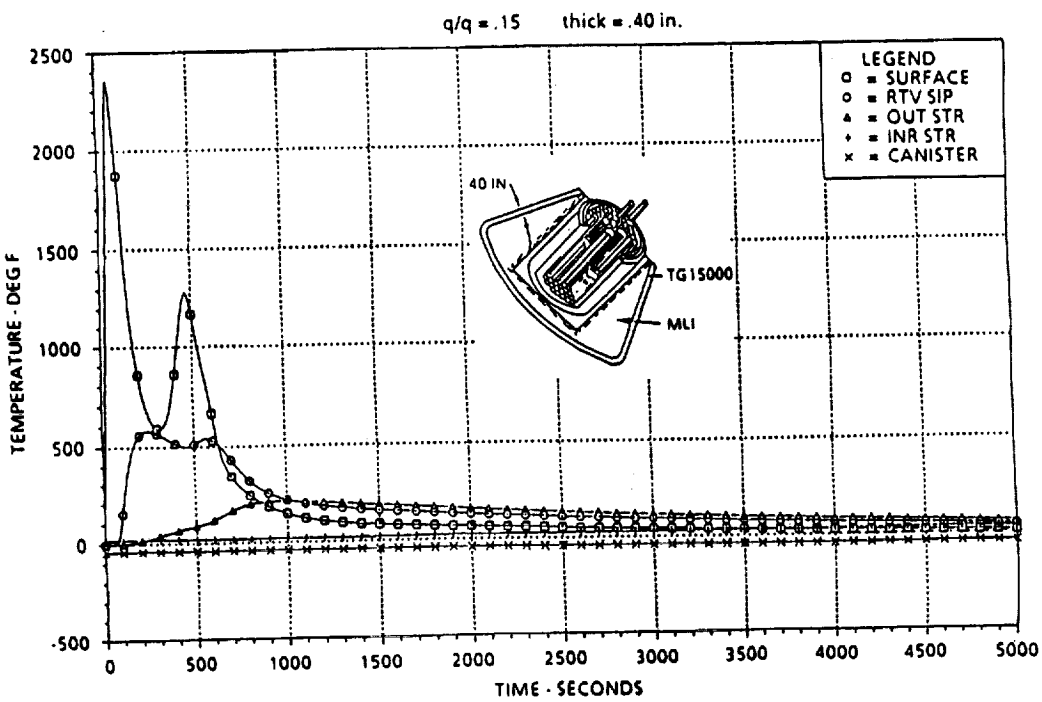
- Stagnation point heating rate for SRC direct entry.

JDG-54, 2/1/89



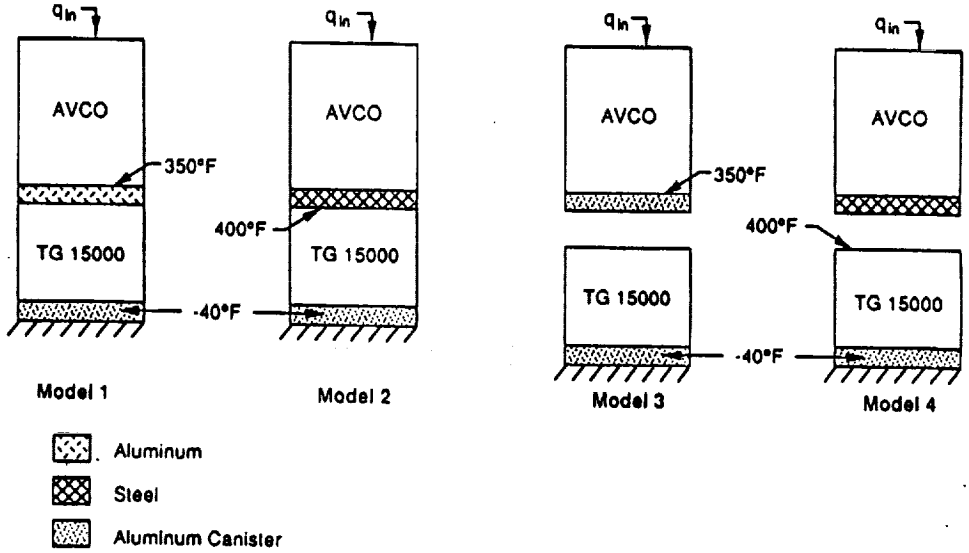
Temperature history for body point 1.

JDG-55, 2/1/89



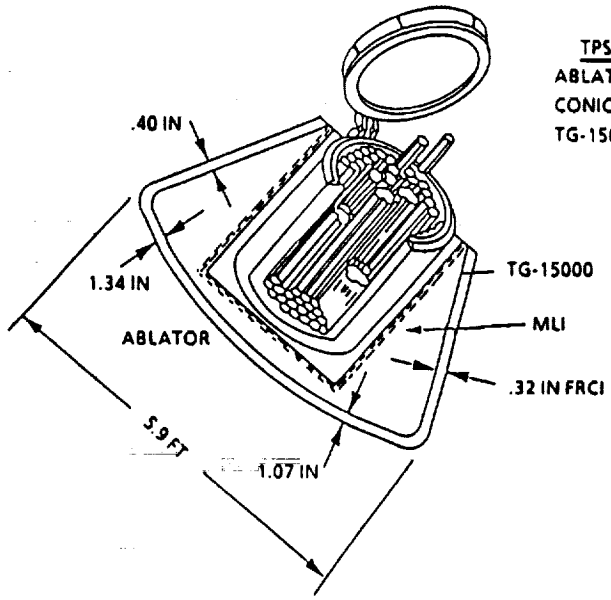
Typical tile configuration.

JDG-56, 2/1/89



Sketch of the thermal models.

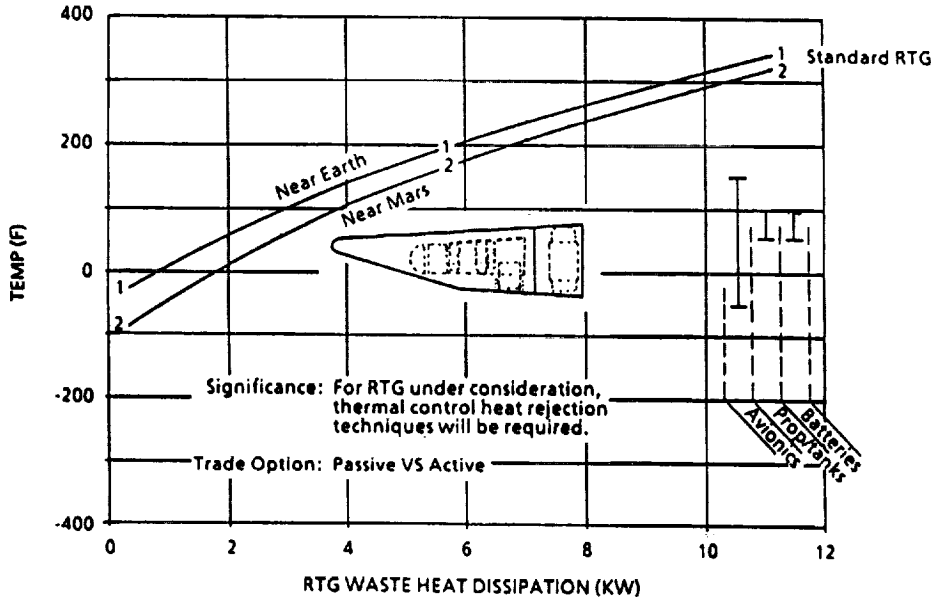
JDG-57, 2/1/89



TPS COMP	WEIGHT, LB
ABLATOR	119.0
CONIC FRCI	25.2
TG-15000 AND MLI	43.8
	178.0

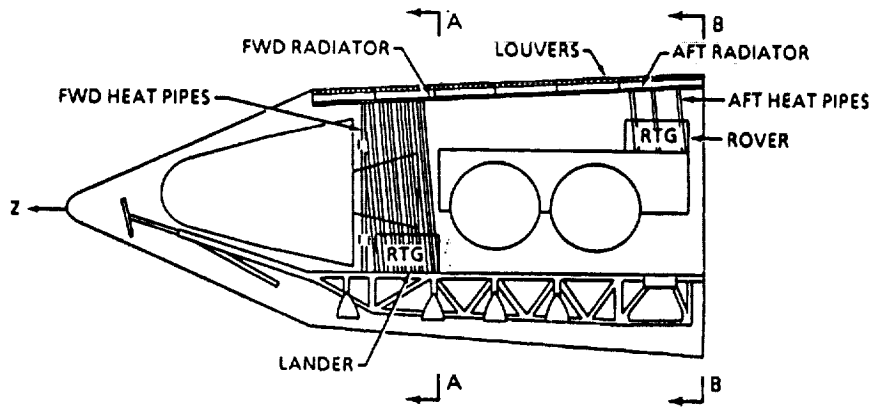
Preliminary TPS design for direct earth entry.

JDG-58, 2/1/89



· Representative transit thermal environment of MLM system, structure, components.

JDG-59, 2/1/89



Configuration D1 - cruise phase.

JDG-60, 2/1/89

MATERIAL	TOTAL	PAYLOAD	STRUCTURE	RINGS	STRINGERS	SKIN	P/L SUPPORT
AL-6061-T6	5583	4855	728	257	19	292	161
BE-38-AL	5466	4855	610	215	15	245	135
TI-6AL-4V	5175	4855	320	113	8	128	70
50V/OB 6061AL	4962	4855	106	38	3	43	23

Mass Summary for 5 G Entry Load Case (masses in kilograms)

MATERIAL	TOTAL	PAYLOAD	STRUCTURE	RINGS	STRINGERS	SKIN	P/L SUPPORT
AL-6061-T6	6644	4855	1789	964	61	292	473
BE-38-AL	6356	4855	1501	809	51	245	396
TI-6AL-4V	5642	4855	787	424	27	128	208
50V/OB 6061AL	5117	4855	261	141	9	43	69

Mass Summary for 10 G Entry Load Case (masses in kilograms)

JDG-61, 2/1/89

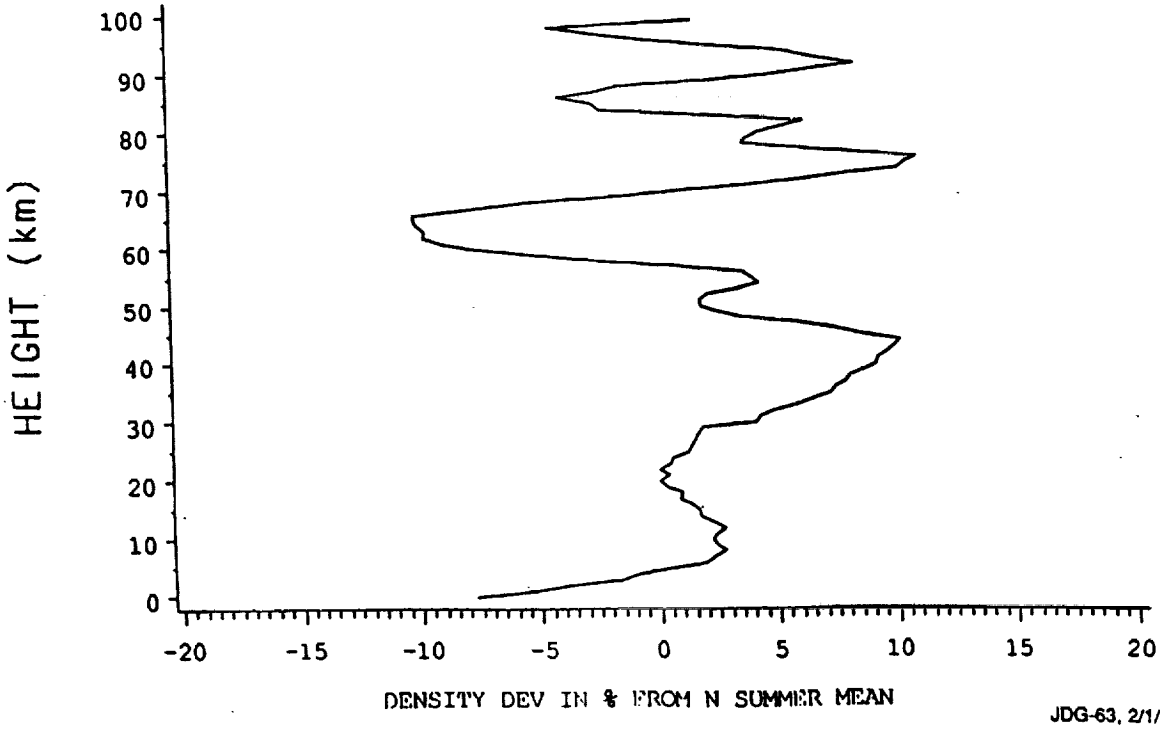
MARS ATMOSPHERE CONSIDERATIONS

- UNCERTAINTY IN MARS ATMOSPHERIC DENSITY CHARACTERISTICS IS A CONCERN.
  - SEASONAL AND LATITUDINAL VARIATIONS
  - EFFECTS OF GRAVITY WAVES, DENSITY GRADIENTS
  - EFFECT OF DUST STORMS
- BOTH VIKING ENTRY TRAJECTORYS SHOWED SIGNIFICANT WAVE STRUCTURE IN THE ATMOSPHERE
- DENSITY GRADIENTS ARE A CONCERN FOR AFE
- MARS OBSERVER WILL BE OBTAINING ATMOSPHERIC DATA
- SOME SUPPORT FOR ADDITIONAL ATMOSPHERIC MEASUREMENTS
- PRELIMINARY MARS ATMOSPHERE MODEL FOR MRSR HAS BEEN DOCUMENTED - PITTS, POLLACK, TILLMAN, ZUREK, STEWART

JDG-62, 2/1/89

MARS ATMOSPHERE DENSITY %

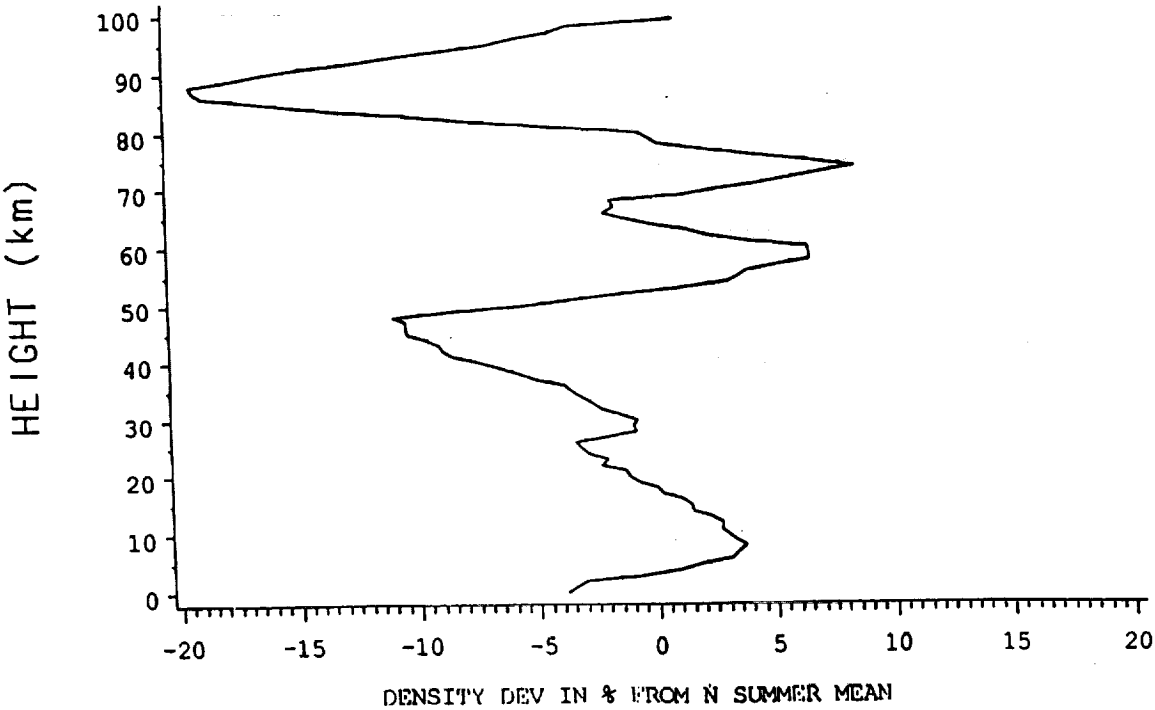
VIKING 1 ENTRY



JDG-63, 2/1/89

MARS ATMOSPHERE DENSITY %

VIKING 2 ENTRY



JDG-64, 2/1/89

MRSR TECHNOLOGY REQUIREMENTS SUMMARY

- DEVELOPMENT OF OPTICAL NAVIGATION FOR MARS APPROACH
- DEVELOPMENT OF BOUNDARY LAYER TRANSISTION CRITERIA FOR MARS AEROCAPTURE
- AEROTHERMO ANALYSIS FOR AEROCAPTURE IN MARS ATMOSPHERE
- LIGHTWEIGHT THERMAL PROTECTION SYSTEMS INCLUDING PROTECTION OF COMPOSITE STRUCTURES MATERIALS
- DEVELOPMENT OF THERMAL CONTROL SYSTEM FOR CONTROLLING RTG HEAT DURING AEROCAPTURE AND ENTRY
- ACCURATE DEFINITION OF MARS ATMOSPHERE INCLUDING DENSITY GRADIENTS
- Development of Non Catalytic Materials/Coatings for Mars Aerocapture

JDG-65, 2/1/89

JSC AEROBRAKING

GN&C EXPERIENCE

GM 2/1/89

HISTORY

PAST TO PRESENT PROGRAMS

- APOLLO LUNAR RETURN
- SHUTTLE ORBITER ENTRY
- AEROASSIST FLIGHT EXPERIMENT

STUDIES

- ORBITAL TRANSFER VEHICLE
- MARS ROVER SAMPLE RETURN

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BACKGROUND

ORGANIZATIONS

- JSC INHOUSE
  - ADVANCED PROGRAMS OFFICE
  - AVIONICS SYSTEMS DIVISION
  - MISSION PLANNING & ANALYSIS DIVISION
- LOCKHEED
- MDAC
- CSDL

EXPERTISE

- NAVIGATION ACCURACY
- NAVIGATION TECHNIQUES
- AUTONOMOUS NAVIGATION
- GUIDANCE DESIGN
- CONTROL SYSTEM DESIGN
- INTEGRATED GN&C DESIGN & ANALYSIS
- MISSION PLANNING
- RENDEZVOUS
- ANALYSIS TOOLS
- VERIFICATION TOOLS
- FAULT TOLERANT PROCESSOR DESIGN

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JSC'S ROLE IN DEVELOPING GN&C FOR AEROASSIST FLIGHT EXPERIMENT

- JSC IS DEVELOPING THE SOFTWARE GUIDANCE AND NAVIGATION REQUIREMENTS FOR ALL PHASES OF AFE FLIGHT
  - STILL CONSIDERING THREE GUIDANCE ALGORITHMS FOR AEROBRAKING:
    - NUMERICAL PREDICTOR CORRECTOR
    - ENERGY CONTROLLER
    - ANALYTICAL PREDICTOR CORRECTOR
  - NAVIGATION A KEY PROBLEM
    - AVOID EXPENSE OF STAR TRACKER ON AFE
    - MAINTAIN SMALL ERROR IN ENTRY I/F FLIGHT PATH (UNKNOWN ERROR < .04 DEG)
- REFERENCE MISSION DESIGN
- MONTE CARLO ANALYSIS
- INTEGRATED GN&C ANALYSIS
- SUPPORT VERIFICATION OF INTEGRATED SYSTEM

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PLANNED FY89 AFE GN&C ACTIVITIES

- PRELIMINARY DESIGN REVIEW - SPRING 1989
  - RELEASE SOFTWARE REQUIREMENTS DOCUMENT FOR REVIEW
  - BASELINE AEROBRAKING GUIDANCE
- STAR ALIGN MANEUVER
  - USE ORBITER STAR TRACKER TO FINE ALIGN AFE IN PAYLOAD BAY
- REFINE GN&C DESIGN FOR CDR IN FALL 1990

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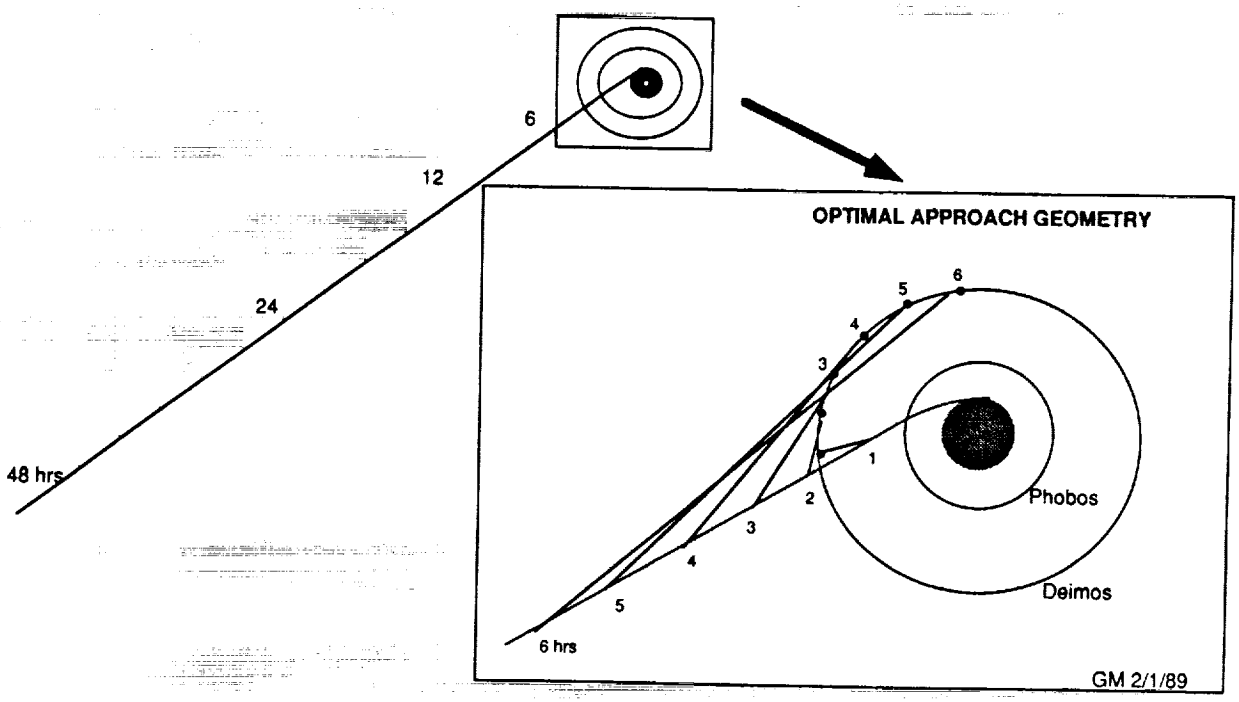
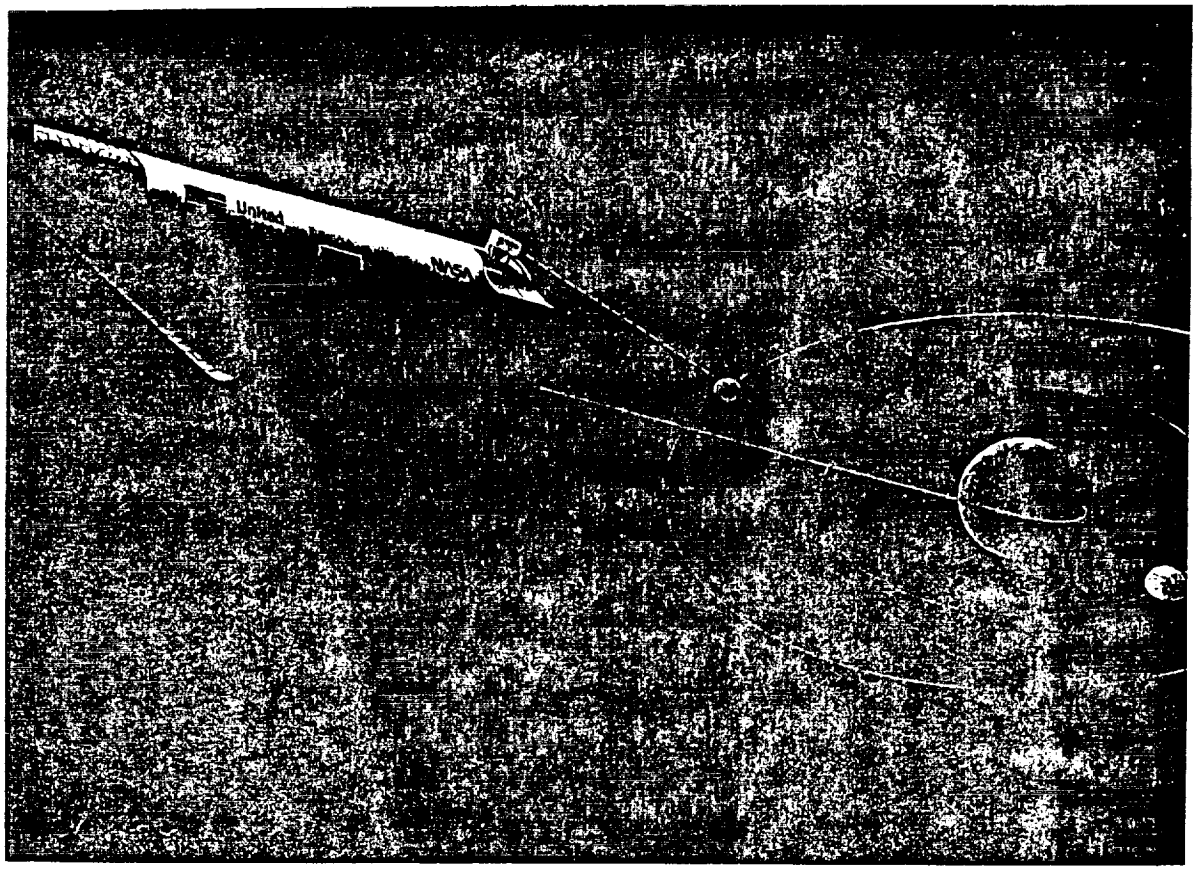
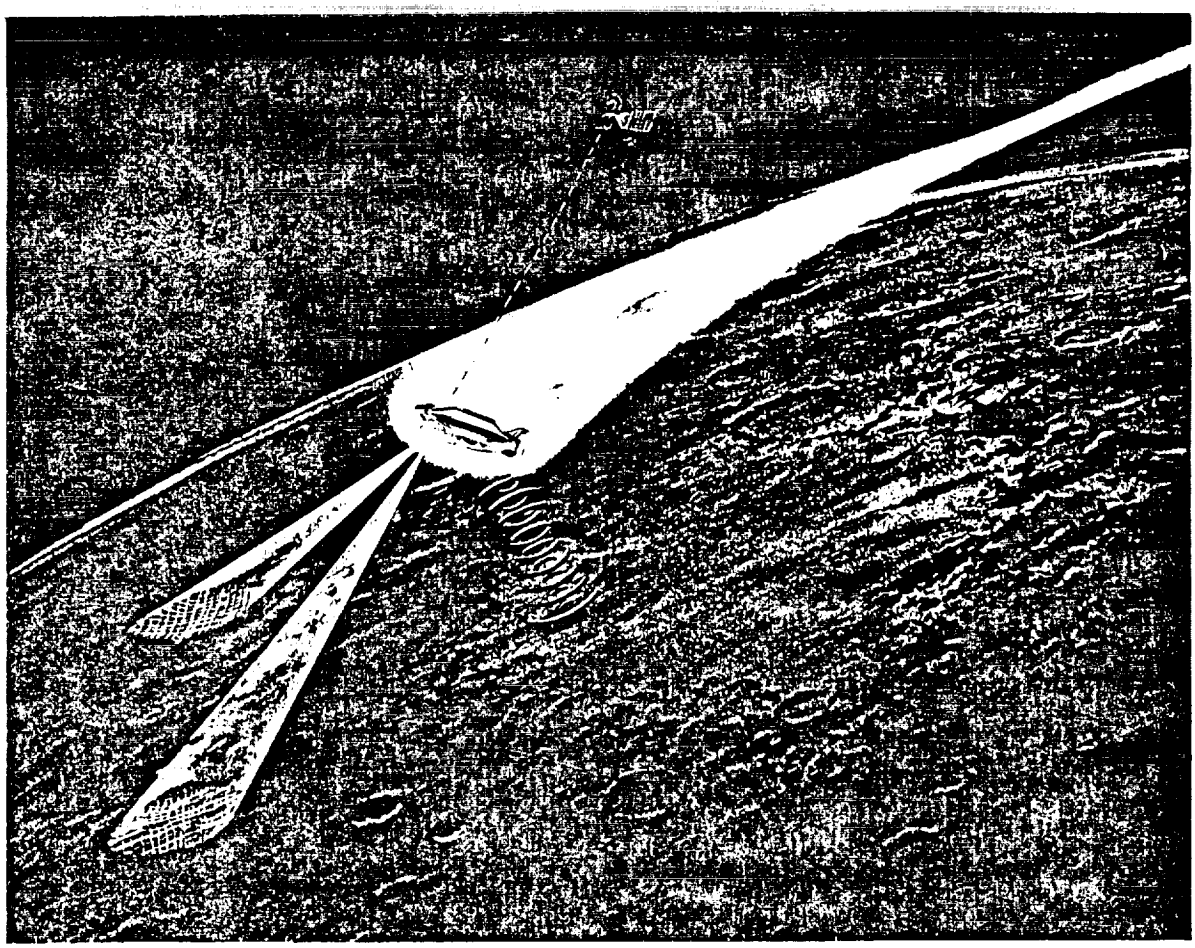
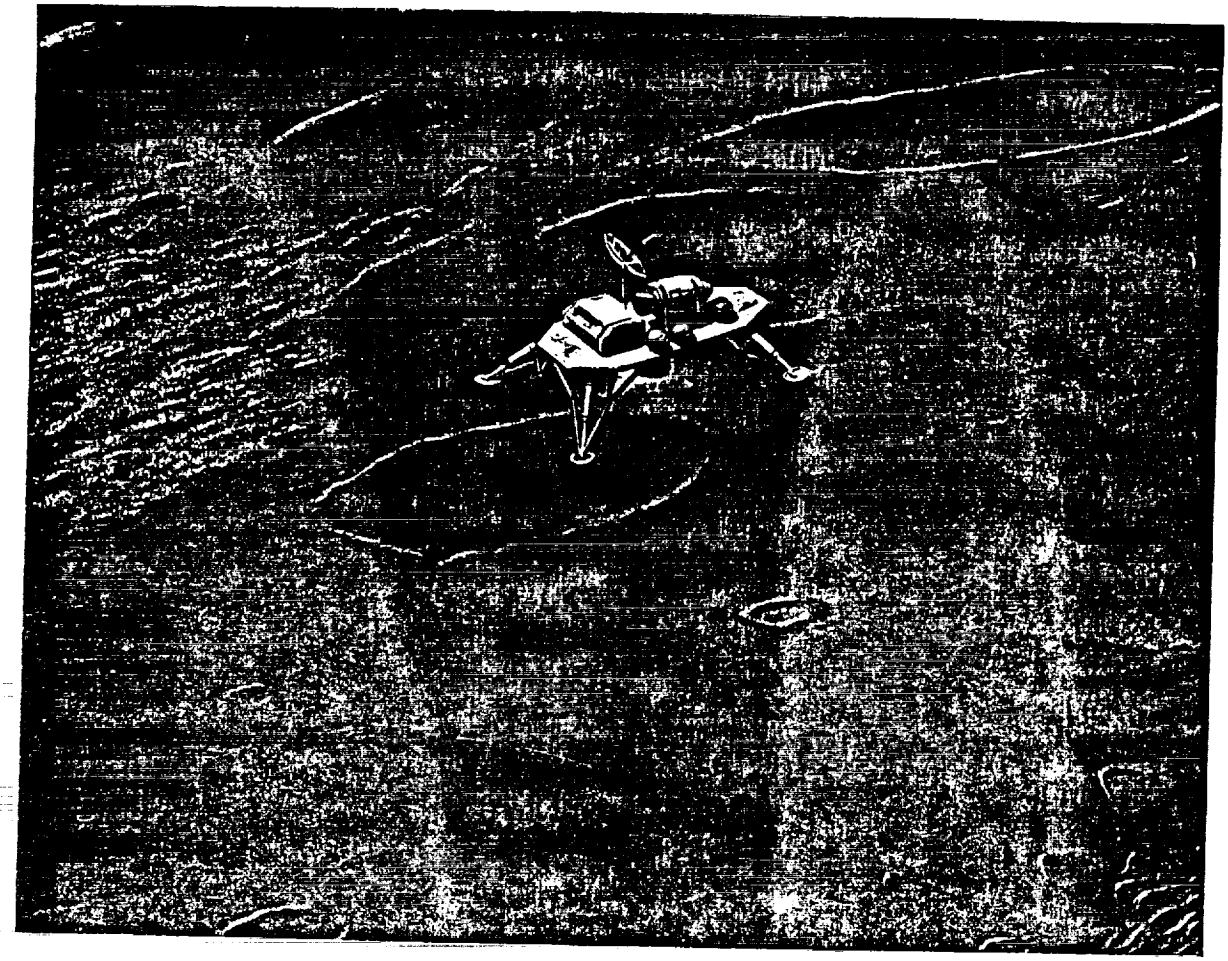
OPTICAL NAVIGATION DURING MARS APPROACH




United
NASA





JSC PLANNED FY 89 MRSR ACTIVITIES

- MARS AEROCAPTURE
  - REFINE CONFIGURATION
  - CFD RESULTS
  - NAVIGATION PERFORMANCE
  - INTEGRATION OF AEROCAPTURE AND ENTRY REQUIREMENTS
  - RISK ASSESSMENT & TECHNOLOGY READINESS
- EARTH AEROCAPTURE FOR MARS RETURN
  - GNC CONCEPTUAL DESIGN
  - CFD RESULTS
  - RISK ASSESSMENT & TECHNOLOGY READINESS

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AEROBRAKING GN&C ISSUES

- NAVIGATION ACCURACY FOR AEROCAPTURE
- ATMOSPHERIC UNCERTAINTY
- AUTONOMOUS GN&C
  - ONBOARD OPTICAL NAVIGATION
  - RETARGETING
- FAULT TOLERANCE SYSTEMS

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CONCLUDING REMARKS

- GOOD KNOWLEDGE BASE EXISTS FOR AEROBRAKING GN&C
  - AEROCAPTURE STUDIES DATE BACK TO 1960'S
  - MARS SAMPLE RETURN FY88 STUDY
  - AEROASSIST FLIGHT EXPERIMENT PROGRAM
- CHALLENGING WORK TO BE DONE
  - NAVIGATION ACCURACY AND ATMOSPHERIC UNCERTAINTIES
  - ROBUST AUTONOMOUS GN&C

GM 2/1/89

NUMERICAL SIMULATION OF AEROBRAKE FLOWFIELD AT JSC

Objectives

- present experiences and current status
- participate in a joint effort to provide vehicle aerodynamics and heating environment;
- select body configurations and free stream conditions representative of Mars and Earth entry flight;
- identify problems areas and sharing data for comparisons.

Capabilities of JSC CFD Codes

- iterative solution of the Navier-Stokes or Euler equations
- inert-gas wind-tunnel environment – air, freon, helium, etc
- air-equilibrium model
- thermal equilibrium and chemical nonequilibrium model
- two-temperature model

Validation and Prediction of Shock-Layer Flowfield Examples

- 70 deg cone – Viking aeroshell
- 60 deg cone – AFE aerobrake
- biconic cone – MRSR JSC study
- Shuttle Orbiter

Issues

- Grid resolution
- Physical modeling
- Transport properties and reaction rates
- Geometrical constraint

Figure 1. Forebody of a flat-faced cylinder, Viking Aeroshell, and AFE vehicle.

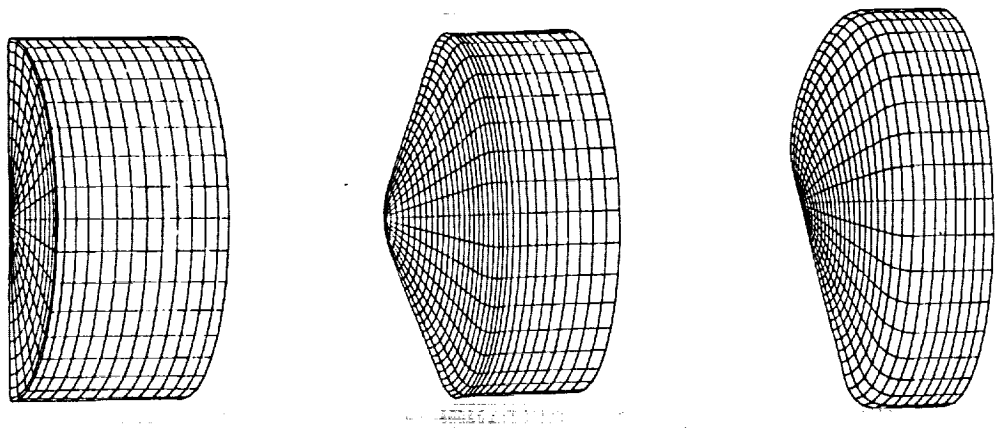


Figure 8. Comparisons of heat-transfer distributions at $\alpha = 0$ and 20 deg with Mach 6 wind-tunnel data.

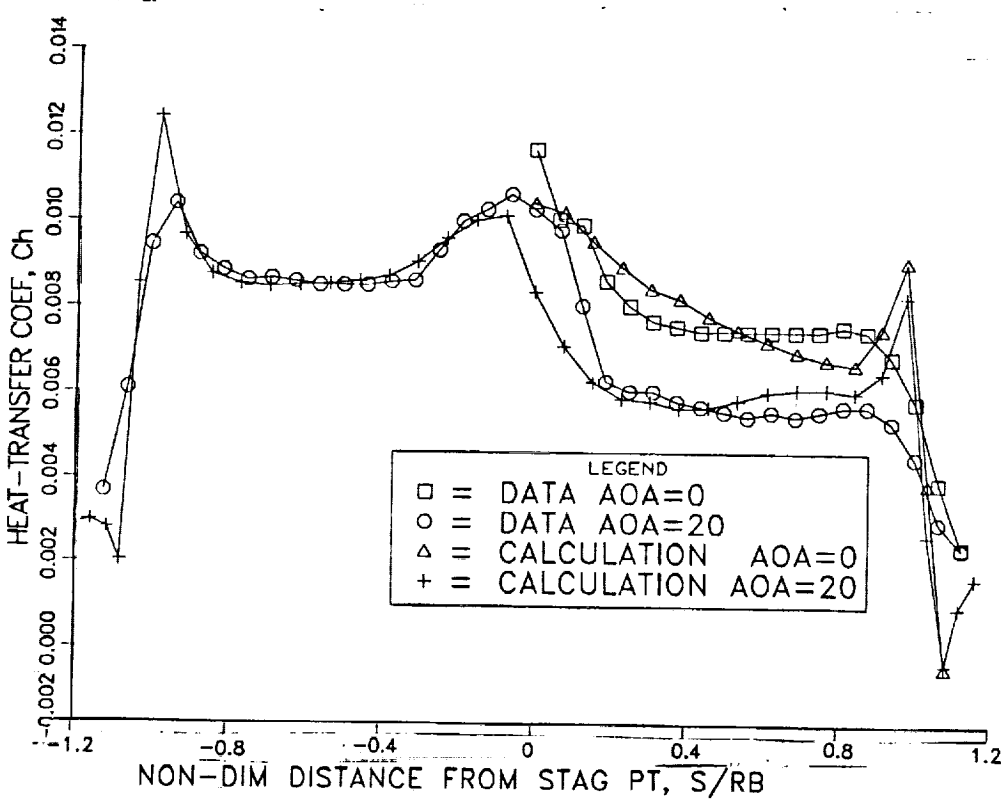
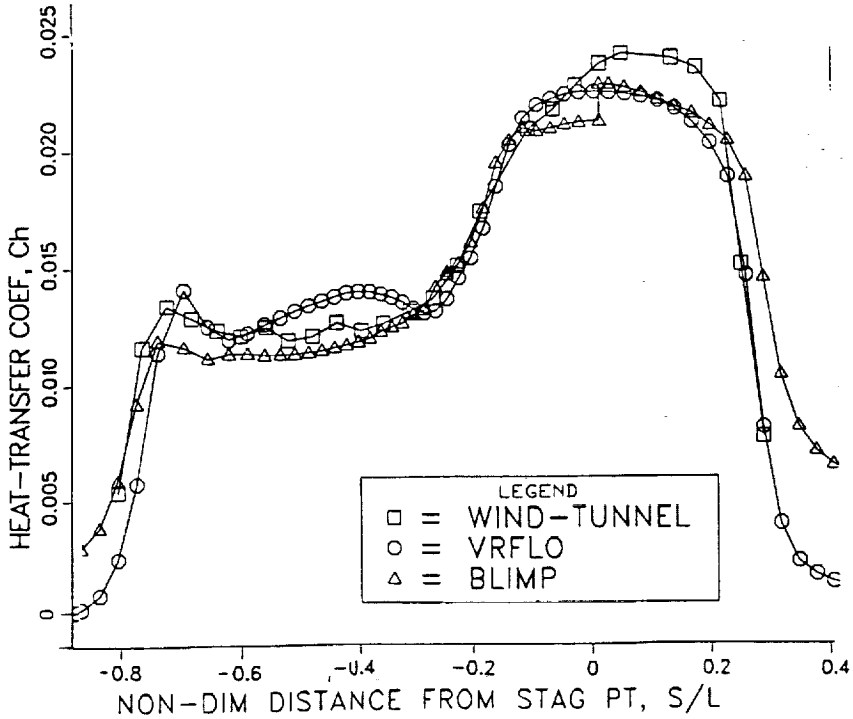
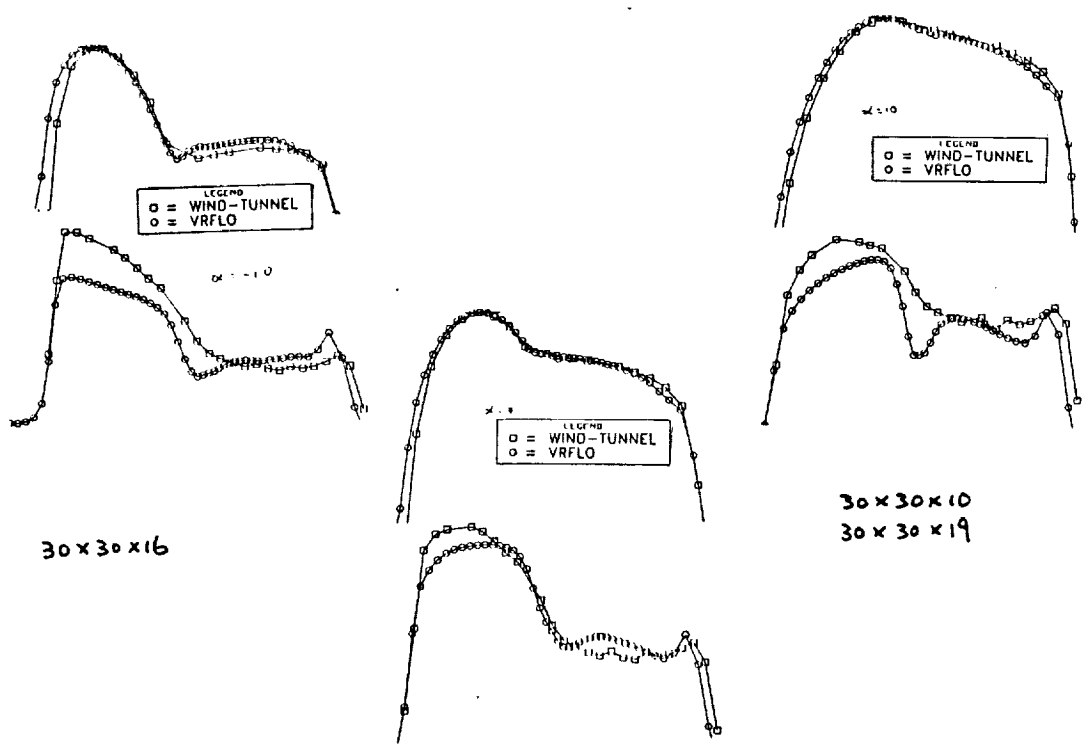


Figure 11. Comparison of AFE computation and wind-tunnel pressure and heat-transfer data.

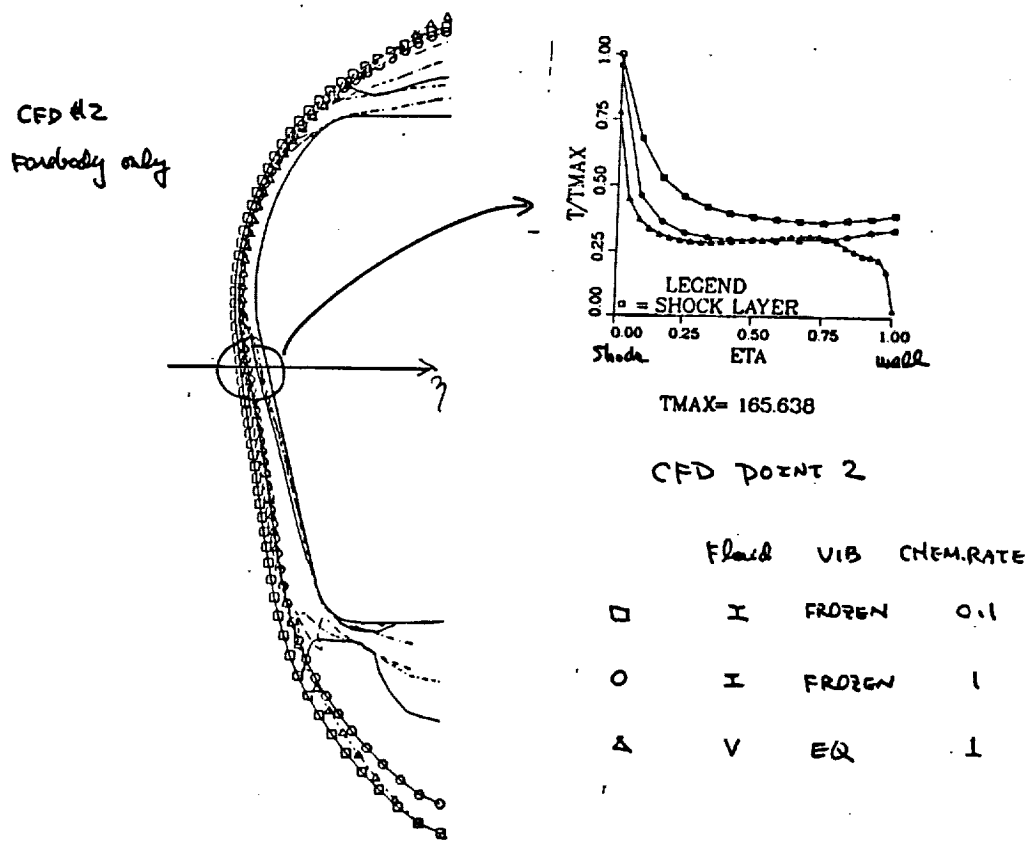


Comparison of pressures and heat transfer at

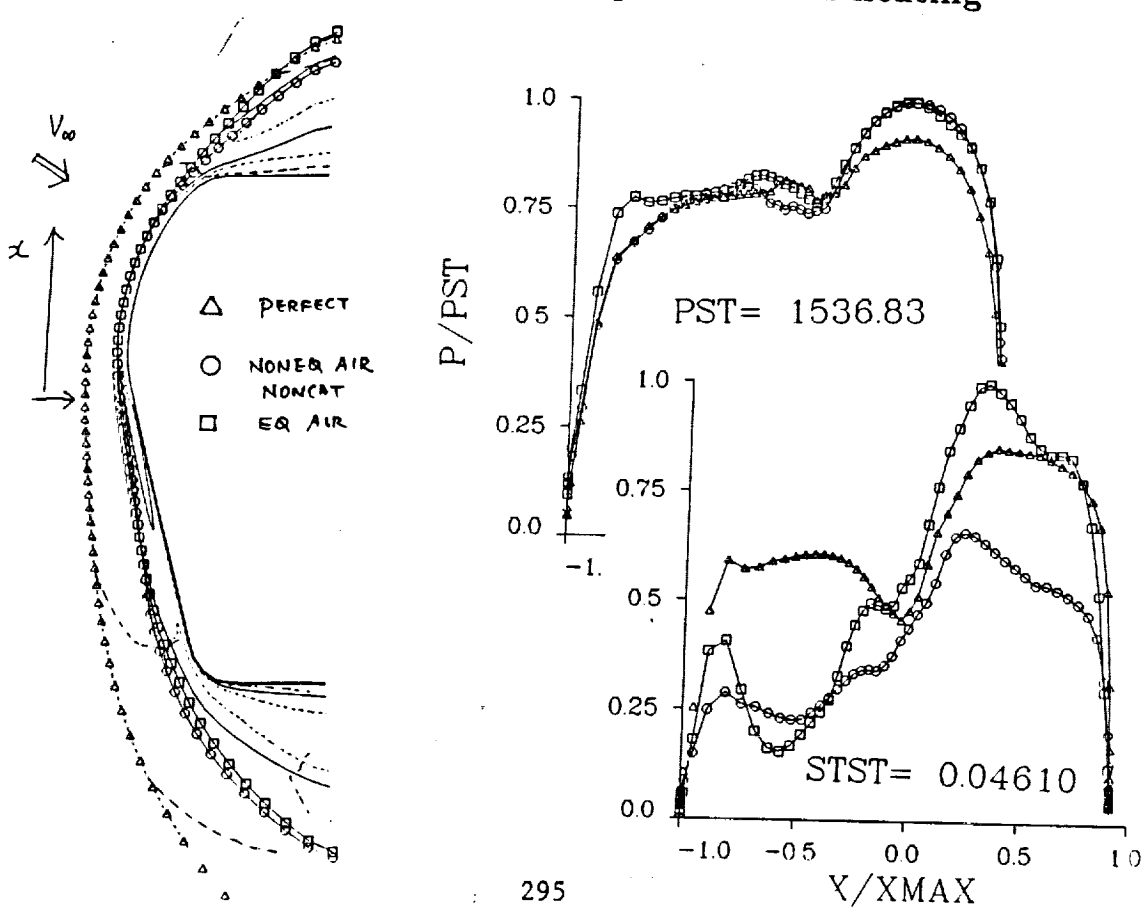
α =-10, 0, 10 deg



Sensitivity of flowfield to modeling and reaction rates



Effects of gas models on pressure and heating



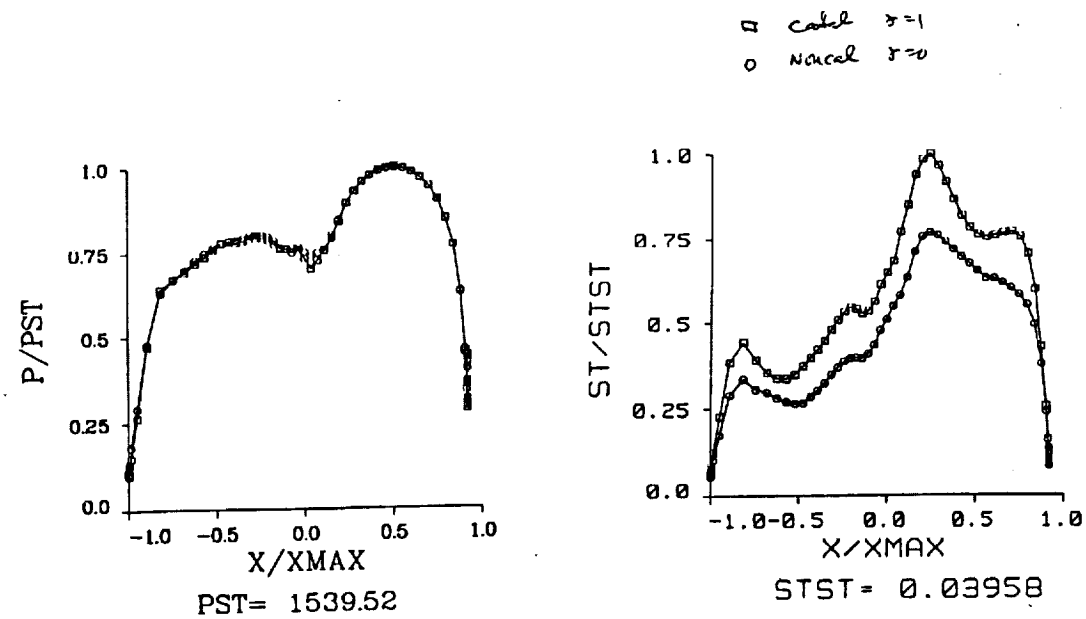
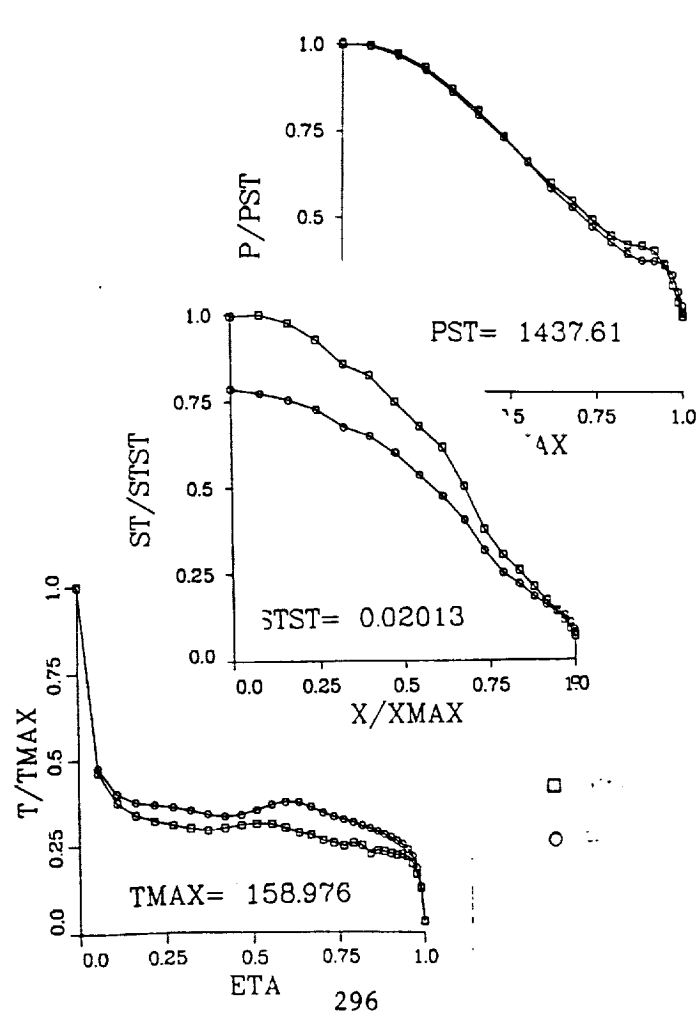
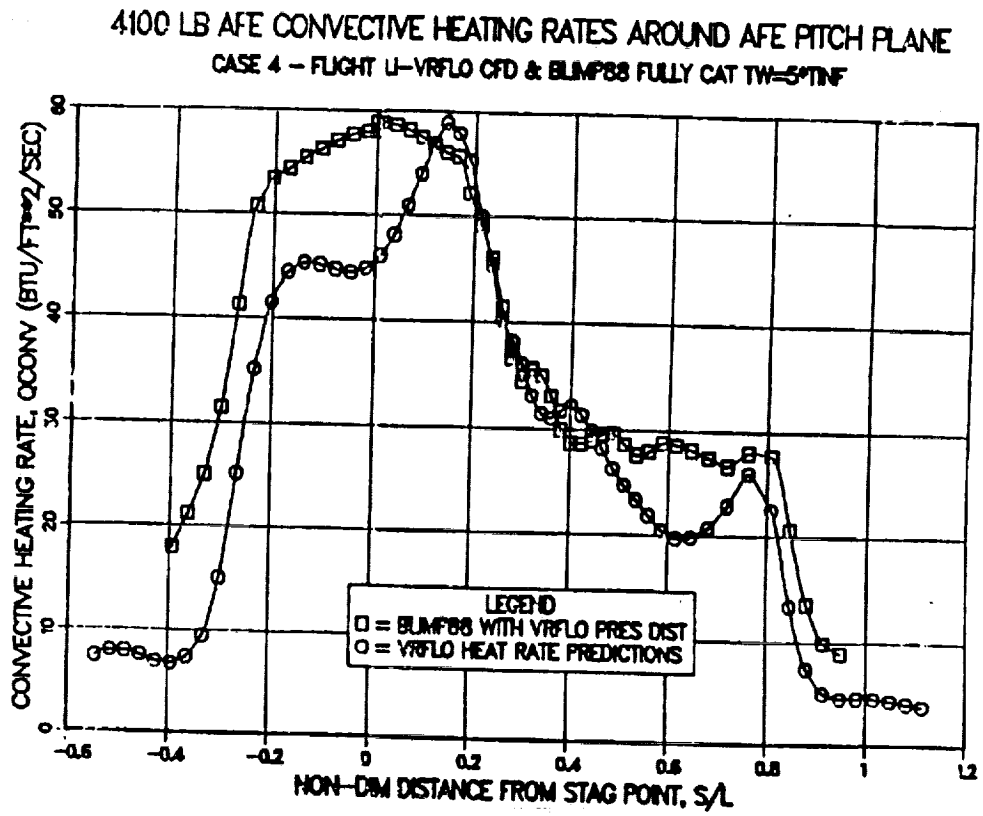


Figure 6.10 Comparison of flowfield results obtained using exact and simplified transport coefficients.
□ Sutherland's formula; ○ Chapman-Enskog's theory.





Comparison of shock shape with data

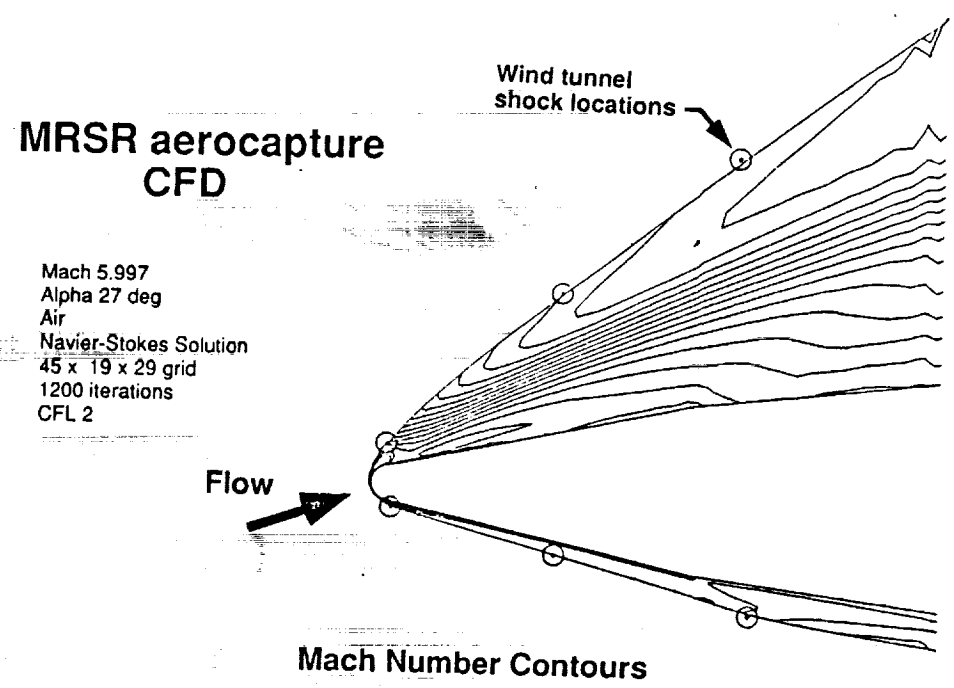


Figure 6.14 Effects of gas models on a blunt cone flowfield at 40 deg angle of attack.
□ equilibrium; ○ nonequilibrium; △ frozen.

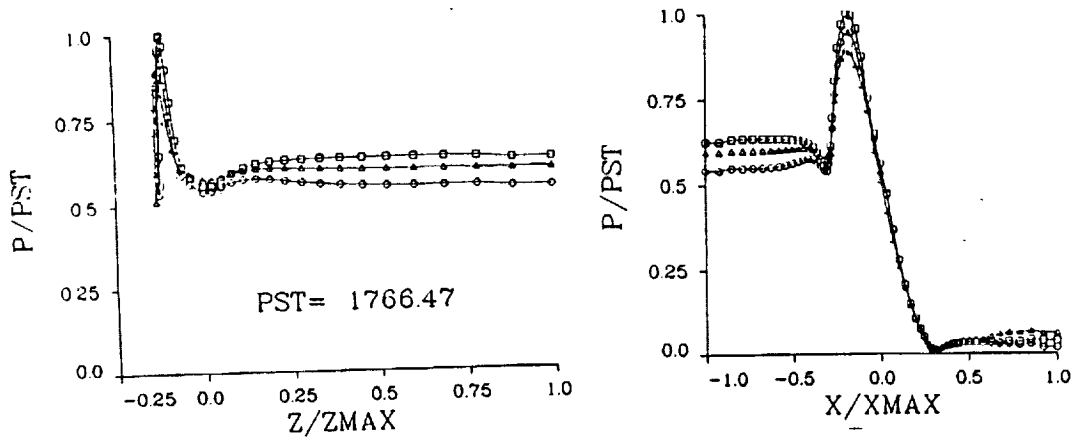
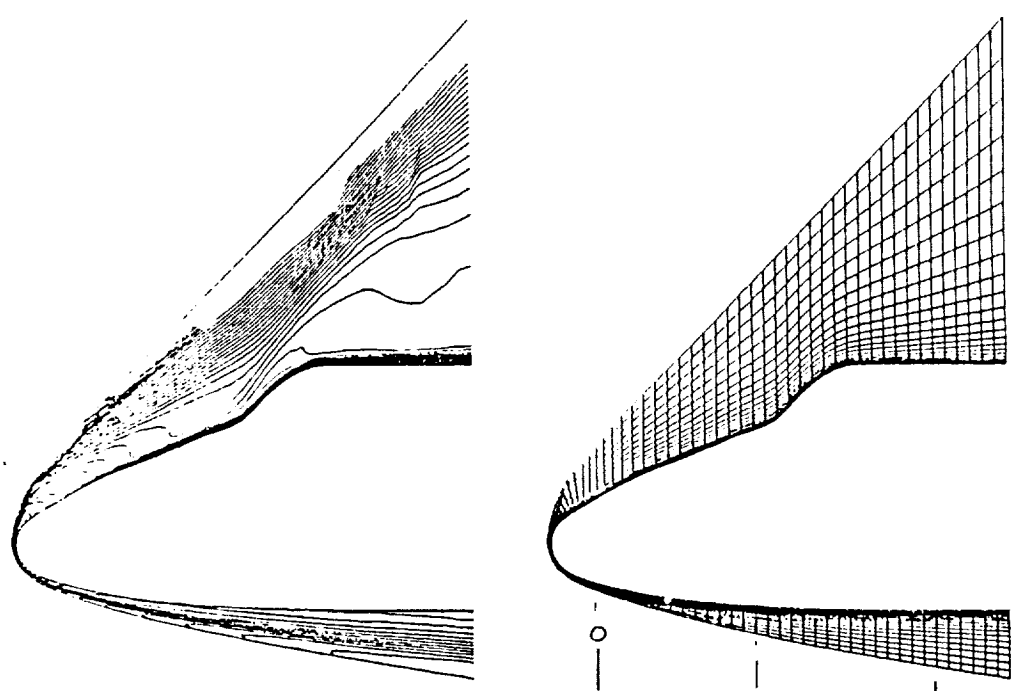


Figure 7.3 Viscous chemical nonequilibrium flow over the Orbiter forebody.
□ top; ○ bottom.
○ M=15; △ M=30; + M=45.



(a) Mach contours in the pitch plane;

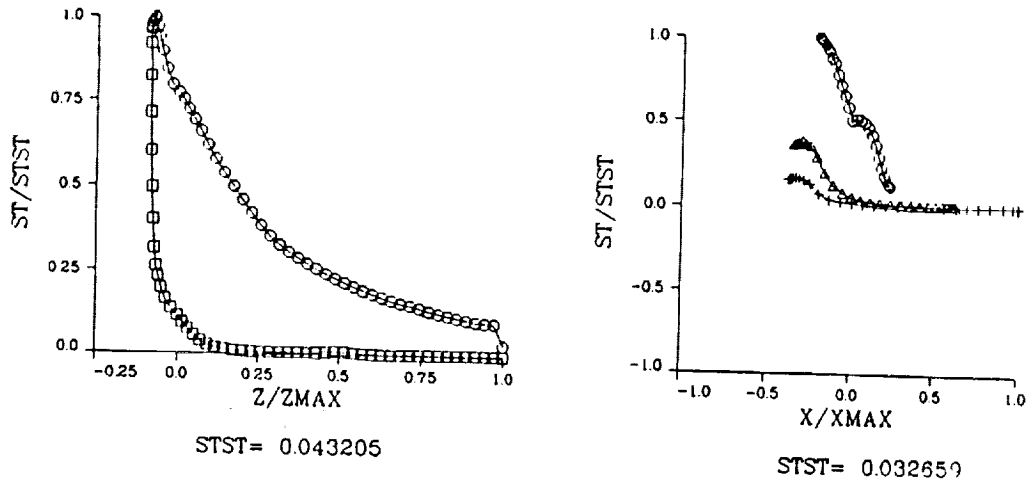
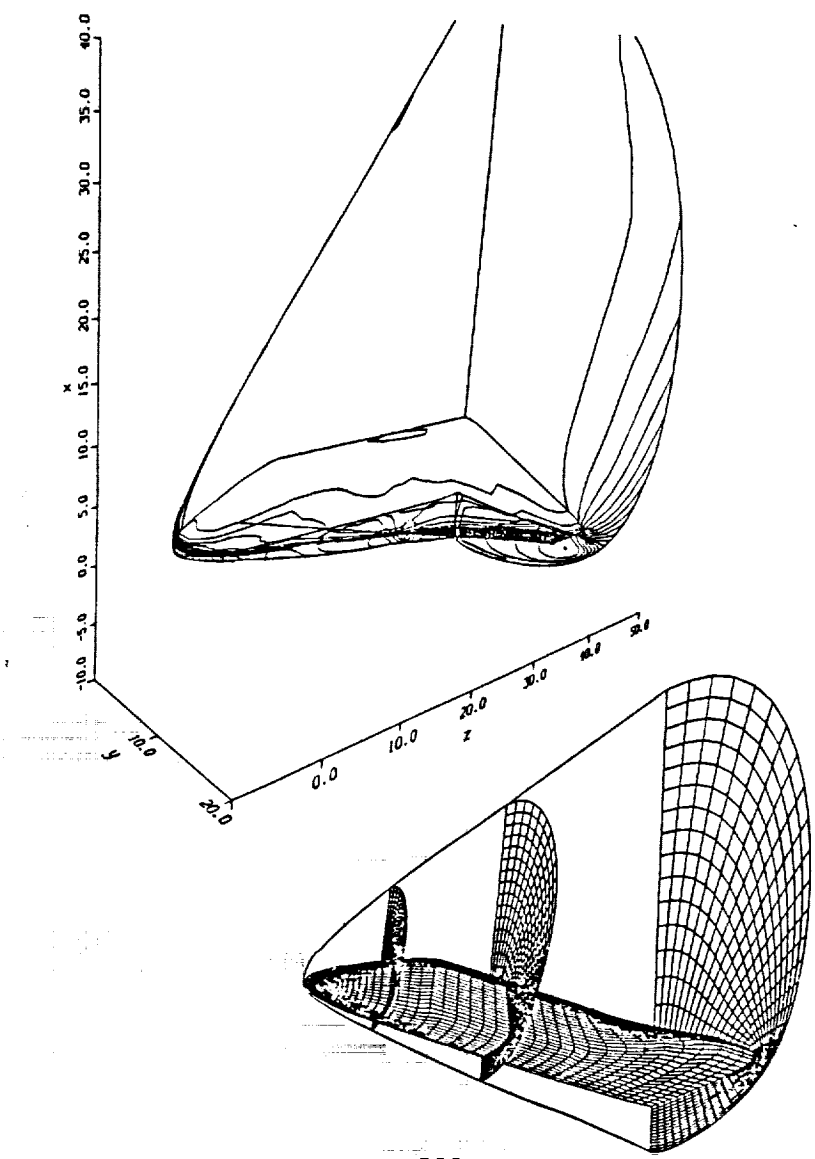


Figure 8.2 Mach 22 flow over a swept-wing vehicle at α=40 deg using chemical nonequilibrium model.



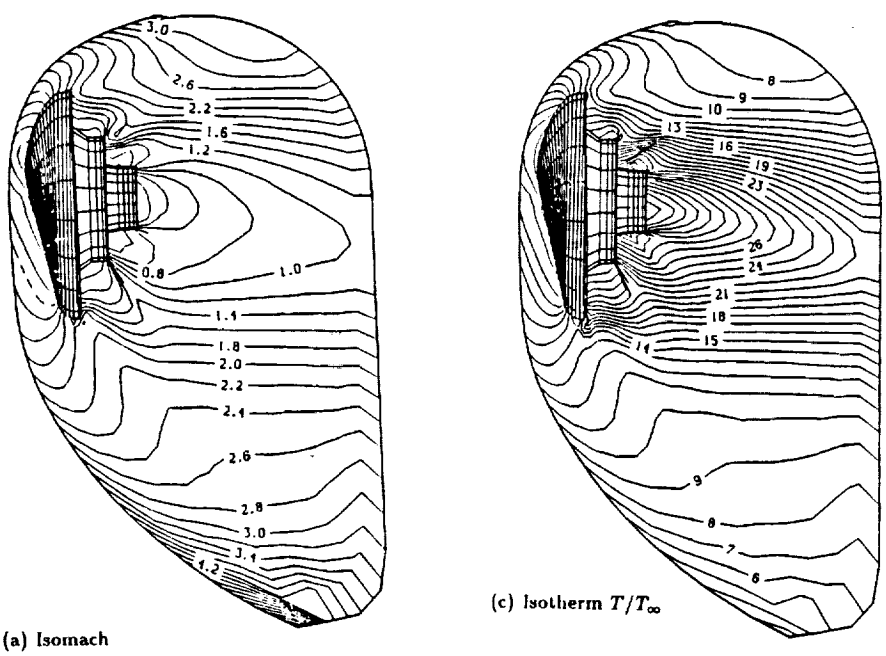
Wake Flowfield

- Viking vehicle with different aftbodies
- AFE vehicle with various base configurations

Issues

- Base flow effects on aerodynamics
- Shear-layer impingement on aftbody
- AFE experiment support

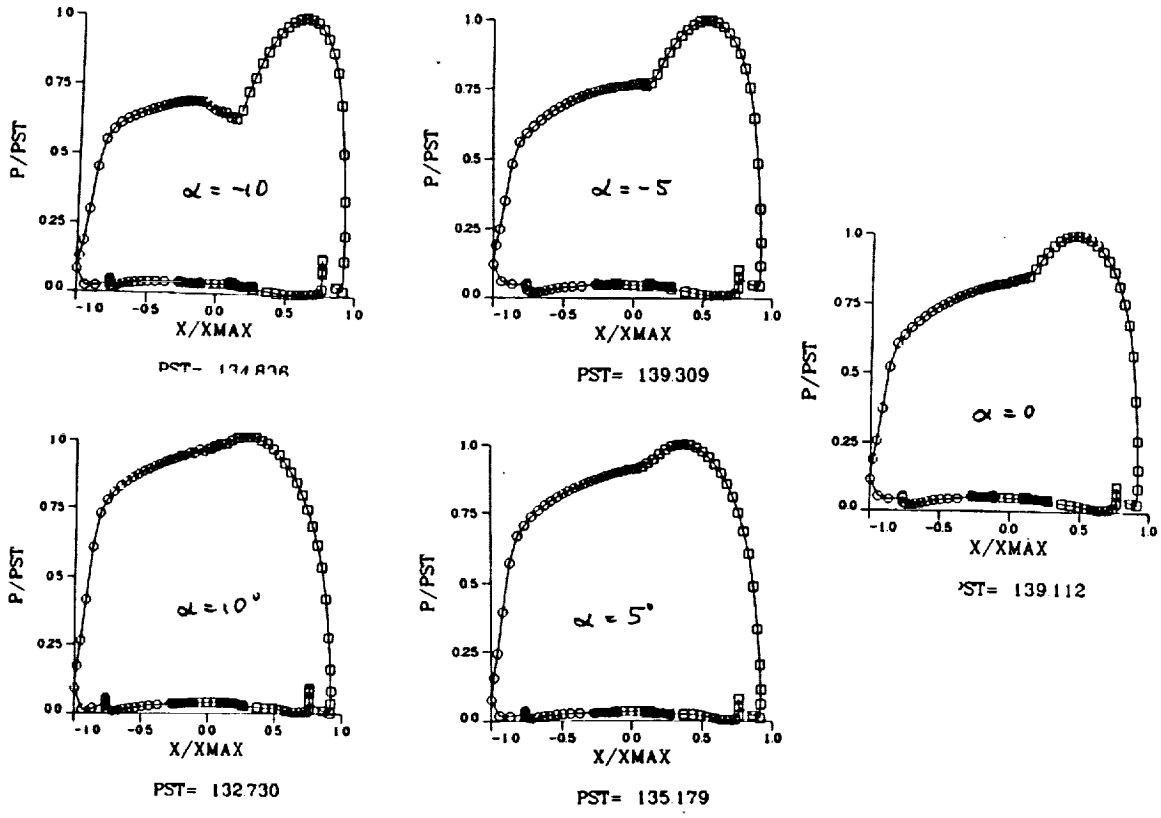
AFE flowfield in wind-tunnel environment



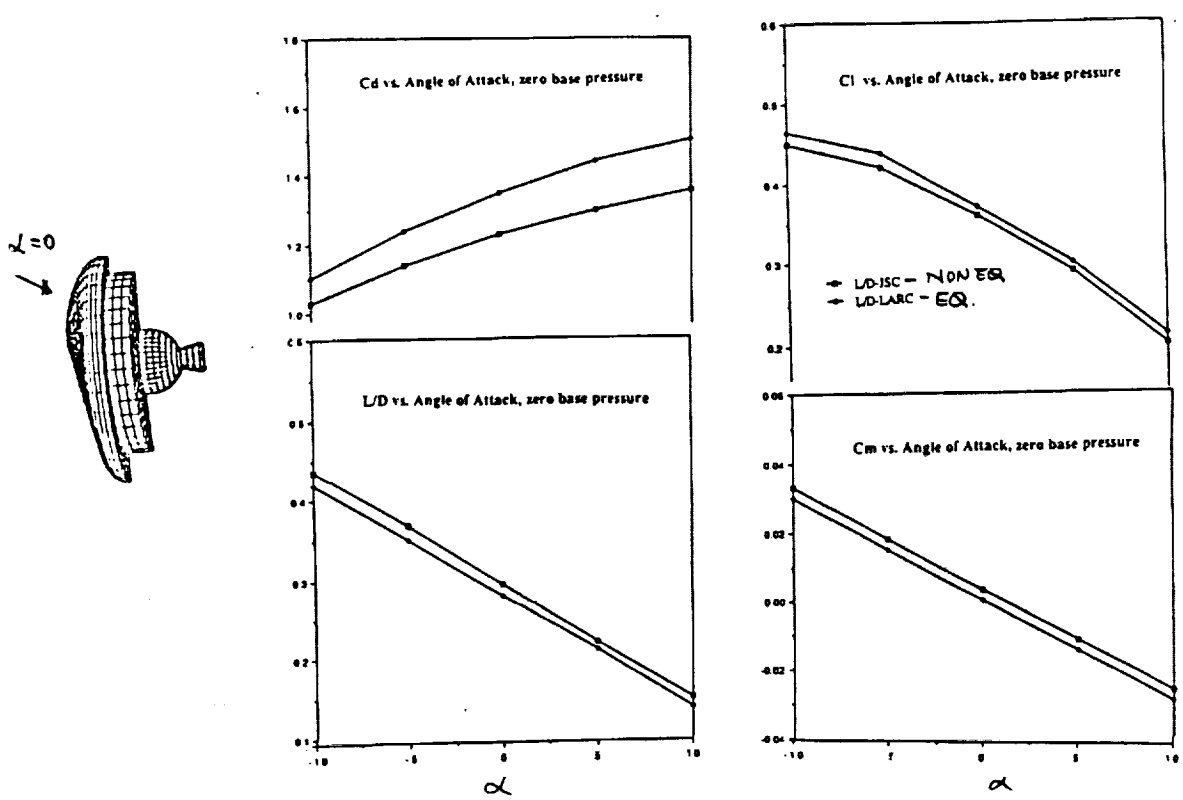
(a) Isomach

(c) Isotherm T/T_∞

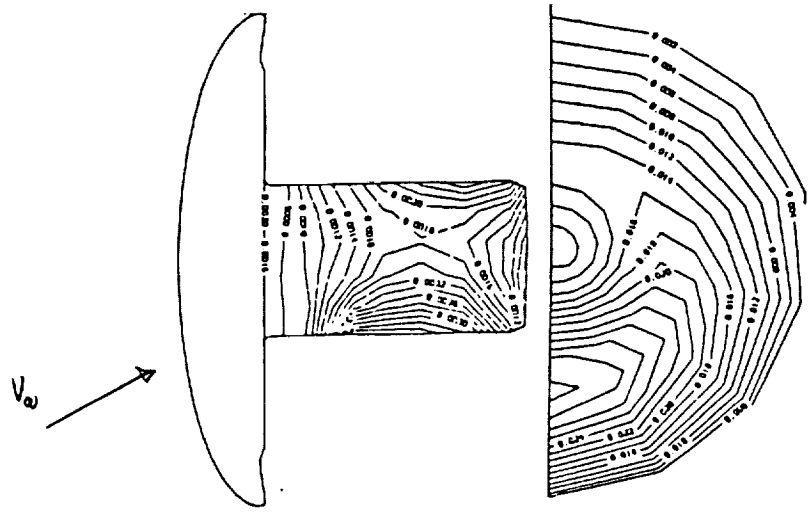
AFE wall pressures at α = -10, -5, 0, 5, 10 deg



Aerodynamic coefficients at flight conditions

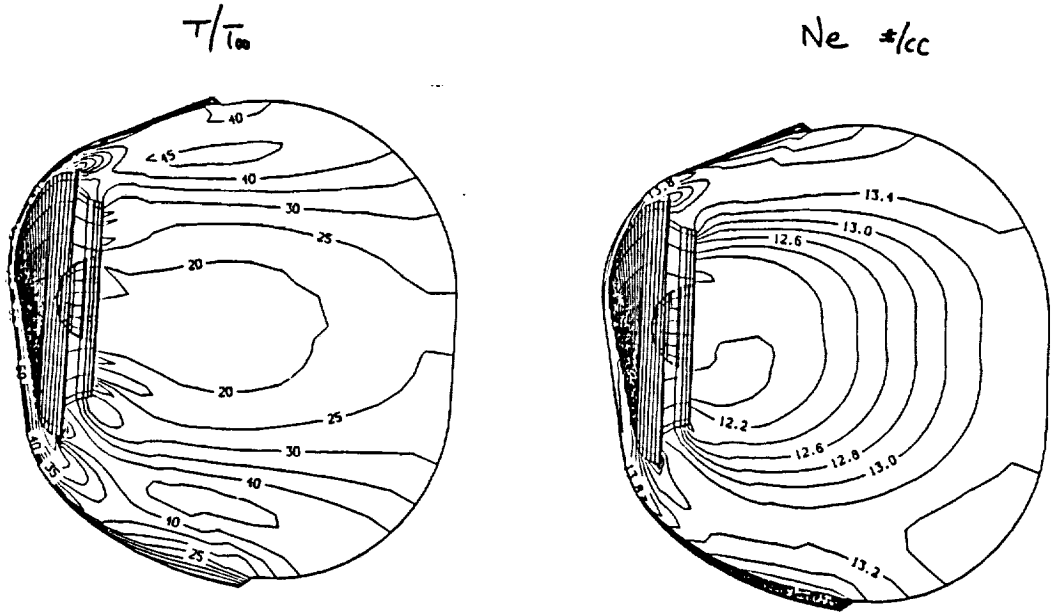


Heat-transfer distributions on the fore- and aftbody



Chemical reactive flow around the AFE vehicle

CFD #2, $\alpha = 0$



FY89 Plan on High-Energy Aerobrake Flow Studies

- continue code validation for a biconic cone at wind-tunnel conditions
- incorporate CO_2 thermodynamic properties at chemical equilibrium into VRAFT code, or
- perform chemically reactive CO_2 flowfield computation for a biconic cone
- collect or develop Mollier-type and mixture-rule for thermodynamic and transport properties

PATHFINDER AEROTHERMODYNAMICS

AT

JOHNSON SPACE CENTER

CARL D. SCOTT
ADVANCED PROGRAMS OFFICE

PREPARED FOR THE
HIGH ENERGY AEROBRAKING WORKSHOP
NASA AMES RESEARCH CENTER
January 31-February 2, 1989

CDS 1/24/89

PLANNED MRSR AEROTHERMODYNAMICS

STAGNATION POINT

- NONEQUILIBIUM VISCOUS SHOCK LAYER
- MARS ATMOSPHERE
- NON-CATALYTIC AND FULLY CATALYTIC

TWO LAYER METHOD - WHOLE BODY

- REACTING EULER SOLUTION WITH MARS ATMOSPHERE
- BOUNDARY LAYER WITH REACTING MARS ATMOSPHERE
    - FINITE RATE CATALYSIS AS DATA BECOMES AVAILABLE
- COUPLING VIA A STREAMLINE CODE
- BICONIC GEOMETRY

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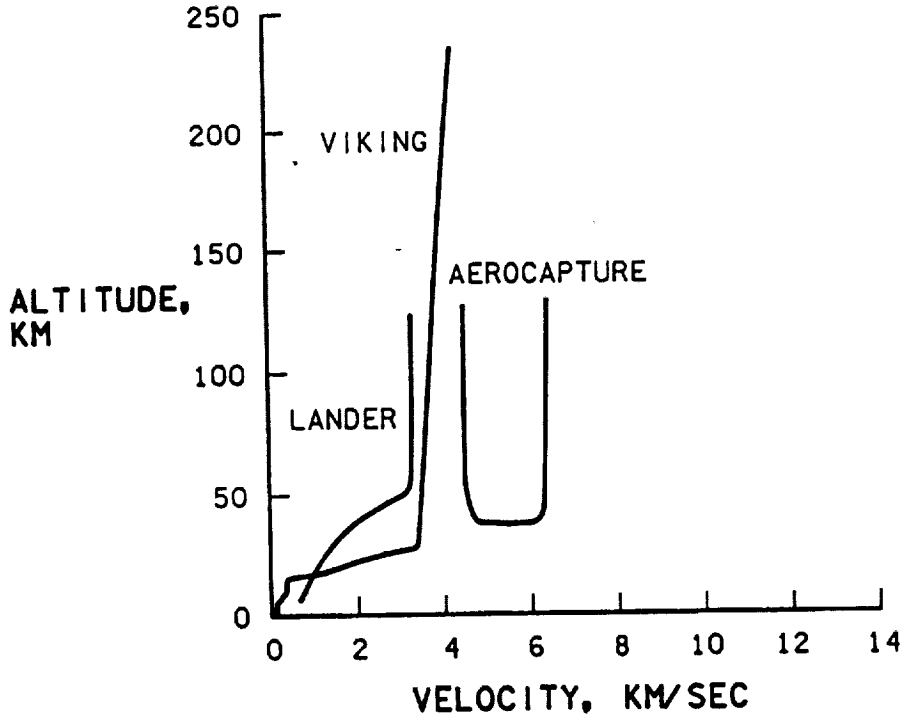
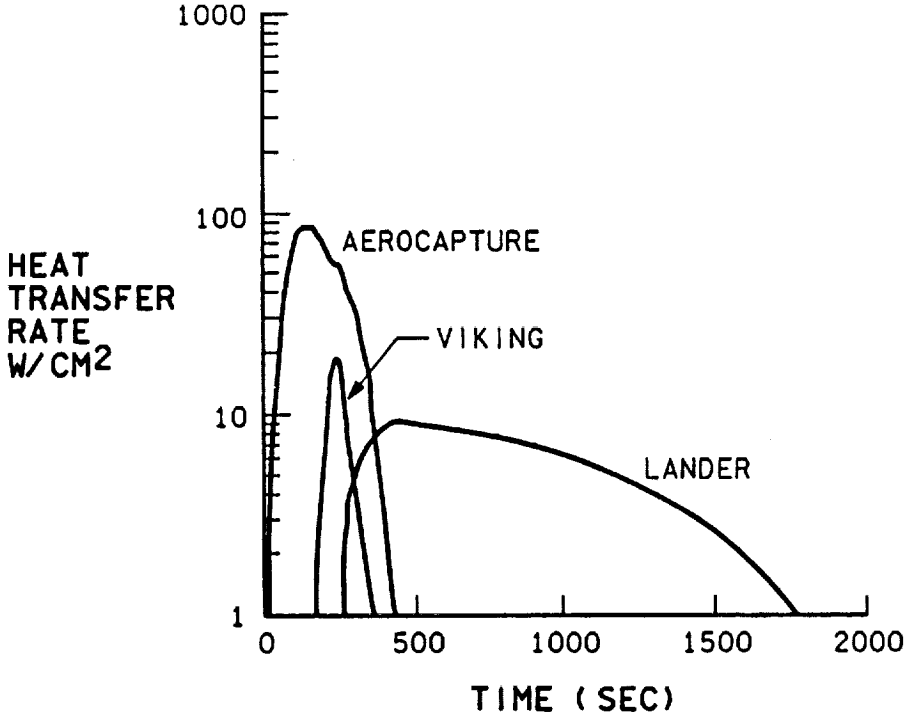
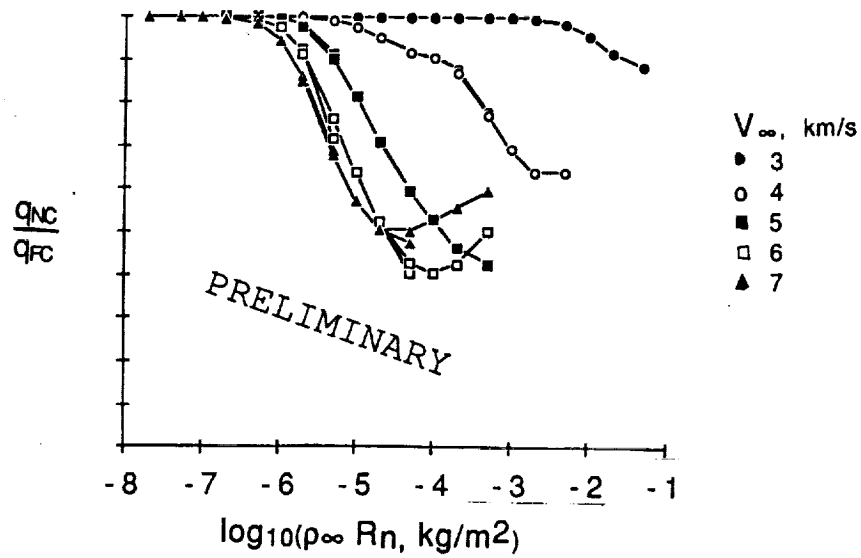
MARS ENTRY FLIGHT REGIMES



TYPICAL HEATING HISTORIES FOR MARS ENTRY



MARS ATMOSPHERE



AEROBRAKING RADIATION STUDIES

ENTRY INTO EARTH

- EMPIRICALLY BASED METHOD OF RIED & ROCHELLE
- LINE BY LINE BASED NONEQUILIBRIUM METHOD OF PARK (NEQAIR)
- STREAMTUBE NONEQUILIBRIUM FLOW WITH BAND (STEP) MODEL OF CARLSON

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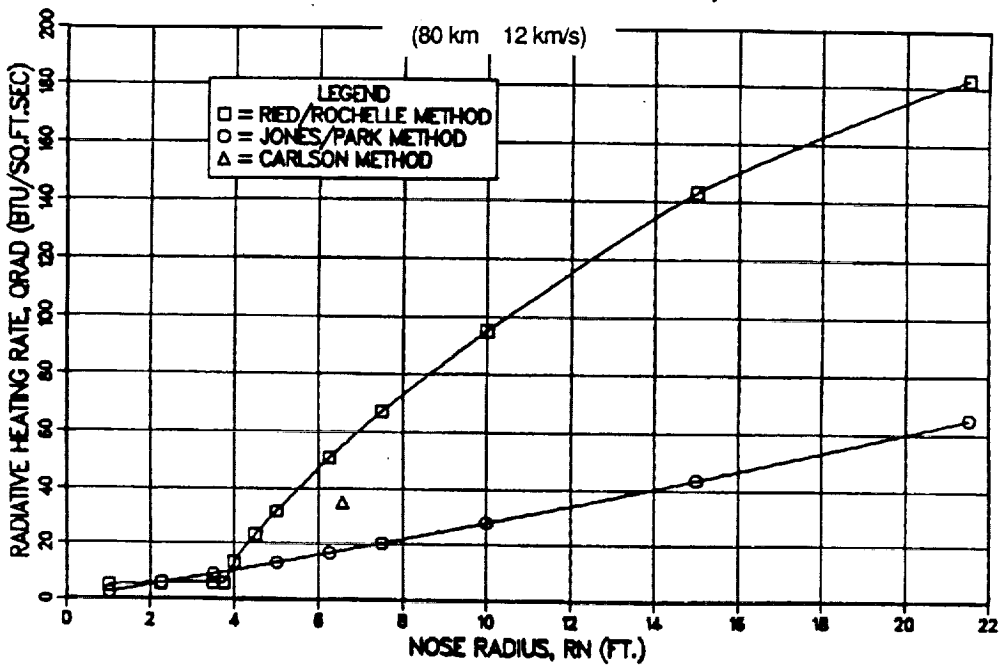
GAS CAP RADIATIVE HEATING RATE FOR EARTH ENTRY FROM MARS

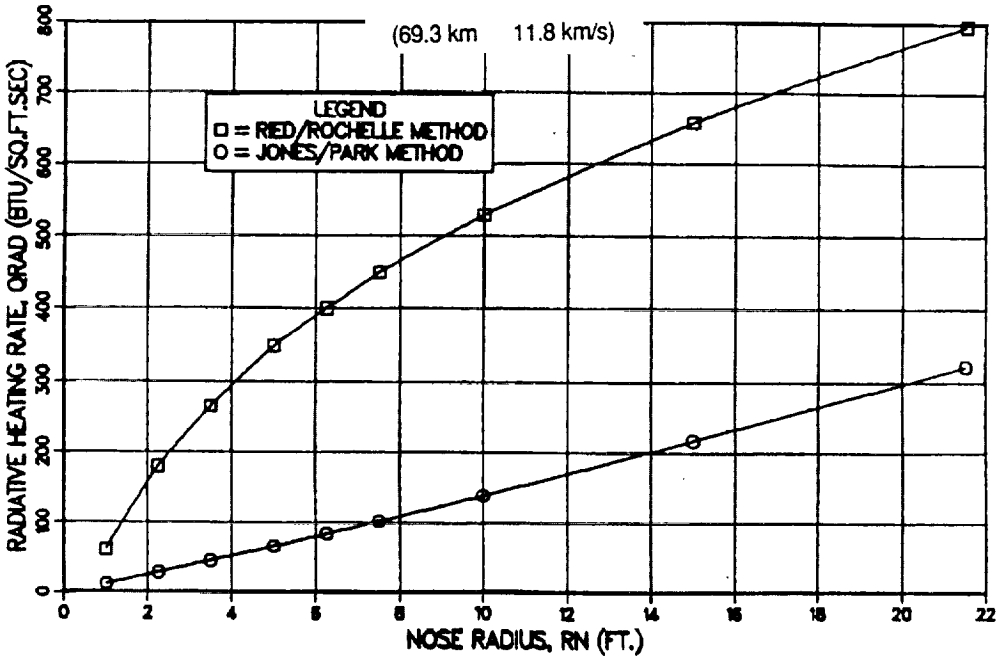
ALTITUDE=262400 FT, VELOCITY=39360 FT/SEC

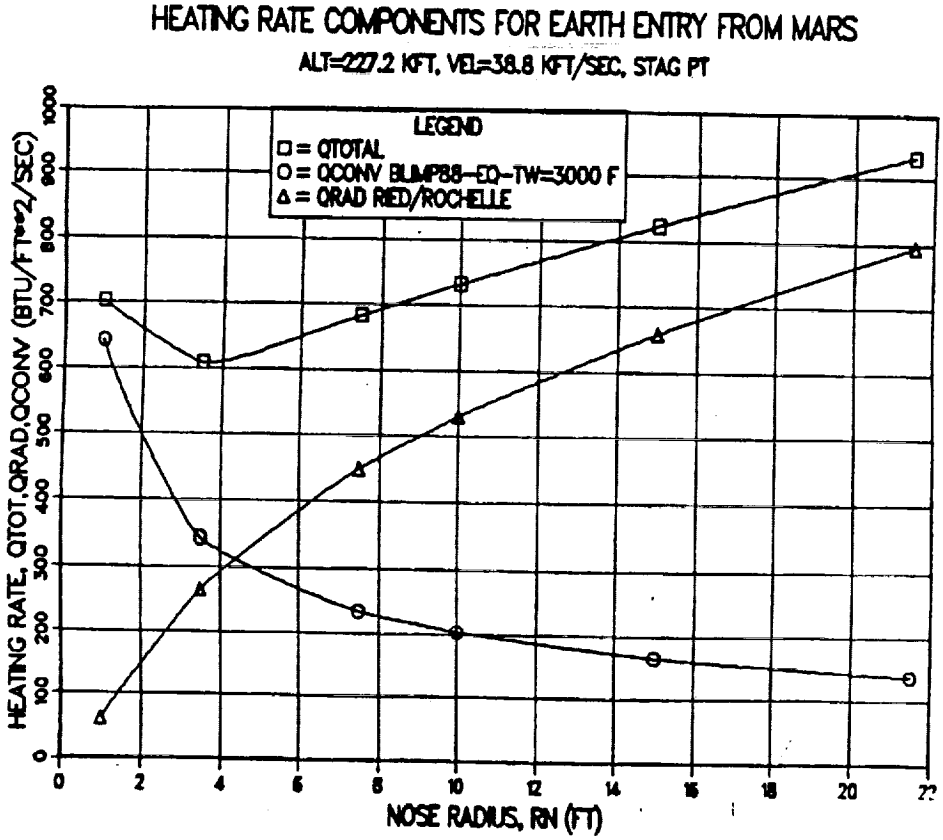


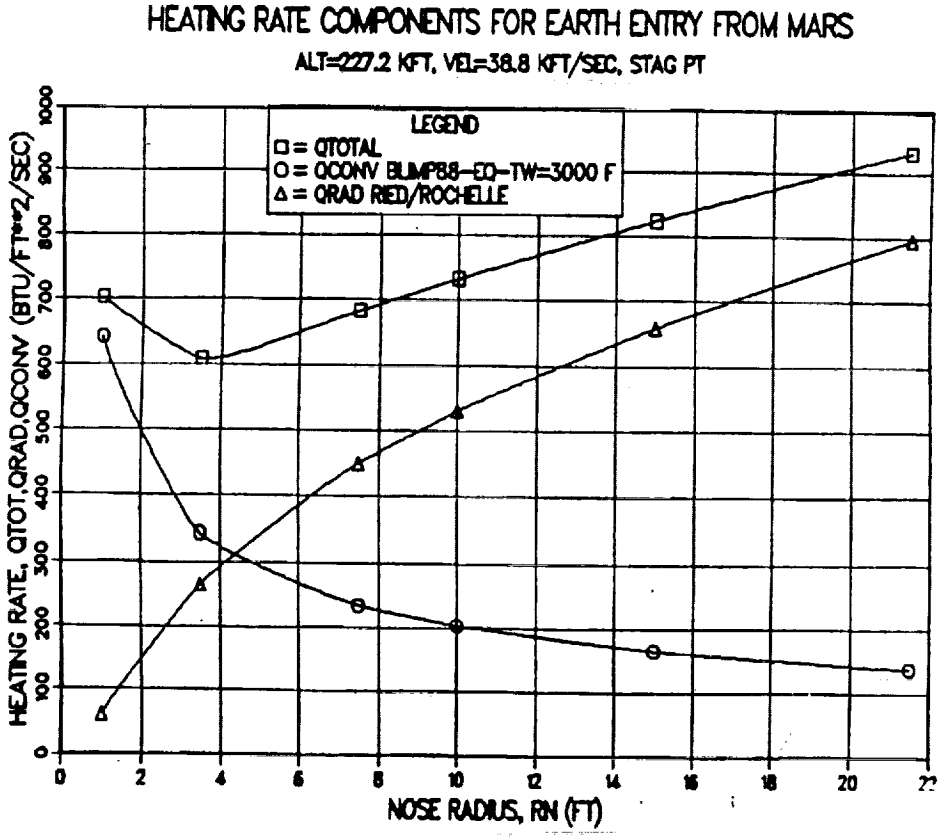
ASTV MANNED MARS MISSION

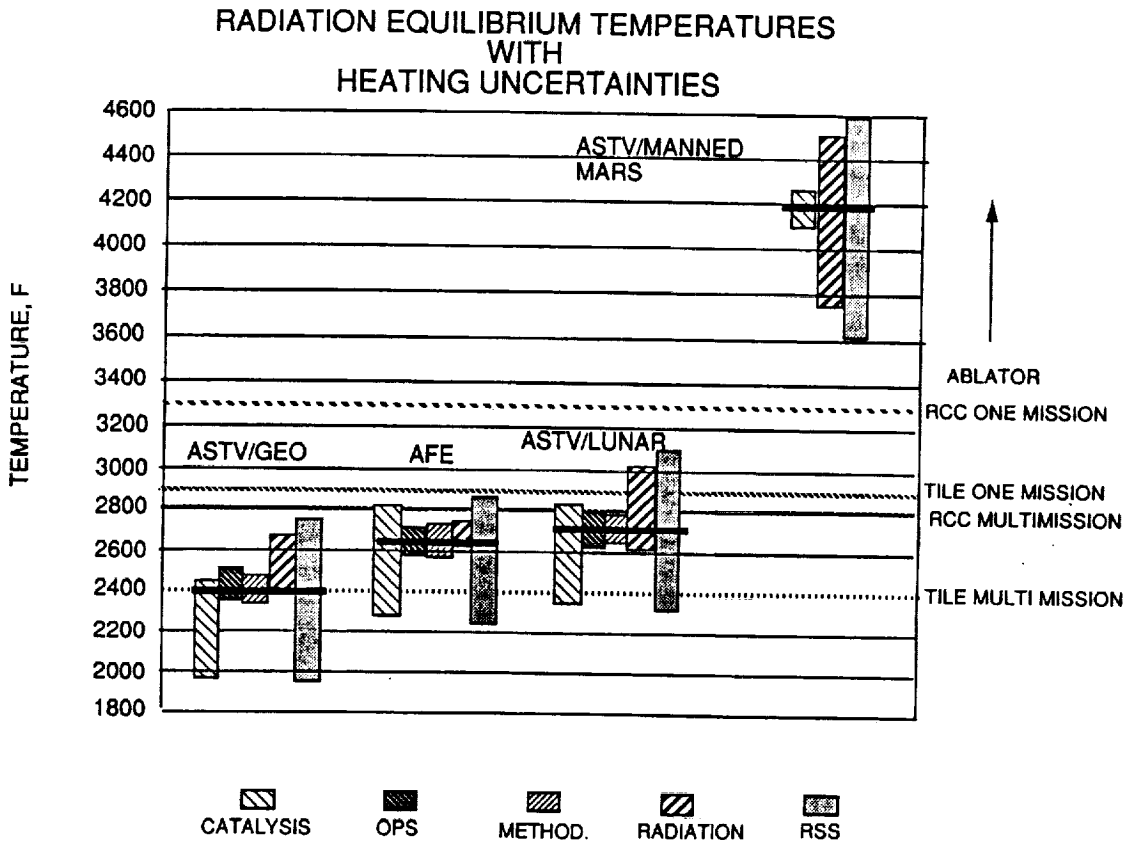
GAS CAP RADIATIVE HEATING RATE FOR EARTH ENTRY FROM MARS

ALTITUDE=227200 FT, VELOCITY=38849 FT/SEC




HEATING RATE COMPONENTS FOR EARTH ENTRY FROM MARS
ALT=227.2 KFT, VEL=38.8 KFT/SEC, STAG PT
LEGEND
□ = QTOTAL
O = QCONV BUMP88-EQ-TW=3000 F
Δ = QRAD RIED/ROCHELLE
HEATING RATE, QTOT,QRAD,QCONV (BTU/FT**2/SEC)
NOSE RADIUS, RN (FT)


HEATING RATE COMPONENTS FOR EARTH ENTRY FROM MARS
ALT=227.2 KFT, VEL=38.8 KFT/SEC, STAG PT
LEGEND
□ = QTOTAL
O = QCONV BUMP88-EQ-TW=3000 F
Δ = QRAD RIED/ROCHELLE
HEATING RATE, QTOT,QRAD,QCONV (BTU/FT**2/SEC)
NOSE RADIUS, RN (FT)



ARC JET FLOW FIELD AND DIAGNOSTICS AT JSC

ARC JET FLOW FIELDS STATUS

- EMPLOYEE HIRED TO DO CFD FOR ARC JET FLOW
- PHASED APPROACH
  - INITIAL CODE
    - EQUILIBRIUM CONSTRICTOR
    - AXISYMMETRIC
    - FROZEN NOZZLE EXPANSION
  - ULTIMATE CODE
    - AXISSYMETRIC WITH SWIRL - POSSIBLY FULL 3-D
    - REACTING FLOW THROUGHOUT
    - TURBULENCE MODELED
    - SEPARATED FLOW
    - MULTI-TEMPERATURE GAS MODEL
    - MHD EFFECTS IN EQUATIONS

ARC JET FLOW FIELD AND DIAGNOSTICS AT JSC

DIAGNOSTICS

- SPECTROSCOPIC EMISSION STUDIES
  - VIBRATIONAL AND ROTATIONAL TEMPERATURES
  - EXCITED STATE POPULATIONS
  - LINE OF SIGHT AND LIMITED SPATIAL RESOLUTION
  - HIGH RESOLUTION CAPABILITY
  - TIME RESOLVED STUDIES

- RING DYE LASER STUDIES (DOPPLER)
  - VELOCIMETRY
  - TRANSLATIONAL TEMPERATURE
  - FEASIBILITY DEMONSTRATED AT PHYSICAL SCIENCES, INC.

- PULSED YAG PUMPED DYE LASER STUDIES
  - INSTALLATION CURRENTLY UNDERWAY
  - RAMAN STUDIES
  - LASER INDUCED FLUORESCENCE
  - POSSIBLE FOR ANAEMOMETRY

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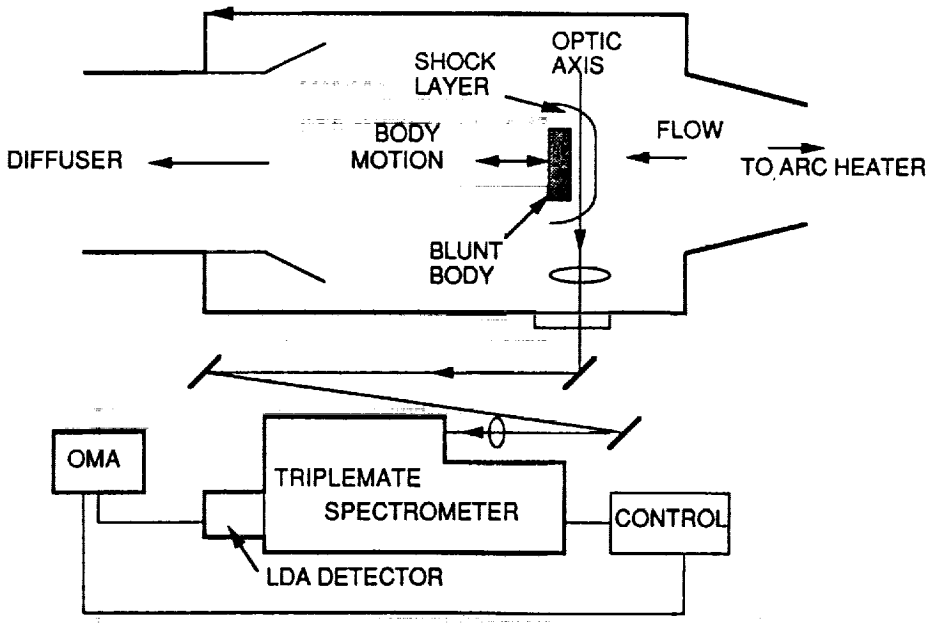
ARC JET SPECTROSCOPIC DIAGNOSTICS



MEASURED AND COMPUTED N_2(1ST POS.)
IN ARC JET

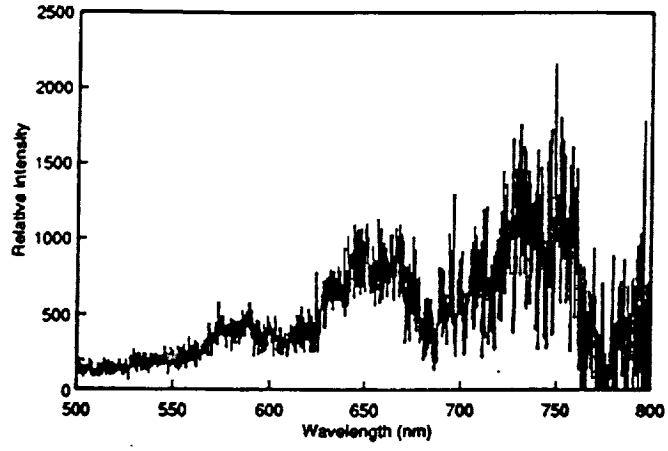


Figure 13.- Measured spectrum of $N_2(1+)$ between 500 nm and 800 nm at 2.5 cm position.

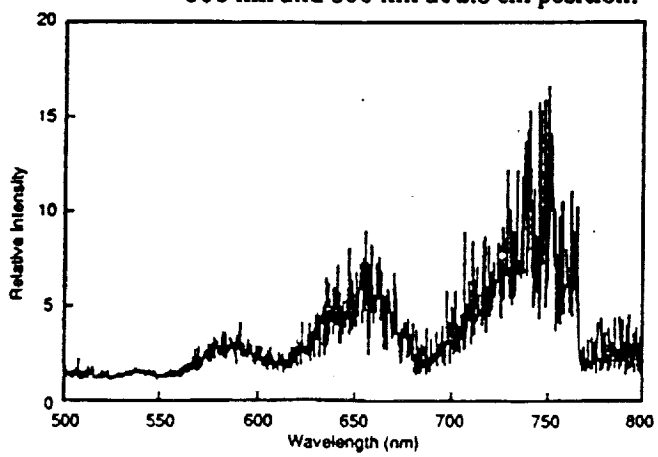
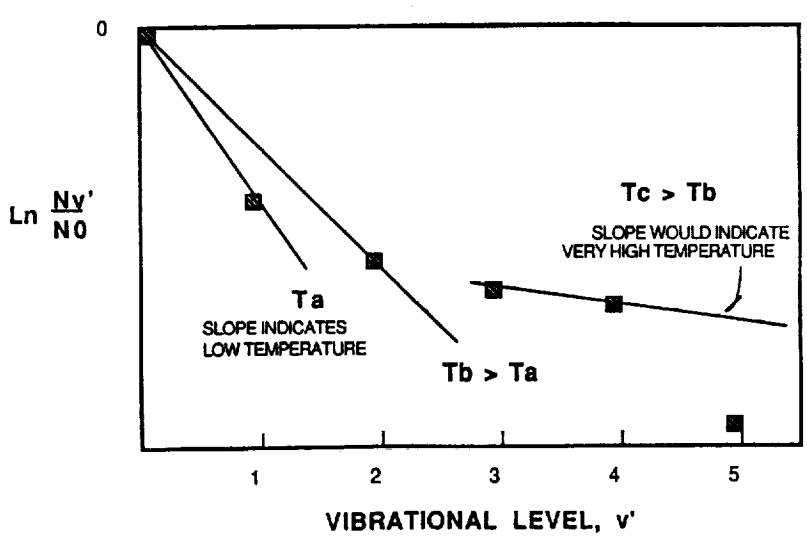


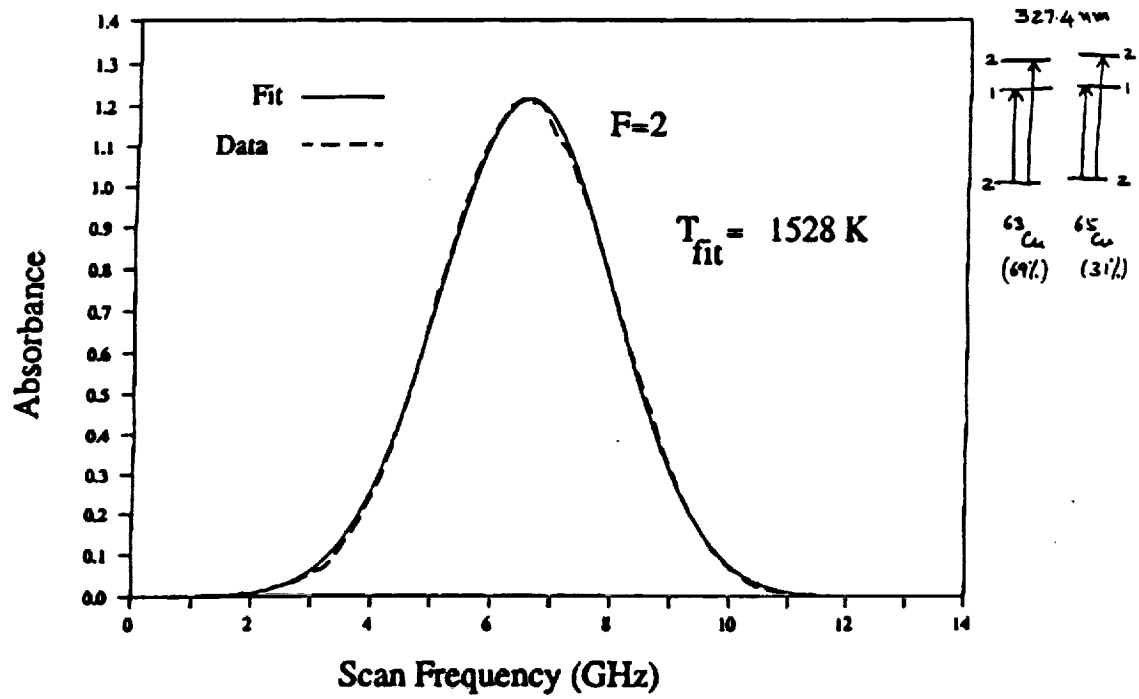
Figure 14.- Computed N_2 spectrum at T_r = 6400 K and T_v = 4500 K.

POSSIBLE DISTRIBUTION OF STATES
BASED ON ARC JET SPECTRAL OBSERVATIONS
IN SHOCK LAYER

$N_{v'}/N_0$ = RELATIVE POPULATION OF UPPER
LOWEST VIBRATIONAL LEVEL v' = 0



Cu Doppler Absorbtion



HIGH ENERGY AEROBRAKING - FY 89 ACTIVITIES
AEROTHERMODYNAMICS AND THERMAL PROTECTION SYSTEM

- DEVELOP AEROTHERMAL ENVIRONMENTS FOR MARS ENTRY AND EARTH RETURN VEHICLES
  - TWO-LAYER METHOD USING BLIMPK - CONVECTIVE HEATING
  - RIED/ROCHELLE PROGRAM - RADIATIVE HEATING
- VEHICLE DEFINITION STUDY
  - GEOMETRY - NOSE RADIUS
  - TRAJECTORY
  - HEATING DISTRIBUTION
- THERMAL PROTECTION SYSTEM DESIGN USING EXISTING ANALYSES
  - MATERIAL DISTRIBUTION
  - MATERIAL RESPONSE
- ASSESS TPS TECHNOLOGY DEVELOPMENT REQUIREMENTS
- DEVELOP AND EMPLOY ARC FLOW DIAGNOSTICS TOOLS
  - EXPERIMENTAL LASER AND SPECTRAL TECHNIQUES
  - COMPUTATIONAL PREDICTIVE TECHNIQUES

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SPECIFICS OF JPL'S AEROBRAKING EFFORTS: PAST, PRESENT AND PLANNED

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GUIDANCE, NAVIGATION, AND CONTROL OF FUTURE AEROMANEUVERING VEHICLES

RECENT WORK PERFORMED WITHIN OAST CONTROLS AND GUIDANCE PROGRAM

LINCOLN J. WOOD

1 FEBRUARY 1989

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91109

GUIDANCE, NAVIGATION, AND CONTROL OF FUTURE AEROMANEUVERING VEHICLES

OBJECTIVE

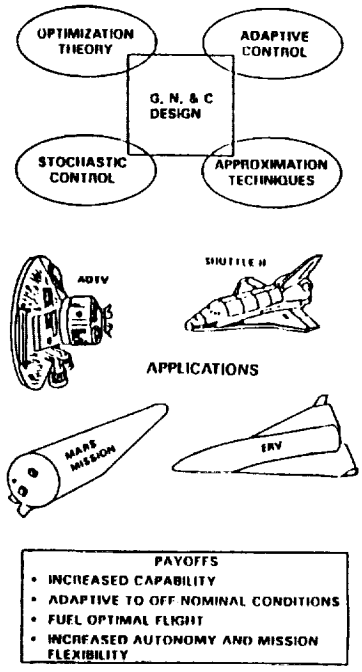
DEVELOP AND VALIDATE HIGH-PERFORMANCE, ADAPTIVE, COST-SAVING GN&C CONCEPTS FOR FUTURE AEROMANEUVERING VEHICLES

FY88 PRODUCTS

- OPTIMAL TRAJECTORIES FOR AEROMANEUVERING PLANE CHANGES
- SIMPLE, NEAR-OPTIMAL, ONBOARD GUIDANCE FOR AEROMANEUVERING PLANE CHANGES
- CONTROL LAWS FOR BANK ANGLE COMMAND FOLLOWING
- GUIDANCE AND NAVIGATION ALGORITHMS FOR AEROMANEUVERING ENTRY TO LANDING

FY89 PLANNED ACCOMPLISHMENTS

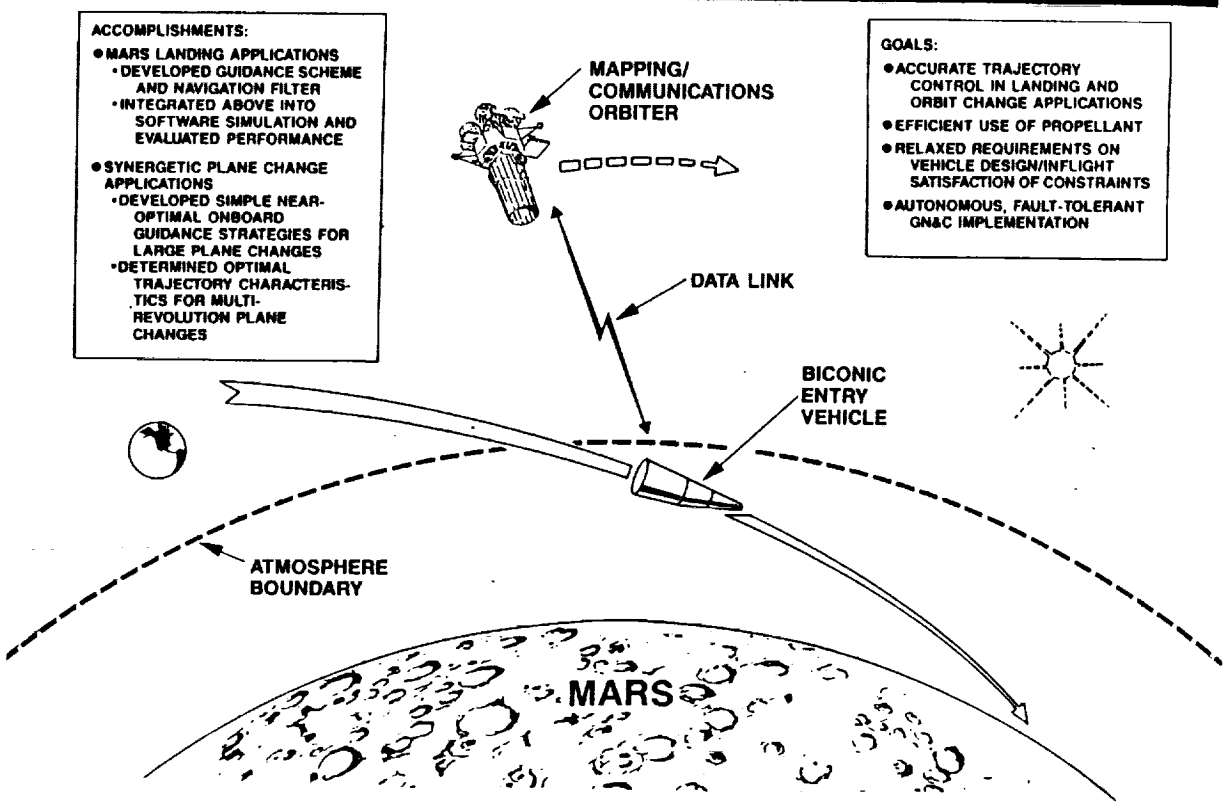
- OPTIMAL TRAJECTORY CHARACTERISTICS FOR NEW PLANE CHANGE SCENARIOS
- ADAPTIVE CONTROL LAWS FOR SYNERGETIC PLANE CHANGES
- IMPROVED GUIDANCE AND NAVIGATION TECHNIQUES FOR AEROCAPTURE AND AEROMANEUVERING ENTRY TO LANDING SCENARIOS



PAYOFFS
- INCREASED CAPABILITY
- ADAPTIVE TO OFF NOMINAL CONDITIONS
- FUEL OPTIMAL FLIGHT
- INCREASED AUTONOMY AND MISSION FLEXIBILITY

LJW-1

GUIDANCE, NAVIGATION AND CONTROL OF FUTURE AEROMANEUVERING VEHICLES



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  - WILLIAM M. McENEANEY – GUIDANCE AND NAVIGATION
  - DHEMETRIOS BOUSSALIS – CONTROL SYSTEMS
  - FAITH A. McCREARY – GUIDANCE AND NAVIGATION SOFTWARE
  - SHYH J. WANG – COGNIZANT SUPERVISOR FOR CONTROL SYSTEMS
- UNIVERSITY OF MICHIGAN – PROFESSOR NGUYEN X. VINH (TRAJECTORY OPTIMIZATION)
- UNIVERSITY OF TEXAS AT AUSTIN – PROFESSORS DAVID G. HULL AND JASON L. SPEYER (GUIDANCE)
- RICE UNIVERSITY – ANGELO MIELE (TRAJECTORY OPTIMIZATION)
- UNIVERSITY OF NOTRE DAME – P. J. ANTSAKLIS (CONTROL SYSTEMS)

FY88 PRODUCTS

- OPTIMAL TRAJECTORY CHARACTERISTICS FOR AEROMANEUVERING PLANE CHANGES
  - MAXIMUM PLANE CHANGE AT CONSTANT ALTITUDE FOR GIVEN FUEL EXPENDITURE
    - SPEED AND ANGLE OF ATTACK HELD CONSTANT IN PREVIOUS WORK
    - WITH SPEED AND ANGLE OF ATTACK ALLOWED TO VARY
      - MAXIMUM PLANE CHANGE INCREASES, ESPECIALLY AT HIGH ALTITUDES
      - OPTIMUM SPEED QUITE CLOSE TO CONSTANT
  - MULTI-REVOLUTION VS SINGLE-REVOLUTION PLANE CHANGES
    - SAME PLANE CHANGE PRODUCED EITHER WAY, FOR GIVEN SPEED DEPLETION
    - OPTIMAL TIME HISTORIES OF LIFT COEFFICIENT, BANK ANGLE, ALTITUDE, AND VELOCITY DETERMINED FOR MULTI-REVOLUTION CASE

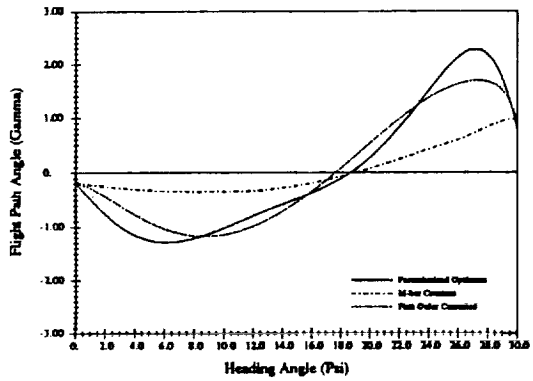
FY88 PRODUCTS (CONTINUED)

- NEAR-OPTIMAL ONBOARD GUIDANCE FOR AEROMANEUVERING PLANE CHANGES
  - COMPUTATION OF TRUE OPTIMAL TRAJECTORIES TOO COMPLEX AND TIME CONSUMING TO PERFORM ONBOARD IN REAL TIME
  - SIMPLE, NEAR-OPTIMAL GUIDANCE LOGIC DEVELOPED IN FY88 FOR PLANE CHANGE APPLICATIONS
    - FINAL VELOCITY MAXIMIZED WHILE MEETING CONSTRAINTS ON FINAL ALTITUDE, FLIGHT PATH ANGLE, AND HEADING
    - HAMILTON-JACOBI-BELLMAN EQUATION OF OPTIMAL CONTROL THEORY EXPANDED IN SMALL PARAMETER (RATIO OF ATMOSPHERIC SCALE HEIGHT TO RADIUS OF PLANET)
      - ZEROTH-ORDER SOLUTION SOLVABLE IN CLOSED FORM
      - FIRST-ORDER SOLUTION SOLVABLE BY QUADRATURE INTEGRATION, WHICH IS FEASIBLE ONBOARD
      - RESULTS MUCH CLOSER TO OPTIMUM THAN USING LOH'S APPROXIMATION

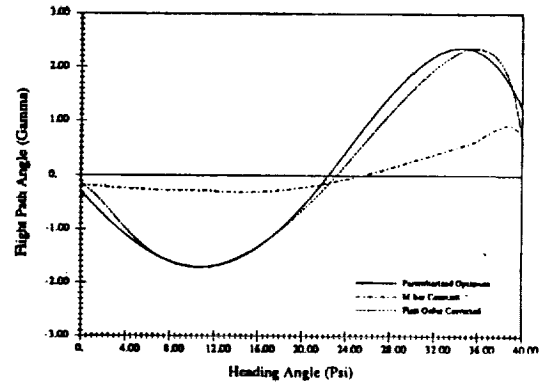
FY88 PRODUCTS (CONTINUED)

- NEAR-OPTIMAL ONBOARD GUIDANCE FOR AEROMANEUVERING PLANE CHANGES (CONTINUED)

30 Degree Plane Change



40 Degree Plane Change



FY88 PRODUCTS (CONTINUED)

- VEHICLE CONTROL ON AN ATMOSPHERIC SKIP TRAJECTORY
  - ATTITUDE CONTROL LAWS DEVELOPED FOR TRACKING A REFERENCE ANGLE OF ATTACK AND/OR BANK ANGLE COMMAND
    - NONADAPTIVE SHUTTLE-LIKE P-D CONTROL LAW BASED ON DIRECT MATCHING OF PARAMETERS TO TRACK A DRAG VS SPEED PROFILE
    - MODEL REFERENCE ADAPTIVE CONTROL LAW
  - CONTROL LAW PERFORMANCE EVALUATED VIA SIMULATION
    - TRACKING OF ALTITUDE-HOLD BANK ANGLE COMMAND
    - EVALUATION OVER ENTIRE SKIP TRAJECTORY
  - ARCHITECTURE OF HIERARCHICAL INTELLIGENT CONTROL SYSTEM DEVELOPED FOR AUTONOMOUS OPERATION OF AEROMANEUVERING VEHICLES ALONG SKIP TRAJECTORIES

FY88 PRODUCTS (CONTINUED)

- GUIDANCE AND NAVIGATION ALGORITHMS FOR AEROMANEUVERING ENTRY TO LANDING
  - SOFTWARE SYSTEM FOR SIMULATING ENTRY AND LANDING OF AEROMANEUVERING VEHICLE WAS DESIGNED, BUILT, TESTED AND RUN
  - SYSTEM SIMULATES ACTUAL VEHICLE STATE AND ONBOARD COMPUTATIONS SEPARATELY; ONBOARD COMPUTATIONS SIMULATED INCLUDE:
    - SEVERAL NAVIGATION OPTIONS
      - ACCELEROMETER AND GYRO DATA PLUS RELATIVE RANGE TO AN ORBITER OR VEHICLE ON SURFACE
      - SIMPLE INTEGRATION OF ACCELEROMETER DATA OR 13-STATE NAVIGATION FILTER
    - GUIDANCE BASED ON SHUTTLE ALGORITHMS BUT WITH NUMEROUS MODIFICATIONS
    - CONTROL DELAYS BUILT INTO SYSTEM THROUGH CONSTRAINTS ON MAXIMUM ALLOWABLE ROLL RATE AND ACCELERATION

FY88 PRODUCTS (CONTINUED)

- GUIDANCE AND NAVIGATION ALGORITHMS FOR AEROMANEUVERING ENTRY TO LANDING (CONTINUED)
  - SIMULATION USED TO GENERATE LANDING ERRORS AT MARS
    - ERROR SOURCES INCLUDE
      - INITIAL STATE KNOWLEDGE AND CONTROL ERRORS
      - ATMOSPHERIC UNCERTAINTIES
      - IMU ERRORS
      - RANGING ERRORS
      - STATE ERRORS OF VEHICLES USED FOR RELATIVE RANGING
    - RESULTS GENERATED FOR DESCENT FROM 500 km ORBIT BY BICONIC VEHICLE WITH L/D=1.5
    - 3-sigma LANDING ERRORS
      - VARY FROM 1.3 km (RANGING TO VEHICLE ON SURFACE)
      - TO 9 km (IMU INTEGRATION ONLY)
      - ARE DOMINATED BY KNOWLEDGE ERRORS
      - WERE ON THE ORDER OF 110 km BY 50 km FOR VIKING
    - SPEEDS AT PARACHUTE DEPLOYMENT RANGE FROM 0.38 km/sec TO 0.66 km/sec

FY87 PRODUCTS

- STATE ESTIMATION AND PARAMETER IDENTIFICATION DURING AEROCAPTURE
  - AERODYNAMIC FORCE ON AEROCAPTURE VEHICLE IMPRECISELY KNOWN
    - ATMOSPHERIC DENSITY/AERODYNAMIC COEFFICIENTS UNCERTAIN
    - ENTRY CONDITIONS UNCERTAIN
  - TWO NAVIGATIONAL APPROACHES COMPARED
    - CONVENTIONAL INERTIAL NAVIGATION - INTEGRATE MEASURED ACCELERATIONS TO OBTAIN VELOCITY AND POSITION
    - EXTENDED INERTIAL NAVIGATION
      - MODEL AERODYNAMIC FORCES IN TERMS OF DRAG & LIFT COEFFICIENTS, DENSITY MULTIPLIER & INVERSE SCALE HEIGHT
      - USE SENSOR DATA IN ONBOARD ITERATED EXTENDED KALMAN FILTER TO ESTIMATE POSITION, VELOCITY, AND 4 PARAMETERS
  - EXTENDED INERTIAL NAVIGATION APPROACH FOUND TO
    - PRODUCE MUCH MORE ACCURATE ESTIMATES OF POSITION AND VELOCITY
    - ESTIMATE AERODYNAMIC PARAMETERS USEFUL FOR GUIDANCE LAW IMPLEMENTATION
    - ACCOMODATE RELATIVELY LARGE UNCERTAINTIES IN ENTRY CONDITIONS, ESPECIALLY WITH ADDITION OF ALTIMETRY DATA

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FY87 PRODUCTS (CONTINUED)

- ORBITAL CHANGES DURING HYPERSONIC AEROCRUISE
  - GENERAL THEORY DEVELOPED FOR ORBITAL PLANE CHANGES DURING AEROCRUISE MANEUVER (CONSTANT ALTITUDE, VELOCITY)
  - APPROACH
    - TURN ANALYZED IN LOCAL FRAME - VELOCITY, ALTITUDE, ANGLE OF ATTACK, THRUST CHOSEN TO MAXIMIZE TURN ANGLE FOR FIXED PROPELLANT EXPENDITURE
    - COORDINATE TRANSFORMATION YIELDS CHANGES IN ORBITAL ELEMENTS RELATIVE TO EQUATORIAL FRAME
  - OPTIMAL LOCATIONS FOR MANEUVERS FOUND
    - CHANGE INCLINATION AT NODAL CROSSING
    - PERFORM NODAL CHANGE AT INCLINATION-DEPENDENT LOCATION (AT APEX ONLY FOR POLAR ORBIT) - NEW RESULT

FY87 PRODUCTS (CONTINUED)

- OPTIMAL TRAJECTORIES FOR AEROASSISTED NONCOPLANAR ORBITAL TRANSFER
  - EXTENSION OF EARLIER WORK ON FUEL MINIMIZATION WITHOUT CONSTRAINT ON HEATING RATE
  - DIFFERENT PERFORMANCE INDICES INVESTIGATED
    - MINIMIZE FUEL CONSUMPTION
    - MINIMIZE MAXIMUM HEATING RATE
    - MINIMIZE $\int \dot{Q}\,dt$
  - DIFFERENT ORBIT TRANSFERS INVESTIGATED
    - 1-IMPULSE, 2-IMPULSE DEORBIT MANEUVERS
    - THREE INITIAL ORBIT RADII
  - MINIMIZATION OF $\int \dot{Q}\,dt$ FOUND TO WORK BEST
    - GOOD TRADEOFF BETWEEN MINIMIZING FUEL AND MINIMIZING MAXIMUM HEATING RATE
    - ENTER ATMOSPHERE DEEP ENOUGH TO TURN EFFECTIVELY, BUT NO DEEPER

FY87 PRODUCTS (CONTINUED)

- VEHICLE CONTROL ON AN ATMOSPHERIC SKIP TRAJECTORY
  - THREE-AXIS MODEL OF VEHICLE ATTITUDE DYNAMICS DEVELOPED
  - TWO ATTITUDE CONTROL LAWS DEVELOPED FOR TRACKING A REFERENCE BANK ANGLE COMMAND DURING CONSTANT-ALTITUDE FLIGHT
    - NONADAPTIVE SHUTTLE-LIKE P-D CONTROL LAW
      - DIRECT MATCHING OF PARAMETERS TO TRACK DRAG VS SPEED PROFILE
      - GAINS RELATED TO UNCERTAIN PARAMETERS
    - MODEL-REFERENCE ADAPTIVE CONTROL
  - CONTROL LAW PERFORMANCE EVALUATED VIA SIMULATION
    - BOTH SCHEMES PERFORM WELL IN TRACKING ALTITUDE-HOLD BANK ANGLE COMMAND
    - ONLY ONE SEGMENT OF SKIP TRAJECTORY STUDIED, HOWEVER; NONADAPTIVE CONTROL LAW MAY PERFORM LESS WELL ON OTHER TRAJECTORY SEGMENTS
  - PRELIMINARY CONCEPTS OF HIERARCHICAL INTELLIGENT CONTROL SYSTEM STRUCTURE DEFINED

FY89 PLANNED ACCOMPLISHMENTS

- CONTINUATION OF UNIVERSITY RESEARCH
  - NEAR-OPTIMAL ONBOARD GUIDANCE FOR AEROMANEUVERING PLANE CHANGES
  - OPTIMAL SYNERGETIC PLANE CHANGES IN AEROCRUISE MODE
  - OPTIMAL AEROASSISTED TRANSFER BETWEEN NONCOPLANAR ELLIPTICAL ORBITS
  - HIERARCHICAL INTELLIGENT CONTROL SYSTEMS
- ATTITUDE CONTROL OF A HYPERSONIC VEHICLE
  - ADAPTIVE CONTROL LAWS FOR SYNERGETIC PLANE CHANGE
  - ONBOARD ESTIMATION OF CONTROL-RELATED PARAMETERS
- DEVELOPMENT OF IMPROVED GUIDANCE AND NAVIGATION TECHNIQUES AND ALGORITHMS
  - FOR DESCENT FROM PLANETARY ORBIT TO SURFACE
  - FOR PLANETARY AEROCAPTURE

GUIDANCE, NAVIGATION, AND CONTROL OF FUTURE AEROMANEUVERING VEHICLES

SUMMARY

- OBJECTIVE: DEVELOP AND VALIDATE HIGH-PERFORMANCE, ADAPTIVE, INTEGRATED GN&C CONCEPTS FOR FUTURE AEROMANEUVERING VEHICLES
- APPROACH: APPLY ADVANCED THEORETICAL TOOLS TO DEVELOP EFFICIENT AND RELIABLE GN&C ALGORITHMS

  VALIDATE ALGORITHMS FOR SPECIFIC APPLICATIONS
- FY88 ACCOMPLISHMENTS:
  - OPTIMAL TRAJECTORY CHARACTERISTICS FOR AEROMANEUVERING PLANE CHANGES DETERMINED
  - SIMPLE, NEAR-OPTIMAL, ONBOARD GUIDANCE LOGIC FOR AEROMANEUVERING PLANE CHANGES DEVELOPED AND TESTED
  - VEHICLE CONTROL LAW FOR ATMOSPHERIC SKIP TRAJECTORY UNDER DEVELOPMENT
  - GUIDANCE AND NAVIGATION ALGORITHMS FOR AEROMANEUVERING ENTRY TO LANDING DEVELOPED AND TESTED
  - 5 CONFERENCE PAPERS PRESENTED
  - 8 JOURNAL ARTICLES PUBLISHED; 1 IN PRESS

MARS ROVER SAMPLE RETURN MISSION

NAVIGATION STUDIES PERFORMED DURING FY 88

LINCOLN J. WOOD

1 FEBRUARY 1989

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91109

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APPROACH-PHASE NAVIGATION

- Navigation errors on approach to Mars evaluated for various combinations of data types, data accuracies, and data processing techniques.
- Earth-based radio tracking:
  - Yields 3-sigma error in entry flight path angle of 1.8 deg for scenario investigated versus requirement of 0.5 deg.
  - Limited by Mars ephemeris error and solar radiation pressure uncertainty — some improvement possible.
- Optical data plus radio tracking:
  - Yields 3-sigma error in entry flight path angle of 0.5 deg for scenario investigated, consistent with requirement.
  - Limited by resolution of imaging system and satellite ephemeris errors.

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ORBIT-PHASE NAVIGATION

- Navigation errors while in orbit about Mars evaluated for various combinations of orbit sizes and geometries, data accuracies, and data processing techniques.
- RSS position uncertainty at periapsis 24 hr ahead less than 0.2 km for 1-sol retrograde orbit, after several days of tracking.
- Similar position uncertainty 24 hr ahead obtained for 463-km circular orbit.
- Uncertainty in Martian gravity field a major limiting factor.
- Results obtained assumed only doppler data — additional data types may be needed for singular geometries.

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ENTRY-PHASE GUIDANCE, NAVIGATION AND CONTROL

- Software system for simulating an aeromaneuvering vehicle Mars entry and landing was designed, built, tested and run.
- System simulates actual vehicle state and onboard computations separately. Onboard computations simulated include:
  - Navigation using accelerometer and gyro data plus relative range to an orbiter or vehicle on surface.
  - Guidance based on shuttle algorithms but with numerous modifications.
  - Control delays built into system through constraints on maximum allowable roll rate and acceleration.

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ENTRY-PHASE GUIDANCE, NAVIGATION AND CONTROL (cont.)

- Simulation used to generate landing errors.
  - Error sources:
    - initial state knowledge and control errors
    - atmospheric errors
    - IMU errors
    - ranging errors
    - state errors of the vehicles used for relative ranging
  - Results generated for descent from 500 km orbit by biconic vehicle with L/D=1.5
  - Combined knowledge and control landing errors (3 sigma) range from 1.3 km (ranging to vehicle on surface) to 9 km (IMU integration only), with knowledge errors dominating.
  - Speeds at parachute deployment range from 0.38 km/sec to 0.66 km/sec.

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HIGH-ENERGY AEROBRAKING ELEMENT OF PROJECT PATHFINDER

GUIDANCE, NAVIGATION, AND CONTROL ACTIVITIES PLANNED FOR FY 89

LINCOLN J. WOOD

1 FEBRUARY 1989

JET PROPULSION LABORATORY
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HIGH-ENERGY AEROBRAKING ELEMENT OF PATHFINDER

- OBJECTIVES OF JPL GUIDANCE, NAVIGATION, AND CONTROL TASKS
  - DEVELOP TECHNIQUES FOR DESIGNING NOMINAL ATMOSPHERIC TRAJECTORIES THAT
    - SATISFY SPECIFIED END CONDITIONS
    - MINIMIZE PROPELLANT CONSUMPTION
    - MEET HEATING RATE AND OTHER CONSTRAINTS
    - ARE RELATIVELY INSENSITIVE TO CHANGES IN FLIGHT CONDITIONS
  - DEVELOP AND COMPARE ONBOARD, REAL-TIME ATMOSPHERIC NAVIGATION APPROACHES EMPLOYING ALTERNATIVE ESTIMATION ALGORITHMS AND MEASUREMENT TYPES; DEVELOP AND COMPARE PERFORMANCE OF VARIOUS ONBOARD, CLOSED-LOOP, ADAPTIVE ATMOSPHERIC GUIDANCE SCHEMES
  - ASSESS PLANETARY APPROACH GUIDANCE AND NAVIGATION ACCURACIES FOR VARIOUS NAVIGATIONAL DATA TYPES, DATA PROCESSING SCENARIOS, AND MANEUVER STRATEGIES
- PLANNED FY89 ACCOMPLISHMENTS FOR JPL GUIDANCE, NAVIGATION, AND CONTROL TASKS
  - PRELIMINARY SOFTWARE FOR REFERENCE ATMOSPHERIC TRAJECTORY DESIGN
  - PRELIMINARY DEVELOPMENT OF ALTERNATIVE REAL-TIME NAVIGATION SCHEMES
  - PRELIMINARY ASSESSMENT OF APPROACH GUIDANCE AND NAVIGATION ACCURACIES

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GUIDANCE, NAVIGATION AND CONTROL OF FUTURE AEROMANEUVERING VEHICLES

DETAIL OF WORK PERFORMED AT JPL WITHIN OAST CONTROLS AND GUIDANCE PROGRAM

William M. McEneaney
1 February 1989

JPL

JPL In-house efforts in 1988

- Aeromaneuvering landing study.
- Near-optimal onboard guidance for aeromaneuvering plane change.

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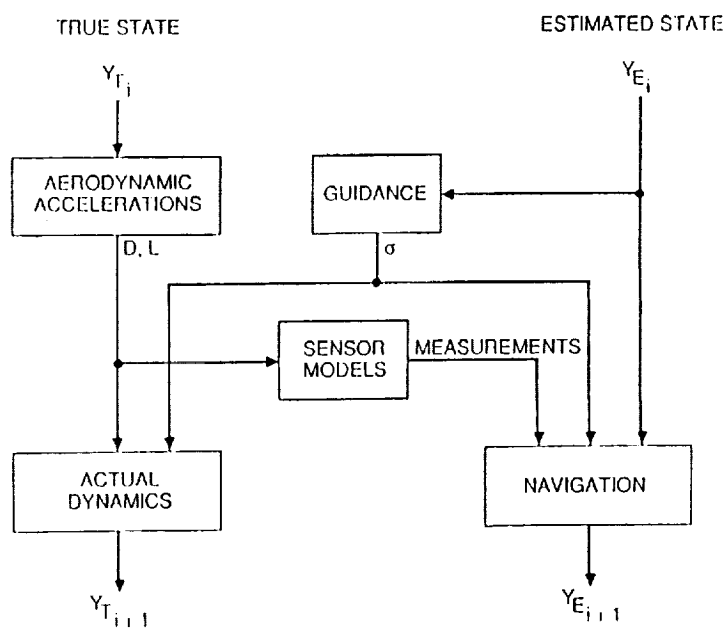
Aeromaneuvering Landing Study

- Development of simulation for study of aeromaneuvering flight from entry to parachute deployment.
- Simulation propagates actual spacecraft state and on-board estimate separately. This allows the combined effects of both Guidance and Navigation errors to be studied.
  - Error sources:
    initial state knowledge and control errors
    atmospheric errors
    IMU errors
    ranging errors
    state errors of the vehicles used for relative ranging

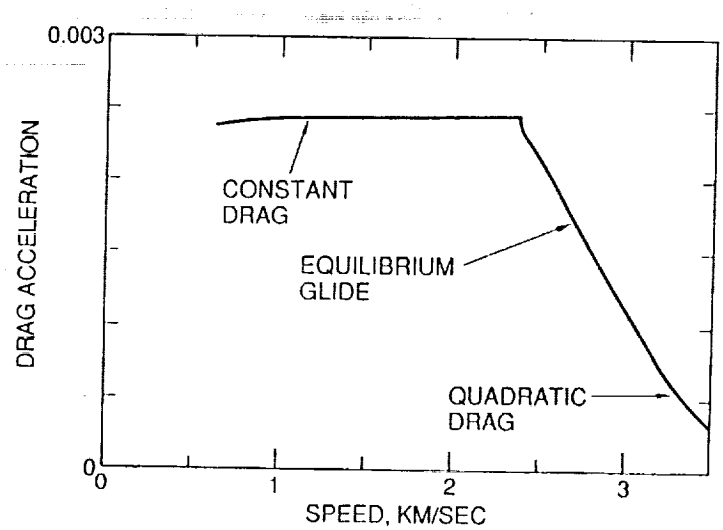
SIMULATION FLOW CHART



GUIDANCE

- Guidance scheme similar to Shuttle.
- Bank angle modulation used for both in-plane and out-of-plane control.
  - constant angle of attack
  - Shuttle used bank angle for primary control, angle of attack for short period control.
- Nominal drag versus speed profile used for in-plane control.
- Drag profile can be designed to stay within boundaries defined by constraints such as maximum allowable dynamic pressure and stagnation heating rate.
- Can integrate drag profile to determine range to termination.

REPRESENTATIVE DRAG PROFILE



DOWNRANGE GUIDANCE

- Three segment drag profile:
  - quadratic drag — $D = C_0 + C_1 v + C_2 v^2$
  - equilibium glide — $D = \frac{g - v^2/r_0}{(L/D)_0}$
  - constant drag — $D = D_0$
  - note that last two segments are one parameter subsets of family of general quadratic profiles.
- For each segment, the vertical L/D profile which nominally corresponds to the drag profile is known.
- A feedback control loop is used to damp out variations from the nominal profile.
- During the last two segments, the profile can be adjusted to match the estimated range to the target.

CROSSRANGE GUIDANCE

- Crossrange controlled by sign of bank angle.
- When the edge of the azimuth error deadband is reached, a bank reversal is triggered.
- The azimuth error deadband width is input as a function of vehicle speed.
- Finite time required for large bank angle changes (eg. bank reversals) due to limits on bank angle rate and acceleration. These constraints are imposed in the software by determination of the minimum time to achieve the change and the corresponding bank profile.

NAVIGATION

- Direct integration of IMU output may be used when no additional data types (such as relative range) are available.
- Navigation filter may be used with or without additional data types.
  - 13 state filter —
    - position and velocity
    - bank angle and angle of attack
    - atmospheric density multiplier and scale height
    - two accelerometer biases
    - range bias
  - Data types include range measurements relative to another vehicle as well as IMU.

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Navigation (cont.)

- For standard Kalman filtering, one must assume some atmospheric error model.
  - Models studied:
    Nominal
    ±50 % constant density multiplier errors
    Viking 1, Viking 2 data
    Warm/high-pressure, Cool/low-pressure envelope limits

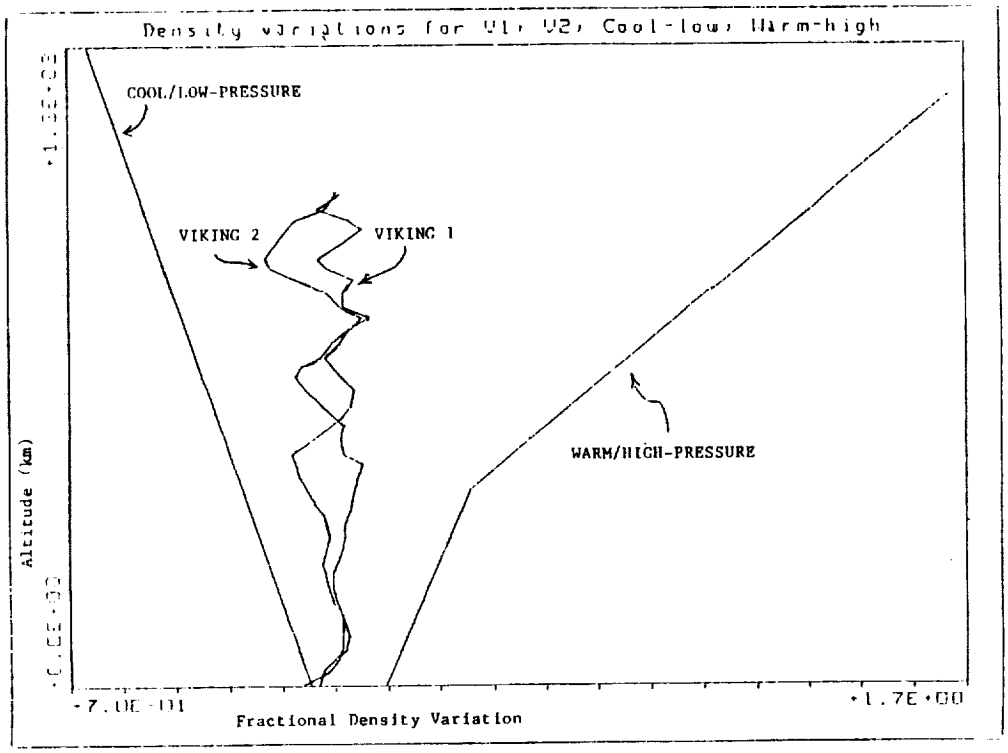

TABLE 1 — ACCELEROMETER INTEGRATION

Atmosphere	Errors					
	Δr_a (km)	$\Delta\theta_a$ (deg)	$\Delta\phi_a$ (deg)	Δr_e (km)	$\Delta\theta_e$ (deg)	$\Delta\phi_e$ (deg)
Nominal	0.01	0.002	0	-0.02	0.002	0
+50%	-0.05	0.002	0.001	-0.03	0.002	0
−50%	-0.04	0.004	-0.006	-0.02	0.003	-0.006
Viking 1	-0.05	0.003	0	-0.02	0.002	0
Viking 2	-0.06	0.004	-0.001	-0.03	0.003	-0.001
Cool/Low	-0.05	0.002	0.002	-0.02	0.002	0.002
Warm/High	-0.04	0.003	-0.001	-0.02	0.002	-0.001

TABLE 2 — FILTER WITH RANGE DATA

Atmosphere	Errors					
	Δr_a (km)	$\Delta\theta_a$ (deg)	$\Delta\phi_a$ (deg)	Δr_e (km)	$\Delta\theta_e$ (deg)	$\Delta\phi_e$ (deg)
Nominal	0.01	0	-0.001	-0.01	0.001	-0.001
+50%	0.6	-0.003	0.004	-0.02	0.002	0.003
−50%	-0.07	0.007	0.003	-0.05	0.004	0.003
Viking 1	0.07	0.001	0.004	-0.03	0.002	0.004
Viking 2	0.02	0.001	-0.003	-0.02	0.002	-0.003
Cool/Low	-0.02	0.003	0	-0.01	0.001	0
Warm/High	0.5	-0.003	0.004	-0.02	0	0.003

TABLE 3 -- FILTER WITHOUT RANGE DATA

Atmosphere	Time Const.	Errors					
		Δr_a (km)	$\Delta\theta_a$ (deg)	$\Delta\phi_a$ (deg)	Δr_e (km)	$\Delta\theta_e$ (deg)	$\Delta\phi_e$ (deg)
Nominal	100	0.01	0	-0.001	-0.01	0.001	-0.001
+50%	100	2.9	-0.137	0.008	0	0	0.001
−50%	100	-0.3	-0.265	-0.003	2.8	-0.421	0.005
Viking 1	100	0.4	-0.011	0.003	-0.01	0.001	0.002
Viking 2	100	-0.1	0.014	-0.004	-0.03	0.003	-0.003
Cool/Low	100	-0.3	-0.026	0	0.8	-0.091	0.004
Warm/High	100	2.7	-0.085	-0.005	-0.02	0.002	-0.010
Nominal	1000	0.01	0	-0.001	-0.02	0.002	-0.001
+50%	1000	0.22	-0.064	0.005	-0.03	0.002	0.001
−50%	1000	-0.3	-0.007	-0.002	0.2	0.037	0
Viking 1	1000	0.7	-0.019	0.007	0	0.001	0.006
Viking 2	1000	0.8	-0.018	0.002	-0.01	0.002	0.002
Cool/Low	1000	0	0.012	0.001	-0.2	0.003	0.001
Warm/High	1000	2.0	-0.032	0.003	-0.03	0.002	0.001

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GUIDANCE AND NAVIGATION 3 SIGMA ERROR SUMMARY

- L/D=1.5 (accelerometer integration)

Component	Downrange	Crossrange
3σ initial state (rss of table columns)	7.8	0.8
3σ bias and scale factor	4.1	0.5
3σ atmospheric density	0.3	0.4
3σ entry angle control	0.1	0.4
total 3σ guidance and nav	8.8	1.1

- L/D=0.5 (accelerometer integration)

Component	Downrange	Crossrange
3σ initial state (rss of table columns)	4.5	1.3
3σ bias and scale factor	2.0	0.1
3σ atmospheric density	0.2	5.8
3σ entry angle control	0.2	0.6
total 3σ guidance and nav	5.0	6.0

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Near-Optimal Onboard Guidance for Aero-maneuvering Plane Change

- Simple near-optimal guidance logic used.
- Final velocity maximized while meeting constraints on final altitude, flight path angle and heading angle.
  - Non-dimensional equations of flight:

$$\frac{d\gamma}{d\psi} = \frac{\delta + M}{\sigma}$$
$$\frac{dw}{d\psi} = \frac{-\gamma}{\sigma}$$
$$\frac{d\nu}{d\psi} = \sigma + \frac{1}{\sigma} + \frac{\delta^2}{\sigma}$$

γ, w, ν and ψ are the non-dimensional flight path angle, altitude, speed and heading angle.
M is Loh's term, and δ and σ are the controls.

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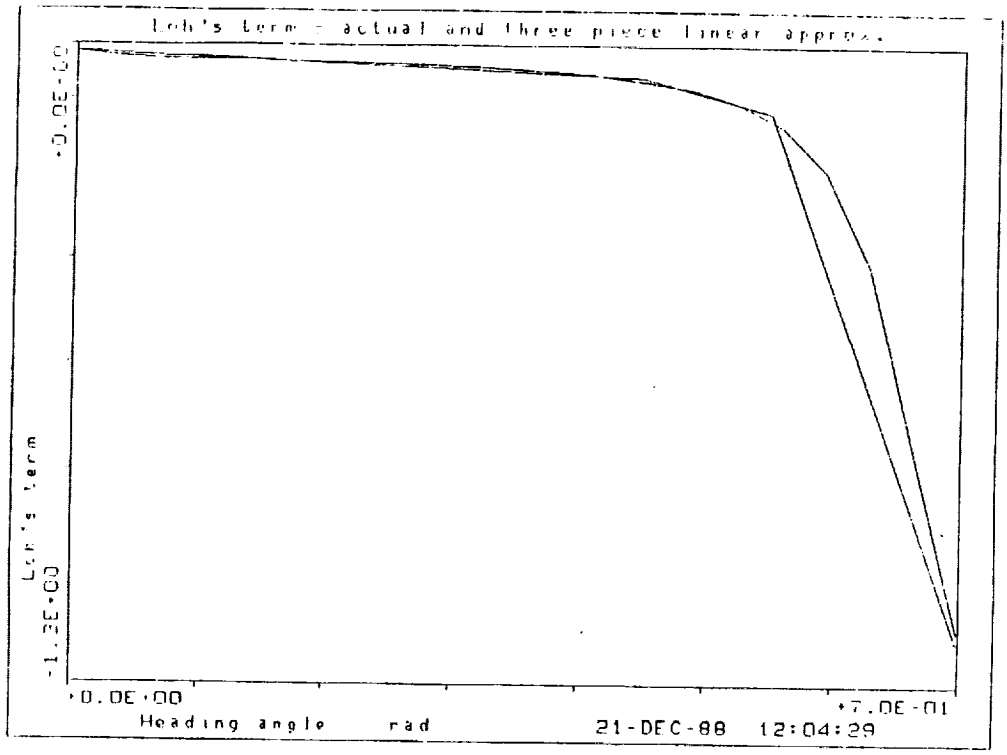
- Piecewise linear approximation to Loh's term used (as opposed to previous two-piece piecewise constant approximation).
- Euler-Lagrange equations may be formulated and solved analytically.

$$\dot{\delta} = -\frac{\lambda_2}{2\sigma}$$
$$\dot{\sigma} = -\frac{\dot{M}\delta}{\sigma}$$

- Constraint integrals may also be solved analytically.
- Solution is similar qualitatively and numerically to "true" optimum.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-1.3E+00
Loh's term
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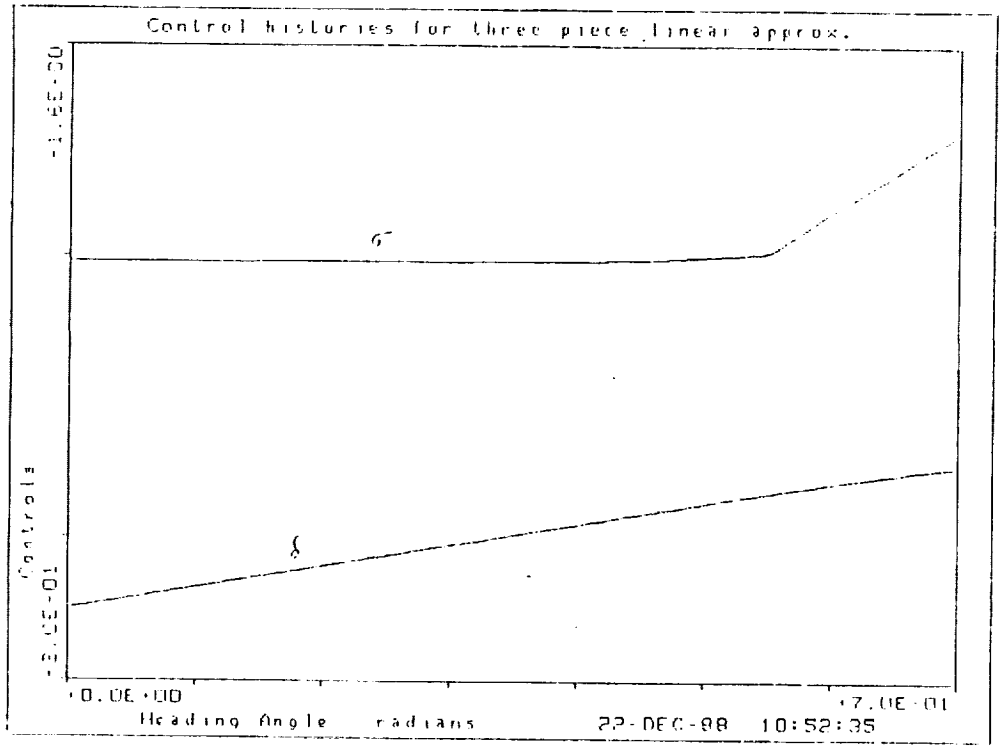
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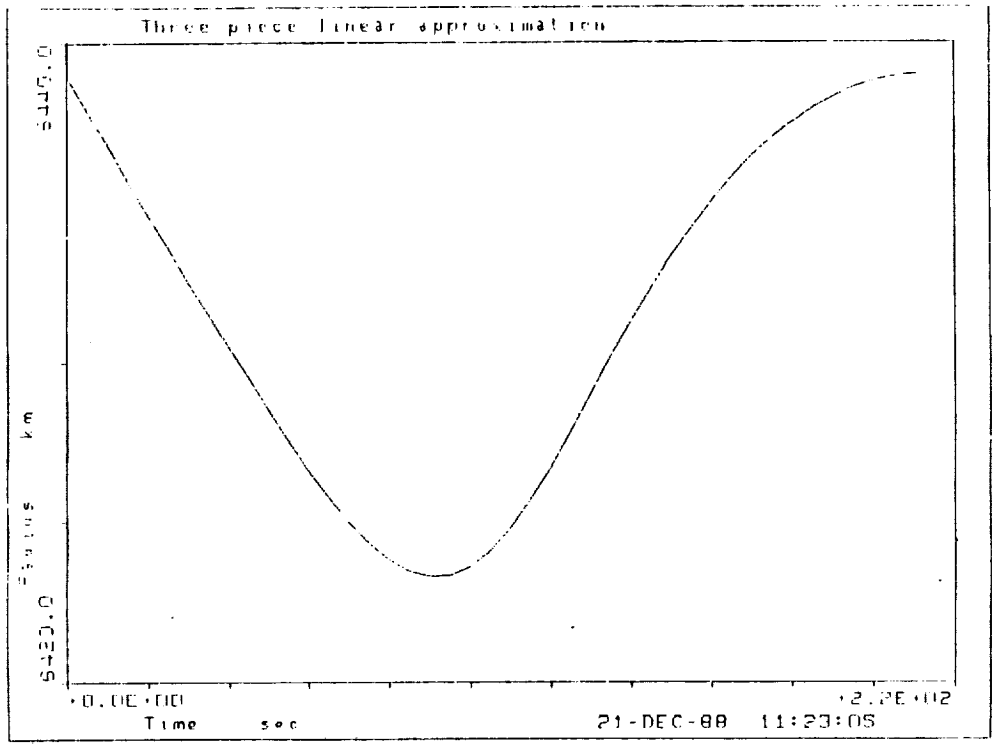
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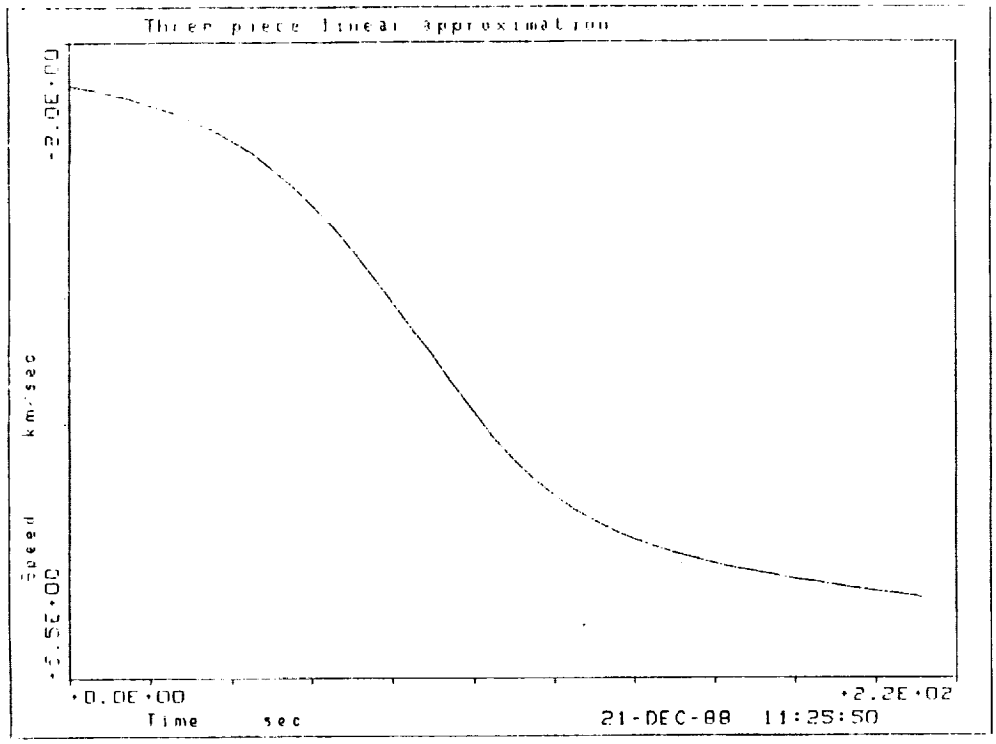
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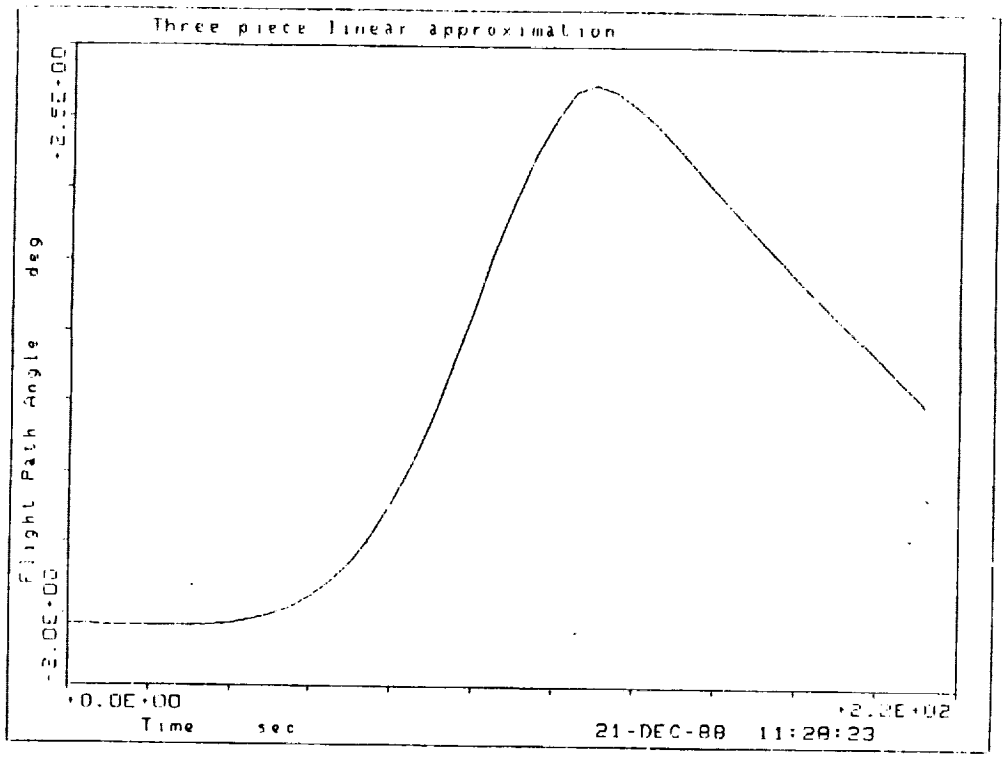
Three piece linear approximation
Flight Path Angle deg
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-2.0E+00
+0.0E+00
Time sec
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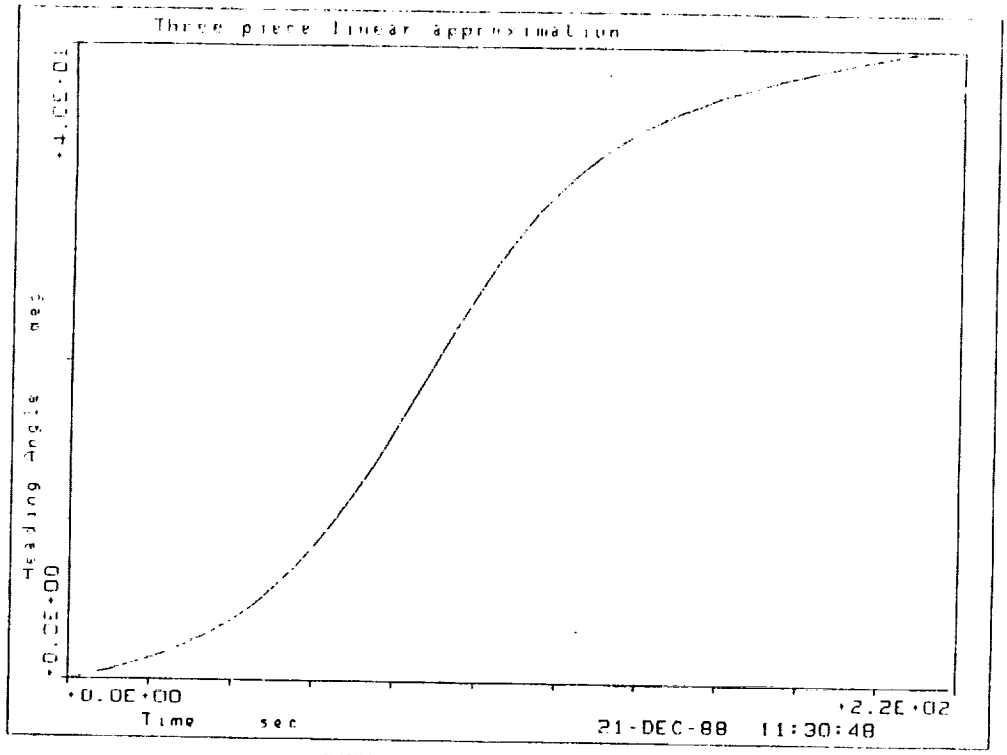
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HIGH ENERGY AEROBRAKING WORKSHOP

MISSION AND VEHICLE CONCEPT STUDIES

BY

JOHNNY H. KWOK
JET PROPULSION LABORATORY

AT
AMES RESEARCH CENTER
JAN 31 – FEB 2, 1989

JHK 1/31/89

OUTLINE

* JPL MISSION ANALYSIS SOFTWARE LIBRARY
* SUMMARY OF MRSR PRE-PHASE A MISSION AND VEHICLE CONCEPTS
* EXAMPLES OF POSSIBLE HEA MISSION AND SYSTEM REQUIREMENTS

JHK 1/31/89

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MISSION ANALYSIS SOFTWARE LIBRARY

- CONTOUR
  - PARAMETRIC CONTOUR PLOTS OF LAUNCH ENERGY, LAUNCH TIME, ARRIVAL VELOCITY, CAPTURE ORBIT ELEMENTS, SOLAR ILLUMINATION ANGLE, ETC.
- KPLOT
  - GRAPHICAL VIEWS OF PLANETARY TRANSFER, ENTRY, CAPTURE, FLYBY, ETC.
- LPLOT
  - COMPUTES RANGE, ANGULAR PARAMETERS, ETC., RELATING THE PLANETS, THEIR NATURAL SATELLITES, S/C, TRACKING STATIONS, ETC. TO EACH OTHER.
- PLATO
  - PLANETARY TRAJECTORY OPTIMIZATION
- CONSAT
  - GLOBAL MULTIPLE IMPULSE OPTIMIZATION
- MRSR FLIGHT VEHICLE PERFORMANCE SPREADSHEET (DEVELOPED BY SAIC)
  - LOTUS SPREADSHEET, INCLUDES LAUNCH/ARRIVAL VELOCITY, S/C DRY MASS, PROPULSION SYSTEM MODELS, HEA VEHICLE SCALING EQUATIONS, ORBIT TRANSFER REQUIREMENTS, ETC.
  - COMPUTES INJECTED MASS

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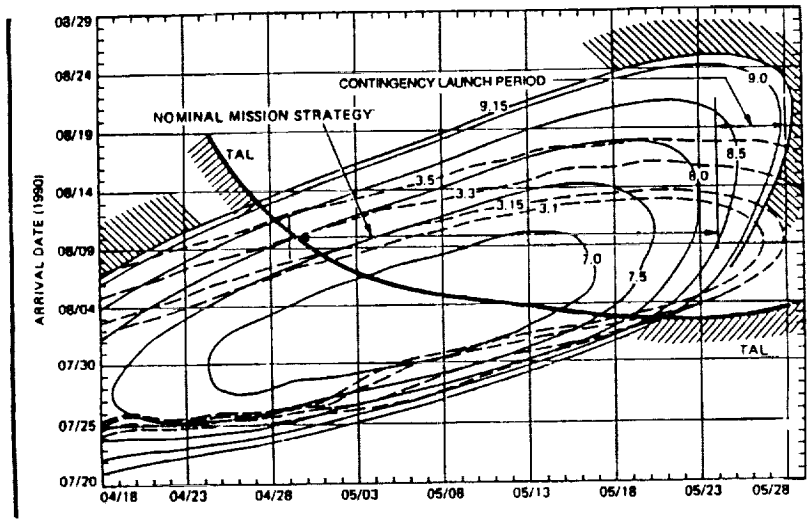

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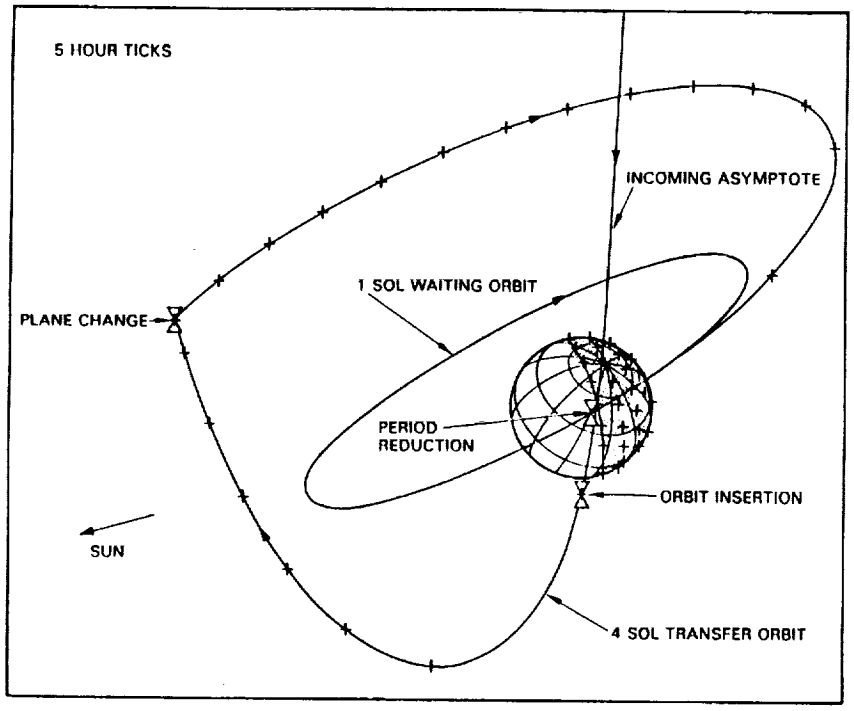


JPL

REFERENCE MISSIONS SELECTION

MRSR LAUNCH CONFIGURATION

FLIGHT SEGMENT	A	B		C		D	
		B1	B2	C1	C2	D1	D2
MAPPING/COMM ORBITER (MCO)	X		X	X			X
SAMPLE RETURN ORBITER (SRO)	X	X			X		X
ROVER	X		X		X	X	
MARS ASCENT VEHICLE (MAV)	X	X		X		X	

JHK-3

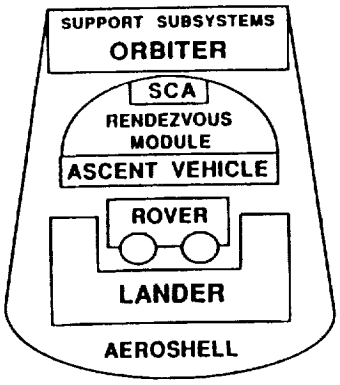
JPL

REFERENCE MISSIONS SELECTION

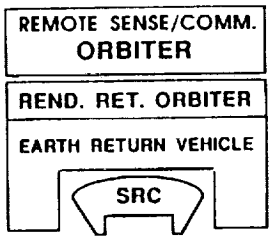
MISSION NAME	LOCALD		AREAL B		AREAL D		AREAL B HEAVY	
LAUNCH CONFIG.	D1	D2	B1	B2	D1	D2	B1	B2
LANDING SITE	ALBA PLAIN 45°N, 130°W		MANGALA 6°S, 147°W		DETERMINED BY D2		CANDOR 10.5°S, 74.5°W	
ROVER TRAVERSE	LOCAL (100M)		AREAL (20-40 KM)		AREAL (20-40 KM)		AREAL (20-40 KM) HEAVY ROVER	
LAUNCH VEHICLE	UPGRADED TITAN IV/CENTAUR G'							
OPPORTUNITY	'98	'98	'98	'98	'98	'96	'98	'98
MARS CAPTURE	AERO	PROP	AERO	PROP	AERO	PROP	AERO	AERO
EARTH CAPTURE		AERO	PROP			PROP	D.E.	

LOCAL D

D1-A



D2-P/A



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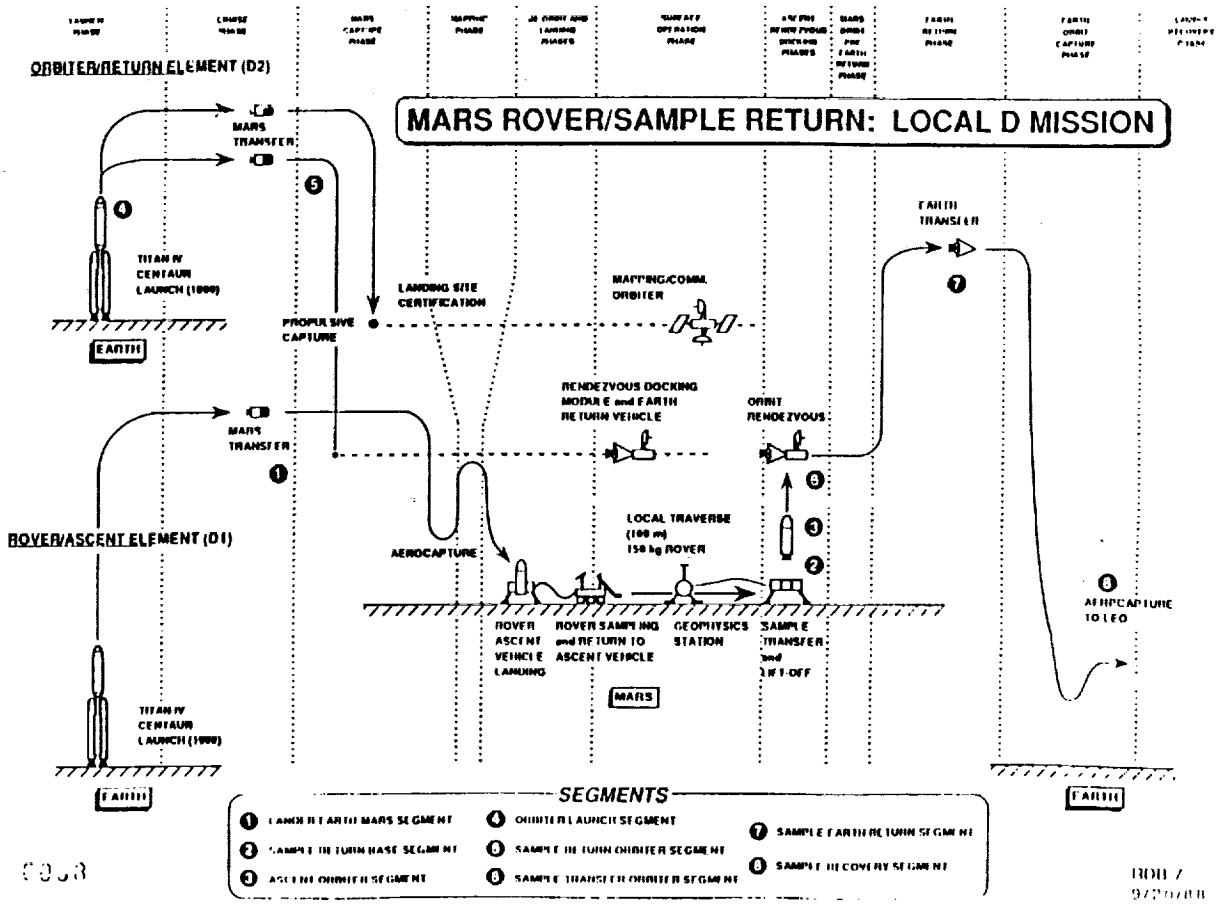
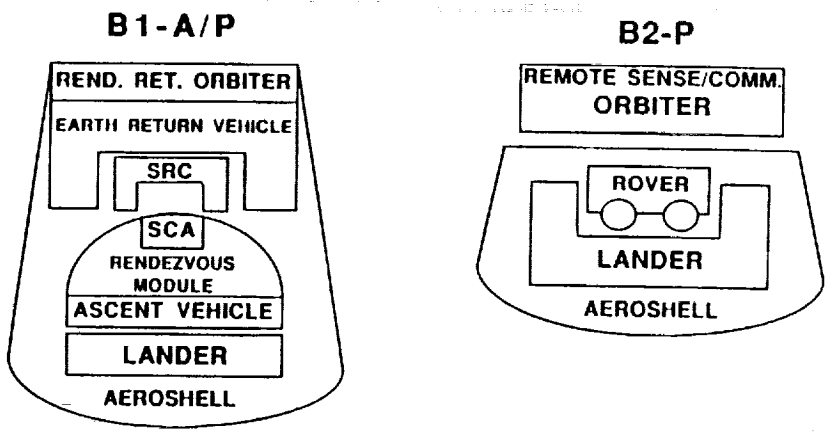
SRC = SAMPLE RETURN CANNISTER



AREAL B



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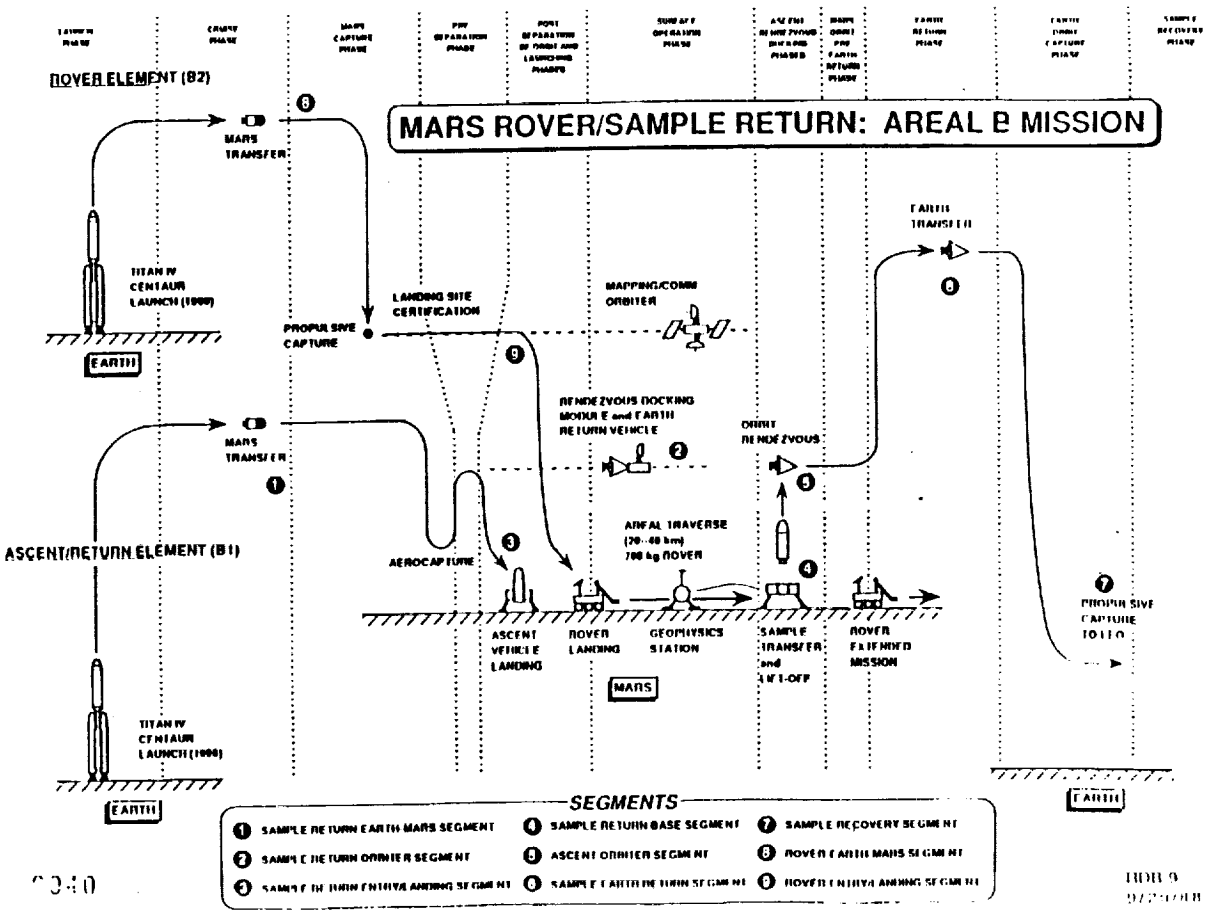
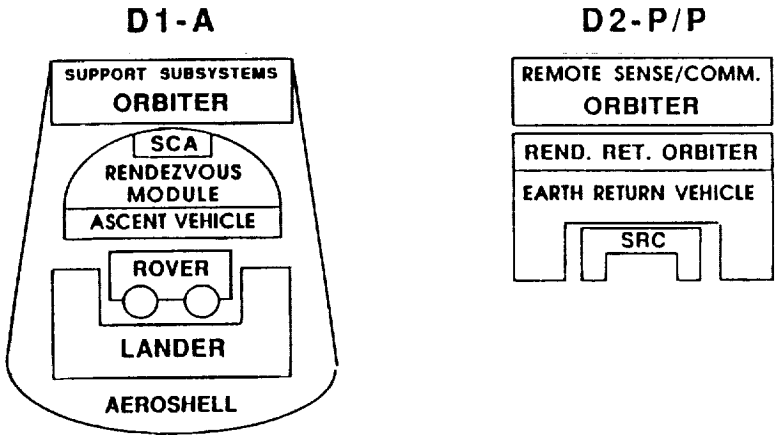


AREAL D



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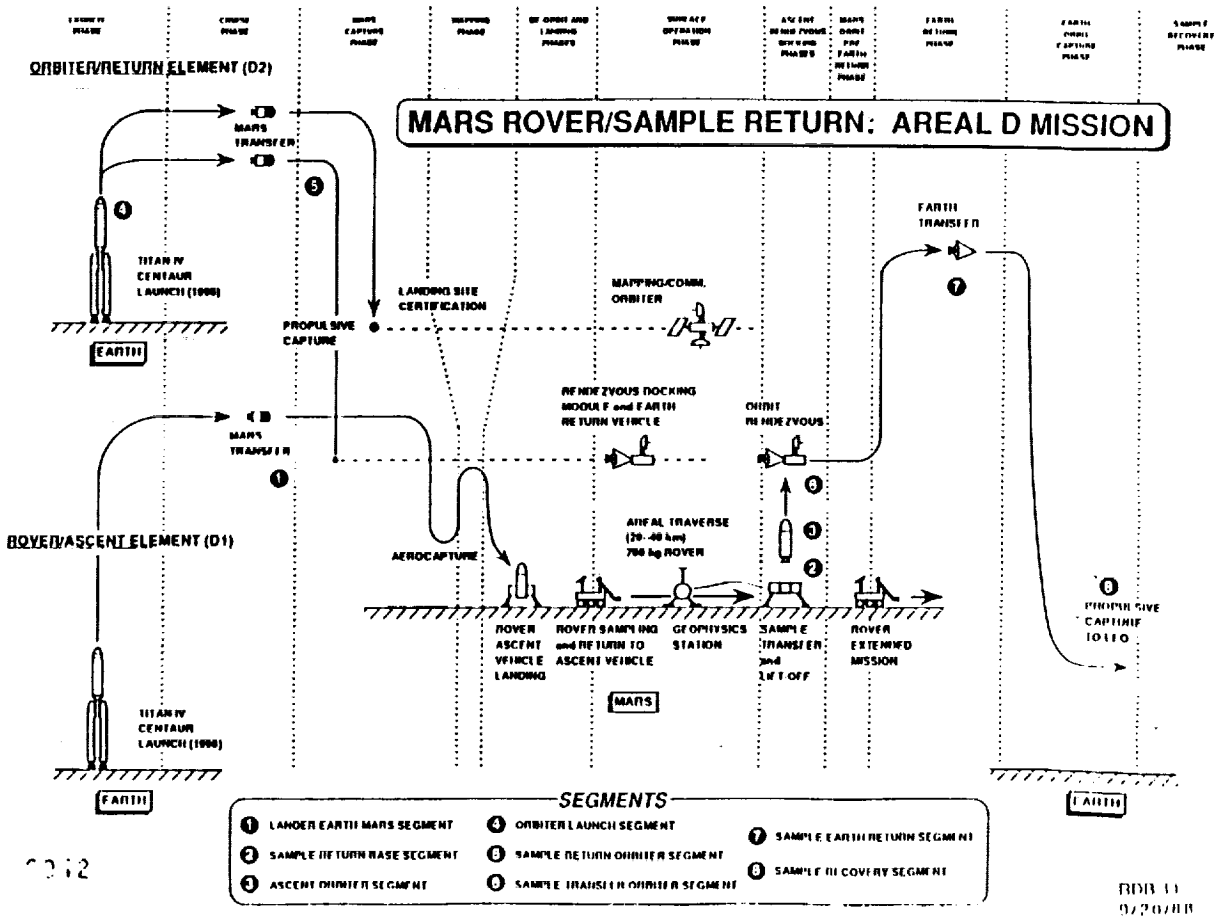
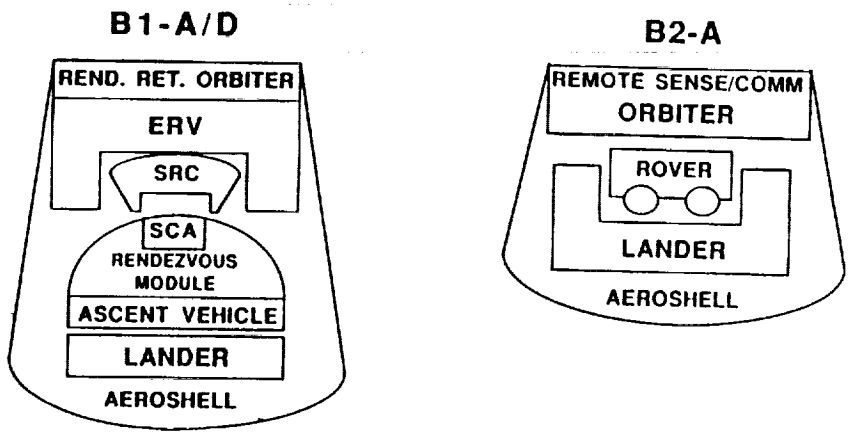


AREAL B (HEAVY)



SCA = SAMPLE CANNISTER ASSEMBLY
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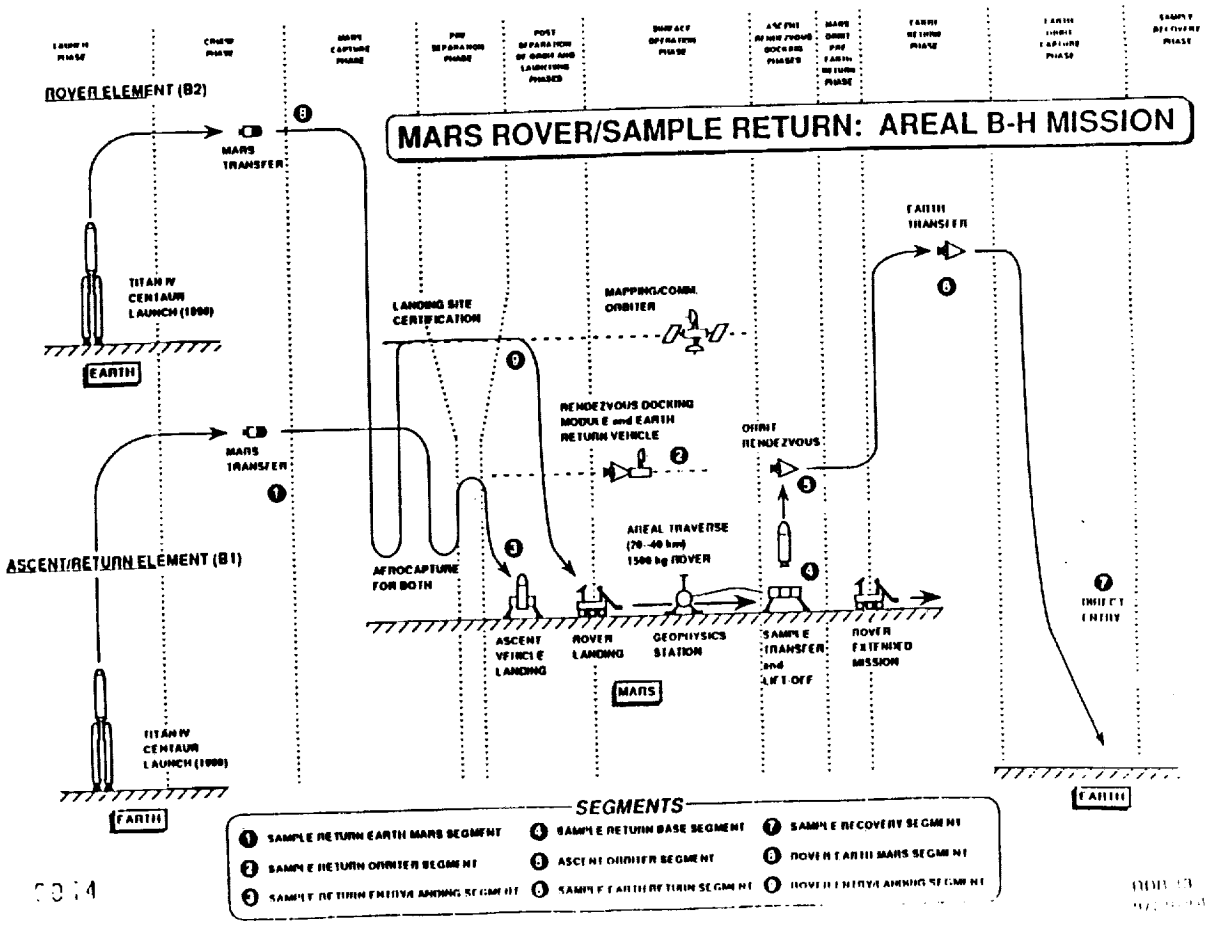

HEA MISSION AND SYSTEM REQUIREMENTS

- REAL TIME TELEMETRY
  - DIRECT TO EARTH, RELAY BY OTHER VEHICLE
- APPROACH NAVIGATION
  - OPTICAL NAVIGATION, VEHICLE TO VEHICLE TRACKING, APPROACH GEOMETRY, MANEUVER ACCURACY, AUTONOMOUS GNC
- ENTRY NAVIGATION
  - ORBITER TO ENTRY VEHICLE RANGING, LANDMARK TRACKING
- ORBIT PLANE CHANGE AND PERIAPSIS ROTATION
  - CRITICAL INCLINATION ORBIT, EQUATORIAL ORBIT, SUN–LIGHT CONDITION, SITE ACCESSIBILITY
- MULTIPLE PASSES
  - WAITING ORBIT, IMAGING ORBIT, COMMUNICATION ORBIT, VEHICLE EJECTION
- DEORBIT FROM ELLIPTICAL ORBITS
  - ENTRY AND LAND AT PERIAPSIS
- DUST STORM
  - AEROCAPTURE, ENTRY, SURFACE OPERATIONS
- PLANETARY PROTECTION AND QUARANTINE
  - ROBOTIC MISSIONS, PILOTED MISSIONS

LIST OF ISSUES

OLD LIST OF QUESTIONS TO CODE Z COPIED FROM BLACKBOARD

FEBRUARY 1, 1989

LIST OF QUESTIONS TO CODE Z FROM THE PATHFINDER HIGH ENERGY AEROBRAKING TEAM

(QUESTIONS GENERALLY APPLY TO BOTH THE MRSR AND MMM MISSIONS)

0.0 IN-SPACE ASSEMBLY OF AEROBRAKES

- FEASIBILITY/PRACTICALLY OF PRODUCING AEROBRAKE TPS FROM LUNAR MATERIAL
- CAPABILITY OF ASTRONAUTS/ROBOTS IN ASSEMBLY OF AEROBRAKE

1.0 TRANSIT

- ALLOWABLE TRANSIT TIME - BOTH WAYS
- EFFECT ON SPACECRAFT THERMAL CONTROL BY ENTRY THERMAL PROTECTION SYSTEM
- EFFECT OF IN-SPACE EXPOSURE ON TPS

LIST OF QUESTIONS TO CODE Z FROM THE PATHFINDER HIGH ENERGY AEROBRAKING TEAM (CONTINUED)

2.0 MARS ENTRY AND LANDING

- RESULTS OF RECENT CODE Z SPONSORED STUDIES
- ACCURATE INFORMATION ON HEIGHT OF FOUR VOLCANOES AT + 20 AND -10 DEGREES LATITUDE - CURRENTLY LISTED AS HIGH AS ABOUT 27 KM AND SHOWN IN VARIOUS PUBLICATIONS AND MAPS WITH FACTORS OF TWO DIFFERENCES
- AMOUNT OF DUST INCLUDING SIZE DISTRIBUTION IN MARTIAN ATMOSPHERE AS FUNCTION OF ALTITUDE AND MARTIAN YEAR-MAY EFFECT TPS DUE TO IMPACT
- DESIRED PARKING ORBIT(S), LANDING SITES AND TIME TO BE SPENT ON SURFACE
- PRACTICAL LIMITS ON MISSION SCENARIOS/DESIRED MASSES TO BE PLACED ON MARTIAN SURFACE
- ACCEPTABLE G-LOADS ON CREW DURING MARS ENTRY FOLLOWING LONG PERIOD OF SPACE FLIGHT

LIST OF QUESTIONS TO CODE Z FROM THE PATHFINDER HIGH ENERGY AEROBRAKING TEAM (CONCLUDED)

13.0 EARTH RETURN

- PRACTICAL LIMITS ON MISSIONS SCENARIOS/DESIRED MASSES BE RETURNED TO EARTHY/CORRIDOR WIDTH - INCLUDE DIRECT ENTRY AND SPACE STATION RENDEZVOUS
- ACCEPTABLE G-LOADS BY CREW DURING EARTH RE-ENTRY FOLLOWING LONG PERIOD OF SPACE FLIGHT
- IMPACT OF AI/ROBOTICS ON EARTH ENTRY MANEUVER/SPACE STATION RENDEZVOUS
- WOULD THE HEAT OF RE-ENTRY SUFFICE TO STERILIZE THE RETURN ENTRY CAPSULE OF MARS "BUGS"

ISSUES

ACTION TO ICWG:

- FUNDING VS DELIVERABLES VS SCHEDULE
- REPORT TO HQ CODES R, M, E & Z
- CO_2 IN ARC JETS

- SOLAR RADIATION & EFFECTS OF VENUS FLYBY
- HEIGHT OF VOLCANOES BY 1993?

  DEFINE CONSTRAINTS, LANDING???
- DIRECT ENTRY ON EARTH RETURN - OPEN ISSUE
- TRADE PROPULSION @ EARTH RETURN TO GET $V_\infty \cong 11$ KM/SEC

  - AVOID PRFE? COST TO IMLEO (CODE Z) B. DURRETT
- MARS DENSITY VARIATION

  - PREDICTABLES (MODELING AT ARC)
  - MEASURE FROM MARS ORBIT
  - SCOUT PROBE? WORK AROUND?
- DO WE NEED PRECURSOR FLIGHT?

ISSUES

(CONTINUED)

- COORDINATE WITH GODDARD MARS AERONIMY ORBITER - MAY 89
- AEROBRAKE REUSE?
- COST OF ON - ORBIT REFURBISHMENT OF AEROBRAKE
- QUALITY FOR CO_2 ENTRY MARS AEROCAPTURE BRAKE
- BY JUNE, DURRETT WILL SPECIFY WHETHER OR NOT MARS AEROBRAKE WILL RETURN TO EARTH
- FOCUS ON SYNERGY OF AEROBRAKE & NUCLEAR PROPULSION - MULTIPLE USE OF AEROBRAKES
- FOLLOW UP/CONNECT/COORDINATE WITH OTHER PATHFINDER ELEMENTS
- DESIGN & CHARACTERIZE LARGE DIA VEHICLES - WORK IN PROGRESS

ISSUES

(CONCLUDED)

- PACKAGING OF MISSION HARDWARE - C.G., ETC.
  - CONFIGURATION & PACKAGING COMPATIBILITY
  - HIGH L/D POSSIBLE?
- IMPORTANCE OF NON-EQUILIBRIUM AT MARS; SCOPE HEATING PROBLEMS
- DEFINE THE BIG DRAGONS - POTENTIAL "SHOW-STOPPERS"
- SYSTEM STUDIES (+ CODE Z) PROVIDE LIMITS ON HEAB

SYSTEMS STUDIES SUBGROUP REPORT

FEBRUARY 2, 1989

STUDY CLASS II (ADVANCED MARS MISSION)
AMBITIONS AEROCAPTURE TECHNOLOGY

(AEROCAPTURE DOES NOT CONSTRAIN MISSION)

- EARTH ENTRY VELOCITIES, $V_{EM} \leq$ 16 KM/SEC
- V_M = 6-10 Km/S
- MAX ACC = 5g
- P/L MASS AND VOLUME CONSISTENT WITH CODE Z FY 88 EIGHT PERSON MISSION
- TECHNOLOGY LEVEL 6 FOR PHASE C/D (~1999)
- γ_E ACCURACIES TO BE DEFINED BY GNIC
- ASSUME 1989 KNOWLEDGE BASE ON MARS ATMOSPHERE [RELATED TECH. ALLOWABLE eg. PROBES, ORBITORS, SCOUTS]
- ALTITUDE CORRIDORS DETERMINED BY JPL
- CROSS RANGE UNCONSTRAINED
- USE SAME AEROBRAKE FOR EARTH AND MARS AEROCAPTURE; SEPARATE MARS ENTRY VEHICLE
- RETURN TRANSIT SYSTEM TO EARTH ORBIT

STUDY CLASS I
MINIMUM AEROCAPTURE TECHNOLOGY

- LIMIT ENTRY VELOCITIES TO APOLLO/AFE RANGE (11-12 Km/Sec) (RETRO-PROPULSION ALLOWED)
- P/L, MASS AND VOLUME CONSISTENT WITH CODE Z FY 89 3-MAN MISSION
- 1995 TECHNOLOGY
- V_m = 6-10 Km/Sec (RETRO-PROPULSION ALLOWED)
- γ_E ACCURACIES TO BE DEFINED BY GN AND C SUB PANEL
- MAX ACC = 5g (TO BE VERIFIED)
- ASSUME RANGE OF MARS ATM'S USED IN MRSR STUDIES
- MINIMUM ALTITUDE UNCONSTRAINED AT MARS
- NO CROSS RANGE REQUIRED
- USE SAME AEROBRAKE FOR BOTH MARS AEROCAPTURE AND ENTRY
- MINIMUM EARTH RETURN MANNED CAPSULE

AEROTHERMODYNAMICS

SUBGROUP REPORT
FEBRUARY 2, 1989

CODE R/Z/E/INDUSTRY
HIGH ENERGY AEROBRAKING HEAB WORKSHOP

1/31/89 - 2/2/89
NASA AMES RESEARCH CENTER

HIGH ENERGY AEROBRAKING

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Chien Li	Johnson Space Center
Tom Edquist	Martin Marietta
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John Howe	Ames Research Center
Mike Green	Ames Research Center
Tony Strawa	Ames Research Center
Graham Candler	Ames Research Center
Grant Palmer	Ames Research Center
Surrendra Sharma	Ames Research Center
Dinesh Prabhu	Ames Research Center
Bill Feiereisen	Ames Research Center
Dave Cooper	Ames Research Center

HIGH ENERGY AEROBRAKING

AEROTHERMODYNAMICS
BROAD ISSUES

AEROTHERMODYNAMICS RESEARCH FOR HEAB SHOULD BE BROAD RANGED

- DEVELOP REFINED TOOLS
- ENHANCE UNDERSTANDING
- DEVELOP ENGINEERING TOOLS
- PERFORM SENSITIVITY STUDIES
- CONFIGURATION INDEPENDENT

FUNDING SHOULD BE ADEQUATE TO SUPPORT EXPERIMENTAL TEST AND CODE DEVELOPMENT AND VALIDATION ACTIVITY

- COMPUTATIONAL TOOL DEVELOPMENT
- GROUND BASED EXPERIMENTS
- COMPUTER RESOURCES
- FLIGHT EXPERIMENTS

HIGH ENERGY AEROBRAKING
AEROTHERMODYNAMICS
VALIDATION REQUIREMENTS

GROUND BASED TEST PROGRAM
- NONEQUILIBRIUM RADIATION/CHEMISTRY
- REAL GAS AERODYNAMICS
- LOW DENSITY FLOWS
- TURBULENCE
- ABLATION
- DUSTY FLOWS
- BASE FLOWS
- UNSTEADY FLOWS
- SURFACE EFFECTS (CATALYSIS)

FLIGHT TEST DEFINITION
- CONVECTIVE & RADIATIVE HEATING
- AERODYNAMICS

FACILITY REQUIREMENTS
- COMPUTER RESOURCES
  - SUPERCOMPUTERS
  - WORK STATIONS/GRAPHICS
- EXPERIMENTAL FACILITIES
  - SHOCK TUBES
  - BALLISTIC RANGES
  - ARC JETS
- INSTRUMENTATION

QUALITY PARAMETER DEFINITION FOR VALIDATION

HIGH ENERGY AEROBRAKING

AEROTHERMODYNAMICS
FLUID PHYSICS

PHENOMENA	RECOMMENDED ACTION	PERF. ORGS.	DATE REQD
REAL GAS AERODYNAMICS	NECESSARY	A/L/J	IMMED.
NONEQUILIBRIUM	CO_2 SCOPE OUT/	A	1 YR
CHEMISTRY	SENSITIVITY		
RADIATION	AIR/CO_2/N_2	A/L/J	3-5 YR
GAS PROPERTIES (AIR, CO_2-N_2)	DEFINITION OF	A	1 YR
THERMODYNAMIC AND TRANSPORT	CRITICAL PROPERTIES		
REACTION RATES & CROSS SECTIONS	CURVE FITS (EQUIL)	A	3-5 YR
HIGH IONIZATION LEVELS	NONEQUILIBRIUM	A	>5 YR
TURBULENCE	NECESSARY	A/L/J	IMMED.
ABLATION	NECESSARY	A/L	3-5 YR
SURFACE EFFECTS	NECESSARY	A/L/J	3-5 YR
DUSTY FLOWS	LOW LEVEL	A	3-5 YR
BASE FLOWS	NECESSARY	A/L/J	3-5 YR
REACTING			
RADIATING			
UNSTEADY			
3-D			
IMPINGEMENT			
UNSTEADY AEROELASTIC (FLUTTER)	NOT CRITICAL		
LOW DENSITY FLOWS (L/D EFFECT)	LOW LEVEL	A/L	IMMED.

HIGH ENERGY AEROBRAKING

AEROTHERMODYNAMICS
RECOMMENDATIONS

PRIORITIZE RESEARCH ACTIVITY FOR LOW L/D CONFIGURATIONS

IDENTIFY SIMPLE GENERIC CONFIGURATION AND BASELINE TRAJECTORIES TO FOCUS RESEACH DEVELOPMENT (CODE Z)

UPGRADE EXISTING ENGINEERING CODES TO INCLUDE CURRENT TECHNOLOGY AND TO CONSIDER 3-D EFFECTS AND BASE FLOWS

EARTH ENTRY ISSUES: ABLATOR OR NONABALTOR (CODE Z)

MARS ENTRY ISSUES: NONEQUILIBRIUM PHENOMENA (CODE R)

PROPOSE PERIODIC AUDIT OF SYSTEM STUDY DESIGNS USING ADVANCED CAT CODES

HIGH ENERGY AEROBRAKING

AEROTHERMODYNAMICS
GENERAL COMMENTS

REAL GAS AERODYNAMICS SHOULD BE CONSIDERED IN ALL CODE ACTIVITY

NONEQUILIBRIUM CHEMISTRY AND RADIATION MUST BE CONSIDERED FOR COMPLETENESS. IN THE NEAR TERM IT IS IMPORTANT TO ASSESS THE SIGNIFICANCE OF NONEQUILIBRIUM. FOCUS ON CO_2 - N_2 ATMOSPHERE AND IDENTIFY CRITICAL REACTIONS USING SENSITIVITY STUDIES.

ANALYTIC DESCRIPTIONS OF GAS PROPERTIES DESIRABLE FOR EQUILIBRIUM FLOWS.

HIGHLY IONIZED FLOWS ARE A CHALLENGE FOR NONEQUILIBRIUM CONDITIONS.
STUDIES TO DETERMINE THE IMPORTANCE OF NONEQUILIBRIUM IONIZATION SHOULD BE PERFORMED.
HIGHLY IONIZED EQUILIBRIUM FLOWS ARE NOT DIFFICULT TO TREAT.

TURBULENCE IS NOT SOMETHING TO BE IGNORED. MASSIVE ABLATORS WILL BE TURBULENT. BASIC STUDIES ARE NEEDED.
TRANSITION WILL BE IMPORTANT FOR BICONICS AND FOR VERY LARGE AEROSHELLS.

IT IS NECESSARY TO INCLUDE ABLATION, INJECTION, AND CATALYTIC BOUNDARY CONDITIONS INTO ADVANCED CAT CODES. EXPERIMENTAL STUDIES ARE CRITICAL.

DUSTY FLOWS ARE NOT OF FIRST ORDER IMPORTANCE. CURRENT ACTIVITY IS AT ABOUT THE PROPER LEVEL.

HIGH ENERGY AEROBRAKING

AEROTHERMODYNAMICS
GENERAL COMMENTS (CONTINUED)

BASE FLOW PREDICTION REQUIRES A LOT OF DEVELOPMENTAL WORK. CRITICAL ISSUES INCLUDE EFFECTS ON AERODYNAMIC PERFORMANCE, RADIATIVE HEATING AND IMPINGEMENT HEATING.

UNSTEADY HYPERSONIC AEROELASTIC STUDIES ARE NOT DEEMED OF HIGH IMPORTANCE AT PRESENT. IF FLEXIBLE HEAT SHIELDS ARE REALLY USED THIS SUBJECT NEEDS ATTENTION.

LOW DENSITY EFFECTS ARE NOT OF FIRST ORDER IMPORTANCE. CURRENT ACTIVITY IS AT ABOUT THE PROPER LEVEL.

HIGH ENERGY AEROBRAKING

EXPERIMENTAL ISSUES
GENERAL COMMENTS

ARCJETS: -FLOWS MUST BE QUANTIFIED FOR AERO/AEROTHERMODYNAMIC TESTING.
-CFD SIMULATIONS SHOULD BE CONSIDERED AN INTEGRAL PART.
-FEASIBILITY STUDIES ARE REQUIRED FOR CO_2 TESTING.

BALLISTIC RANGES: -VALUABLE FOR
1) AERODYNAMIC COEFFICIENTS
2) BASE FLOW DEFINITION
3) 3-D FOREBODY TEMPERATURE DISTRIBUTION
4) ABLATION STUDIES
5) GAS/SURFACE ABSORBTION STUDIES
6) TRANSITION STUDIES

SHOCK TUBES: -SHOULD BE USED FOR:
1) NONEQUILIBRIUM CHEMISTRY/RADIATION STUDIES.
2) GAS PROPERTIES
3) GAS/SURFACE INTERACTION/ABSORPTION STUDIES.
4) EXPANDING FLOWS

CODE R/Z/E/INDUSTRY

HIGH ENERGY AEROBRAKING HEAB WORKSHOP

THERMAL PROTECTION SYSTEMS SUB-GROUP REPORT

BY

HOWARD GOLDSTEIN (LEADER, ARC)
DON CURRY (JSC)
WILLIAM HENLINE (ARC)
DANIEL LEISER (ARC)
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REQUIRE NEW THERMAL PROTECTION SYSTEMS/CONCEPTS FOR PATHFINDER

- DEVELOP ADVANCED ABLATOR THERMAL PROTECTION SYSTEMS
  - REFLECTIVE
  - NONCATALYTIC
  - OPTIMIZED DENSITY
  - OPTIMIZED THERMOPHYSICAL AND MECHANICAL PROPERTIES
- DEVELOP ADVANCED INSULATION SYSTEMS
  - REFLECTIVE
  - NONCATALYTIC
  - STABLE TO TEMPERATURE 3500-4000°F AND HEAT FLUXES IN EXCESS OF 100 BTU/FT^2-SEC.
  - OPTIMIZED THERMOPHYSICAL AND MECHANICAL PROPERTIES
- DEVELOP COMBINATION ABLATOR/INSULATIVE SYSTEMS: REUSABLE AT LOW HEAT FLUX ABLATIVE AT HIGH FLUXES
  - UTILIZE ON BOARD RESOURCES
- DEVELOP APPROPRIATE ANALYTICAL MODELS FOR CHARACTERIZATION AND DESIGN
  - THERMOCHEMICAL
  - THERMOSTRUCTURAL
- PERFORM SYSTEMS PARAMETRIC STUDIES TO DEFINE THERMAL PROTECTION MATERIAL CHARACTERISTICS
  - INDUCED ENVIRONMENTS (RADIATIVE, CONVECTIVE HEATING, PRESSURE, ACOUSTIC).
  - NATURAL ENVIRONMENTS (LONG TERM SPACE EXPOSURE, RADIATION, SOLAR FLARES, DUST, METEOROIDS, ETC.).
  - SYSTEMS TRADEOFFS BETWEEN RIGID AND FLEXIBLE SYSTEMS

ORG: AMES, LANGLEY, JSC, MARSHALL

TIME: REQUIRED BY END OF FY99

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NON-WEIGHT FACTORS INFLUENCE TPS SELECTION

EVALUATION CRITERIA	ABLATIVE	INSULATIVE		RADIATIVE	
		RSI	RFC	METAL	CARBON-CARBON
MATURITY	HIGH	HIGH	EMERGING	HIGH	HIGH
MAX USE TEMP	5000 °F	2800 °F	4000 °F	1800 °F	3500 °F
OUTGASSING	HIGH	INTERMEDIATE	LOW	NIL	LOW
STRENGTH	LOW	LOW	LOW	HIGH	INTERMEDIATE
DENSITY (PSF)	2.0-3.0	0.6-2.0	1.0-3.0	2.0-3.0	1.0-2.0
OXIDATION RESISTANCE					
• ATOMIC	POOR	GOOD	GOOD	GOOD	REQUIRES COATING
• DIATOMIC	LOW	LOW	HIGH	HIGH	
SIZE LIMITS	NONE	1 FT X 1 FT	2 FT X 6 FT*	NONE	5 FT X 5 FT*
MAN-RATED	YES	YES	NO	YES	YES
DAMAGE TOLERANCE	INTERMEDIATE	LOW	LOW	HIGH	INTERMEDIATE
REPAIRABILITY	POSSIBLE	POSSIBLE	UNDEVELOPED	YES	POSSIBLE
MULTI-USE	NO	YES	YES	YES	YES
REFURBISHMENT	NO	YES	UNDEVELOPED	YES	UNKNOWN
LONG TERM SPACE EXPOSURE	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN	UNKNOWN

*FURNACE/EQUIPMENT LIMITED

FLIGHT TEST

- RECOMMEND A FOLLOW ON FLIGHT AS SOON AS POSSIBLE AFTER AFE (ONE YEAR DESIRED) TO EVALUATE THERMAL PROTECTION SYSTEMS, AEROTHERMAL, AND GN & C REQUIREMENTS FOR MARS RETURN MISSION.

  - ENTRY VELOCITY IN EXCESS OF 14 KM/SEC
  - MIGHT USE AFE STRUCTURAL TEST ARTICLE
  - ADVANCED TPS FOR MANNED MISSION
  - MINIMUM (SIMPLE) INSTRUMENTATION
  - MUST RECOVER VEHICLE

- JUSTIFICATION

  - MUST CERTIFY TPS FOR MANNED FLIGHT TO MARS.
  - TPS PERFORMANCE AND VALIDATION - NOT AVAILABLE ANY OTHER WAY
  - REQUIRED TO MINIMIZE MANNED VEHICLE WEIGHT, OPTIMIZE DESIGN.

ORG: AMES, LANGLEY, JSC, MARSHALL

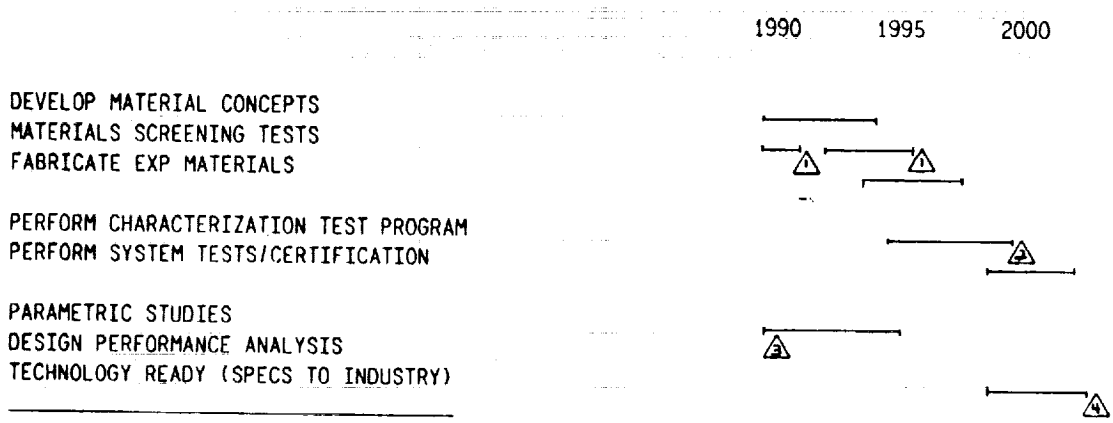
TIME: START NOW, FLIGHT FY95

FACILITIES REQUIREMENTS

- UPGRADE ARC-JETS FOR APPROPRIATE PLANETARY ATMOSPHERES
  - EARTH - NEED RADIATION SOURCE (PERHAPS GD LASER) AND HIGHER ENTHALPY
  - MARS - NEED CO_2 AND POSSIBLY RADIATION SOURCE
  - OTHER PLANET GASES: AS MISSIONS DEFINED
- UPGRADE ARC-JET STREAM/MODEL DIAGNOSTIC
- SPECTROSCOPIC AND LASER DOPPLER VELOCIMETRY, ETC., INCLUDING HIGH SPEED DATA ACQUISITION AND TRANSMISSION SYSTEM.

ORG: AMES AND JSC
TIME: BY FY92

SCHEDULE TO DEVELOP REQUIRED MATERIALS



1. SCREEN CANDIDATES
2. SELECT CANDIDATE MATERIALS
3. DEFINE MATERIAL REQUIREMENTS
4. COMPLETE DEVELOPMENT

HIGH ENERGY AEROBRAKING GN&C SUBGROUP REPORT

LIST OF ISSUES

ATMOSPHERIC DENSITY UNCERTAINTIES

AERODYNAMIC UNCERTAINTIES

APPROACH NAVIGATION ERRORS

TIME CRITICALITY OF PLANETARY AEROBRAKING

GN&C IMPACT ON VEHICLE DESIGN (L/D, W/CDA, HEATING)

APPROACH

ATMOSPHERIC DENSITY UNCERTAINTIES

GAIN INFORMATION ABOUT MARS ATMOSPHERE

PRECURSOR MISSION - LIDAR, ETC

DESIGN ROBUST GN&C TO HANDLE WORST DISPERSIONS

ADAPTIVE GN&C SYSTEM

AERODYNAMIC UNCERTAINTIES

WIND TUNNEL TESTS

CFD

PLANETARY RETURN FLIGHT EXPERIMENT

DESIGN ROBUST GN&C TO HANDLE WORST ERRORS

ADAPTIVE GN&C SYSTEM

APPROACH NAVIGATION ERRORS

BEST USE OF GROUND BASED SYSTEM WITH OPTICAL NAVIGATION

RADIOMETRIC TRACKING WITH IMPROVED MARS EPHEMERIS

AUTONOMOUS NAVIGATION FOR LAST PORTION OF APPROACH PHASE

TIME CRITICALITY AND SENSITIVITY TO FAILURES OF PLANETARY AEROBRAKING

ONBOARD AUTONOMOUS FAULT TOLERANT GN&C

SENSOR OPTIONS

GN&C IMPACT ON VEHICLE DESIGN (L/D, W/CDA, HEATING)

EVALUATION OF DIFFERENT VEHICLE CONFIGURATIONS

EARLY INTERACTION WITH AEROTHERMODYNAMIC, TPS, SYSTEMS DESIGN ACTIVITIES

CODE Z QUESTION: IS PLANE CHANGE CAPABILITY REQUIRED?
(PLANE CHANGE DURING AEROCAPTURE AND CROSSRANGE IN DESCENT AND LANDING)

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HIGH ENERGY AEROBRAKING

GUIDANCE, NAVIGATION & CONTROL

TASK AREAS	MILESTONES									
	FY 89		FY 90		FY 91		FY 92		FY 93	
- Reference Trajectory Design		1		3		6		10		14
- Atm. G, N & C Algorithm Development		2		4		7		11		15
- Planetary Approach G, N & C				5				12		16
- Sensors, Effectors & Computers						8				17
- Test Bed / Simulation Development						9		13		18

Schedule for the Guidance, Navigation and Control Work Area.

GUIDANCE, NAVIGATION AND CONTROL

1. Preliminary trajectory optimization software (9/89).
2. Preliminary evaluation of alternative atmospheric guidance and navigation schemes for Mars missions (9/89)
3. Preliminary atmospheric trajectories for Mars missions (9/90).
4. Improved navigation schemes for flight through poorly known atmospheres (9/90).
5. Preliminary approach guidance and navigation accuracies for Mars missions (9/90).
6. Multipass aerobraking study for Mars missions (9/91).
7. Real-time, onboard, adaptive guidance schemes (9/91).
8. Sensor, effector, and computer capability assessment (9/91).
9. Non-real-time test bed/simulation developed (9/91).
10. Updated atmospheric trajectories for Mars missions (9/92).
11. Real-time, onboard, adaptive control schemes (9/92).
12. Preliminary design of autonomous guidance and navigation system for approach phase (9/92).
13. Real-time test bed/simulation operational (9/92).
14. Study of aerobraking enhancement by thrusting (9/93).
15. Integrated, adaptive, fault-tolerant guidance, navigation, and control system design (9/93).
16. Updated approach guidance and navigation accuracies for Mars missions (9/93).
17. Fault-tolerant GN&C system hardware defined (9/93).
18. Integrated GN&C system tested in real-time test bed/simulation (9/93).

Milestones and Deliverables for the Guidance, Navigation and Control Area.

HEAB WORKING GROUP RECOMMENDATIONS

FLIGHT EXPERIMENTS

ISSUE	RECOMMENDED ACTION	PERFORMING ORG.	DATE NEEDED
MISSION DEFINITION INCLUDING ENTRY VELOCITY	SYSTEM STUDIES TO DEFINE MISSION		2 YEARS PRIOR TO PRFE NEW START
CONFIGURATION DEFINITION	SYSTEM STUDIES TO DEFINE CONFIGURATION		"
EXPERIMENT SCALE	ANALYSIS AND EXPERIMENTS TO DEFINE OPTIMUM AND MINIMUM SIZE AEROBRAKE FOR EXPERIMENT	ARC, LaRC	"
RADIATION EXPERIMENT IN ABLATING ENVIRONMENT	ANALYSIS AND EXPERIMENT OF PROTO-TYPE CONCEPT	ARC	"
CFD SIMULATION	FLOW FIELD SIMULATION WITH ABLATION, TURBULENCE AND COUPLED RADIATION	ARC, LaRC, JSC	PRELIMINARY RESULTS 2 YEARS PRIOR TO NEW START
GROUND BASED SIMULATION	OBTAIN DATA FOR MODEL DEVELOPMENT	ARC, LaRC, JSC	"
TPS MATERIALS	DETERMINE FEASIBILITY AND DEVELOP NON CATALYTIC ABLATORS AND RE-FLECTIVE ABLATORS	ARC	AT NEW START

FLIGHT EXPERIMENTS RECOMMENDATIONS

(CONCLUDED)

ISSUE	RECOMMENDED ACTION	PERFORMING ORG.	DATE NEEDED
GN&C ALGORITHM	DEVELOP GN&C ALGORITHMS FOR PRFE	JPL, JSC, LaRC	PRELIMINARY VERSIONS 2 YEARS PRIOR TO NEW START
SPACE ASSEMBLY OF AEROBRAKE*	DETERMINE FEASIBILITY OF SPACE ASSEMBLY FOR PRFE	LaRC, MSFC, JSC TO NEW START	2 YEARS PRIOR
LIGHTWEIGHT STRUCTURES	DEFINE STRUCTURE OPTIONS FOR PRFE	MSFC, LaRC, JSC	"
EFFECT OF PARTICULATES IN MARS ATMOSPHERES	ANALYSIS AND EXPERIMENT TO DETERMINE EFFECTS	ARC	1 YEAR AFTER NEW START

*Synergy with other elements of Pathfinder.

MANNED MARS MISSION EARTH ENTRY ISSUES VS. TEST PRODUCTS

DISCIPLINE	ISSUE	AFE PRODUCT	GROUND TEST/ COMPUTATIONAL MODELING PRODUCT	PREE REQUIRED
AERODYNAMICS	• ABLATION EFFECTS	NO	NO	YES
	• REAL GAS EFFECTS	PARTIAL (BLUNT BODY)	PARTIAL	YES
	• B.L. TRANSITION	NO	NO	YES
	• BASE FLOW EFFECTS	PARTIAL (BLUNT BODY)	PARTIAL	YES
	• PRESSURE DISTRIBUTION	PARTIAL (BLUNT BODY)	PARTIAL	YES
	• RAREFIED FLOW EFFECTS	BLUNT BODY	NO	YES
AEROTHERMODYNAMICS	• NON EQUILIBRIUM HIGHLY IONIZED FLOW FIELD WITH RADIATION COUPLING	CFD VALIDATION FOR NON EQUILIBRIUM DISSOCIATED FLOW FIELDS	PARTIAL	YES
	• BOUNDARY LAYER TRANSITION	NO	NO	YES
	• ABLATION EFFECTS	NO	PARTIAL	YES
	• RADIATION HEATING	NO	PARTIAL	YES
	• CONVECTIVE HEATING	PARTIAL	PARTIAL	YES
TPS	• RADIATION HEATING	NO	PARTIAL	YES
	• CONVECTIVE HEATING	FOR BLUNT BODY	YES	NO
	• TURBULENT FLOW	NO	NO	YES
	• CATALYTIC EFFECTS	NO	PARTIAL	YES
	• MATERIAL PERFORMANCE	PARTIAL	PARTIAL	YES
GN&C	• FAULT TOLERANT SYSTEMS	NO	YES	NO
	• ALGORITHM VERIFICATION	FOR LOW L/D	YES	NO
STRUCTURES	• IN-SPACE ASSEMBLY	NO	PARTIAL	YES
	• FLEXIBLE STRUCTURE/ FLOW FIELD INTERACTION	NO	PARTIAL (SMALL SCALE)	YES
	• THERMAL-STRUCTURAL RESPONSE	NO	PARTIAL (SMALL SCALE)	YES

M^3 MARS ENTRY ISSUES VS. TEST PRODUCTS

DISCIPLINE	ISSUE	AFE PRODUCT	COMPUTATIONAL MODELING/ GROUND TEST PRODUCT
AERODYNAMICS	• CO_2 EFFECTS	NO	PARTIAL (NON-ABLATING)
	• PARTICULATE EFFECTS	NO	PARTIAL
AEROTHERMODYNAMICS	• NON EQUILIBRIUM GAS PROPERTIES	PARTIAL	YES
	• NON EQUILIBRIUM RADIATION PROPERTIES	PARTIAL (ATOMS & DIATOMICS ONLY)	YES
TPS	• CO_2 CATALYSIS EFFECTS	NO	YES
	• PARTICULATE EFFECTS	NO	PARTIAL
ATMOSPHERE EFFECTS	• DENSITY VARIATIONS	NO	PARTIAL
	• DUST/ICE PARTICULATES	NO	PARTIAL

EXPERIMENTAL AND COMPUTATIONAL FACILITIES

SUBGROUP REPORT
FEBRUARY 2, 1989

CODE R/Z/E/INDUSTRY
HIGH ENERGY AEROBRAKING HEAB WORKSHOP

1/31/89 - 2/02/89
NASA AMES RESEARCH CENTER

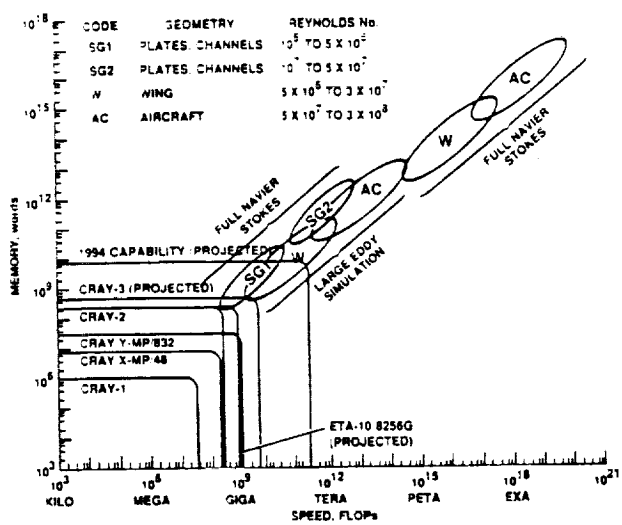
EXPERIMENTAL FACILITIES

- Current Facilities Adequate for All But TPS Needs [Mars and Return Missions
  - Improve Arc-Jet Capability to 25,000 BTU/lb.
  - Add Adequate Radiation Source
- Upgrade, Improve, and Increase Instrumentation and Dignostic Tools in All Facilities
  - Shock Tube
  - Ballistic Range
  - Arc-Jet
- Code Validation Critical
- Existing Facilities Provide Information/Simulation of Individual Phenomenon. Flight Tests Must Prove Interaction Assumptions.

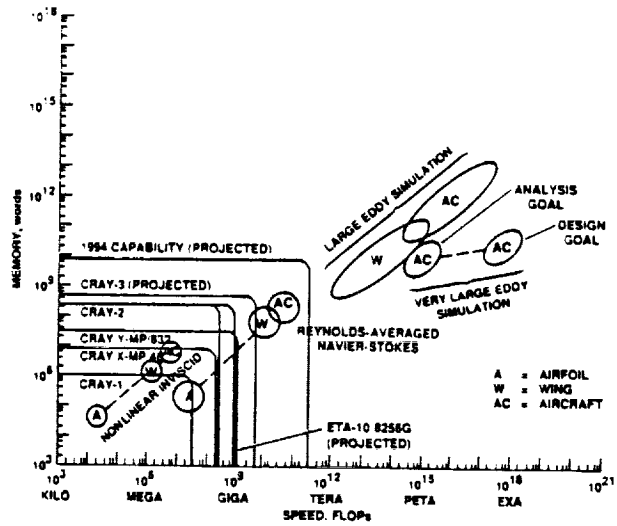
COMPUTATIONAL FACILITIES

- Capability Must Handle Coupled Radiative Calculations which Include Turbulence and Ablation - Products/Flow Field Interactions.
- Need Significant Increases in Memory and Speed for Both CFD and Chemistry Calculations.
- Computer Requirements (CPU Time) Cannot Be Estimated Until Mission Parameters Are Defined/Reduced.

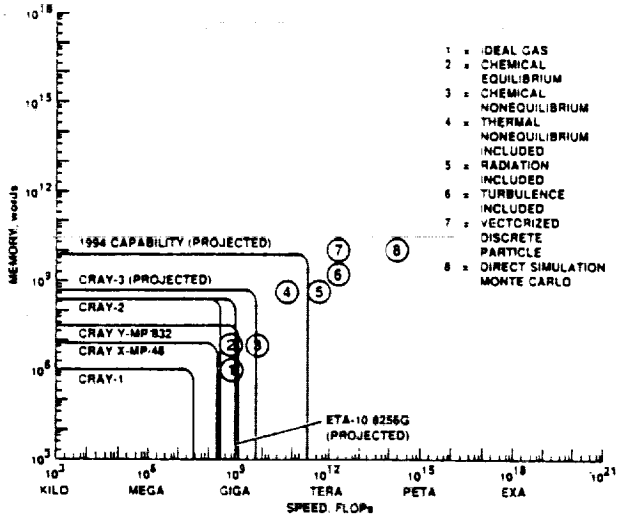
TURBULENCE PHYSICS RESEARCH

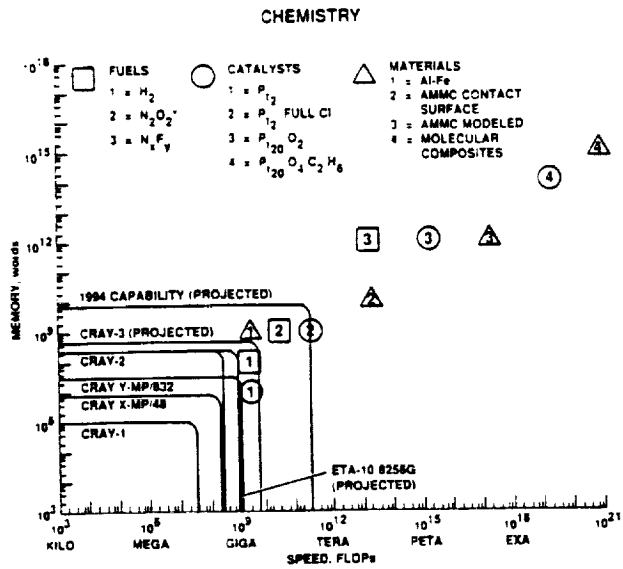


AEROTHERMODYNAMICS



AERODYNAMICS





EXPERIMENTAL AND THEORETICAL FACILITIES REQUIREMENTS/ISSUES

- CO_2 in Arc-Jets
- CO_2 Non-Equilibrium
- Improved Instrumentation
- Up-Grade Arc-Jet Capability
- Code Validation
- Quantity/Define Flow in Arc-Jet

FACILITIES

Issue	Recommended Action	Performing Org.	Date Needed
CO_2 in Arc-Jets	Determine Feasibility and Cost of Running CO_2 in Arc-Jets	ARC/JSC	ASAP
CO_2-Non-Equilibrium	Determine/Evaluate Rule of Non-Equilibrium Effects-Shock-Tube Studies	ARC	
Improved Instrumentation	Define Needs-Obtain Funds	All	ASAP
Up-Grade Arc-Jet Capability	Define Needs, Costs, and Obtain Funds	ARC	
Quality of Flow in Arc-Jets	Measure and Define Flow in Arc-Jets	ARC/JSC	

FACILITIES

Issue	Recommended Action	Performing Org.	Date Needed
Code Validation	Validated Codes for: 1.) Non-Equilibrium Effects 2.) Real Gas Aerodynamics 3.) Turbulence 4.) Ablation Products 5.) Dusty Flows 6.) Base Flows 7.) Unsteady Flows 8.) Catalysis 9.) Arc-Jet Flow	ARC/JSC/LaRC	

FOLLOW - UP COMMENTS

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AMES HEAB WORKSHOP FOLLOW-UP COMMENTS FROM BOEING

1. The planned Ames paper summarizing current knowledge about human limits for HEAB is desirable as soon as possible. The workshop ended with a consensus of 5 g peaks as a reasonable limit, but Dr. Cohen's actual statements did not lead directly to that result. Our sense was that the real limits for Gx are high and open-ended, and consequently not a problem.

2. Although the workshop was dominated by the needs of OEXP scenarios for human missions, the research community should be clear about the variable leverage of aerobraking for such missions. For example, conjunction trajectories with low encounter velocities may not warrant "super" aerobraking at all; also, there is an "availability tradeoff" between developing fascinating and advanced capabilities versus using those which could already work and be on-line in time.

3. Assembly considerations, which the workshop recognized to be critical to the systems studies, derived partly from data emergent from other Code R work. Technologists need to be cognizant that data which they may have and which may appear ancillary to their primary purpose, may in fact be extremely important for integration planning. For example, we need to know not just how TPS will perform in flight, but also how large joints can be sealed and how it can be folded.

4. The non-HEAB subject of artificial gravity came up three involved times during the first day of the workshop. Our inclusion of artificial gravity as a requirement derives from four observations. (1) Until we know certainly that it is not necessary, prudence surely dictates assuming it is. (2) The minority of astronauts who call for artificial gravity g for Mars missions just happen to be those (Soviet and American) with the longest-duration experience. (3) The performance requirements is not simply to be alive after many months in micro-g, nor to survive brief acceleration peaks, but rather to be able to carry useful weight around on the surface of Mars. A surface EVA suit light enough to let a person feel on Mars only as heavy as on Earth before flight, will stress suit technology development quite a bit as it is. (4) Aside from the technology and integration complications of tethers, artificial gravity can be accomplished for these missions at a weight penalty of about 10%, comparable to the weight benefits available from some other workable technology advancements, such as Earth departure engine Isp.

5. There was some confusion about whether or not computational codes for blunt non-axisymmetric bodies would be substantially different from those for axisymmetric bodies. Axisymmetric shapes constrain leeward payload to small volumes at (non-axisymmetrical flow) nonzero angles of attack which generate even low amounts of lift, and are therefore undesirable. The only aerobrake to fly during OEXP planning studies will be AFE, a non-axisymmetric shape, albeit a hybrid one more complicated than some other types, such as the Boeing hyperboloids. One of the splinter group conclusions was to develop symmetrical codes "for simplicity". If the two families of codes are in fact different enough to warrant such a development choice, then our original statement of the need for non-symmetrical analysis codes still obtains.

6. The research community explicitly said (in the systems groups) that it depends on the contractor community to tell it how much development programs might cost. However, a major factor in developing cost estimates is an understanding of the scope of work necessary. (Examples: 50-100 hrs of Cray time to characterize one molecular transition; 10 yr to bring new TPS from concept to qualification). The contractor community can use any estimates the research community can provide about the amount of research activity required to achieve specified levels of technical capability.

7. The value of a flight demonstration either designed to, or forced by size to, include a demonstration of assembly/deployment before its aeropass, cannot be overemphasized, particularly if a PRFE or AFE-II is approved.

APPENDICES

1. WORKSHOP AGENDA
2. ATTENDANCE LIST

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CODE R/Z/E/INDUSTRY HIGH ENERGY AEROBRAKING HEAB WORKSHOP

1/31/89 - 2/2/89 NASA AMES RESEARCH CENTER

MAIN AUDITORIUM (Bldg. 201)

January 31, 1989

8:00 - 8:10	WELCOME TO AMES RESEARCH CENTER	V. PETERSON
8:10-8:20	PURPOSE & EXPECTED PRODUCT OF WORKSHOP	J. ARNOLD
8:20 - 8:40	PERSPECTIVE FROM OFFICE OF EXPLORATION SPACE TRANSPORTATION INTEGRATION AGENT	B. DURRETT
8:40 - 9:00	NASA OFFICE OF SPACE FLIGHT OVERVIEW	G. AUSTIN OR F. HUFFAKER
9:00 - 9:15	HUMAN TOLERANCE TO HEAB	M. COHEN
9:15 - 9:25	QUESTION/ANSWER SESSION	
9:25 - 9:30	Break	
9:30 - 11:30	REVIEW OF MARTIN-MARIETTA STUDIES OF SPACE TRANSPORTATION VEHICLE CONCEPTS	B. CLARK
11:30 - 12:30	LUNCH - AMES CAFETERIA	
12:30 - 2:00	REVIEW OF BOEING STUDIES OF PATHFINDER MISSIONS INVOLVING HIGH ENERGY AEROBRAKING	G. WOODCOCK
2:00 - 2:05	BREAK	

NASA - OAST STUDIES OF HIGH ENERGY AEROBRAKING

2:05 - 2:15	OPENING REMARKS FROM OAST PATHFINDER PROGRAM OFFICE	J. MANKINS
2:15 -2:30	OVERVIEW OF OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY OAST HIGH ENERGY AEROBRAKING PROGRAM (MANAGEMENT)	S. WANDER

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SPECIFICS OF AMES' AEROBRAKING EFFORTS: PAST, PRESENT AND PLANNED

2:30 - 2:40	OVERVIEW OF AMES TRANSATMOSPHERICS PROGRAM	J. ARNOLD
2:40 - 2:50	AMES' MISSIONS ANALYSIS/SYSTEM STUDIES	M. TAUBER
2:50 - 3:20	AMES' AEROTHERMODYNAMICS PROGRAM	S. DEIWERT
3:20 - 3:50	AMES COMPUTATIONAL CHEMISTRY ACTIVITY AND APPLICATIONS TO DETERMINING PROPERTIES OF SHOCK-HEATED AIR AND MARS ATMOSPHERIC GASES	D. COOPER
3:50 - 4:00	BREAK	
4:00 - 4:30	AMES' PROGRAM IN THERMAL PROTECTION MATERIALS	H. GOLDSTEIN
4:30 - 6:30	OPEN HOUSE - TOUR OF AMES' HIGH ENTHALPY FACILITIES: ARC JETS, BALLISTIC RANGE AND ELECTRIC ARC SHOCK TUBE	

February 1, 1989

8:00 - 8:20	TECHNICAL OVERVIEW OF OAST HEAB PROGRAM	G. WALBERG

SPECIFICS OF LANGLEY AEROBRAKING EFFORTS: PAST, PRESENT AND PLANNED

8:20 - 8:30	LANGLEY OVERVIEW	G. WALBERG
8:30 - 9:00	SYSTEMS STUDIES	R. POWELL
9:00 - 9:30	ANALYTICAL AND EXPERIMENTAL AEROTHERMODYNAMICS	K. SUTTON
9:30 - 10:00	OTHER APPLICABLE LANGLEY ACTIVITY	G. WALBERG
10:00-10:10	BREAK	

SPECIFICS OF JSC AEROBRAKING EFFORTS: PAST, PRESENT AND PLANNED

10:10-10:20	INTRODUCTION	J. GAMBLE
10:20-10:45	AFE AEROBRAKE TECHNOLOGY STATUS	D. CURRY
10:45-11:10	MRSR SYSTEM & TECHNOLOGY STATUS	J. GAMBLE

11:10-11:30	AEROBRAKING GN&C EXPERIENCE	G. MCSWAIN
11:30-11:50	CFD STATUS	C. LI
11:50-12:10	AEROTHERMODYNAMICS/GROUND FACILITY STATUS	C. SCOTT
12:10 - 1:10	LUNCH	
1:10 - 2:10	**SPECIFICS OF JPL AEROBRAKING EFFORTS: PAST, PRESENT AND FUTURE**	L. WOOD
2:10 - 2:20	BREAK	
2:20 - 5:20	**OPEN DISCUSSION AND TABULATION OF CHALLENGES, ISSUES AND TECHNOLOGY REQUIREMENTS FOR THE PATHFINDER PROGRAM IN HIGH ENERGY AEROBRAKING PROGRAM FACING NASA AND INDUSTRY.**	

DINNER AT RESTAURANT (TBD)

February 2, 1989

8:00 -2:00	**SUBGROUP WORKING MEETINGS TO EXPAND ON ITEMS SPECIFIED AT END OF DAY ON 2/1/88 AND PREPARATION OF SUMMARY CHARTS.**	
2:00 - 2:25	REPORT BY SUBGROUP LEADER ON SYSTEMS STUDIES	G. WALBERG
2:25 - 2:50	REPORT BY SUBGROUP LEADER ON AEROTHERMODYNAMICS	S. DEIWERT
2:50 - 3:15	REPORT BY SUBGROUP LEADER ON TPS	H. GOLDSTEIN
3:15- 3:40	REPORT BY SUBGROUP LEADER ON G. N. & C	L. WOOD
3:40 - 4:05	REPORT BY SUBGROUP LEADER ON FLIGHT EXPERIMENTS	J. GAMBLE
4:05- 4:30	REPORT BY SUBGROUP LEADER ON EXPERIMENTAL AND COMPUTATIONAL FACILITIES	D. COOPER

ADJOURN

HIGH ENERGY AEROBRAKING WORKSHOP
ATTENDANCE LIST

NAME	ORGANIZATION	PHONE NO.	MAILING ADDRESS
Alexander, Steve	NASA/LeRC	216-433-5377	Lewis Research Center, MS 501-6, Cleveland, OH 44135
Arnold, Jim	NASA/ARC	415-694-5365	Ames Research Center, MS 229-3, Moffett Field, CA 94035
Balakrishnan, Bala	NASA/ARC	415-694-4497	Ames Research Center, MS 258-1, Moffett Field, CA 94035
Berry, William	NASA/ARC	415-694-4930	Ames Research Center, MS-240-1, Moffett Field, CA 94035
Bershader, Daniel	Stanford University	415-424-1124	Stanford University, Dept. Aero/Astro, Stanford, CA 94305
Boyd, Iain	NASA/ARC	415-694-4907	Ames Research Center, MS 230-2, Moffett Field, CA 94035
Bull, Jeff	NASA/ARC	415-694-5377	Ames Research Center, MS 234-1, Moffett Field, CA 94035
Candler, Graham	NASA/ARC	415-694-4227	Ames Research Center, MS 230-2, Moffett Field, CA 94035
Chapman, Dean	Stanford University		Stanford University, Dept. Aero/Astro, Stanford, CA 94305
Chin, Amanda	NASA/ARC	415-694-5370	Ames Research Center, MS 234-1, Moffett Field, CA 94035
Cohen, Malcom	NASA/ARC	415-694-6441	Ames Research Center, MS 239-7, Moffett Field, CA 94035
Cooper, Dave	NASA/ARC	415-694-6213	Ames Research Center, MS 230-3, Moffett Field, CA 94035
Covington, Alan	NASA/ARC	415-694-5263	Ames Research Center, MS 229-3, Moffett Field, CA 94035
Craig, Roger	NASA/ARC	415-694-4762	Ames Research Center, MS 229-3, Moffett Field, CA 94035
Curry, D. M.	NASA/JSC	713-483-8865	Johnson Space Center, Code ES321, Houston, TX 77058
Dahms, Dick	NASA/ARC	415-694-5275	Ames Research Center, MS 229-3, Moffett Field, CA 94035
Davies, Carole	NASA/ARC	415-694-6204	Ames Research Center, MS 230-2, Moffett Field, CA 94035
Davy, Bill	NASA/ARC	415-694-4761	Ames Research Center, MS 229-3, Moffett Field, CA 94035
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HIGH ENERGY AEROBRAKING WORKSHOP
ATTENDANCE LIST (Continued)

NAME	ORGANIZATION	PHONE NO.	MAILING ADDRESS
Desautel, Dick	San Jose St. Univ.	408-924-3841	SJSU, Dept. Aerospace Engineering, San Jose, CA 95112
Durrett, Bob	NASA/MSFC	205-544-0628	Marshall Space Flight Center, Bldg. 4200, Marshall Space Flight Center, AL 35812
Edquist, Tom	Martin Marietta	303-971-6458	
Feiereisen, William	NASA/ARC	415-594-4225	Ames Research Center, MS 230-2, Moffett Field, CA 94035
Gamble, Joe	NASA/JSC	713-483-4662	Johnson Space Center, Code ED311, Houston, TX 77058
Gillespie, Walter	Stanford University	415-424-1124	Stanford University, Dept. Aero/Astro, Stanford, CA 94305
Goldstein, Howard	NASA/ARC	415-694-6103	Ames Research Center, MS 234-1, Moffett Field, CA 94035
Green, Mike	NASA/ARC	415-694-6103	Ames Research Center, MS 258-1, Moffett Field, CA 94035
Henline, William	NASA/ARC	415-694-6623	Ames Research Center, MS 234-1, Moffett Field, CA 94035
Howe, John	NASA/ARC	415-694-6113	Ames Research Center, MS 229-3, Moffett Field, CA 94035
Hui, Frank	NASA/ARC	415-694-4852	Ames Research Center, MS 237-1, Moffett Field, CA 94035
Kwok, Johnny	JPL	818-354-6776	Jet Propulsion Laboratory, Code 301-140L, 4800 Oak Grove Drive, Pasadena, CA 91109
Laursen, Eric	LMSC	408-756-6676	
Li, Chen	NASA/JSC	713-483-4684	Johnson Space Center, Code ED311, Houston, TX 77058
Lockman, William	NASA/ARC	415-694-5235	Ames Research Center, MS 230-2, Moffett Field, CA 94035
Lumpkin, Forrest	NASA/ARC	415-694-3475	Ames Research Center, MS 230-2, Moffett Field, CA 94035
Mankins, John	NASA/HQ	202-453-3658	NASA Headquarters, Code RS, Washington, DC 20546
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HIGH ENERGY AEROBRAKING WORKSHOP
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