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Space Mechanisms Technology Workshop Proceedings

Robert L. Fusaro, editor
Glenn Research Center, Cleveland, Ohio

Proceedings of a conference
held at the Westlake Holiday Inn, Westlake, Ohio
and cosponsored by NASA Lewis Research Center and the Ohio Aerospace Institute
September 22–23, 1992

National Aeronautics and
Space Administration

Glenn Research Center

October 1999

Note that at the time of printing, the NASA Lewis Research Center
was undergoing a name change to the
NASA John H. Glenn Research Center at Lewis Field.
Both names appear in these proceedings.

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SPACE MECHANISMS WORKSHOP

PREFACE

Future NASA space missions such as the Space Exploration Initiative (SEI), the Mission to Planet Earth, and advanced weather and communications satellites will require advanced performance standards, increased life, and improved reliability of all mechanically moving equipment (mechanisms). In the past the mechanism needs of spacecraft appeared to be well within the state of the art. The electronic systems were deemed to be the biggest impediment to producing long life and reliable operation. As a result satellites were designed with requirements to last for only 3 to 5 years. The electronics industry has made great strides over the last few years in reducing the size and increasing the life and reliability of satellite electronic systems. The question is, have mechanical moving mechanisms kept up in improving their life, reliability and performance?

To determine what the obstacles will be in meeting NASA's future missions goals, NASA-Lewis Research Center and the Ohio Aerospace Institute (OAI) planned and sponsored a workshop for the fall of 1992. The workshop, entitled the Space Mechanisms Technology Workshop, took place September 22-23, 1992 at the Westlake Holiday Inn in Westlake, Ohio.

The workshop lasted for two days. The first half day was dedicated to a set of plenary papers. The following papers were presented:

(1) OVERVIEW OF FUTURE NASA MISSIONS AND REVIEW OF MECHANISM'S NEEDS SURVEYS -- ROBERT FUSARO, NASA/LERC

(2) SPACE MECHANISMS TECHNOLOGY NEEDS -- PAUL FLEISHAUER, THE AEROSPACE CORPORATION

(3) DOD SPACE MECHANISMS PROGRAMS -- KARL MECKLENBURG, WPAFB

(4) PLANETARY SURFACE REQUIREMENTS AND ENVIRONMENT -- BENTON CLARK, MARTIN MARIETTA

(5) POWER REQUIREMENTS FOR SPACE -- JOHN BOZEK, NASA/LERC

(6) PROPULSION REQUIREMENTS FOR SPACE -- JAMES DILL, MECHANICAL TECHNOLOGIES INC.

Following the opening plenary session, the workshop broke into three concurrent groups to look at the issues and problems of future mechanism's operations. Because the Satellites and Space Platforms group was deemed to be too large it was divided into two working groups. The four groups and group leaders were:

(1) Satellites and Space Platforms #1, Doug Rohn, NASA LeRC and Paul Fleischauer, Aerospace Corporation

(2) Satellites and Space Platforms #2, Roamer Predmore, NASA GSFC, and Stuart Loewenthal, Lockheed

(3) Power and Propulsion, Bob Hendricks, NASA LeRC and Jerry Kannel, Battelle

(4) Planetary Surface Operations, Bob Fusaro, NASA LeRC and David Thrasher, Boeing Aerospace.

Each group was given seven tasks, they were as follows:

1. Identify space mechanism"s (mechanical components/lubrication) current and perceived future mission obstacles.
    - (A) Brainstorm current space mechanisms obstacles.
    - (B) Brainstorm future space mechanisms obstacles.
    - (C) Prioritize current and future space mechanisms obstacles.

2. For each obstacle, list or describe:
    - (A) Technology deficiencies (known or perceived).
    - (B) The current state-of-the-art.
    - (C) Applicable NASA, DOD, AND industry missions
    - (D) Active research in the area.
        - -- Where it is being conducted.
        - -- What are the current facilities.
        - -- Number of personnel involved.
    - (E) Technology needs for current missions.
    - (F) Technology needs for future missions.
    - (G) Concerns.

3. What is needed to improve the reliability of mechanisms?

4. NASA is planning to develop a space mechanisms guidelines handbook. What sort of information should be included? What sort of information should be considered industry privileged?

5. Can anything be done to improve technology development and the dissemination of information?

6. Other issues?

7. What do we do next?
   - Future meetings
   - Formalized working group(s)
   - Publications

The workshop closed with a final half-day plenary session in which group chairman presented the results of their sessions and the attendees then engaged in discussion of those results. The working group results follow the preface.

Approximately 70 individuals attended the workshop. Their backgrounds and interests were diverse, ranging from basic research to satellite design and program management. A listing of the members of each group are given with the results of that group.

WORKSHOP ORGANIZERS

Donald Bailey
Ohio Aerospace Institute

Kathy Bogart
Ohio Aerospace Institute

Robert Fusaro
NASA Lewis Research Center

Theo Keith
Ohio Aerospace Institute

T. Michael Knasel
Ohio Aerosapce Institute

Vannel Hassett
Ohio Aerospace Institute

Norma Navarro
Ohio Aerospace Institute

Jeananne Nicholls
Ohio Aerospace Institute

Doug Rohn
NASA Lewis Research Center

Janet White
Berkshire Group

Richard Ziegfeld
Sverdrup Technology

OHIO AEROSPACE INSTITUTE BACKGROUND

A UNIVERSITY-INDUSTRY-GOVERNMENT CONSORTIUM

COLLABORATIVE RESEARCH
GRADUATE AND CONTINUING EDUCATION
TECHNOLOGY TRANSFER

9 OHIO UNIVERSITIES
PRIVATE SECTOR COMPANIES
NASA LEWIS RESEARCH CENTER
WRIGHT PATTERSON AIR FORCE BASE

Michael J. Salkind
President
Ohio Aerospace Institute

OAI BOARD OF TRUSTEES

PERSPECTIVE

STRATEGIC DRIVERS

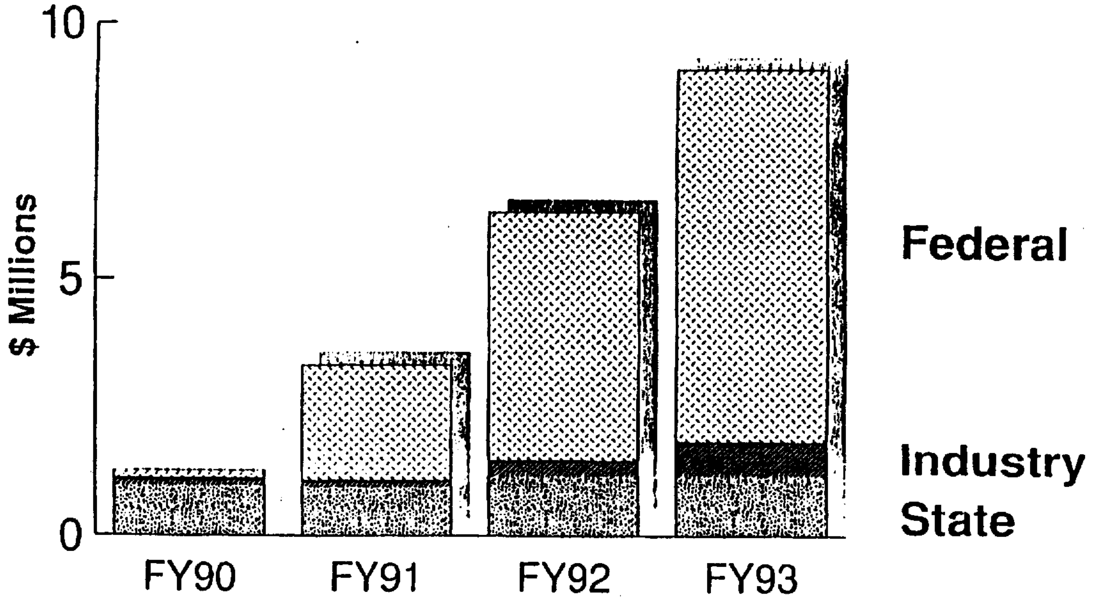
- GLOBAL ECONOMIC COMPETITIVENESS
- EFFECTIVE TECHNOLOGY TRANSFER
- MORE COLLABORATION
- POOL EXPENSIVE RESEARCH FACILITIES
- MORE INTERDISCIPLINARY RESEARCH
- MORE PHDs FOR INDUSTRY, GOVERNMENT, AND UNIVERSITIES
- MORE AMERICANS IN GRADUATE SCHOOL
- MORE MINORITIES AND WOMEN IN SCIENCE AND ENGINEERING
- GREATER EMPHASIS ON SCIENCE AND MATH LITERACY IN SCHOOLS

PERSPECTIVE

ASSUMPTIONS

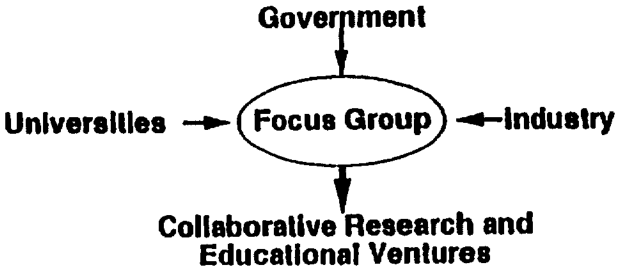
- TECHNOLOGY TRANSFER IS A BODY CONTACT SPORT
- FEDERAL LABS — FACILITIES AND FUNDING MAGNETS
- COMPLEMENTARY EQUIPMENT AT CAMPUSES AND COMPANIES
- DEVELOP COMPETITIVE CRITICAL MASS
- DISTANCE EDUCATION IS BECOMING MORE ACCEPTABLE
  - — TECHNOLOGY, ECONOMICS IMPROVING
  - — FITS CHANGING LIFESTYLE
- INCREASING NEED FOR TRUE LIFE-LONG LEARNING

OAI Funding Sources



RESEARCH FOCUS GROUPS

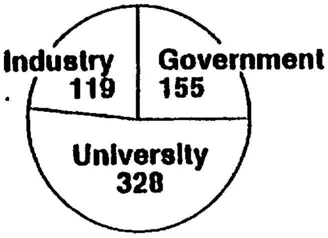
- WORKING GROUPS OF EXPERTS FROM UNIVERSITIES, GOVERNMENT, and INDUSTRY
- FOSTER COLLABORATION AMONG DISCIPLINES and COMMUNITIES
- ASSESS PRESENT AND FUTURE AEROSPACE RESEARCH THAT WOULD BENEFIT FROM COLLABORATIVE RESEARCH



Government

Universities → Focus Group ← Industry

Collaborative Research and Educational Ventures



OAI FOCUS GROUPS

- ADVANCED INTERDISCIPLINARY SIMULATION
- AEROSPACE POWER
- COMMUNICATION, ELECTRONICS, AND INFORMATION SYSTEMS
- COMPOSITES
- DIAGNOSTICS / IMAGING / VISUALIZATION
- DYNAMIC SYSTEMS AND CONTROLS
- FLUID DYNAMICS AND PROPULSIVE SYSTEMS
- ICING
- POLYMERS / MOLECULAR MODELING
- SPACE PROPULSION AND TECHNOLOGY
- TRANSDUCERS
- TRIBOLOGY
- TURBO MACHINERY FLUID MECHANICS

STATEWIDE COLLABORATIVE EDUCATIONAL NETWORK

- The University of Akron
- Case Western Reserve University
- University of Cincinnati
- Cleveland State University
- The University of Dayton
- The Ohio State University
- Ohio University
- The University of Toledo
- Wright State University

- **Link universities by TV network**
- **Deliver graduate education to the workplace**

OAI STUDENTS

- INDUSTRY - GOVERNMENT COLLABORATION ATTRACTING OUTSTANDING STUDENTS TO OAI UNIVERSITIES
- 52 GRADUATE, 78 UNDERGRADUATE SINCE 1989

"I had my choice of seven fellowship opportunities throughout the country. I chose OAI and Ohio State University because of the NASA involvement."

"Combining universities and industry is great. We get the theoretical side but not always the direct application."

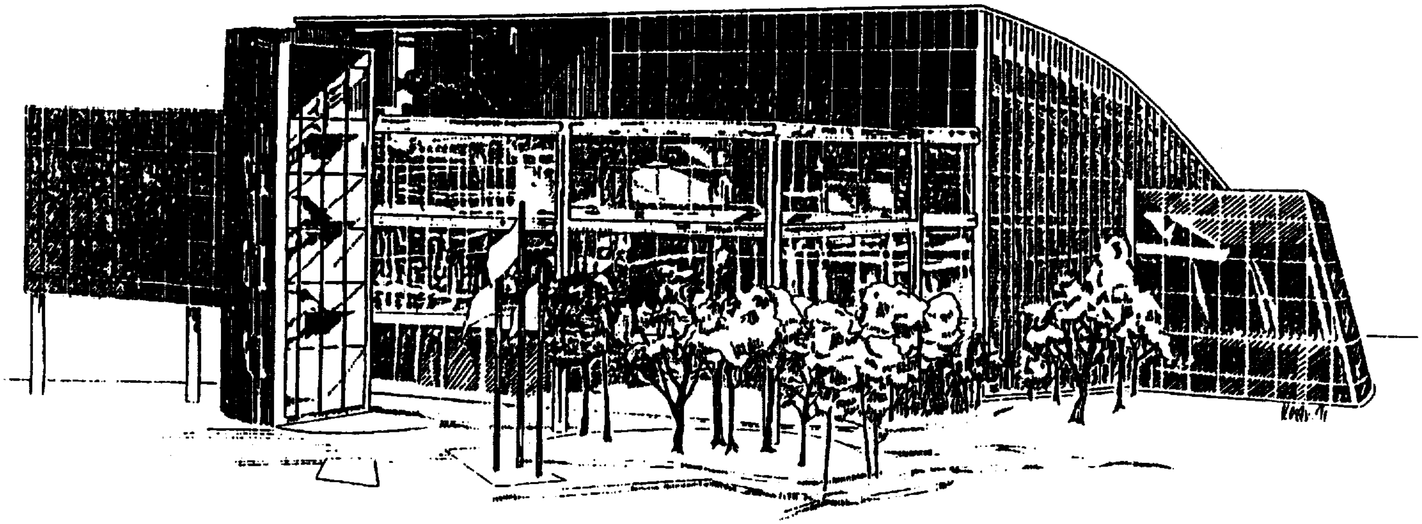
"I saw OAI as a major advantage in making contacts in industry and learning from people who have experience in more than an academic setting."

" OAI is a great step forward in laying the groundwork to make Ohio competitive in the aerospace field. It offers the opportunity to do things I couldn't do elsewhere."

INDUSTRY PARTICIPATION

- ALLISON - G.M.
- ANALEX
- ALLIED SIGNAL
- APPLICATION TECHNOLOGY
- ARGO-TECH
- BATTELLE
- BF GOODRICH
- BROOKS ASSOCIATION
- BRUSH WELLMAN
- CAMP
- EATON
- EDJEWISE SENSOR PRODUCTS
- EMTEC
- EPIC
- FERRO
- GATEWAY TECHNOLOGY
- GENERAL ELECTRIC
- IMAGE ANALYSIS RESEARCH
- KEITHLY INSTRUMENTS
- LORD CORPORATION
- LUBRIZOL
- PARKER HANNIFIN
- PRATT & WHITNEY
- ROCKWELL
- SUNDSTRAND
- SVERDRUP
- TELEDYNE
- TEXTRON LYCOMING
- TIMKEN
- TRW

31 participating business organizations



OAI
OHIO
AEROSPACE
INSTITUTE

WORKSHOP INFORMATION AND OBJECTIVES

Robert L. Fusaro
NASA Glenn Research Center
Cleveland, Ohio

Objectives

- To obtain an industry/university/government perspective on what are the known or perceived obstacles to successfully achieving NASA's current and future space missions.
- To determine the industry/university/government community's capabilities of solving these obstacles.
- To obtain input to help guide NASA in the formation of a growing R&T program.

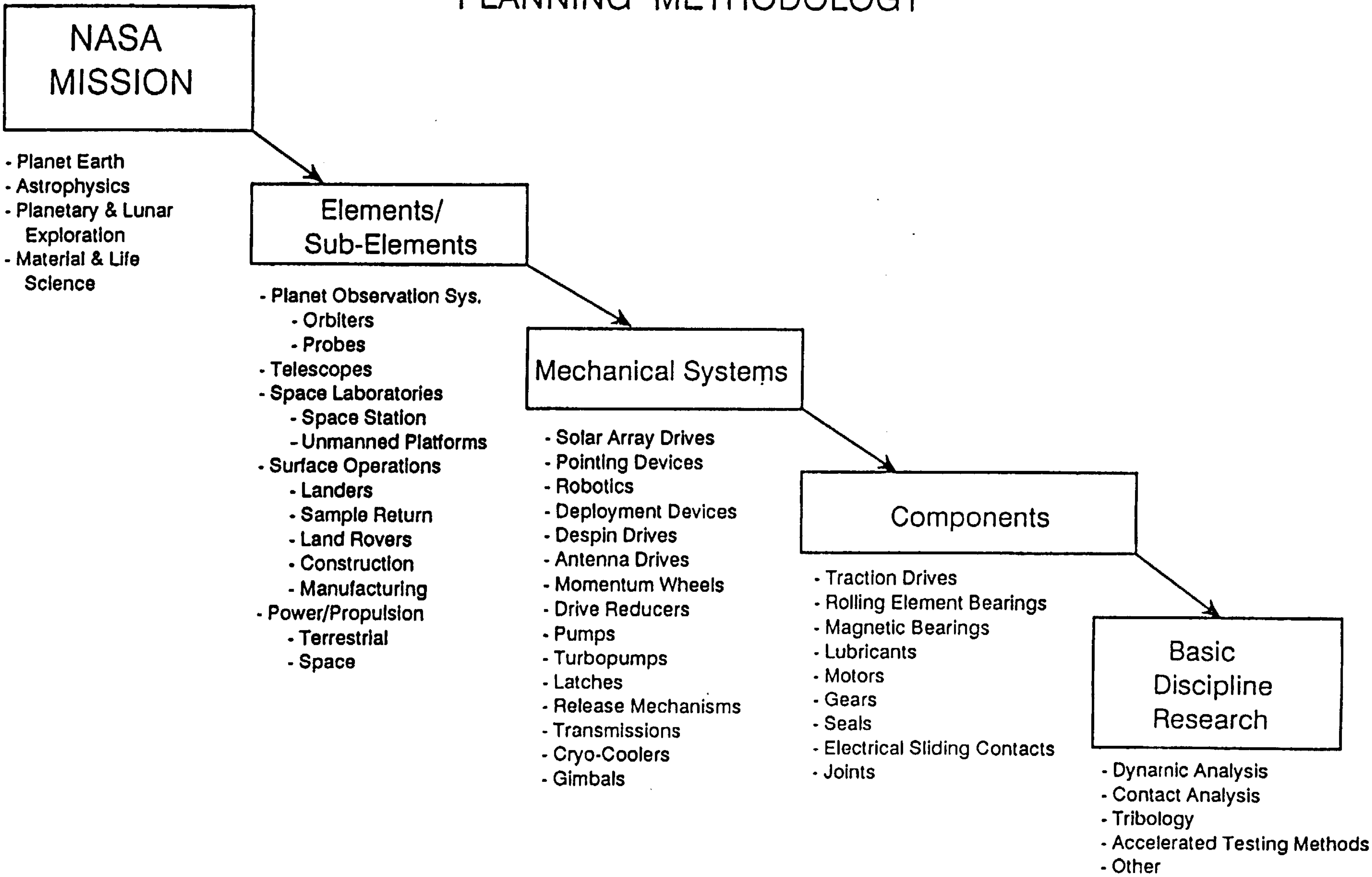
Space Mechanisms Workshop

Definition

WHAT IS A SPACE MECHANISM

- Any moving assembly or component used in a space application
  - -- Rolling element bearings
  - -- Magnetic bearings
  - -- Power transmission drives
  - -- Lubricants
  - -- Seals
  - -- Electrical sliding contacts
  - -- Motors
  - -- Deployment devices, latches, connectors
  - -- etc. etc.

SPACE MECHANISMS PROGRAM
PLANNING METHODOLOGY



NASA MISSION

- Planet Earth
- Astrophysics
- Planetary & Lunar Exploration
- Material & Life Science

Elements/ Sub-Elements

- Planet Observation Sys.
  - Orbiters
  - Probes
- Telescopes
- Space Laboratories
  - Space Station
  - Unmanned Platforms
- Surface Operations
  - Landers
  - Sample Return
  - Land Rovers
  - Construction
  - Manufacturing
- Power/Propulsion
  - Terrestrial
  - Space

Mechanical Systems

- Solar Array Drives
- Pointing Devices
- Robotics
- Deployment Devices
- Despin Drives
- Antenna Drives
- Momentum Wheels
- Drive Reducers
- Pumps
- Turbopumps
- Latches
- Release Mechanisms
- Transmissions
- Cryo-Coolers
- Gimbals

Components

- Traction Drives
- Rolling Element Bearings
- Magnetic Bearings
- Lubricants
- Motors
- Gears
- Seals
- Electrical Sliding Contacts
- Joints

Basic Discipline Research

- Dynamic Analysis
- Contact Analysis
- Tribology
- Accelerated Testing Methods
- Other

Space Mechanisms Workshop

Issues

- Operating Parameter Effects
  - -- Endurance life, and Reliability
  - -- Pointing Accuracy -- Stability, Vibrations, etc.
- Environmental Effects
  - -- Space Radiations, Atomic Oxygen, etc.
  - -- Temperature, vacuum, dust, etc.
  - -- Contamination of and from Environment
- Electrical Effects
  - -- Power and Signal Transfer
- Tribological Effects
  - -- Friction, Wear, Lubrication
- Storage Effects
- Launch Effects
- Ground Based Testing Methods

Space Mechanisms Workshop

Potential NASA Funding

- Proposed Code R Funding
  - -- $4.9M for Technology Development (FY94)
- Proposed Code Q Funding
  - -- Lesson Learned Study (FY93)
  - -- Space Mechanisms Guidelines Manual (FY93)
  - -- Reliability Improvement Research (FY 94)

SPACE MECHANISMS TECHNOLOGY WORKSHOP
AGENDA

TUESDAY MORNING

9:00	OVERVIEW OF FUTURE NASA MISSIONS AND REVIEW OF MECHANISM'S NEEDS SURVEYS -- ROBERT FUSARO, NASA/LERC
9:30	SPACE MECHANISMS TECHNOLOGY NEEDS -- PAUL FLEISHAUER, THE AEROSPACE CORPORATION
10:00	DOD SPACE MECHANISMS PROGRAMS -- KARL MECKLENBURG, WPAFB
10:30	BREAK
11:00	PLANETARY SURFACE REQUIREMENTS AND ENVIRONMENT -- BENTON CLARK, MARTIN MARIETTA
11:20	POWER REQUIREMENTS FOR SPACE -- JOHN BOZEK, NASA/LERC
11:40	PROPULSION REQUIREMENTS FOR SPACE -- JAMES DILL, MECHANICAL TECHNOLOGIES INC.
12:00 - 1:00	LUNCH (Corker's Lounge)

SPACE MECHANISMS TECHNOLOGY WORKSHOP
AGENDA

TUESDAY AFTERNOON

1:00 - 5:00	WORKING GROUP SESSIONS	
	-- SATELLITES/PLATFORMS (2 Groups)	(Dover)
	-- PLANETARY SURFACES	(Canterbury)
	-- PROPULSION/POWER	(Bradley)
3:00 - 3:30	BREAK	
6:00	SOCIAL HOUR (Corker's Lounge)	
	-- CASH BAR	
7:00	BANQUET AND KEYNOTE SPEAKER (Dover Ballroom)	
	-- RED WHITTAKER, CARNEGIE MELLON UNIVERSITY	

SPACE MECHANISMS TECHNOLOGY WORKSHOP
AGENDA

WEDNESDAY MORNING

7:30	BREAKFAST (Corker's Lounge)
8:00	PLENARY REVIEW OF PROGRESS ON TUESDAY
8:30	WORKING GROUP SESSIONS CONTINUE
10:00 - 10:20	BREAK
12:00	LUNCH (Corker's Lounge)

WEDNESDAY AFTERNOON

1:00	PLENARY SESSION -- WORKING GROUP CONCLUSIONS
3:20	CONCLUDING REMARKS -- THEO KEITH, OAI
3:30	ADJOURN

WORKSHOP WORKING GROUP OBJECTIVE QUESTIONS

1. IDENTIFY SPACE MECHANISM'S (MECHANICAL COMPONENTS/LUBRICATION) CURRENT AND PERCEIVED FUTURE MISSION OBSTACLES.
   (A) BRAINSTORM CURRENT SPACE MECHANISMS OBSTACLES
   (B) BRAINSTORM FUTURE SPACE MECHANISMS OBSTACLES
   (C) PRIORITIZE SPACE MECHANISMS OBSTACLES

2. FOR EACH OBSTACLE, LIST OR DESCRIBE:
   (A) TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED?)
   (B) THE CURRENT STATE-OF-THE-ART
   (C) APPLICABLE NASA, DOD, AND INDUSTRY MISSIONS
   (D) ACTIVE RESEARCH IN THE AREA
      -- WHERE IS IT BEING CONDUCTED AND THE FACILITIES
      -- NUMBER OF PERSONNEL INVOLVED
   (E) TECHNOLOGY NEEDS FOR CURRENT MISSIONS
   (F) TECHNOLOGY NEEDS FOR FUTURE MISSIONS
   (G) CONCERNS

WORKSHOP WORKING GROUP OBJECTIVE QUESTIONS

3. WHAT IS NEEDED TO IMPROVE THE RELIABILITY OF MECHANISMS?

4. NASA IS PLANNING TO DEVELOP A SPACE MECHANISMS GUIDELINES HANDBOOK. WHAT SORT OF INFORMATION SHOULD BE INCLUDED? WHAT SORT OF INFORMATION SHOULD BE CONSIDERED INDUSTRY PRIVILEGED?

5. CAN ANYTHING BE DONE TO IMPROVE TECHNOLOGY DEVELOPMENT AND THE DISSEMINATION OF INFORMATION?

6. OTHER ISSUES?

7. WHAT DO WE DO NEXT?
   -- FUTURE MEETINGS
   -- FORMALIZED WORKING GROUP(S)
   -- PUBLICATIONS

WORKING GROUP ASSIGNMENTS

SATELLITES/SPACE PLATFORMS (I)	SATELLITES/SPACE PLATFORMS (II)	POWER/ PROPULSION	PLANETARY SURFACES
DOVER	DOVER	BRADLEY	CANTERBURY
● ROAMER PREDMORE ● STU LOEWENTHAL	● DOUG ROHN ● PAUL FLEISHAUER	● BOB HENDRICKS ● JERRY KANNEL	● BOB FUSARO ● DAVID THRASHER
-- TED NYE -- HERB SINGER -- KENT ROLLER -- ROGER SLUTZ -- RALPH JANSEN -- WILLIAM JONES -- ED KINGSBURY -- BERT HAUGEN -- ROY MARANGONI -- STEVE PEPPER -- DAVE FLEMMING -- PILAR HERRERA-FIERRO -- BEN EBIHARA -- YNGVE NAERHEIM -- LARRY PINSON -- RICHARD WEINSTEIN -- Gary Walker	-- JOHN BOHNER -- WILLIAM LOGUE -- DENNIS SMITH -- PETER WARD -- ROBERT GRESHAM -- KARL MECKLENBURG -- WILLIAM CLARK -- JOANNE UBER -- MICHAEL KHONSARI -- ROBERT WOODS -- WAYNE BARTLETT -- GEORGE STEFKO -- ERV ZARETSKY -- FRAN MARCHON -- KEVIN RADIL -- MARK SIEBERT	-- JAMES DILL -- JOHN BOZEK -- BRUCE STEINETZ -- STERLING WALKER -- HOOSHANG HESMAT -- ROBERT THOM -- CHUCK LAWRENCE -- THEO KEITH -- HAROLD SLINEY -- JIM GLEESON -- DAVE BREWE -- WILLIAM ANDERSON -- JOHN COY -- CHRIS DELLACORTE -- ERIC MELLBERG -- JIM WALKER -- JEFFREY SCHEIBER -- KURT STIDHAM	-- JEFF MILLER -- WILLIAM WHITTAKER -- DALE FERGUSON -- BEN CLARK -- LEE MASON -- TALY SPALVINS -- MIKE KNASEL -- MICHAEL SOCHA -- RICHARD HALL -- K MIYOSHI -- GERALD LILIENTHAL -- MIROSLAW OSTASZEWSKI -- JOHN ALRED -- JEFF LANDIS

FUTURE NASA MISSIONS AND TECHNOLOGY NEEDS RESULTS TO DATE

Robert L. Fusaro
NASA Glenn Research Center
Cleveland, Ohio

PROPOSED FUTURE NASA MISSIONS

- **SPACE EXPLORATION INITIATIVE (SEI)**
  - Expand human presence to the moon, Mars, and beyond
- **MISSION TO PLANET EARTH**
  - Understand the interaction between
    - Oceans/atmosphere/solid Earth (weather)
    - Living organisms and environment
    - Environment and pollution
    - Composition and evolution of the Earth
- **ASTROPHYSICS**
  - Understand the universe
    - Laws of physics
    - Birth of stars and planets
    - Advent of life
- **MATERIAL AND LIFE SCIENCES**
  - Understand and develop new processes
    - Fluid dynamics
    - Combustion fundamentals
    - Material processing
    - Physics and Chemistry
    - Space Medicines

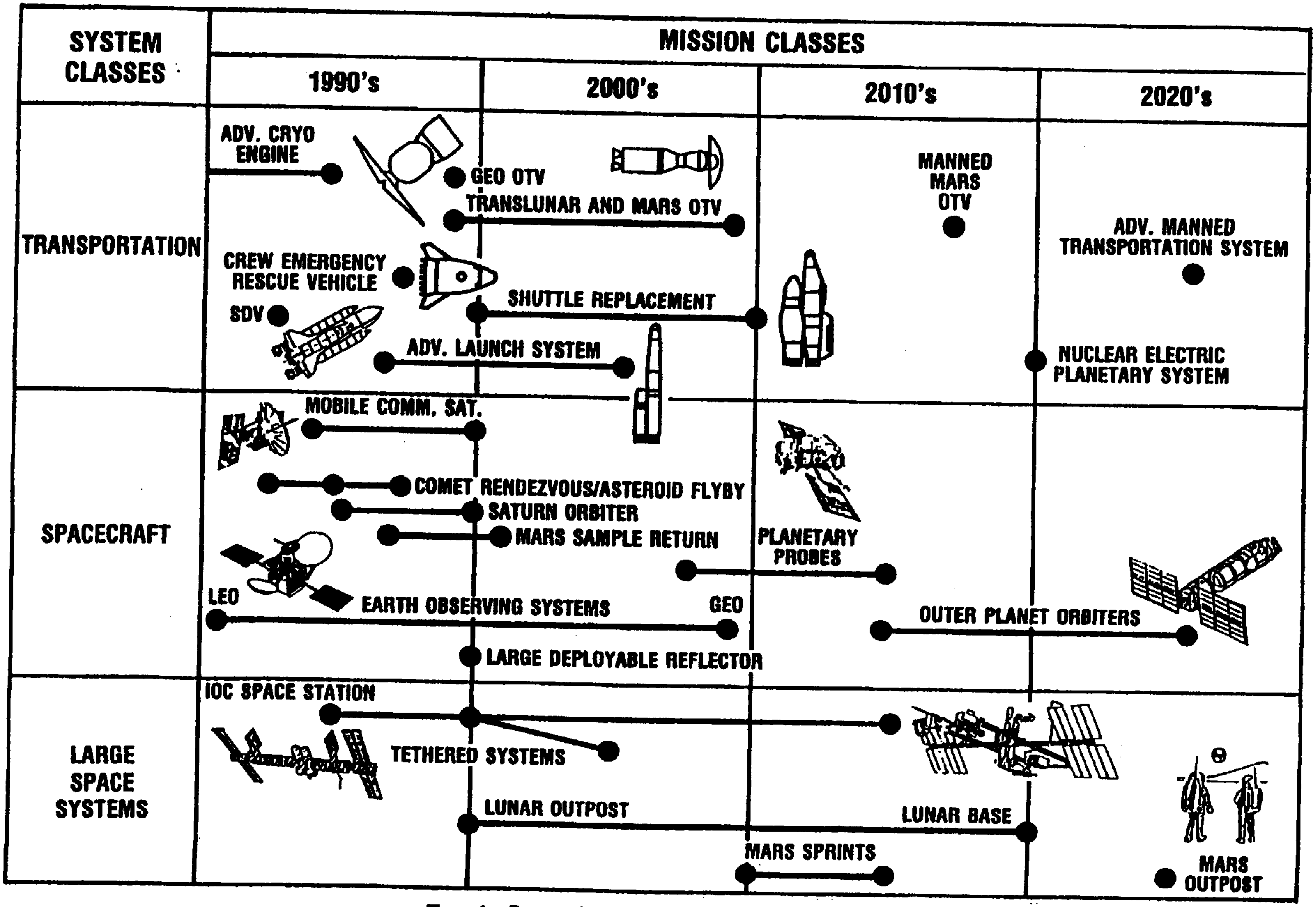


Figure 1.—Proposed time frame for future NASA missions.

TECHNOLOGIES FOR MISSION SUCCESS

In-Space Operations

- Cryogenic Fluid management
- Autonomous rendezvous and docking

Earth-to-Orbit Transportation

- Vehicle structures
- Automated systems diagnostics

Nuclear Power

- Mature lunar outpost
- Propulsion system option

Surface Systems

- Surface solar power with chemical energy storage
- Mobility mechanisms

Lunar and Mars Science

- Sample acquisition, analysis and preservation
- Probes and penetrators

Automation and Robotics

- Lunar and Mars surface systems
- Flight systems

SPACE MECHANISMS INITIATIVE

ACCOMPLISHMENTS TO DATE

- LITERATURE SURVEY
- GOVERNMENT AND INDUSTRY LABORATORY TOURS
- QUESTIONNAIRES SENT OUT ON TECHNOLOGY NEEDS
- SET-UP A SPACE MECHANISMS WORKING GROUP -- GOVERNMENT ONLY (NASA, DOD, DOE)
- WORKSHOP AT LeRC (November 1990)
- REGULARLY SCHEDULED VIDEO CONFERENCES

Government/Industry Survey

300 designers & program managers- 130 respondents

IS STATE-OF-THE-ART ADEQUATE FOR FUTURE NEEDS?	Yes (%)	No (%)	Not sure (%)
government(57)	8	84	2
industry (73)	19	76	5
IS THERE A NEED FOR NEW OR IMPROVED METHODS?			
government	98	0	2
industry	96	4	0
SHOULD NASA ESTABLISH INFRASTRUCTURE TO:			
Coordinate new technology?	91	8	1
Develop standards for U.S. use?	63	30	7
Provide consultation and advice?	77	16	7
Maintain capabilities/solutions database?	95	3	2
Maintain testing facilities for U.S.?	86	8	6
Facilitate technology transfer?	95	3	2
Encourage government industry crosstalk?	91	5	4
Insure NASA/DOD research coordination?	91	5	4

Space Mechanisms - August 1992

QUESTIONNAIRE RESPONSE

SPACE MECHANISMS TECHNOLOGY ISSUES

--- Currently it is left to each project to fund any mechanisms development to meet mission requirements, this leads to wheel reinvention

--- The contractors we deal with are hesitant to reveal the best solution to a problem because it was developed for another customer.

--- Mechanisms are typically mission critical devices that cannot be redundant in many cases and have little tolerance for error.

QUESTIONNAIRE RESPONSE

SPACE MECHANISMS TECHNOLOGY ISSUES

--- There is a need for long term commitment to an IR&D program that has direction and is technology focused not project oriented.

--- Past NASA Missions have been compromised by not developing enabling technology as part of the pre-project activities.

--- All efforts on space mechanisms have been program driven, long time goals have been lacking.

SPACE MECHANISMS WORKSHOP FINDINGS

SIGNIFICANT PROGRAMMATIC ISSUES

- NASA FACES IMMINENT FAILURES IF SPACE MECHANISM'S TECHNOLOGY ISSUES ARE NOT BETTER ADDRESSED
- FUTURE LONG DURATION MISSIONS WILL BE JEOPARDIZED IF THE TECHNOLOGY BASE IS NOT IMPROVED
- LACK OF ADEQUATE NASA FACILITIES FOR ACCELERATED , LIFE, ENVIRONMENTAL AND FUNCTIONAL TESTING
- NASA EXPERTISE RETIRING, NEW PEOPLE NOT BEING TRAINED, CREATING A LOSS OF CORPORATE MEMORY
- NO ONE AT NASA HQS TO DEAL WITH MECHANISMS TECHNOLOGY, MECHANISMS NEEDS RECOGNITION AS A DISCIPLINE

SPACE MECHANISMS WORKSHOP FINDINGS

SIGNIFICANT TECHNOLOGY ISSUES

- CAN'T DESIGN FOR DECADES OF USEFUL LIFE
- MECHANISMS/TRIBOLOGY TECHNOLOGY BASE 20 YEARS OLD
- NO GUIDELINES, HANDBOOKS, OR STANDARDS FOR DESIGNERS
- AN INADEQUATE UNDERSTANDING OF FAILURE MODES
- ACCELERATED TESTING FOR "30 YEAR LIFE" IS AN UNKNOWN
- POTENTIAL ENVIRONMENTAL EFFECTS DIFFICULTIES MAY EXIST
- STORAGE PRIOR TO LAUNCH A SIGNIFICANT PROBLEM
- OPERATION AT LOWER CRYOGENIC TEMPS (2.6°K VS 77°K)
- SERVICEABILITY OF MECHANISMS NOT BEING CONSIDERED
- VIBRATION ISOLATION IMPORTANT ON LARGE PLATFORMS

SPACE MECHANISMS WORKSHOP FINDINGS

TECHNOLOGY IMPLEMENTATION NEEDS

- MECHANISM DESIGN RULES AND GUIDELINES MANUAL
- VALIDATED ACCELERATED TEST METHODS
    - -- FOR CRITICAL COMPONENTS
    - -- FOR HARSH ENVIRONMENTS
- CATALOG OF HISTORICAL MECHANISM/TRIBOLOGICAL PROBLEMS AND SOLUTIONS FROM PREVIOUS NASA MISSIONS
- AEROSPACE MECHANISMS SYMPOSIUM TO PRESENT MORE PAPERS ON SPACE MECHANISMS TECHNOLOGY
- FOCUSED WORKING GROUPS ON SPECIFIC PROBLEM AREAS

SPACE MECHANISMS TECHNOLOGY NEEDS

Paul D. Fleischauer
The Aerospace Corporation
El Segundo, California

Space Mechanisms Technology Needs

Introduction

- The Aerospace Corporation Functions as an "Architect-Engineer" for National Security Programs
- Specializes in Advanced Military Space Systems
- Technology Operations Conducts Scientific Research and Promotes the Insertion of Advanced Technologies
- Support is Provided to Programs in Launch Vehicles, Navigation, Meteorology, Communications, & Surveillance

Space Mechanisms Technology Needs

Outline

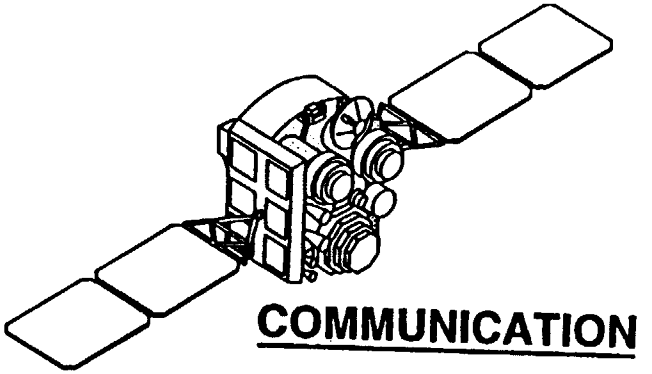
- Introduction to S/C Mechanisms, Moving Mechanical Assemblies, Mechanical Subsystems
- MMA Functions - Program Requirements & Technology Needs
- Mechanical Subsystem/Component Performance
- New Technologies - Research and Testing
- MMA Case Studies
- Summary and Conclusions

Major Spacecraft Subsystems

- Guidance, Navigation, & Control
- Communications - "Up/Down" & "Cross"
- Command & Data Handling
- Power - Solar Cells, Batteries, etc.
- Thermal - Passive, Semi-passive, & Active
- Structures & Mechanisms

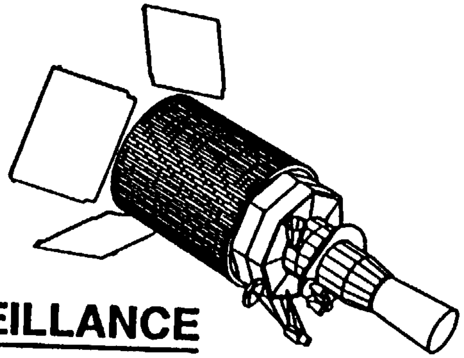
Other systems have advanced and made mechanisms life-limiting

Lubricants for Space



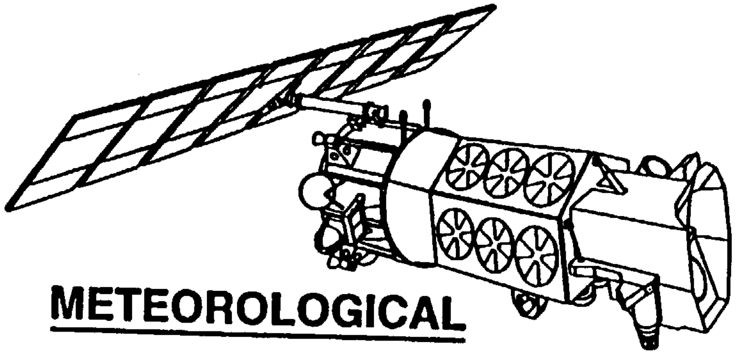
COMMUNICATION

SLIP RINGS
SOLAR ARRAY DRIVE
REACTION WHEEL



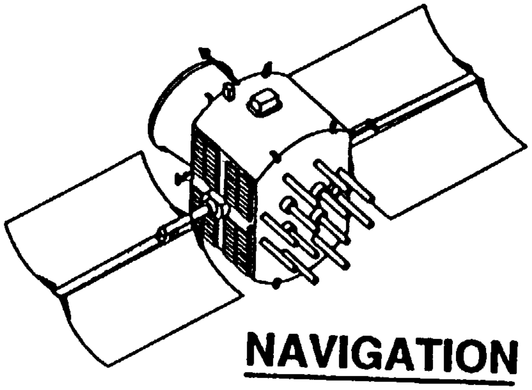
SURVEILLANCE

MOMENTUM WHEEL
ANTENNA POINTING



METEOROLOGICAL

GIMBAL BEARINGS
SLIP RINGS
MOMENTUM WHEEL
SOLAR ARRAY



NAVIGATION

REACTION WHEELS
SLIP RINGS
SOLAR ARRAY DRIVE

5558-92

Mechanical Subsystems

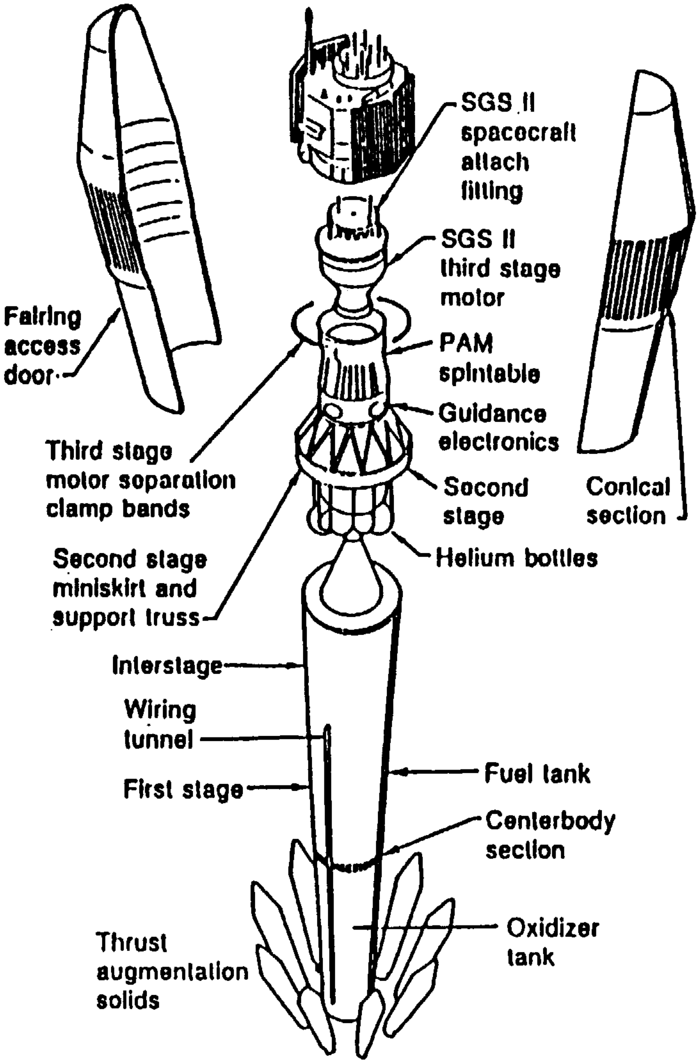
High-Cycle Mechanisms

- Antenna Pointing & Tracking
- Solar Array Pointing & Tracking
- Attitude Control - Reaction, Momentum Wheels, CMGs
- Boom Extensions

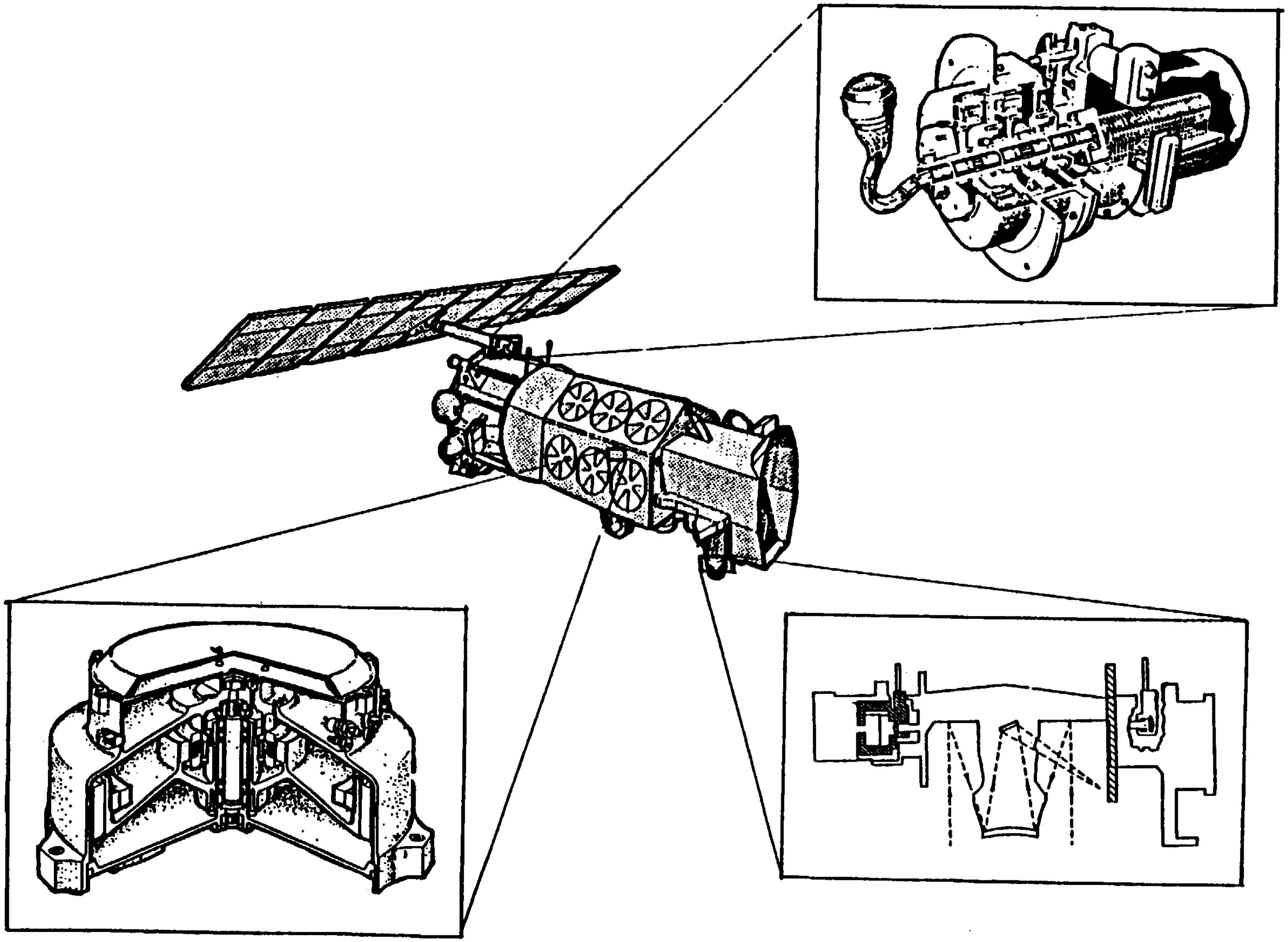
Low-Cycle Mechanisms

- Antenna Launch Retention/Deployment
- Solar Array Retention/Deployment
- Contamination Cover Removal
- Spacecraft/Launch Vehicle Separation

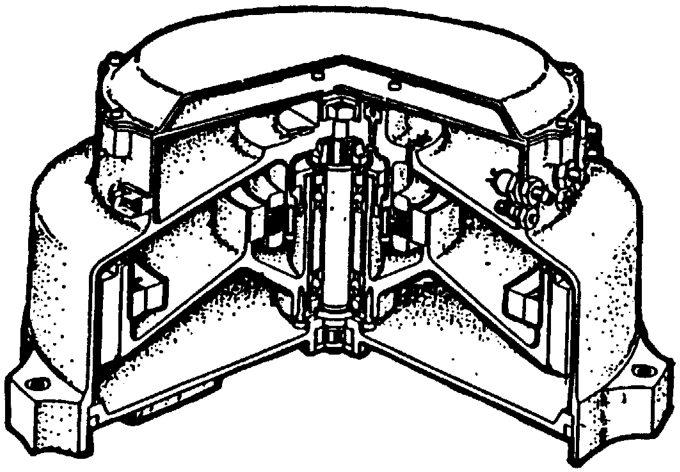
Typical Deployment Mechanisms



Moving Mechanical Assembly Functions



Reaction Wheel Assembly



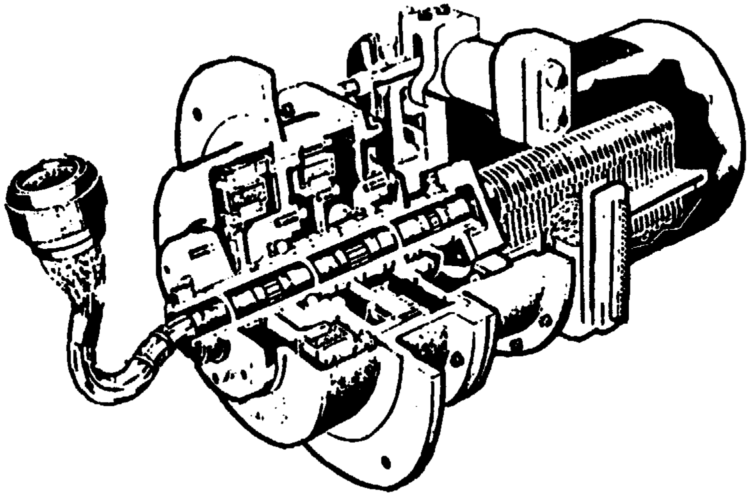
Issues

- Lifetime
- Torque Stability
- Reliability
- Producibility

Technologies

- Ceramic & Ceramic-Like Coatings/Parts
- Synthetic Lubricants
- Feedback Control
- Sensors/Systems (Health Monitoring)

Solar Array Drive Mechanism



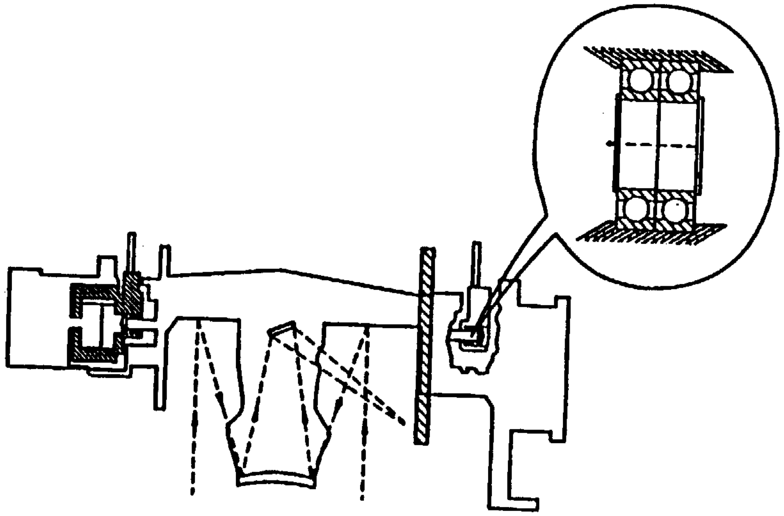
Issues

Environmental Stability
Low Noise Slip Rings
Reliability
Producibility

Technologies

Conductive Solid Lubricants
Ceramic & Ceramic-Like
Coatings/Parts

Sensor Pointing Gimbal



Issues

- Low, Constant Torque
- Low Torque Noise
- Reliability
- Wide Temp. Range
- Long Life

Technologies

- Ceramic & Ceramic-Like Coatings/Parts
- Ultra-Low Friction Solid Lubes
- Synthetic Lubes, Selected Systems
- Adaptive Bearing Designs

Mechanical Subsystem/Component Performance

Current Tribology Problems with Active Spacecraft

- Recurrent Problem with Bearings in Reaction/Momentum Wheels, CMGs, & Gyroscopes
- Problems with Actuators, Gears, & Gimbals Operating in Boundary Lubrication Regime
- Consistent Difficulties with Low-Noise Operation of Slip Rings
  - Noise not Understood
  - Materials Development Missing
  - Primary Application in Solar Array Drives
- Other Problems with Turbo-Machinery, Cryopumps, Coolers
- Occasional Problems with Release & Deployment Mechanisms
  - Need for Proper Guidance from "Tribologists"

TRIBOMECHANISM/COMPONENT PERFORMANCE

Momentum/Reaction Wheel, CMG & Gyro Experience

Program	Wheel Type	Problem	Cause	Action
Navstar/GPS	Reaction Wheel 4 per satellite	On orbit and test failures - high torque	Lubricant depletion	New lube qualification
GPS IIR	Reaction Wheel	High speed cage instability	Force, mass resonance	Force, mass biased cages
DMSP	Reaction Wheel	Bearings/lube could not be delivered	Lube degradation	Extensive bearing run in and screening
DSP	Large Momentum Wheel	Torque/temp. anomalies	Lubricant starvation	Passive oil delivery system
DSCS III	Reaction Wheel	Torque noise, vibration	Unknown	Redundant wheels
MILSTAR	Rate Gyroscopes	Drift rate/torque instability	Lubricant starvation	Improved lube, cage processing
CDP	Large CMGs; >1 per satellite	Excessive torque	Lube loss, cage instab.	Active oiler system, new oil

New Technologies - Solutions to Problems

Lubricants

- Synthetic Oils
    - Tailored Properties, Low Volatility, Viscosity of Choice, Low Pour Point, Low Reactivity
    - Increased Life, Factor of 10

- Sputter-Deposited Solid Lubricant Thin Films
    - Ultra-Low Friction
    - Low Noise, Debris
    - Long Life
    - Conductive Films

Wear Resistant Materials

- Hard Coatings & Ceramic Parts
    - Ultra-Smooth Surfaces, Low Torque Noise
    - Little or No Wear
    - Need for Designer Lubricants - Additive Criteria

New Technologies - Solutions to Problems
(Cont'd.)

Health Monitoring - Feedback Control

- Sensors
  - Performance Monitoring
  - Lubricant Failure Criteria
  - Structure, Balance Shift
  - Induced Vibration

- Data Processing
  - On Board
  - Minimum Interrogation

- Remedies
  - Lubricant Replenishment

Adaptive Bearing Designs

- Built-In Jitter Control
  - Low Torque Noise

Surface Studies of Lubricant Additives

Function and Performance of Additives Depend on Type of Surface Interaction

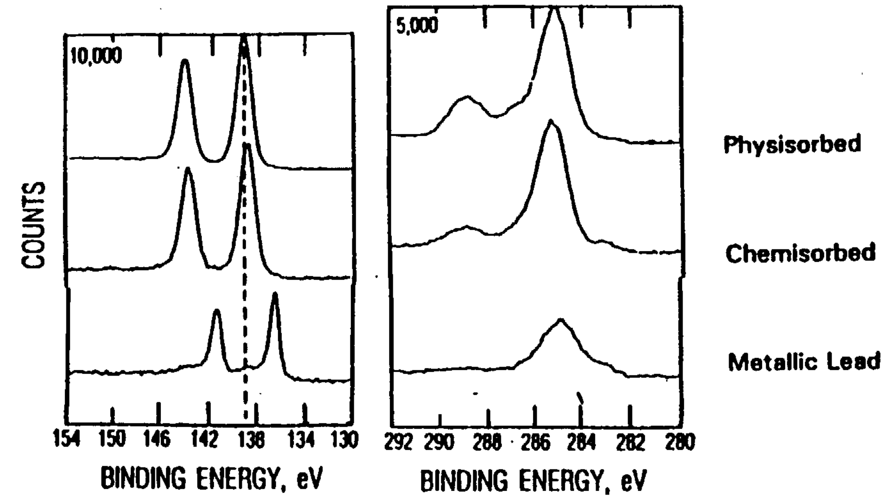
Antiwear, Film-Forming Additives

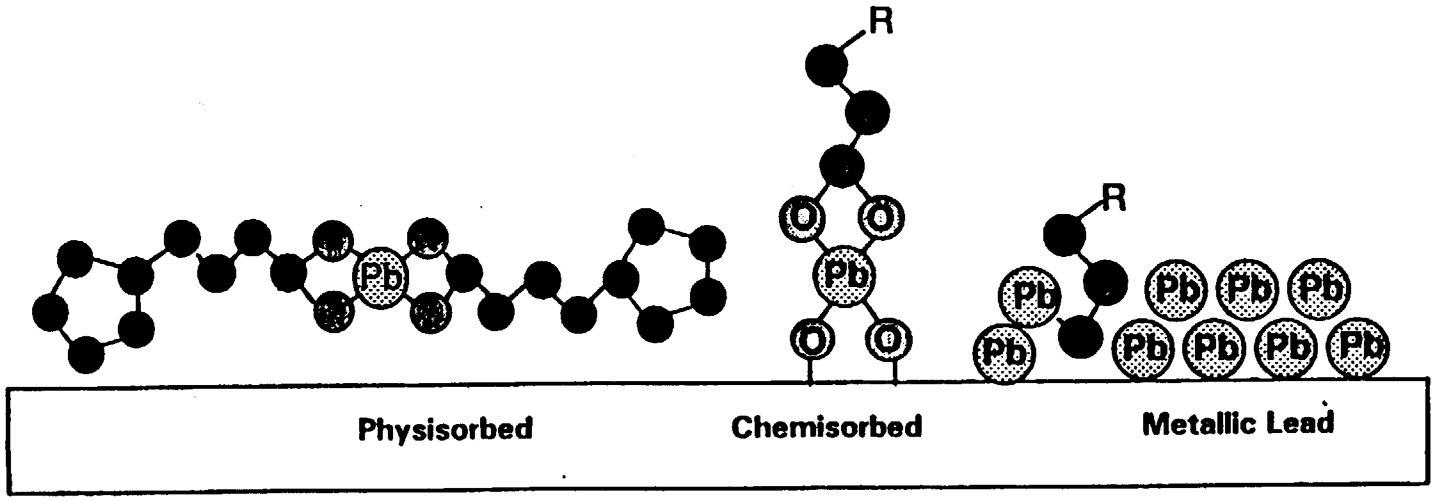
- Film Thickness Increases with Use
- Reduces Wear
- Can Increase Friction/Torque

Friction Reducing Additives

- Form Very Thin Reaction Layer on Contacting Surfaces
- Friction Modification Influences Fluid Properties
- Synthetic Oils Affected Differently Compared to Mineral Oils

Chemical States of PbNp on Bearing Steel





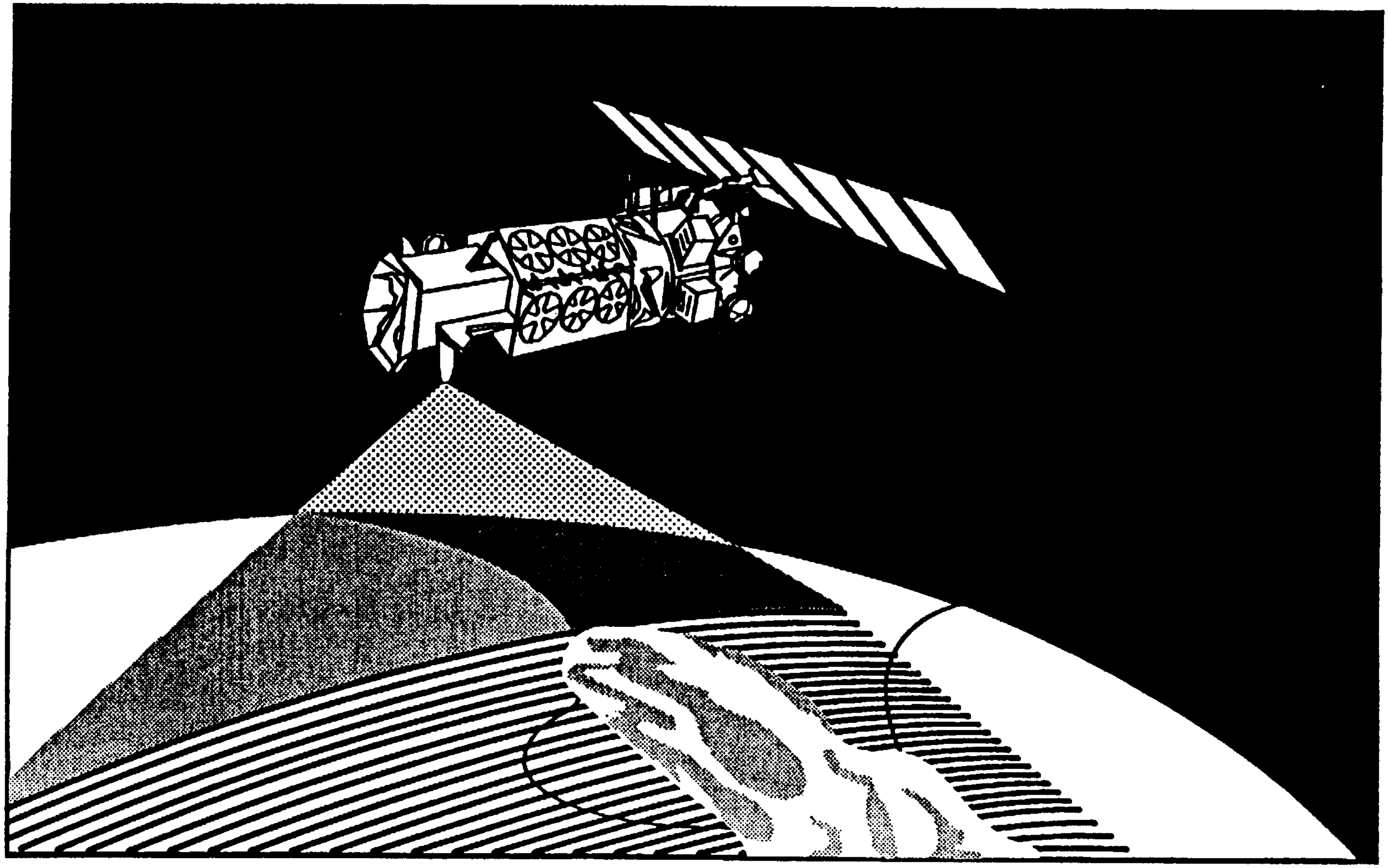
Lubrication of Spacecraft Mechanisms

Case Studies

Scanner Gimbal

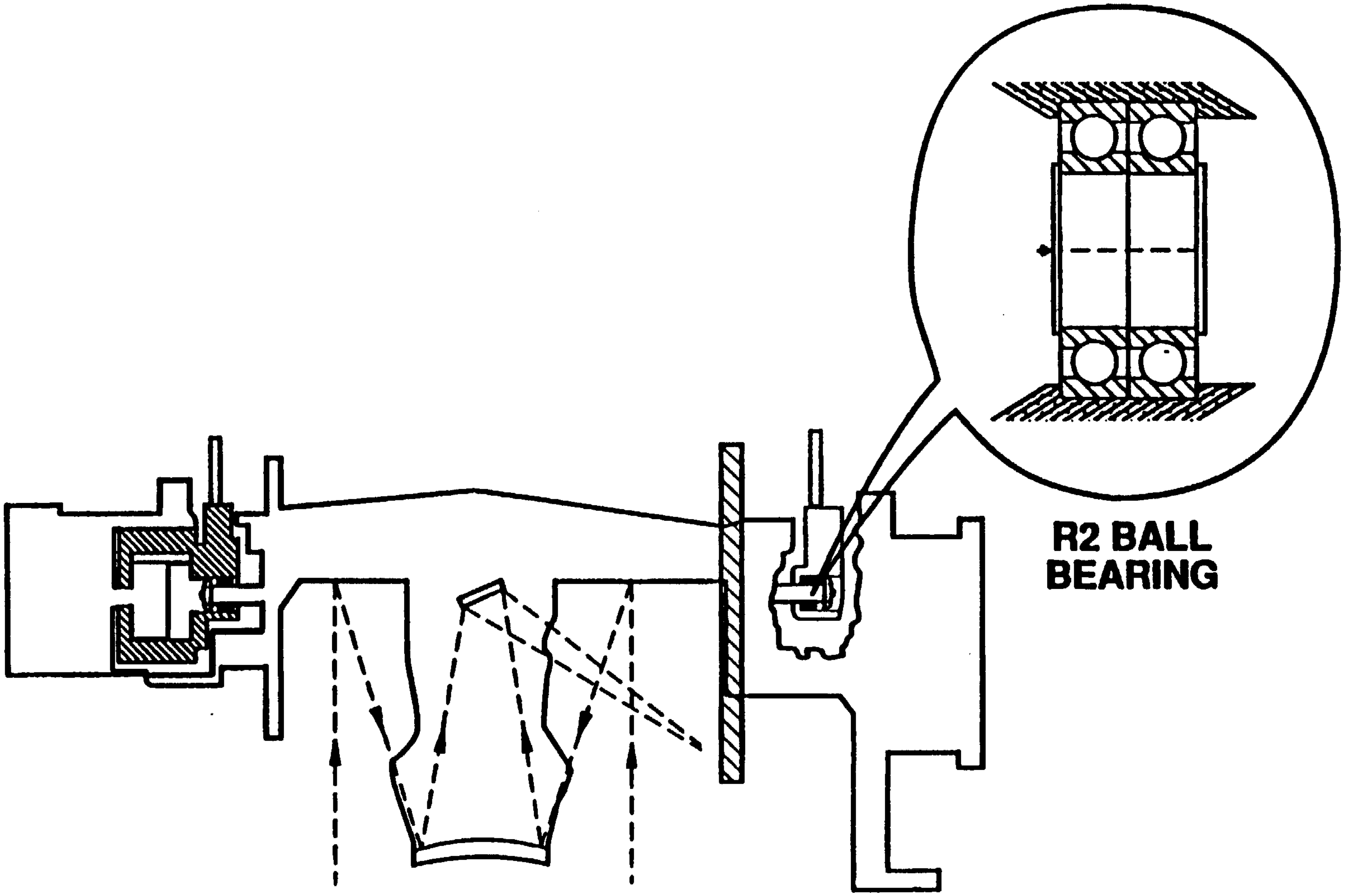
Reaction Wheel Assembly

DMSP Operation



DD-862

Operational Line Scanner (OLS)
Oscillating Assembly



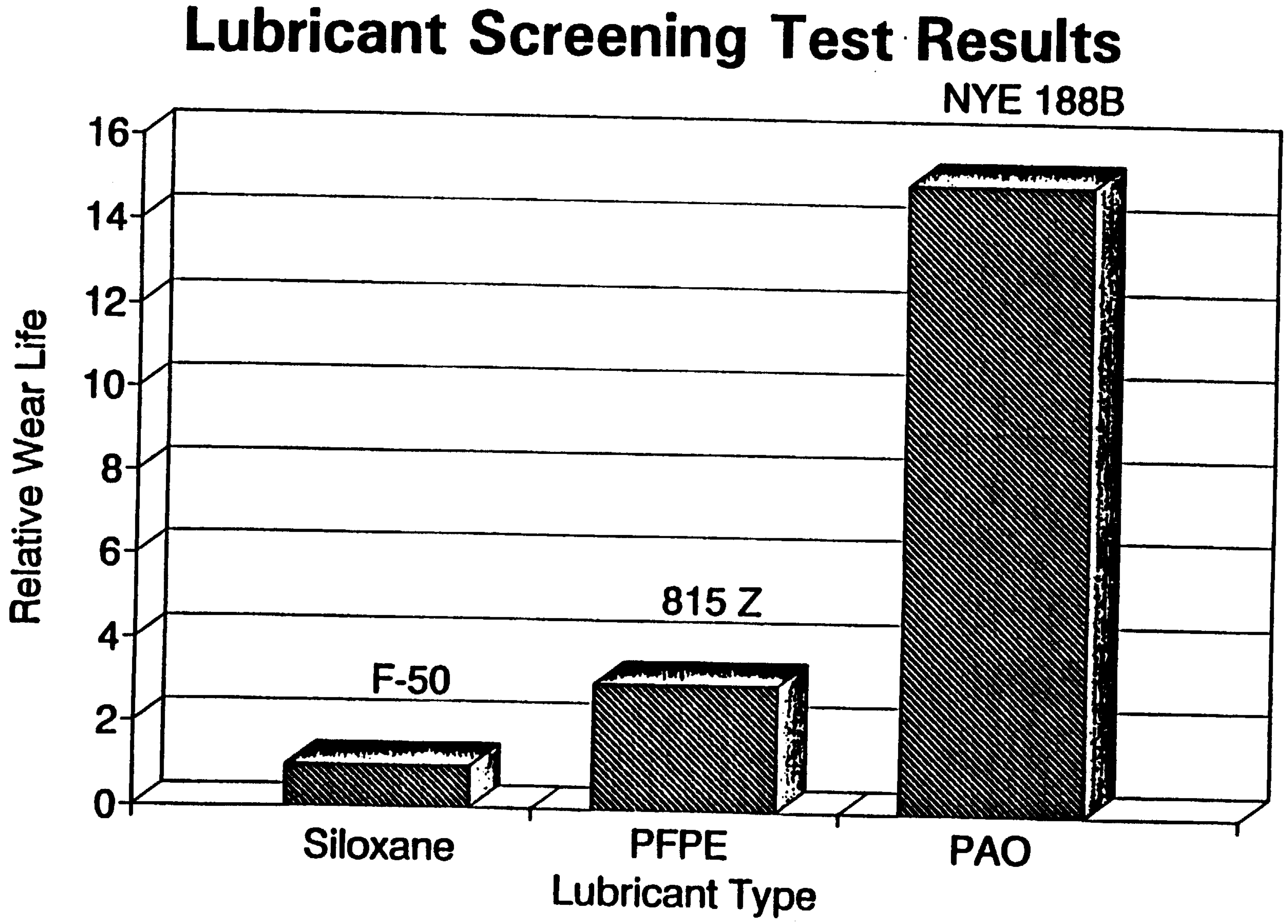
Lubricant Test Approach

Screening Tests

Sensor Simulation Test

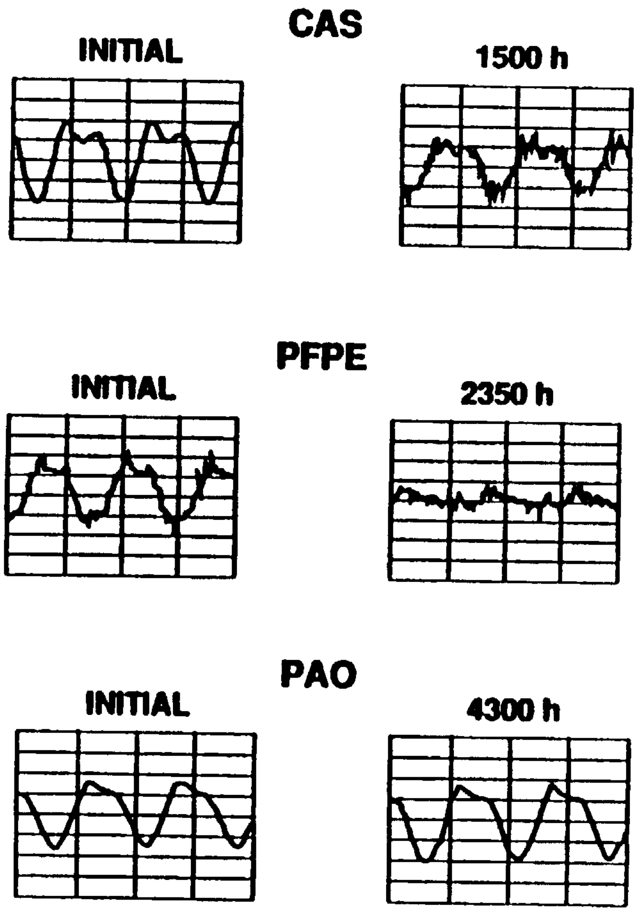
Continuous Torque, Temperature
Measurement

Detailed Post-Test Chemical, Physical,
& Mechanical Analyses

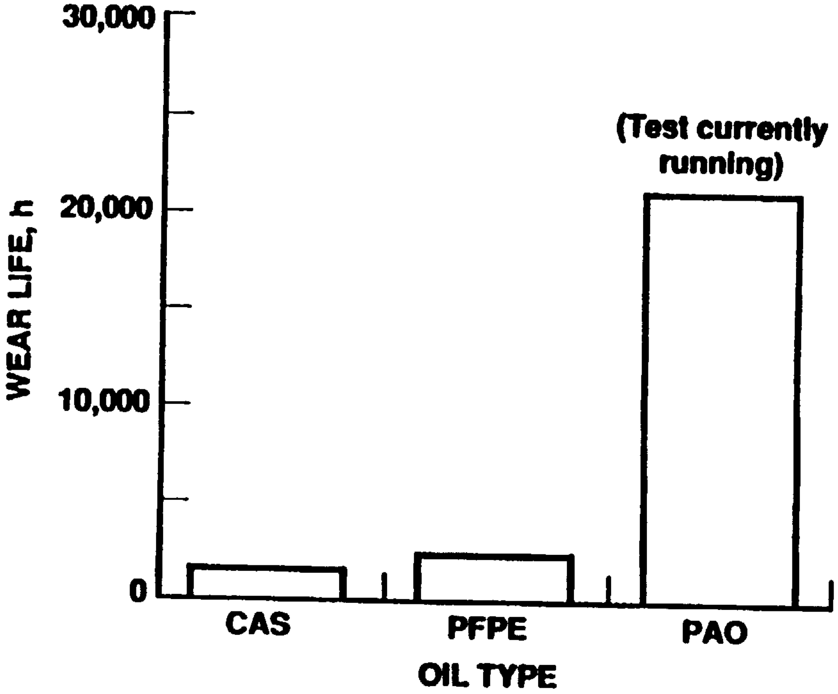

Lubricant Screening Test Results
Relative Wear Life
16
14
12
10
8
6
4
2
0
F-50
815 Z
NYE 188B
Siloxane
PFPE
PAO
Lubricant Type

Bearing Verification Test

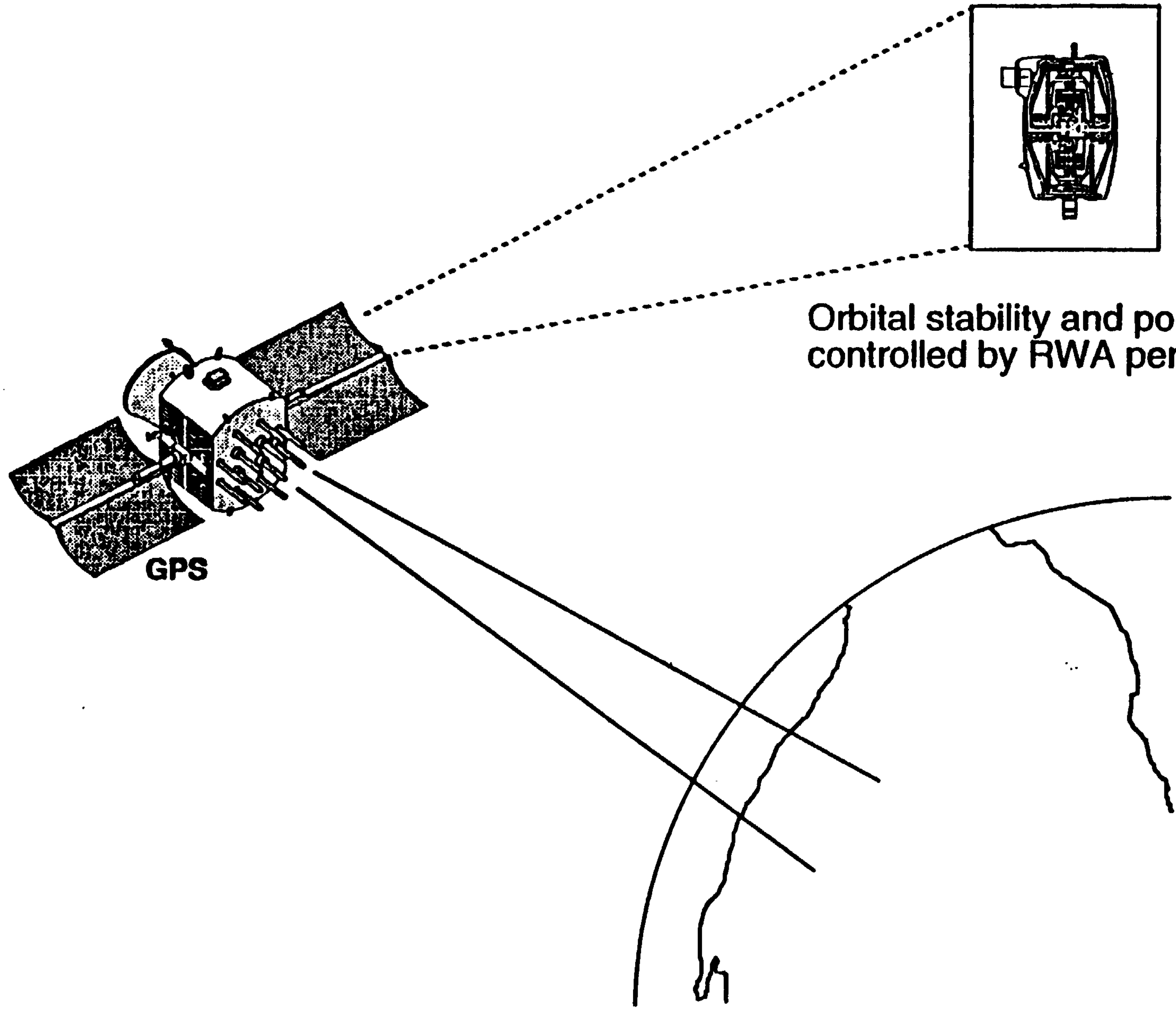
TORQUE DATA



LIFE-TEST RESULTS

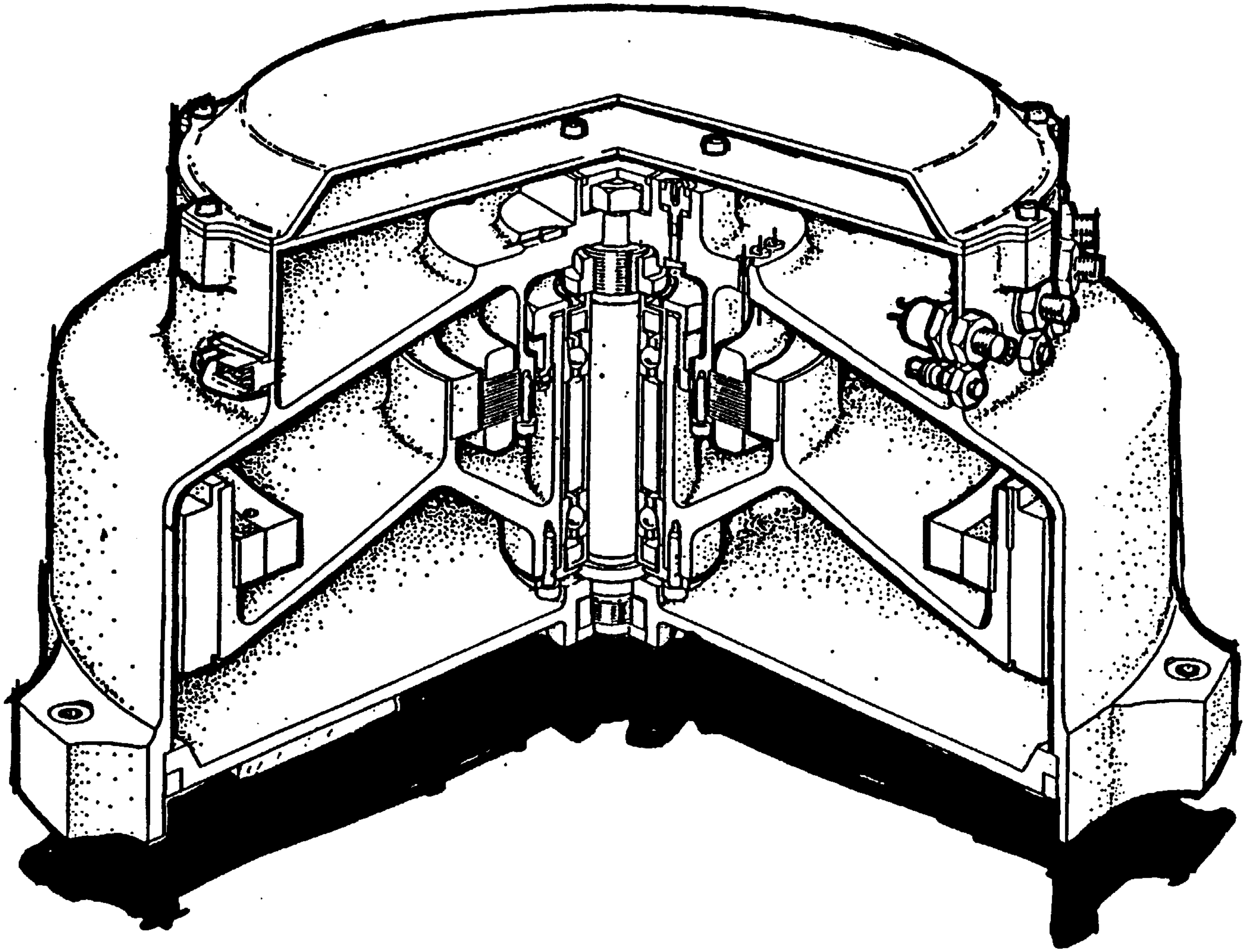


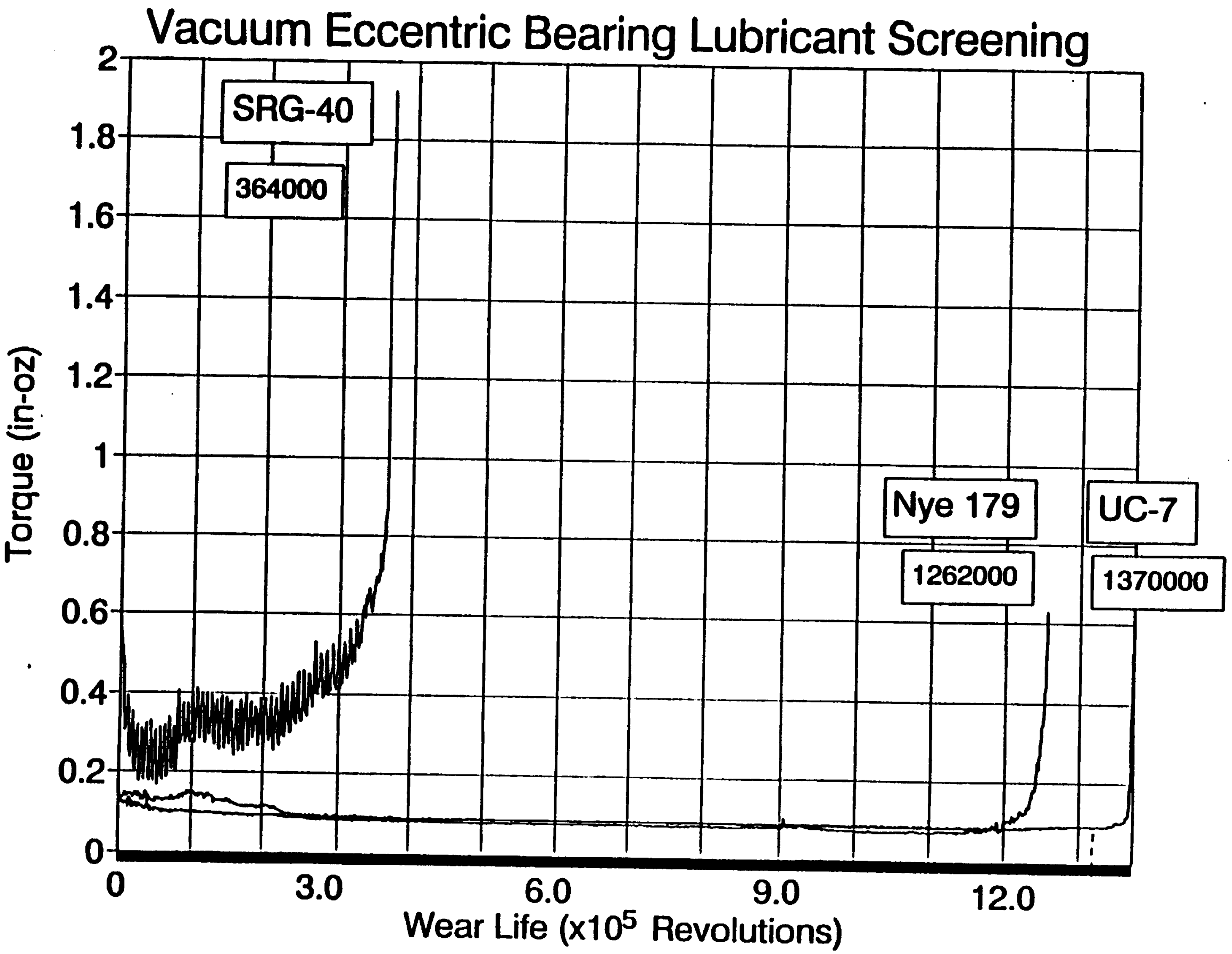
GPS Reaction Wheel Assembly



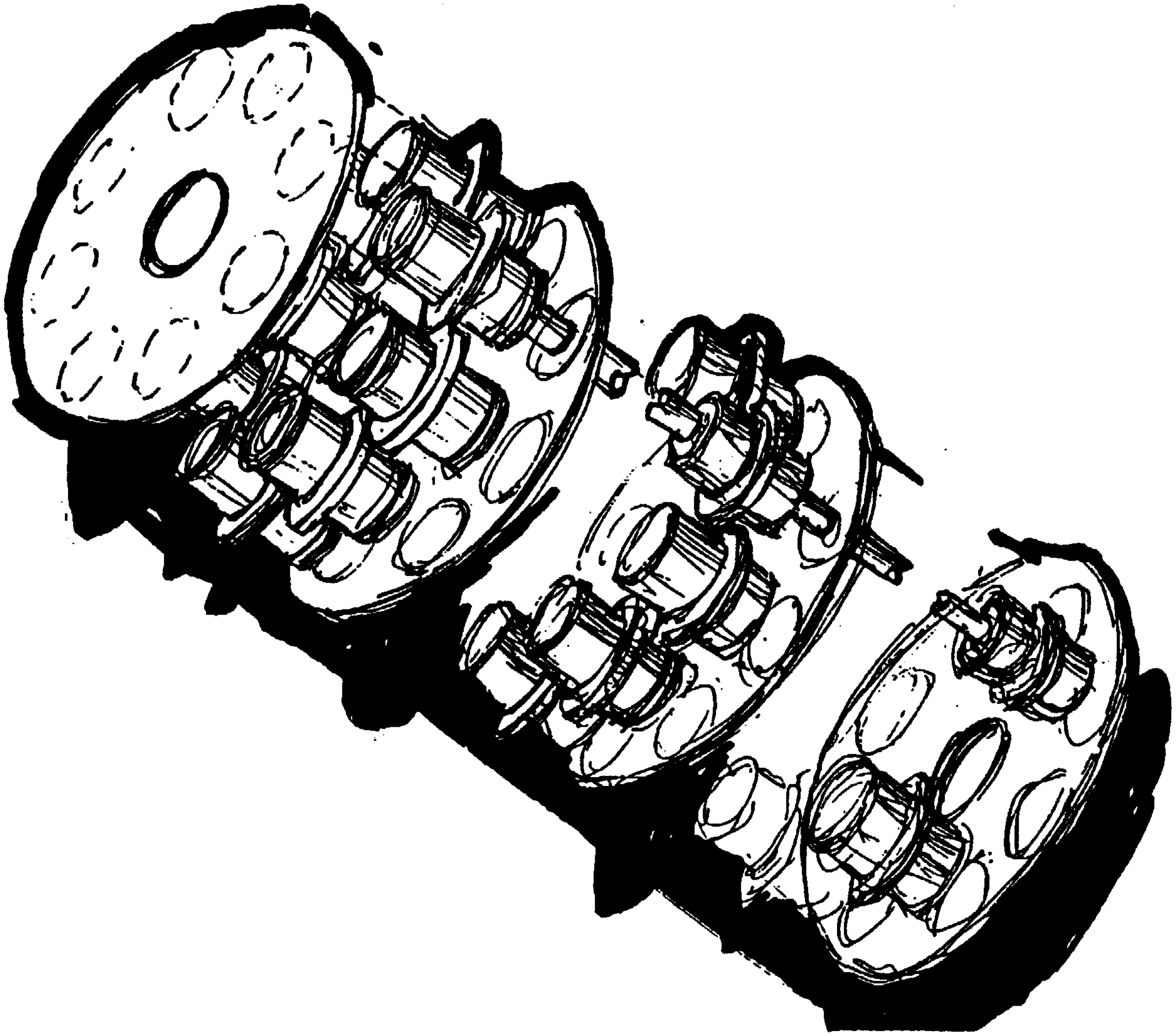
Orbital stability and pointing accuracy
controlled by RWA performance

Typical Reaction Wheel




Vacuum Eccentric Bearing Lubricant Screening
SRG-40
364000
Nye 179
1262000
UC-7
1370000
Torque (in-oz)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Wear Life (x10^5 Revolutions)
0
3.0
6.0
9.0
12.0

LUBRICATION TEST APPARATUS



Lubrication of Spacecraft Mechanisms

Summary

- Mechanical Subsystems Anomalies/Failures due to Lubrication Problems
- Other Subsystems Technologies Advancing More Rapidly
  - Lubrication (Tribology) Becoming the Limiting Technology
- Two Primary Types of Lubrication Problems
  - Supply or Loss of Lubricant
  - Chemical Reaction (Oxidation, Polymerization) of Lubricant
- Subsystems with the Most Problems Include Momentum Stabilization Devices (Wheels), Gimbals & other Boundary Lubricated Devices, Sliding Electrical Contacts, Gyroscopes
- Technological Solutions Include Synthetic Lubricants and Hard, Anti-wear Coatings for Contacting Parts

Space Mechanisms Technology Needs

Conclusions

- Technologies (New Materials, Processes) Exist to Solve Most Lubrication Problems
- Testing Needed to Demonstrate Technologies for Program Insertion
- Contractors Typically Hesitant to do Testing at Screening and Component Level
- Independent Testing Capabilities Needed to Assist Programs and Contractors

SPACE-RELATED TRIBOLOGY PROGRAMS

K.R. Mecklenburg
Wright Laboratory
Wright-Patterson Air Force Base, Ohio

TOPICS THAT COULD BE PRESENTED:

SDIO ULTRA LOW FRICTION FILM

SDIO MOMENTUM TRANSFER DEVICE LUBRICATION

SDIO HEALTH MONITORING

DARPA CERAMIC INSERTION

DARPA CERAMIC BEARING TECHNOLOGY

LIQUID LUBRICANTS FOR SPACE

SOLID LUBRICANTS FUNDAMENTALS

STRESSES IN THIN FILMS
  WEAR AND FRICTION

PULSED LASER DEPOSITION

PROPULSION LABORATORY
  POWDER LUBRICATION
  COMPUTER ANIMATION

NASP LIQUID LUBRICANTS

METAL MATRIX COMPOSITES

DIAMOND COATING OF BALLS

AFOSR PROGRAMS
  CERAMIC UNIVERSITY INITIATIVE
  CORROSION UNIVERSITY INITIATIVE

PMA: F1504 **TASK#4 - TRIBOMECHANISMS** **DATE:** 22 Sep 92

PROJECT TITLE: ULTRA LOW FRICTION FILM TECHNOLOGY BASE

EXISTING	X	NEW		CONTRACT	X	IN-HOUSE	X

DESCRIPTION: TECHNOLOGY BASE SUPPORT FOR THE ULTRA LOW FRICTION FILM DEVELOPMENT AND TRANSITION, INCLUDING QUALITY CONTROL AND DEMONSTRATION OF PERFORMANCE POTENTIAL. ULFF CAPABILITY HAS BEEN DEMONSTRATED IN SLIDING AND PARTIALLY DEMONSTRATED IN ROLLING WITH THE EXPECTED COMPLETION OF THIS EFFORT IN EARLY '93.

CONTRACTOR LOCATION: AEROSPACE, NATIONAL CENTRE FOR TRIBOLOGY, INSA, TA & T, NRL, SNL

PROJECT GOALS & OBJECTIVES

- COMPLETE TECH REPORT
- COMPLETE QUALITY CONTROL SPECIFICATIONS
- COMPLETE PERFORMANCE EVALUATIONS/DETERMINATIONS
- PUBLISH ENGINEERING DESIGN PARAMETERS
- CONCLUDE BEARING PERFORMANCE TESTING
- CONCLUDE BEARING LIFE TESTING
- ESTABLISH LIFE PREDICTION CAPABILITIES USING FILM PERFORMANCE
- DETERMINE FRETTING PERFORMANCE OF ULFF
- CONTINUE DEMO CONTRACTOR SUPPORT
- GAIN EXPERIENCE OF FILM IN TECH SAT APPLICATIONS

BENEFITS

- IMPROVED FILM RELIABILITY
- REPRODUCIBLY DEPOSITED FILMS
- INCREASED FILM TECHNOLOGY UTILIZATION
- DEMONSTRATION OF FILM CAPABILITY FOR CONTRACTOR TECHNOLOGY TRANSITION
- ENHANCED VALIDATION OF EXPECTED PERFORMANCE
- UTILIZATION OF ULFF IN OTHER MECHANISMS (SAD, GEARS, ETC).
- UTILIZATION OF ULFF IN TECH SAT ANTENNA AND OTHER BEARINGS

PROGRAM ELEMENT

- SUPPORTS:
  - BRILLIANT PEBBLES
  - BRILLIANT EYES
  - GLOBAL PROTECTION AGAINST LIMITED STRIKES
  - GROUND BASED INTERCEPTOR
  - TECH SAT

PMA: F1504 — **TASK#4 - TRIBOMECHANISMS** — **DATE:** 22 Sep 92

PROJECT TITLE: ULTRA LOW FRICTION FILM DEMONSTRATOR PROGRAM

EXISTING	X	NEW		CONTRACT	X	IN-HOUSE	

DESCRIPTION: DEMONSTRATION, TRANSITION, AND INSERTION OF ADVANCED SOLID LUBRICATION TECHNOLOGY INTO VARIOUS SDI MOVING MECHANICAL ASSEMBLY SYSTEMS. CONTRACTOR ACCEPTANCE OF THIS GENERIC TECHNOLOGY WOULD UPGRADE THE 20-30 YEAR OLD LUBRICATION TECHNOLOGY PRESENTLY BEING USED IN SATELLITE CONSTRUCTION.

CONTRACTOR LOCATION: HUGHES AIRCRAFT COMPANY, EL SEGUNDO, CA
LOCKHEED MISSILES AND SPACE, SUNNYVALE, CA

PROJECT GOALS & OBJECTIVES

- DEVELOP/VALIDATE LUBRICANT SYSTEM TECHNOLOGY INTO PRECISION GIMBAL MECHANISMS TO MEET FUTURE GIMBAL PERFORMANCE REQUIREMENTS:
  - DEMONSTRATE BEARING LUBRICATION
  - DEMONSTRATE BEARING LIFE IMPROVEMENT (10 YEAR)
  - DEMONSTRATE GIMBAL SYSTEM IMPROVED ACCURACY (1 MICRORADIAN)

BENEFITS

- TECHNOLOGY INSERTION
- USER ACCEPTANCE OF TECHNOLOGY
- UNIFORM BEARING TORQUE (LESS NOISE)
- LOWER FRICTIONAL TORQUE (REDUCED POWER)
- LESS DEBRIS
- LOWER CONDENSABLE CONTAMINATION
- LONGER OPERATIONAL LIFE
- REDUCED MOISTURE SUSCEPTIBILITY
- LESS COMPLICATION IN DESIGN

PROGRAM ELEMENT

- SUPPORTS:
  - BRILLIANT PEBBLES
  - BRILLIANT EYES
  - GLOBAL PROTECTION AGAINST LIMITED STRIKES
  - GROUND BASED INTERCEPTOR

PMA: F1504 **TASK#4 - TRIBOMECHANISMS** **DATE:** 22 Sep 92

PROJECT TITLE: MOMENTUM TRANSFER DEVICES TECHNOLOGY BASE

EXISTING		**NEW**	X	**CONTRACT**	X	**IN-HOUSE**	X

DESCRIPTION: TECHNOLOGY BASE SUPPORT FOR THE LUBRICATING ASPECTS OF AN ADVANCED MOMENTUM TRANSFER DEVICE. APPLICATION OF ADVANCED LIQUID LUBRICANT INTO TECH SAT REACTION WHEELS.

CONTRACTOR LOCATION: AEROSPACE, NATIONAL CENTRE FOR TRIBOLOGY, TA & T, NRL, SNL, WL/UD

PROJECT GOALS & OBJECTIVES

- IDENTIFY LUBRICANTS, PARTS, PROCESSING, AND RETAINERS THAT PROVIDE 10 YEAR LIFE PERFORMANCE WITH MINIMUM TORQUE/NOISE
- VALIDATE SPIN BEARING SYSTEM WITH REDUCED VIBRATION AND INCREASED BEARING LIFE FOR MTD'S
- DIRECT SUBSTITUTION OF ADVANCED LIQUID LUBRICANT INTO TECHSAT REACTION WHEELS FOR SPACE EXPERIENCE

BENEFITS

- DEVELOP MTD'S THAT WILL MEET PERFORMANCE, RELIABILITY, AND LIFE REQUIREMENTS:
  - TRANSIENT INPUTS
  - OPERATIONAL STABILITY
  - PERFORMANCE CONSISTENCY
  - REDUCED BEARING VIBRATION NOISE
  - REDUCED ACOUSTIC NOISE
  - LOW VAPOR PRESSURE REQUIREMENTS
  - OBTAIN SPACE OPERATIONAL EXPERIENCE WITH ADVANCED LIQUID LUBRICANT

PROGRAM ELEMENT

- SUPPORTS:
  - BRILLIANT PEBBLES
  - BRILLIANT EYES
  - GLOBAL PROTECTION AGAINST LIMITED STRIKES
  - TECH SAT

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PMA: F1504 **TASK#4 - TRIBOMECHANISMS** **DATE:** 22 Sep 92

PROJECT TITLE: MOMENTUM TRANSFER DEVICE DEMONSTRATOR PROGRAM

EXISTING		NEW	x	CONTRACT	x	IN-HOUSE	

DESCRIPTION: DEMONSTRATION, TRANSITION, AND INSERTION OF ADVANCED LIQUID LUBRICATION TECHNOLOGY INTO VARIOUS SDI MOMENTUM TRANSFER DEVICES DEMONSTRATION PROGRAMS. CONTRACTOR ACCEPTANCE OF THIS GENERIC TECHNOLOGY WOULD UPGRADE THE 20-30 YEAR OLD LIQUID LUBRICATION TECHNOLOGY PRESENTLY BEING USED IN SATELLITE MOMENTUM WHEEL CONSTRUCTION.

CONTRACTOR LOCATION: BENDIX/ALLIED SIGNAL, TETERBORO, NJ
SPERRY/HONEYWELL, PHOENIX, AZ

SPECIFIC CONTRACTORS DEPEND ON PROGRAM FINDINGS & DIRECTIONS

PROJECT GOALS & OBJECTIVES

- DEVELOP/VALIDATE LUBRICANT SYSTEM TECHNOLOGY INTO MOMENTUM TRANSFER DEVICES TO MEET FUTURE MOMENTUM WHEEL PERFORMANCE REQUIREMENTS:
  - DEMONSTRATE BEARING LUBRICATION
  - DEMONSTRATE BEARING LIFE IMPROVEMENT (10 YEAR)
  - DEMONSTRATE MOMENTUM WHEEL LUBRICATION PERFORMANCE SYSTEM AND LUBRICANT CHEMICAL STABILITY

BENEFITS

- TECHNOLOGY INSERTION
- USER ACCEPTANCE OF TECHNOLOGY
- UNIFORM BEARING TORQUE (LESS NOISE)
- LOWER FRICTIONAL TORQUE (REDUCED POWER)
- LESS CHEMICAL DEGRADATION
- LOWER CONDENSABLE CONTAMINATION
- LONGER OPERATIONAL LIFE
- REDUCED MOISTURE SUSCEPTIBILITY
- LESS COMPLICATION IN DESIGN

PROGRAM ELEMENT

- SUPPORTS:
  - BRILLIANT PEBBLES
  - BRILLIANT EYES
  - GLOBAL PROTECTION AGAINST LIMITED STRIKES
  - GROUND BASED INTERCEPTOR

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PMA: F1504 **TASK#4 - TRIBOMECHANISMS** **DATE:** 22 Sep 92

PROJECT TITLE: HEALTH MONITORING TECHNOLOGY BASE

EXISTING	X	NEW	X	CONTRACT	X	IN-HOUSE	X

DESCRIPTION: DETERMINE, DEVELOP, AND DEMONSTRATE SENSING SYSTEM TECHNOLOGY NECESSARY TO CONTROL/ALTER BEARING PERFORMANCE IN VARIOUS SDI MOVING MECHANICAL ASSEMBLY SYSTEMS. HEALTH MONITORING CAPABILITY WOULD PROVIDE NECESSARY PERFORMANCE CORRECTION TO CONTROL SATELLITE OPERATION.

CONTRACTOR LOCATION: AEROSPACE, NATIONAL CENTRE FOR TRIBOLOGY, TA & T, NRL, SNL, LANL, JPL

PROJECT GOALS & OBJECTIVES

- IDENTIFY BEARING FAILURE VIBRATION SIGNATURES
- IDENTIFY/VALIDATE PROCEDURES NECESSARY FOR OPERATIONAL STATUS INFORMATION
- DEVELOP ON-BOARD ALARM/CONTROL SYSTEM CONCEPTS/CORRECTIVE ACTION TECHNIQUES
- DEVELOP CONCEPTS FOR BEARING DATA ANALYSIS (VIBRATION, PRELOAD, TEMPERATURE, OPERATIONAL SIGNATURE)

BENEFITS

- ON-ORBIT CAPABILITY TO CONTROL/ALTER OPERATIONAL PERFORMANCE OF MOVING MECHANICAL ASSEMBLIES
- HEALTH MONITORING TECHNOLOGY DEVELOPMENT/TRANSFER

PROGRAM ELEMENT

- SUPPORTS:
  - BRILLIANT EYES
  - GLOBAL PROTECTION AGAINST LIMITED STRIKES

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PMA: F1504 **TASK#4 - TRIBOMECHANISMS** **DATE:** 22 Sep 92

PROJECT TITLE: HEALTH MONITORING DEMONSTRATOR PROGRAM

EXISTING		NEW	X	CONTRACT	X	IN-HOUSE		

DESCRIPTION: DEMONSTRATION, TRANSITION, AND INSERTION OF HEALTH/CONDITION MONITORING TECHNOLOGY INTO VARIOUS SDI MOVING MECHANICAL ASSEMBLY SYSTEMS. CONTRACTOR ACCEPTANCE OF THIS GENERIC TECHNOLOGY WOULD LENGTHEN OPERATIONAL LIVES OF SDI SYSTEMS SATELLITES

CONTRACTOR LOCATION:
BENDIX/ALLIED SIGNAL, TETERBORO, NJ
HUGHES AIRCRAFT, EL SEGUNDO, CA
SPERRY/HONEYWELL, PHOENIX, AZ
LOCKHEED MISSILES & SPACE, SUNNYVALE, CA

SPECIFIC CONTRACTORS
DEPEND ON PROGRAM
FINDINGS & DIRECTIONS

PROJECT GOALS & OBJECTIVES

- DEVELOP/VALIDATE HEALTH MONITORING TECHNOLOGY INTO SATELLITE MOVING MECHANICAL SYSTEMS
- DEMONSTRATE CONTROL OF BEARING PRELOAD
- DEMONSTRATE VIBRATION CONTROL/SUPPRESSION IN COMBINED DEMO EFFORT WITH STRUCTURES/VIBRATION CONTROL TASKS

BENEFITS

- TECHNOLOGY INSERTION
- USER ACCEPTANCE OF ADVANCED TECHNOLOGY OF BEARING PRELOAD DETERMINATION AND CONTROL, CRITICAL TEMPERATURE MEASUREMENT AND CONTROL, FRICTIONAL TORQUE AND TORQUE NOISE

PROGRAM ELEMENT

- SUPPORTS:
  - GENERIC
  - BRILLIANT EYES
  - GLOBAL PROTECTION AGAINST LIMITED STRIKES

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DARPA
CERAMIC TECHNOLOGY INSERTION PROGRAM

CONTRACTOR	SYSTEM/ COMPONENT	AGENT POC	PROGRAM MANAGER
DETROIT DIESEL 13400 OUTER WEST DRIVE, WEST DETROIT, MI 48239-4001	M109 ENGINE VALVE TRAIN WEAR COMPONENTS	ERNIE SCHWARTZ TACOM/ AMSTA-VCA 313-574-5656	T. MICHAEL KEELAN 313-592-5973
GENERAL DYNAMICS ELECTRO DYNAMIC 150 AVENEL STREET AVENEL, NJ 07001	ROTATING MACHINERY BEARINGS	PAT HUGHES 703-780-7943	JIM SMITH 203-433-6949
RAYTHEON COMPANY MISSILE SYSTEMS DIVISION 50 APPLE HILL DRIVE TEWKSBURY, MA 01876	SPARROW MISSILES IR SEEKER BEARINGS	ROD KENLY NAVAL WEAPON CTR. 619-939-3331	DUNCAN BOYCE 508-858-1088
UNITED TECHNOLOGIES- PRATT & WHITNEY P.O. BOX 109600 WEST PALM BEACH, FL. 33410-9600	F-100 ENGINE DIVERGENT NOZZLE	ROGER SPENCER ASD/YZJ 513-255-4169	RICH DICKENSON 407-796-4464
GENERAL ELECTRIC AIRCRAFT ENGINES ONE NEUMANN WAY CINCINNATI, OH 45215	EXHAUST NOZZLE FLAP AND SEAL	ROGER SPENCER ASD/YZJ 513-255-4169	REED OLIVER 513-786-4708
ALPHA OPTICAL 1611 GOVERNMENT STREET OCEAN SPRINGS, MI 39564	AV-8B ARBS SPINEL DOME	HUGH BLACKWELL NAVAVN DEPOT 919-466-8034	JOHN FAHNSTOCK 601-875-0211

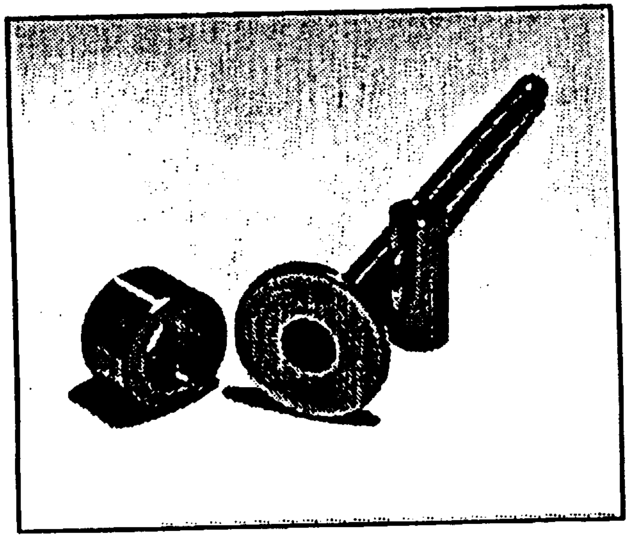
DARPA
CERAMIC TECHNOLOGY INSERTION PROGRAM

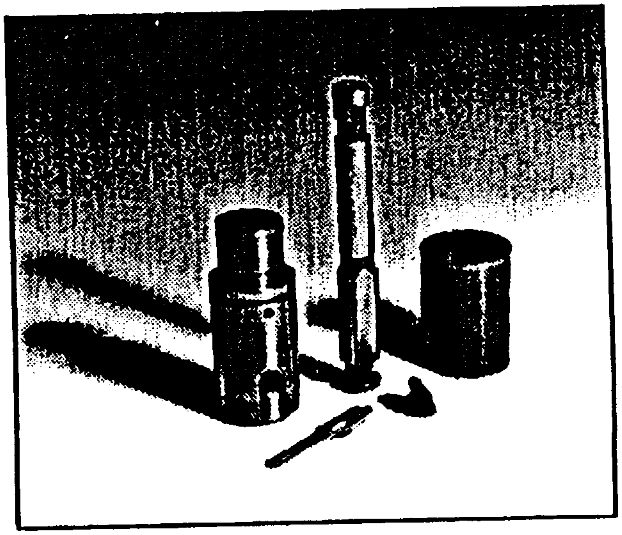
CONTRACTOR	SYSTEM/ COMPONENT	AGENT POC	PROGRAM MANAGER
UNITED TECHNOLOGIES-PRATT & WHITNEY P.O. BOX 109600 WEST PALM BEACH, FL 33410-9600	F-117 ENGINE MAINSHAFT BEARINGS	JOHN DELL WL/POSL 513-255-7230	JOHN MINER 407-796-5951
ALLIED SIGNAL AEROSPACE CO.- GARRETT AUX. POWER DIVISION 2739 EAST WASHINGTON STREET P.O. BOX 5227 PHOENIX, AZ 85010-5227	POWER CART SiN4 NOZZLE	MONTY SIEVER SA/ALC/LDPG 512-925-8411	ED TASCHNER 602-365-5712
TELEDYNE CAE 1330 LASKEY ROAD P.O. BOX 6971 TOLEDO, OH 43612	J402 ENGINE MAINSHAFT BRGS	JIM O'DONNELL NAWC-TRENTON 609-538-6513	JOHN LAW 419-470-3881
SUNDSTRAND 4747 HARRISON AVE. P.O. BOX 7002 ROCKFORD, IL 61125-7002	S3A/A-10 CONST. SPEED DRIVES	JIM O'DONNELL NAWC-TRENTON 609-538-6513	DR. JONG-YEONG YUNG 815-394-2870
ALLIED SIGNAL AEROSPACE CO. AIRESEARCH 19201 SUSANA ROAD RANCHO DOMINGUEZ, CA 90221-5710	C-130, F-111, F-15 AIR CYCLE MACHINE BEARINGS	MATTHEW POURSABA OC/ALC-LIIRE 405-736-5080	LYMAN BURGMEIER 213-512-4578

ADVANCED CERAMIC TECHNOLOGY INSERTION PROGRAM

PROGRAM OBJECTIVE:

DEMONSTRATE PRODUCTION VIABILITY (EQUIVALENT RELIABILITY) FOR CERAMIC ENGINE COMPONENTS WHICH ARE EXPECTED TO ENABLE THE POWER EXTENSION OF THE CURRENT 8V-71T (440 BHP) FOR THE M109 SELF-PROPELLED HOWITZER, TO 500 BHP.





DELIVERABLES:

- CERAMIC COMPONENT DRAWINGS AND MATERIAL/PROCESS SPECIFICATIONS
- TEST DEMONSTRATOR ENGINE

OBJECTIVES

- Exploit ceramic technology to provide improved bearing.
- Combine ceramic ball properties, appropriate race material properties and lubricants to improve bearing useful life.
- Qualify a domestic source for bearing manufacture.
- Qualify the bearing for a military application.
- Field the new bearing in operational platform.

Missile Systems
Laboratories

Electro-Optics
Laboratories

Raytheon

ACTI - Bearings
Objective

- Objective
  - Develop Form-Factored Silicon Nitride Spin and Gimbal Bearings for Missile Homing Improvement Program (MHIP) Common IR Seeker

Electro-Optics
Laboratories

Approach

- Design Gimbal With Silicon Nitride Spin and Gimbal Bearings
- Fabricate Bearings
- Assemble Gimbals
- Retrofit Gimbal/Gyro Assemblies Into 3 MHIP Prototype Seekers
- Deliver 1 Seeker to Naval Air Warfare Center for Evaluation
- Baseline MHIP Performance Testing on 2 Remaining Seekers
- Repeat Performance Tests

Pratt & Whitney

Objectives

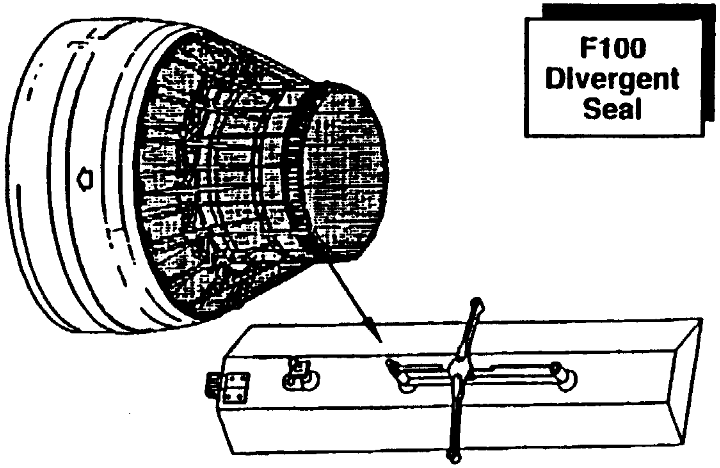
- Demonstrate the benefits of state-of-the-art ceramic matrix composites in order to increase the insertion rate of these materials into production military systems

Approach

- Build On Successful CMC Engine Experience
- Involve Suppliers By Integrated Product Team (IPT)
- Finalize Material Selection With Critical Screening Tests
- Optimize Material Process
- Verify Design Methods and Specification Data Through Subelements
- Test to Supplement Design Database
- Fabricate Seals For Test Verification / Engine Demonstration

Expected Major Results

- Establish an Optimized Repeatable Material Process
- Demonstrate Reliability, Durability, and Producibility of F100 Ceramic Matrix Composite Divergent Seal
- Ready Ceramic Matrix Composite Component for Insertion in F100 Engine Family



F100
Divergent
Seal

22143

OBJECTIVE

- INTRODUCE CERAMIC MATRIX COMPOSITE COMPONENTS TO F110 PRODUCT ENGINES, AS FOLLOWS:
    - HOT SECTION APPLICATION, CONSISTENT WITH TEMPERATURE CAPABILITIES OF THE CMC;
    - LOW RISK APPLICATION, CONSISTENT WITH THE MATERIAL PROPERTIES OF CMC;
    - CURRENT HIGH MAINTENANCE COMPONENT, TO PRODUCE A BENEFIT FOR THE PRODUCT LINE;
    - INTRODUCTION AS EARLY AS POSSIBLE, CONSISTENT WITH ENGINE SUBSTANTIATION AND QUALIFICATION TOLLGATES AND REQUIREMENTS.

ALPHA
α OPTICAL SYSTEMS, INC.

OBJECTIVES:

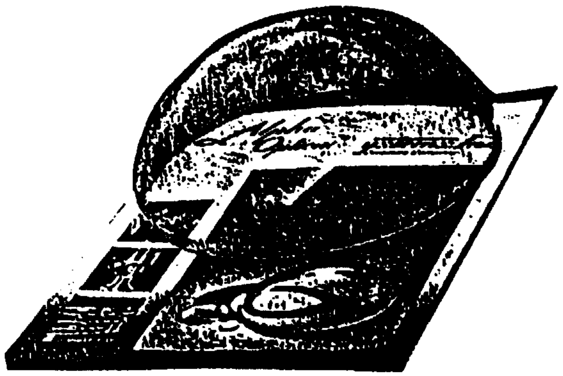
- Demonstrate system benefits of replacing ZK-N7 Glass domes on Harrier ARBS system with transparent spinel
- Maintain Optical compatibility to ensure interchangability
- Demonstrate potential benefits of using transparent spinel in similar systems

APPROACH:

- Focus on Producing Spinel ARBS domes with excellent optical quality
- Compare Spinel with ZK-N7 Glass optical performance: resistance to solid particle/rain/hail environments
- Compare Spinel with ZK-N7 in respect to birdstrike resistance
- Perform optical testing to demonstrate interchangability of Spinel with ZK-N7

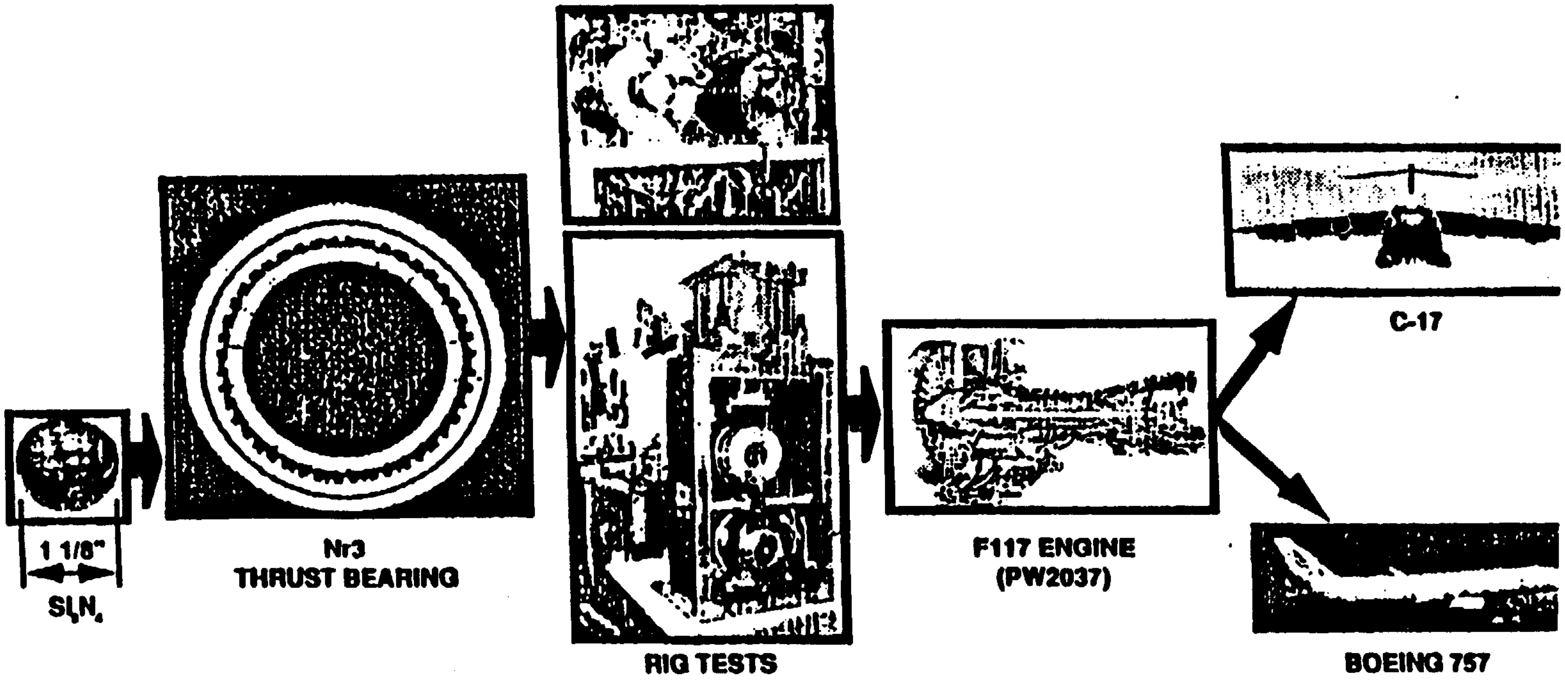
EXPECTED MAJOR RESULTS:

- Spinel domes can be substituted for ZK-N7 Glass with no loss in optical performance
- Replacement of Domes, (if needed at all) will occur in increments of years rather than months
- Dramatic reduction in Life Cycle Costs



CERAMIC TECHNOLOGY INSERTION PROGRAM

- P&W CONTRACT INITIATED 3 APR 92
- FUNDED BY DARPA - $1.5M (FY91-94)
- HYBRID CERAMIC (Si_3N_4 BALLS/STEEL RACES) REPLACES ALL-STEEL BEARING
- DURABILITY IMPROVEMENT
- HIGH TEMP/HIGH DN IHPTET GOALS NECESSITATE CERAMIC ROLLING ELEMENTS



Allied-Signal Aerospace Company
Garrett Auxiliary Power Division

Objective

Demonstrate integrity and durability of ceramic turbine nozzles in long-term engine endurance and fielded ground cart tests

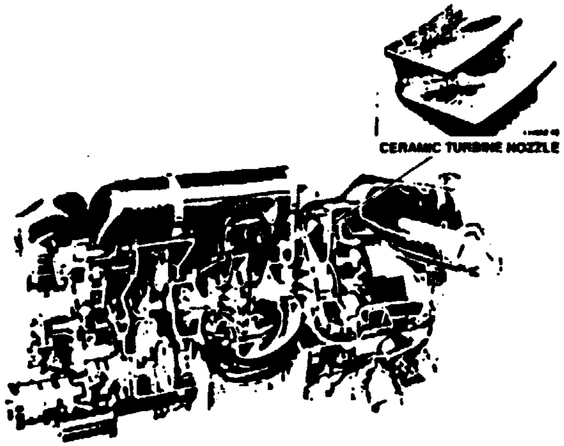
Approach

- Design and demonstration testing completed under Allied-Signal funding
- Fabricate metal and ceramic hardware to convert nine GTCP85-180 gas turbine engines (GTEs) to the ceramic turbine nozzle configuration
- Perform endurance testing at GAPD
    - Two units for one year will operate for 5,000 hours
    - Two units for 2.5 years will operate for 15,000 hours
- Perform field testing of five units at Luke AFB for 2.5 years

Expected Major Result

Generate test experience that will facilitate the use of ceramic components in turbine engine production

Ceramic Turbine Nozzle Insertion



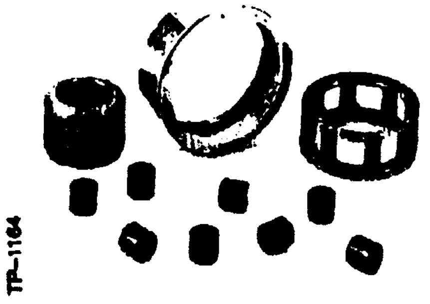
Allied-Signal Aerospace Company
Garrett Auxiliary Power Division

Allied Signal

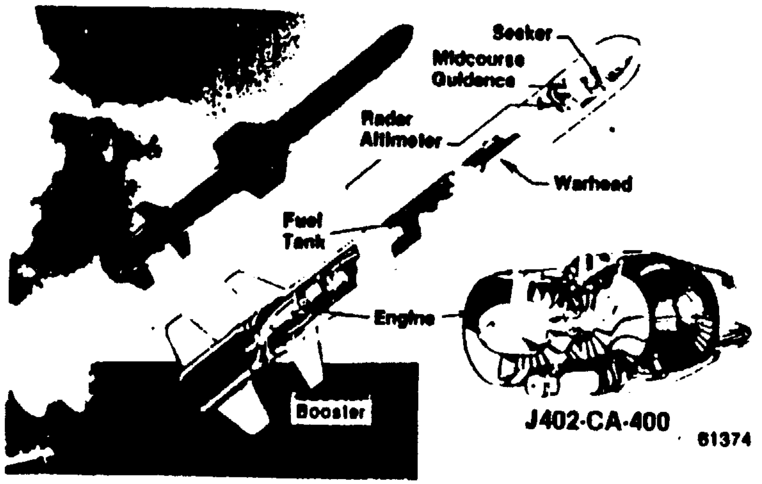
TELEDYNE CAE

DESILUBE, SPLIT BALL BEARING, SURFACE RESEARCH & APPLICATION, WEDEVEN ASSOC.

SOLID LUBRICATED HYBRID CERAMIC BEARINGS



HARPOON / SLAM MISSILE



BENEFITS

- REDUCED ACQUISITION COST ($6K/UNIT)
- IMPROVE RELIABILITY
  - ACCEPTANCE / STORAGE / OPERATION
- EXTENDED STORAGE LIFE
- REDUCED SUPPORT COST

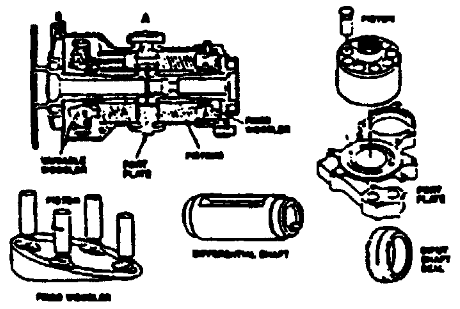
APPROACH

- SOLID LUBE ELIMINATES LIQUID LUBE, REDUCES COOLING REQUIREMENTS AND ENABLES FRONT FUEL ENTRY.
- CERAMIC ROLLING ELEMENTS ENABLE HIGH TEMI ATURE SOLID LUBE OPERATION.
- EARLY RIG TEST OF EXISTING BEARING TO EVALU CONCEPT.
- MATERIAL/LUBE SCREENING OF TRACTION AND W PROPERTIES.
- RIG DEVELOPMENT OF DETAIL DESIGN
- ENGINE OPERATIONAL/ENVIRONMENTAL EVALUAT OF FINAL DESIGN.

68098
TELEDYNE CAE
Turbine Engines

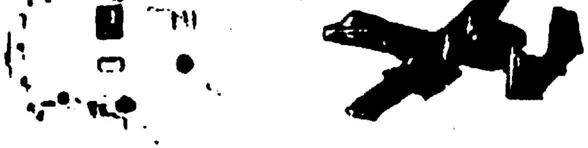
Sundstrand Aerospace

Ceramic Components



S-3A Constant Speed Drive

A-10 Constant Speed Drive



OBJECTIVES

- Apply Engineering Ceramics to Wear Critical Components in the S-3A/A-10 Constant Speed Drive Increasing Reliability and Performance

BENEFITS

- Increased MTBF Through Reduced Wear
- Increased Catapult Start Reliability Through Improved Low Lube Tolerance
- Increased Survivability Through Increased Contamination Resistance
- Increased Efficiency Through Higher PV-Wear Capability

APPROACH

- Comparative Wear Testing of Ceramic Materials
- Iterative Design Approach Using Finite Element Analysis, NASA-CARES, and Concurrent Engineering for Design to Cost
- Design Interchangeability for Easy Insertion
- Proof, Rig and CSD Testing for Performance Including Endurance, Oil Deprivation, Cold Start, High Temperature, and Efficiency

INSERTION PLAN

- NATC Flight Testing in Non-Dedicated S-3As
- Preferred Spares Substitution in S-3A, A-10
- Coordinated Through S-3A Class Desk, Wash. DC, NAWC, Pax River, OC-ALC, Tinker AFB

CERAMIC BEARING PROGRAM

OBJECTIVES

- DEMONSTRATE ABILITY TO INCORPORATE CERAMIC HYBRID BALL BEARINGS IN EXISTING COOLING TURBINES, WITH MINIMUM IMPACT ON TURBINE DESIGN
- DEMONSTRATE SUCCESSFUL OPERATION OF COOLING TURBINES DURING LABORATORY TESTING
- DEMONSTRATE SUCCESSFUL FLIGHT TESTS; RETROFIT FLEET

APPROACH

- ANALYZE EXISTING BEARING DESIGNS FOR CONVERSION TO CERAMIC HYBRID BEARINGS
- CONDUCT LIFE CYCLE COST STUDY TO VERIFY HYBRID BEARING ADVANTAGE
- INCORPORATE HYBRID BEARINGS IN 3 COOLING TURBINES AND CONDUCT 50 HOUR ACCELERATED TESTS:
  - MONITOR BEARING AND OIL MIST TEMPERATURE
  - MONITOR VIBRATION
- PERFORM FLIGHT EVALUATION TESTS:
  - USE C130, F111 AND F15 COOLING TURBINES
  - EVALUATE UP TO 10 UNITS OF EACH CONFIGURATION

FLIGHT TEST EVALUATION

- ONE YEAR TEST PROGRAM
- CONDUCTED BY USAF OC/ALC; ASSISTED BY AIRESEARCH
- AIRESEARCH TO PROVIDE DISASSEMBLY AND BEARING ANALYSIS FOLLOWING FLIGHT TEST

MILESTONES

- DESIGN AND ANALYSIS OF BEARINGS AND MOUNTING METHODS (JANUARY 1993)
- COMPLETION OF FIFTY HOUR ACCELERATED TEST PROGRAM ON THREE DIFFERENT COOLING TURBINES (JULY 1993)
- COMPLETION OF FLIGHT TEST OF TEN COOLING TURBINES OF EACH CONFIGURATION (OCTOBER 1994)

MATERIALS DIRECTORATE - THRUST 6
NONSTRUCTURAL MATERIALS

LUBRICATED CERAMIC BEARING TECHNOLOGY

CONDITION MONITORING
OF CERAMIC BALL MATERIALS

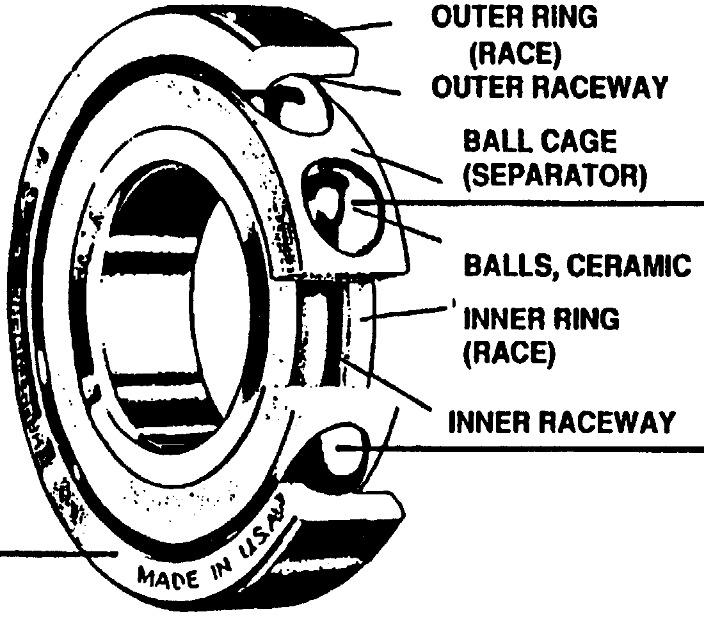
SIMULATED ENGINE TESTING OF
HYBRID BEARINGS

NEW, LESS EXPENSIVE PROCESSING
OF SILICON NITRIDE CERAMICS

LAYERED CERAMICS FOR HIGHER
COMPRESSIVE STRESSES AND
LOADING

TWO HARDENING TECHNIQUES
FOR STEEL OUTER RACES

CERAMIC COATING TECHNIQUES
FOR GREATER DURABILITY



6 MATERIALS TO BE
STUDIED AND
COMPARED

BALL FINISHING
TECHNIQUES -
GENTLE GRINDING
FLOAT POLISHING

FATIGUE OF CERAMICS
AS BALLS TO BE
STUDIED

COMPUTERIZED BEARING
DESIGN USING CERAMIC
BALL PROPERTIES

FINISHING TECHNIQUES

SEPARATOR / BALL INTERACTION

CERAMIC BEARING TECHNOLOGY PROGRAM

OBJECTIVE: ENHANCE PROCESSING TECHNOLOGY BASE FOR HIGH QUALITY CERAMIC ROLLING ELEMENTS AND CERAMIC BEARINGS

APPROACH: Provide Impetus to Ceramic Bearing Industry and Bearing User Community to Develop Production, Finishing, and Inspection Capabilities for All-Ceramic and Ceramic Hybrid Bearings

- Alternate Methods of Making Si_3N_4
- Inspection Techniques
- Finishing Techniques
- Operational Performance Data Base
- Comparative Property Data

DARPA
CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR	CONTRACT NUMBER	SYSTEM/COMPONENT	PROGRAM MANAGER
ADVANCED CONTROLS TECHNOLOGY INC 19151 PARTHENIA ST., UNIT G NORTHRIDGE, CA 91324	F33615-92-C-5908	COMPUTERIZED DESIGN AND LIFE PREDICTION BEARINGS	CRAWFORD MEEKS 818-886-0250
CERAMATEC, INC. 2425 SOUTH, 900 WEST SALT LAKE CITY, UT 84119	F33615-92-C-5915	CERAMIC COMPOSITE BEARINGS	RAYMOND CUTLER 801-972-2455
CERBEC 10 AIRPORT PARK ROAD EAST GRANBY, CT 06026	F33615-92-C-5917	CERAMIC BEARING DEVELOPMENT	JOHN LUCEK 203-653-8071
CERCOM 1960 WATSON WAY VISTA, CA 92083	F33615-92-C-5903	CERAMIC BEARING SPECIMEN TECHNOLOGY	ANDRE EZIS 619-727-6200 FAX 619-727-6209
GE AIRCRAFT ENGINES 1 NEUMAN WAY CINCINNATI, OH 45215	F33615-92-C-5926	ENGINE CERAMIC BEARINGS	MICHAEL PRICE 513-243-4227 FAX 513-243-3250
MECHANICAL TECHNOLOGY, INC. 968 ALBANY-SHAKER ROAD LATHAM, NY 12110	F33615-92-C-5909	CERAMIC BEARING TECHNOLOGY	JIM DILL 518-785-2136 FAX 518-785-2420
NORTHWESTERN UNIVERSITY BIRL-INDUSTRIAL RESEARCH LABORATORY 1801 MAPLE AVE. EVANSTON, IL 60201-3135	F33615-92-C-5935	CERAMIC COATED BEARINGS	WILLIAM SPROUL 708-491-4108 FAX 708-491-4486

OKLHOMA STATE UNIVERSITY 218 ENGINEERING NORTH STILLWATER, OK 74078-0545	F33615-92-C-5933	CERAMIC BEARING TECHNOLOGY PROGRAM	RANGA KOMANDURI 405-744-5900 FAX 405-744-6187
TORRINGTON CO. 59 FIELD STREET TORRINGTON, CT 06790-4942	F33615-92-C-5922	IMPROVED HYBRID BEARINGS	PHILIP PEARSON 203-482-9511 FAX 203-496-3605
TORRINGTON CO. 59 FIELD STREET TORRINGTON, CT 06790-4942	F33615-92-C-5910	ROTATING BEAM FATIGUE BEARINGS	Y.P. CHIU 203-482-9511 FAX 203-496-3605
WEDEVEN ASSOCIATES, INC 5068-A WEST CHESTER PIKE EDGMONT, PA 19028-0646	F33615-92-C-5925	RUN-IN FINISHING AND TRIBOLOGICAL PERFORMANCE	LAVERN WEDEVEN 215-356-7161
ARGONNE NATIONAL LAB 9700 S. CASS AVE. ARGONNE, IL 60439		NDI FOR CERAMICS	BILL ELLINGSON 703-252-5068
QUATRO 4300 SAN MATEO BLVD NE ALBUQUERQUE, NM 87110		RESONANT ULTRASOUND INSPECTION FOR CERAMIC BEARINGS	GEORGE RHODES 505-883-1994
NIST 223/A327 GAITHERSBURG, MD 20899		DUCTILE GRINDING OF CERAMICS	SAID JAHANMIR 301-975-3671
AEROSPACE CORP. 2350 E. EL SEGUNDO EL SEGUNDO, CA 90509		LUBRICATION TECHNOLOGY FOR CERAMICS	STEVE DIDZIULIS 310-336-0460

PROGRAM SUMMARIES

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR:	CERCOM, Inc
TITLE:	Ceramic Bearing Specimen Technology
OBJECTIVE:	Provide Rolling Contact Fatigue Specimens and Ball Blanks from Sintered Reaction Bonded Silicon Nitride Process
APPROACH:	Develop and Optimize Process Starting with Silicon Powder and Addition of TiO_2 as Sintering Aid
NDE:	Use High Resolution Computed Tomography on Green State Specimens as Quality Control Technique
PROGRAM:	Program Funded as Proposed

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR: Ceramatec, Inc

TITLE: Layered Ceramic Composite Bearings

OBJECTIVE: Develop Bearings with Si_3N_4 Layer on SiC Substrate Having Residual Compressive Stresses in Si_3N_4 Layer

APPROACH: Use Slipcasting and Co-Sintering Approaches to Fabricate Layered Ceramic Composite with Compressive Stresses Produced by Thermal Mismatch

PROGRAM: Program Limited to Two Tasks - Approaches for Introducing Compressive Stresses and Fabrication of Layered Ceramic Composites

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR:	BIRL, Northwestern University
TITLE:	Ceramic Coated Bearings
OBJECTIVE:	Deposition of Hard Ceramic Coatings on M50 and Si_3N_4 Balls and RCF Rods
APPROACH:	Deposit TiN, $TiAlN_2$, and CrN Coatings via Sputter Deposition Process. Thoroughly Characterize Coatings via Acceptable Techniques Prior to Delivery
PROGRAM:	Program Limited to Two Tasks - Deposition of Hard Coatings and Coating Characterization

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR: Wedeven Associates, Inc

TITLE: Run-In Finishing and Tribological Performance

OBJECTIVE: Develop Techniques for Providing Final Polishing of Ceramic Components via Run-In Concepts in Assembled Bearings

APPROACH: Use Si_3N_4 Balls and Discs with Rough Ground Surfaces to Demonstrate Run-In Self-Polishing Concept. Characterize Surfaces and Evaluate for Tribological Performance

PROGRAM: Program Funded as Proposed

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR:	The Torrington Company
TITLE:	Rotating Beam Fatigue - Hybrid Bearings
OBJECTIVE:	Develop Improved Reliability Prediction Techniques and Establish Defects/Fatigue Performance Relationships for Si_3N_4
APPROACH:	Use Rotating Beam Fatigue Tests to Establish Relationship Between Material Microstructure and Fatigue Performance. Verify in Endurance Tests with Hybrid Ceramic Bearings
PROGRAM:	Program Funded as Proposed

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR:	Oklahoma State University
TITLE:	Ceramic Bearing Program
OBJECTIVE:	Develop Improved Manufacturing Technologies for Si_3N_4 Ceramic Bearing Materials. Investigate NDI Methodologies for Optimal Techniques for Assessing Surface Damage
APPROACH:	Use Gentle Grinding Process to Reduce Damage to Ground Surfaces. Extend Gentle Processes to Polishing Concepts via Magnetic Field Assisted Polishing. Correlate Surface Properties with Tribological Performance
NDE:	Investigate Raman Scattering, RF Absorption, Brillouin Scattering, and Direct Coupling Photo-Acoustic NDI Techniques
PROGRAM:	Program Limited to Two Tasks - Gentle Grinding and Polishing Techniques and Most Promising NDI Techniques (above)

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR:	CERBEC, Inc
TITLE:	Ceramic Bearing Development
OBJECTIVE:	Develop Improved Characterization and Inspection Techniques for Si_3N_4 Ceramic Bearings
APPROACH:	Develop General Methodology for Understanding How Defects Affect Tribological Performance and Role that Production Processes Have on Producing Basic Defects
NDE:	Application of Ultrasound and Scanning Acoustic Inspection Techniques to Finished Balls
PROGRAM:	Program Limited to Four Tasks - Bearing Tests with Artificial Flaws; Thermal Quench Proof Tests; Wear and Fatigue Tests; Tribochemical Finishing Techniques

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR: The Torrington Company

TITLE: Improved Hybrid Bearings

OBJECTIVE: Develop Nitrided Metallic Races with Hardness and Surface Properties Approaching Si_3N_4. Use M50 and M50NiL Substrates

APPROACH: Investigate Nitriding and Ferritic Nitrocarburizing Techniques. Consider Combinations of Nitriding and Nitride Coatings from BIRL Program (TiN, $TiAlN_2$, CrN). Evaluate with Si_3N_4 Rolling Elements

PROGRAM: Program Funded as Proposed

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR:	GE Aircraft Engines
TITLE:	Engine Hybrid Ceramic Bearings
OBJECTIVE:	Develop Improved Performance Data and Condition Monitoring Techniques for Si_3N_4 Hybrid Bearings
APPROACH:	Establish Induced Defect Performance Relationships for Si_3N_4 Bearings. Obtain Comparative Test Data for All-Steel and Hybrid Si_3N_4 Bearings. Develop Condition Monitoring Device for Detecting Onset of Bearing Failure
PROGRAM:	Program Limited to Three Tasks - Induced Defect Tests; High Speed Bearing Tests; Condition Monitoring Techniques/Prototype Development

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR:	AVCON, Inc
TITLE:	Computerized Design and Life Prediction - Bearings
OBJECTIVE:	Develop Improved Si_3N_4 Bearing Design Concepts via Modifying Metal Bearing Computer Design Codes with Si_3N_4 Material Properties/Characteristics
APPROACH:	Tailor Existing Computer Algorithms to Include Si_3N_4 Properites and Develop Integrated, Efficient Program for Design of Ceramic Bearings. Seek Input from Bearing Manufacturers for Guidance
PROGRAM:	Program Funded as Proposed

CERAMIC BEARING TECHNOLOGY PROGRAM

CONTRACTOR: Mechanical Technology, Inc

TITLE: Ceramic Bearing Technology

OBJECTIVE: Develop Improved Performance Prediction and Tribological Test Techniques for Si_3N_4 Bearings

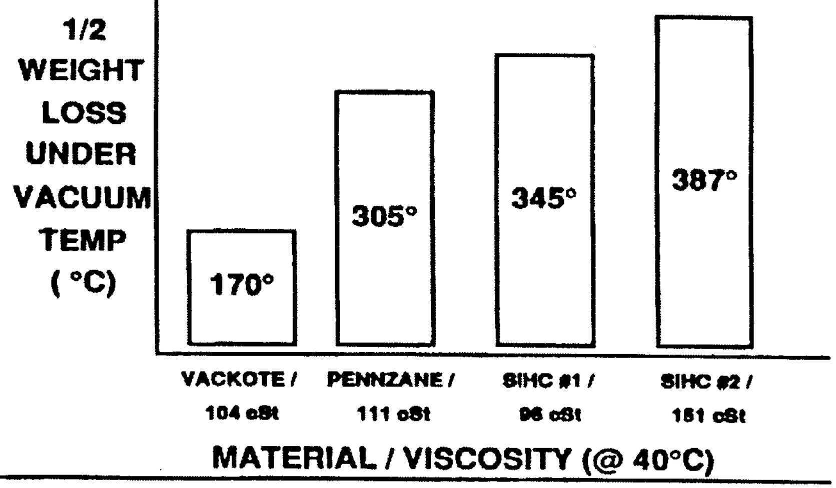
APPROACH: Establish Material Property Performance Relationships for Two Baseline Si_3N_4 Materials and Comparative Data on Four Additional Si_3N_4 Materials from Other DARPA Contractors. Develop Guidance for Optimizing Production Processes

PROGRAM: Program Funded as Proposed

MATERIALS TECHNOLOGY AREA PLAN

NONSTRUCTURAL MATERIALS

- PROBLEMS IN SEVERAL SYSTEMS WITH CURRENT MINERAL OIL - (VACKOTE)
  - OIL TOO VOLATILE
  - LOW TEMPERATURE TORQUE TOO HIGH
  - EXCESSIVE BEARING WEAR



- SOLUTION: REPLACE VACKOTE WITH LOW VOLATILITY, REPRODUCIBLE SYNTHETIC BASE STOCK
  - SILAHYDROCARBON #1
  - SILAHYDROCARBON #2
- CANDIDATE ADDITIVES AVAILABLE FROM OTHER PROGRAMS

MILESTONES:

FY93 - OPTIMIZE BASE FLUIDS

FY94 - OPTIMIZE FORMULATIONS

FY95 - VALIDATE OPTIMIZED CANDIDATES IN SPACE BEARING SIMULATION CHAMBER

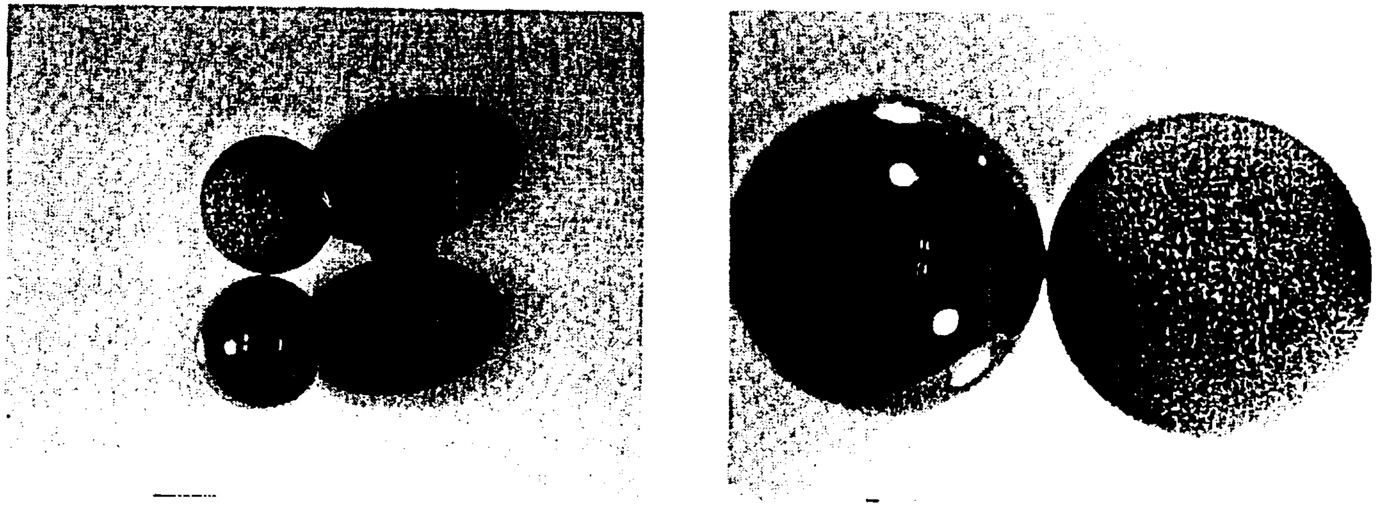
LOW FRICTION DIAMOND FILMS FOR HIGH PAYOFF CERAMIC BEARING APPLICATIONS

Goals:

- Develop Diamond Ceramic *Application*
- Greater Understanding of Diamond Film Wear Behavior

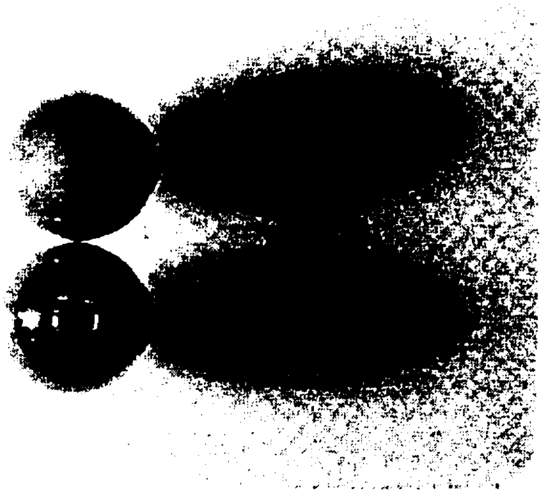
Crystallume

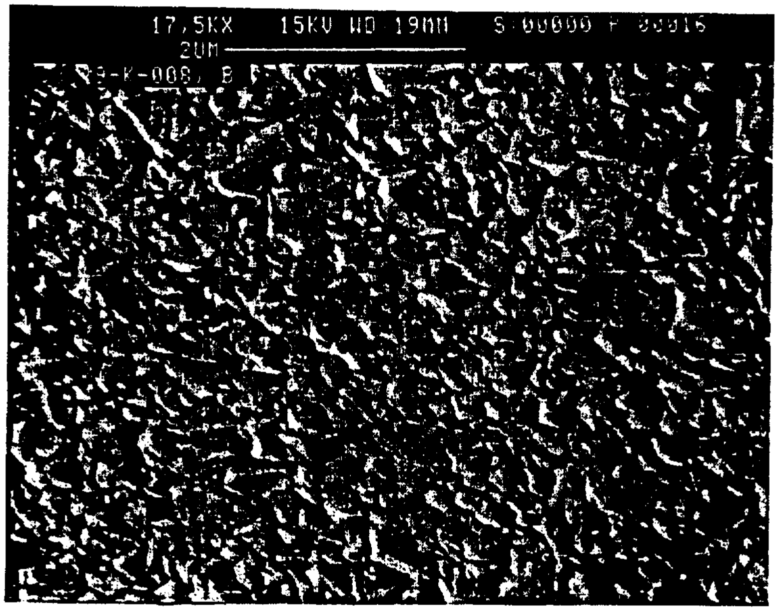
DIAMOND COATED BALL BEARING



Diamond-Coated Ball Bearing

Silicon Nitride Ball
3mm Diameter
Grade 5
Spheric, Inc.

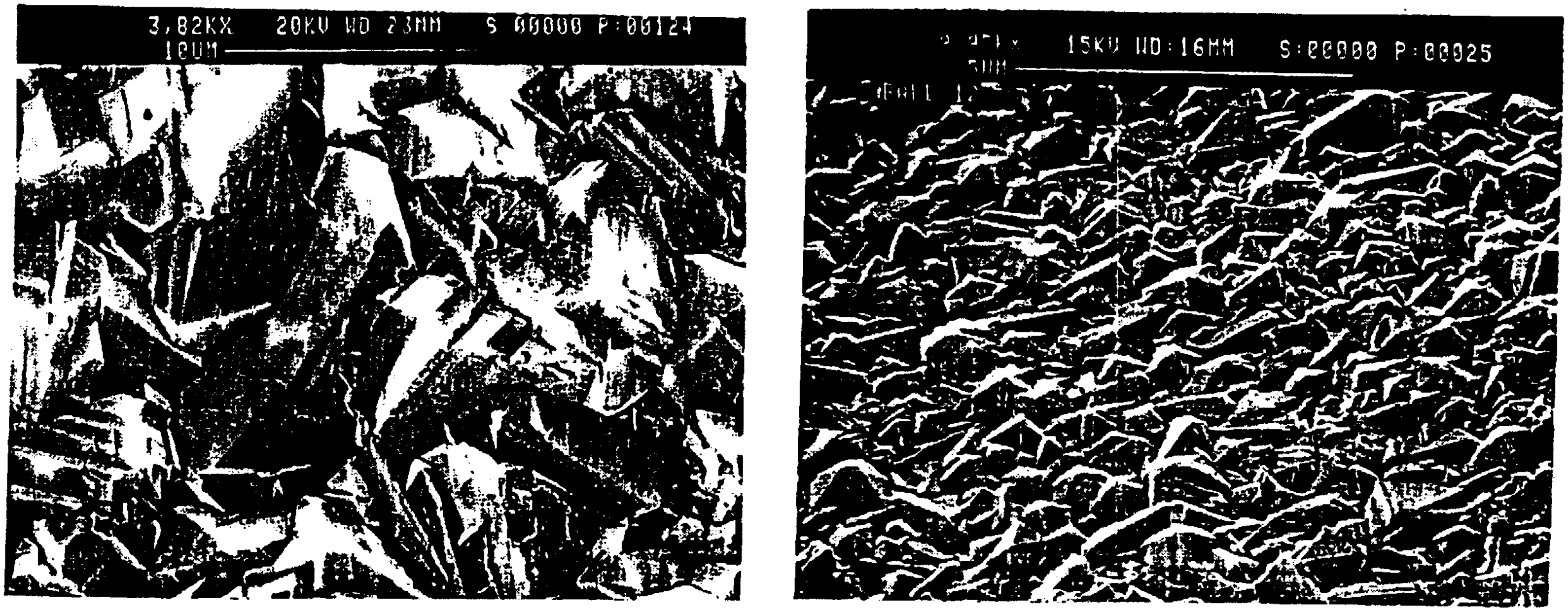




Crystallume

DIAMOND COATED BEARINGS

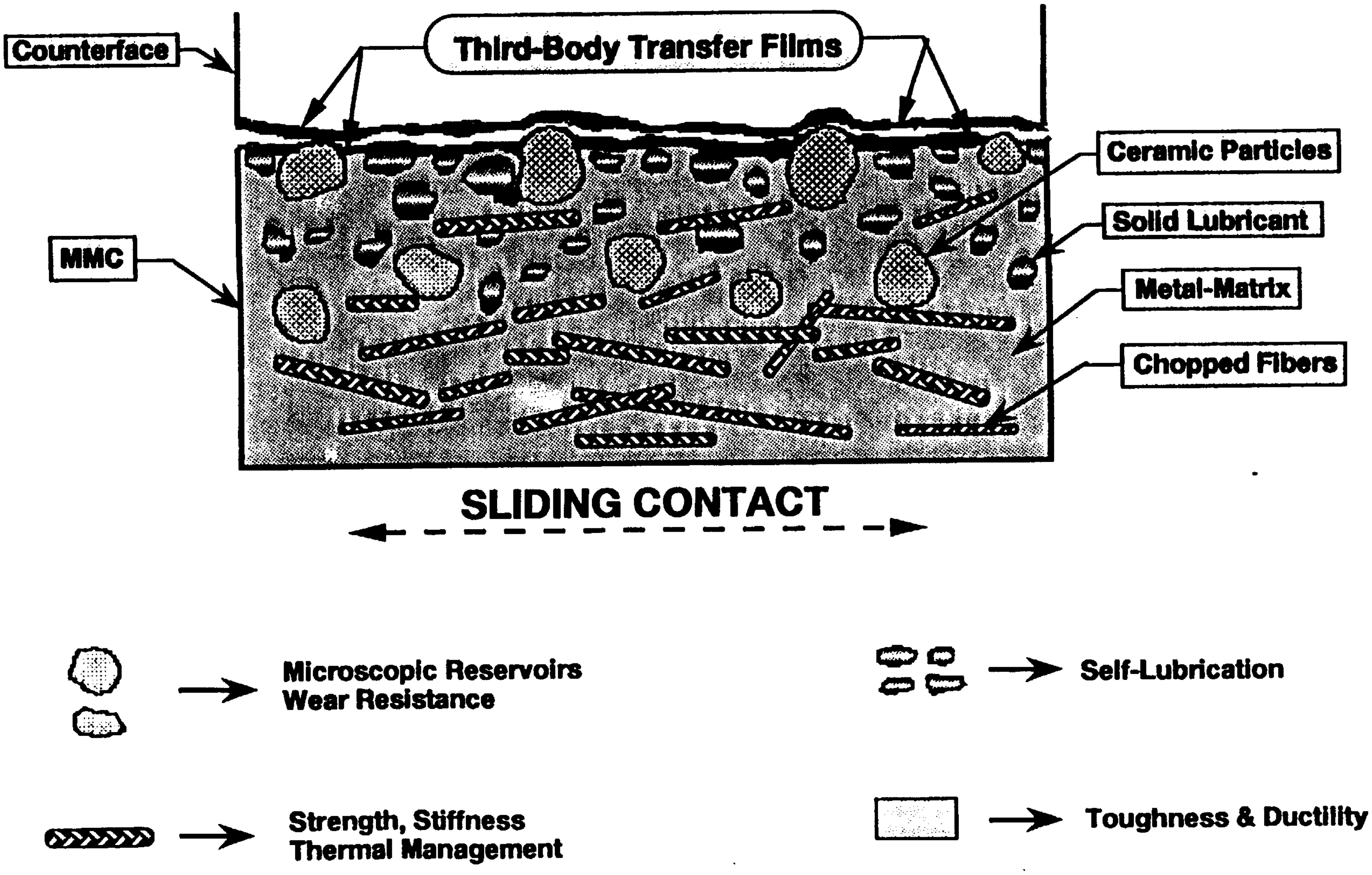
Silicon Nitride Ball
3mm, Grade 5
Spheric, Inc.



Reduced Grain Size →

Crystallume

Self-Lubricating Metal-Matrix Composites: A Schematic Illustration



SPACE EXPLORATION TECHNOLOGIES
Moon and Mars Comparison

Benton Clark
Martin Marietta Astronautics Group
Denver, Colorado

National Goals

Moon --->

"Return"
Astropysics observatories
Earth monitoring
LLOX manufacture
'Stepping stone to Mars'

Mars --->

Leap into Deep Space
Exciting comparative planetology
Settlements, living off the land

Science: Objectives at the Moon

Astrophysics

Radioastronomy

Vis, UV, IR, gamma, x-ray Astronomy

Solar wind

Cosmic ray and solar flare radiation

Geology

Highland and mare formation

Internal structure

Exotic components in the soil (e.g., KREEP, volatile-enriched material)

Impact history

Polar volatiles?

Science: Objectives at Mars

Geology
Volcanism, many styles; active volcanism?
Seismic activity?
Eolian activity
Water: channels, permafrost, water-laid sediments?

Atmosphere
Weather systematics
Photochemistry
Climatology; analogous ice ages?

Life on Mars?
Endolithic organisms
Sulfur-based metabolism
Beneath the superoxidized zone
Oases (warm, wet spots from volcanic, impact processes)
Fossils (microfossils, unique structures and signs)
Survival of terrestrial organisms on Mars

Moons (Phobos, Deimos)
Composition, resource potential
Age and Origin
Effects on Martian surface?

Environments

	Moon	**Mars**
Gravitational accel at surface	0.168 Earth-g	0.383 Earth-g
Atmosphere		
pressure	hard vacuum	6 mb
winds	N/A	up to 100 m/s
shielding	none	16 g/cm^2 minimum (zenith)
composition	--	CO_2, N_2, Ar, O_2, CO
Soil composition	silicates, iron oxides	silicates, salts (S, Cl), H_2O carbonates?, nitrates?
Polar deposits	none detected	CO_2, H_2O ices
Surface temp at equator	-170° to +120° C	-100° to +15° C
Diurnal cycle	665 hrs	24.6 hrs
Solar energy flux, equatorial	1000 W/m^2 (daytime)	100-200 W/m^2 ave.
Dust	ballistic when disturbed	suspends in atmosphere; dust storms (always some dust in atmos)

Radiation Hazard

- Mars and moon both have Cosmic Ray and Solar Flare Particle Events (SPE)
- Mars missions entail longer periods outside geomagnetic shield
  1 to 3 years GCR dose for Mars
  0.03 to 0.5 yr GCR does for moon
- Solar Monitoring:
  Lunar: from Earthbased observatories (ala Apollo)
  Mars: must be provided on-board
- Martian atmosphere provides significant shielding
  (16 g/cm^2 at zenith -- much more at oblique angles)

Descent Technologies

Moon

De-orbit and landing technique

- All-propulsive. Major deorbit burn
- Very wide-range throttling required, especially if use turbopumped propulsion

Navigation

- Landmark updates for orbital state vector
- Earth-link to aid descent landing accuracy
- Terminal navigation by astronauts to achieve pinpoint landing (deployed radio beacons not required)

Mars

De-orbit, entry and landing technique

- Combination of
    - minor burn for deorbit retro-propulsion (15 m/s)
    - aerobraking
        - numerous L/D options
        - zoom, glide maneuver options
    - parachute-assisted deceleration may be possible
    - terminal descent propulsion and maneuvering

Navigation

- Deimos or Mars ComSat reference navigation
- Earth nav not adequate
- Deployed radio beacon(s) on surface may be required for pinpoint landings

Ascent Vehicle Design

Moon

- No requirement for aerodynamic shaping to minimize drag
- Direct-to-Earth option; low lunar circular orbit option
- For resources exploitation, requires major surface payload launch capabilities

Mars

- Aerodynamic drag, dynamic pressure, thermal protection are design considerations
- Rendezvous in high elliptical orbit
  (intermediate staging in LMO, then time-synchronized apoapsis raise)

Surface Power Generation and Storage

Solar Electric - Photovoltaic or Solar Dynamic Conversion

***Lunar*:**	Disturbed dust protection (ballistic shadowing)
	Lunar night outages, cold thermal stresses (-170 ° C)
***Mars*:**	Disturbed dust, man-induced
	Disturbed dust, natural (windstorms)
	Settling from atmosphere (multiple monolayers per season)
	Direct flux attenuation; skylight omnidirectionality (scattered flux)
	24.6 hr temperature cycling (-100° to 0° C)

Solar Thermal - Direct Concentration

***Lunar*:**	High grade heat for chemical processing
***Mars*:**	Not feasible because of atmospheric scattering
	(also faster slews required, outages every 12 hrs)
***Phobos*:**	Similar to Lunar, but much faster slew

Nuclear - RTG, SP-100, Advanced Reactor, Fusion

***Lunar*:**	SP-100: vacuum environment; nighttime temp concern(?)
	Fusion: ^{3}He based system, ultimately?
***Mars*:**	Oxidizing atmosphere
	Dust effects on heat radiators
	Windblown dispersal renders release accident more catastrophic

Note: Lunar Base resource production implies power-rich facility.
Lower power anticipated for Mars, especially if nuclear reactors forbidden on martian surface.

Mission Operations

Communication Time Delays
Lunar: 3 seconds roundtrip
Mars: 8 to 40 minutes roundtrip

Daytime synchronization
Lunar: astronauts adopt Mission Control time standard
Mars: Every 3 weeks, day/night become opposite that of Earth reference time zone

Astronaut corps size (assumes 8 person crews)
Lunar: up to 32 per year (90 day duty tours)
Mars: less than 4 per year

Medical contingencies rescue times
Lunar: 3 days minimum delay to return to Earth
Mars: up to 3 year delay to return to Earth

Orbital Activities

Earth Orbit

Mars mission: 5 to 15 HLLV launches per mission
Assembly/docking required to configure for flight
Propellant loading on-orbit
Expendable vehicles more likely

Lunar mission: 1 to 3 HLLV launches per mission
System launched in all-up configuration
Propellant loading on-orbit for reuse
Refurbishment/inspection of returned vehicles

Mars Orbit

Optimally, interplanetary transfer vehicle remains in high elliptical orbit at Mars (e.g., 250 km x 1 sol)

Lunar Orbit

Use direct return to Earth), *or*
return ship could be staged in low lunar orbit (LLO), but not high elliptical orbit

Interplanetary Mission Modules (IMM)

IMM design

Mars: human factors driven; larger volumes
artificial gravity (spinner) *or* microgravity countermeasures facilities
Moon: minimal volume and capabilities (ala Apollo Cmd Module or LEM)

Science

Mars: extensive interplanetary science program (astrophysics, solar observatory, physiological effects, ICE psychosocial)
Moon: no interplanetary science (much of the above is accomplished on lunar surface)

Roundtrip travel times

Mars:	400 days	(Sprint)
	700 days	(Opposition)
	1000 days	(Conjunction)
Moon:	6-14 days	

ECLSS and Resupply

Mars: Recycling of water and air considered obligatory
Moon: Water loop less closed because hydrated/frozen food resupply?
No indigenous water. Indigenous O_2 mfg power intensive, hazardous

Surface Operations

	Moon	Mars
Operations Major Objectives		
Near-term	Observatories	Exploration
Long-term	Manufacture LLOX	Settlement
Spacesuit		
Mass (upper limit)	180 lbs	80 lbs
Micrometeoroid protection req'd	yes	no
UV resistance needed	yes	near UV only
Oxidizing atmos resistance req'd	no	yes
Dust seals	coarse grains	submicron dust?
Locomotion method	hop/skip	conventional walking
Radiation shielding required		
Habitat, Rover	all directions	overhead only (16 g/cm^2 atmosphere)
Rover		
Trafficability of surface	excellent	drift deposit hazards aa lava hazards?
Power source	PVPA feasible	chemical
Planetary quarantine		
Sterile collection technique?	no	yes
Forward contamination precautions	not necessary	yes
Communications		
Major node(s)	Earth, TDRSS or GeoSat	Mars orbiting vehicle; Mars com satellites and DSN
ECLSS		
Design class	Space Station	Advanced, low power
Thermal		
Insulation	MLI	Closed-cell foam; air barrier
Heat rejection	Radiators	Radiation and/or convective heat exchange

Risk/Safety

	Safety Factors	Risks
Lunar missions		
Transport Vehicle	Capabilities are proven (Apollo success)	New hardware developments HLLV (in lieu of Saturn V) LTV (in lieu of Apollo Cmd Module) LDV, LAV (in lieu of LEM)
Fall-back modes	Early return	Disabled propulsion Requires availability of rescue vehicle
Mars mission		
Transport Vehicle	Multiple compartments	Much new hardware HLLV, SS, MTV, MDV, MAV
Fall-back modes	Abort returns	Not all modes amenable DSM, MOC, ARD execution errors
	Rescue	Disabled propulsion Infeasible, unless large food cache and follow-up mission in progress
	SSF-Proven LSS	Disabled LSS Mass shedding, plus H/O propellant use

Martian vs Lunar Surface as an Experiment Observation Base

- **Cosmic dust collection**
  Lunar: excellent; superior to Earth orbit because of lack of man-made orbital debris
  Mars: unusable because of atmospheric shielding and airborne dust

- **Radioastronomy**
  Lunar: requires backside location to avoid interference from terrestrial emissions
  Mars: relatively low data rate link with Earth, but longer baseline for VLBI

- **Optical and IR astronomy**
  Lunar: excellent, especially during lunar night
  Mars: relatively poor because of atmosphere/dust interferences

- **UV and X-ray astrophysical observations**
  Lunar: excellent
  Mars: poor to non-existent for all but near-UV

- **Solar wind observations**
  Lunar: excellent, including study of surface materials for long-term record
  Mars: not possible from surface

- **Cosmic ray and solar flare radiation studies**
  Lunar: excellent
  Mars: far superior to observations from Earth and LEO, but inferior to Lunar

- **Gamma ray astronomy**
  Lunar: excellent
  Mars: acceptable

* ***Caveat***: the Martian moons – Phobos and Deimos – could provide observational bases with Lunar-like capabilities, but the problems of operations in milli-g environment and at great distance limit their use, except for long baseline comparison studies.

In situ Resources Production (ISRP) on the Moon

- **Oxygen** (Lunar oxygen -- LLOX)
  high temperature or highly chemically reactive processes, from
  silicates or iron minerals (e.g., ilmenite)
- **Metals**
  aluminum, magnesium, titanium, iron
  (high temperature processes, from silicates)
- **Glass**
  fusion of separated silicates

From trace constituents:

- **Sulfur**
  rocket fuel, many other uses
- **Hydrogen**
  rocket fuel, many other needs for base items
- **^{3}He**
  release of solar-wind implanted isotope
  production of solar wind hydrogen as by-product

In situ Resources Production (ISRP) on Mars

- **Water**
  from permafrost ice, surface ice, vapor in atmosphere

- **Oxygen**
  separated from Martian atmosphere (0.13 % constituent), OR
  chemically derived from atmospheric CO_2 (zirconia cell, Bosch, or Sabatier), OR
  electrolysis of $H_2O$from soil or atmosphere

- **Make-up Gas**
  separated nitrogen (2.7 %) and/or argon (1.6 %) from atmosphere

- **Food**
  plant growth using Martian H_2O and CO_2

○ **Propellant Candidates**
  Chemical: CH_4, CO, LOX, N_2H_4, NTO, CO_2
  Nuclear thermal rocket: CO_2 , H_2O

- **Metals**
  Magnesium -- from Epsomite (salt molten electrolysis)
  Iron -- from amorphous Fe-oxides, magnetic minerals
  Titanium -- from titanomagnetite, ilmenite

- **Miscellaneous**
  Sulfur; Duricrete; Glass; Salt; MgO; Carbon black

- **Mars Gold**
  Hydrogen Peroxide (H_2O_2) -- from water

Commonality/Differences

Potential Common Hardware

ECLSS: Mars spaceborne + Lunar landed + Space Station
Ascent vehicles: MAV and LAV, except ΔV disparities
EELS (except as noted below)
PVPA: MSS, LLMM, SS

Potential Hardware Differences

Propellants: long-term cryo storage (Mars) vs cryo upper stage (moon)
Interplanetary transfer vehicle (including artificial gravity)
Landing systems: aeroassisted profiles; differing nav implementations
Rover drive-power
Orbital capture: all-propulsive for moon (or, direct landing); aeroassist for Mars
Descent vehicle
Landed ECLSS
Landed power (PVPA/batteries for Mars; nuclear/RFC for moon)
EELS: retropropulsion for high Earth-encounter C_3 (from Mars)
Communication systems
LEO assembly fixtures and robotic aids

additional items

( ) Radiation

( ) MTV will have consumables which can provide solar storm shelter. LTV will require dedicated shielding or else careful design for equipment locations

( ) May be able to forecast SPE-safe period for LTV launches, or at least for the Lunar landers. But Mars launch must go on time

( ) GCR is potentially a major problem for MMM, but not for lunar because tours are short, and then can spend most of the time underground

( ) Pressurized rovers are different

( ) energy/km because of gravity

( ) rad protection -- moon doesn't have the atmos shielding. Need omni-shielding on the lunar pressurized rover (of course, can accommodate more mass because of lower gravity)

( ) Crew members may go several times to moon; Mars crewmembers probably go to Mars only once.

( ) SPE dose situation much different. $1/R^2$ to $1/R^4$ for Mars (conj missions go out, opp missions go inward. hence, much different possibilities.

( ) SHOULD HAVE a lower gravity test facility in LEO before committing to a Lunar Base, to find the physiological tolerance to 1/6 gee. If think 1/6 gee really isn't a problem, then why would you need to go to the moon to simulate a Mars mission?

( ) Lunar vehicles have through-the-brake designs. Mars vehicles do not.

( ) No reactors on the martian surface. Wind transport hazard!

HUMAN MISSIONS TO THE MOON AND MARS: A COMPARISON

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The Moon and Mars are the solar system bodies most often cited in considerating man-tended outposts or permanently occupied bases. Commonality of purpose, hardware, and mission operations seem to provide a basis for cost-savings and accumulating experience that would be applicable to both. It is the purpose of this paper to examine these perceived similitudes. The areas that will be addressed can be categorized into science objectives, environment, engineering systems, operations, and national goals.

Environment. Surface environments are quite different on the moon and Mars -- the one a vacuum with long periods of constant illumination by the sun, then darkness; the other a cold, low pressure gaseous environment with winds and an Earth-like diurnal cycle. Thermal balance, one radiatively dominated and the other with a major convective component, must be handled quite differently at the two locations. The gravitational force is two and one-half times higher on Mars. Both surfaces are dusty, but martian dust, once disturbed, remains suspended for long periods. The present martian atmosphere provides 16 g/cm^2 shielding overhead against cosmic rays, solar flare particles, and hypervelocity micrometeoroids. The lunar surface is unprotected from all of these. The martian soil and atmosphere contain an abundance of light elements (especially, H, C, N, O, S) and includes both CO_2 and H_2O, the ingredients necessary to grow plants. The moon is impoverished in the light elements, except for O bonded in silicate minerals (which could, in principle, be used to manufacture lunar liquid oxygen, LLOX). Production of metals would probably be quite different on the two bodies because of the apparent availability of salts on Mars, compared with the necessity to use igneous rocks on the moon. A whole host of valuable H-containing commodities can be manufactured on Mars, including hydrogen perioxide, but only with extreme difficulty on the moon.

Engineering systems. Propulsion systems for primary access to the moon and Mars may be significantly different because of delta-V disparities, although tankage stretch options might span the gap. Multiple heavy-lift launch vehicles (HLLVs) will be required just to depot propellant for the Mars mission, but LLOX availability would reduce this load, except for the very marginal payback on export of LLOX to LEO and the demonstrable couterproductive approach of sending the Mars spaceship first to the moon to on-load propellant. Mars missions require long-term cryo-storage (up to 1.5 yr.) in Mars orbit, but Lunar missions require storage for relatively short times (~ weeks), except on the lunar surface. Ascent vehicles might be similar. However, the propellant of choice for Mars is storable bipropellant to avoid problems of storage of cryopropellants in the relatively warm martian atmosphere. For the moon, there is no obvious reason why cryopropellants, with their more mass efficient performance, should not be used for lander and ascent applications. Descent vehicles are expected to be quite unlike because of the anticipated use of aerobraking and possibly also parachutes at Mars. Likewise, orbital insertion will very likely employ aerocapture at Mars, but can only be accomplished by retro-propulsion at the moon. Different communication hardware systems are expected for the two missions as well as the receiver and relay links at Earth. Power supply at the surface can be direct-solar on the moon, but may require nuclear at Mars and for the lunar night. Fission reactors can be vacuum rated (ala SP-100) for the moon, but would be of different design for the martian surface. The use of nuclear power on Mars may actually be forbidden because of the additional complication of widespread redistribution by the winds of any spilled radionuclides. Thermal control designs will be quite different. Life support systems for Mars would have to be much more power conservative than the high-mass, power-intensive infrastructure most likely available on the moon. Habitats on the moon will require much greater wall thicknesses (more likely, burial under lunar soil) to compensate for the lack of atmospheric shielding against solar flare particle events and micrometeoroid bombardment. Astronauts going to the moon will receive very minor doses from galactic cosmic rays because of the short in-transit exposure time and the massive shielding possible on the lunar surface. Spacesuits and EVA operations will be different in the two locations -- the former because of the weight differential, and the latter because of the danger in long sorties (e.g., one week) because of the radiation and meteoroid hazards just mentioned, and the darkness and excessive cold during the lunar night. Indeed, exploration sorties for more than one week may generally be out of the question.

Operations. The round-trip propagation time for communications to the moon is 3 seconds; for Mars, it ranges from 8 to 40 minutes. Mission operation control at the moon can be Earth-based, as in the past; for Mars, the style of mission operations will be entirely different and require greater autonomy for the crew. On the martian surface, the 24.6 hour day/night cycle would dictate most operations and be desynchronized from the day/night at mission control on Earth; on the moon, any cycle can be chosen, but the astronauts will have to cope with the long lunar night. The isolated and confined environment of a Mars-bound crew is different in scope and intensity (especially, length-of-time); rescue for stranded Marsnauts is mostly out of the question. The number of Mars astronauts needed per decade will be about an order of magnitude below that needed for Space Station and Lunar Base. Preparations for a single Mars mission includes many more HLLV launches (for propellant) and assembly/checkout in low Earth orbit. Solar flares can be monitored from the Earth's surface and orbit for lunar missions, but require sophisticated on-board instrumentation and expert systems to provide similar monitoring during much of the Mars mission.

Science objectives. Geologic exploration will be of high priority on both the moon and Mars, with emphasis on the search for ancient pristine materials and new geologic provinces. In addition to much greater variety in styles of volcanism and the more likely possibility of contemporaneous volcanic or seismic activity, the martian surface has experienced eolian forces and apparently some or all of the effects of liquid water (catastrophic floods, channels, sapping, chemical weathering, sediment deposition) and ice (polar caps, permafrost, thermokarst, glaciation). Mars has an atmosphere, invoking investigations related to weather systems and climatology. A warm, wet paleoclimate leads to the possibility of extant life in oases or relics of extinct life forms (fossils). Mars also has two satellites that deserve thorough study.

Both may be good locations for observational investigations, although the moon would be better for many astronomical observations, cosmic dust collection, and Earth observation. Radio astronomy would benefit from backside location on the moon, to avoid interferences from Earth; Mars would create a longer baseline for VLBI.

National goals. International cooperation could be arranged in either case, but is more often invoked for the more ambitious and more politically neutral Mars missions, although the practical difficulties might be more severe. The moon can serve as an Earth-monitoring base. Mars missions specifically require Space Station Freedom involvement, including zero-g physiological countermeasures development and/or artificial gravity research and free-flyer testbed support. Lunar missions could involve SSF, but need not. Use as a transportation node for storage, refurbishment, and refueling of lunar vehicles may entail major comprimises of scientific objectives and increases in operating costs for Station Freedom.

Colonization is reasonable on Mars because of the abundance of light-elemelnt natural resources and the distinct possibility of ore deposits. A settlement on the moon seems difficult because of resource limitations and unecessary in view of its close proximity to Earth and the possibility of short-notice access for man-tended base management.

Going to Mars would be the first leap by man into deep space -- beyond the gravitational influence of the Earth. No other act is so likely to galvanize world enthusiasm and inspire the youth of our country.

(FUTURE) POWER REQUIREMENTS FOR SPACE (AND EXTRATERRESTRIAL SURFACES)

John Bozek
NASA Glenn Research Center
Cleveland, Ohio

CONTENTS

- SPACE POWER
- EXTRATERRESTRIAL POWER
  - STATIONARY
  - MOBILE
- TECHNOLOGY
  - PASSIVE
  - DYNAMIC
  - FUTURE
- CONCLUDING REMARKS

SPACE

- **LEO**
  - **SSF - ~ 100 kW (CONVENTIONAL TECHNOLOGY)**
    - JOINTS
- **GEO**
  - **COMMUNICATION - 10's OF kW**
    - DIRECTIONAL ANTENNA/PV ARRAY
- **INTERPLANETARY**
  - **PROPULSION - 10's TO 100's OF kW**
    - NUCLEAR/DYNAMIC (NEP)

SPACE POWER

EXTRATERRESTRIAL

LUNAR

FIRST LUNAR OUTPOST (FLO) (1992)

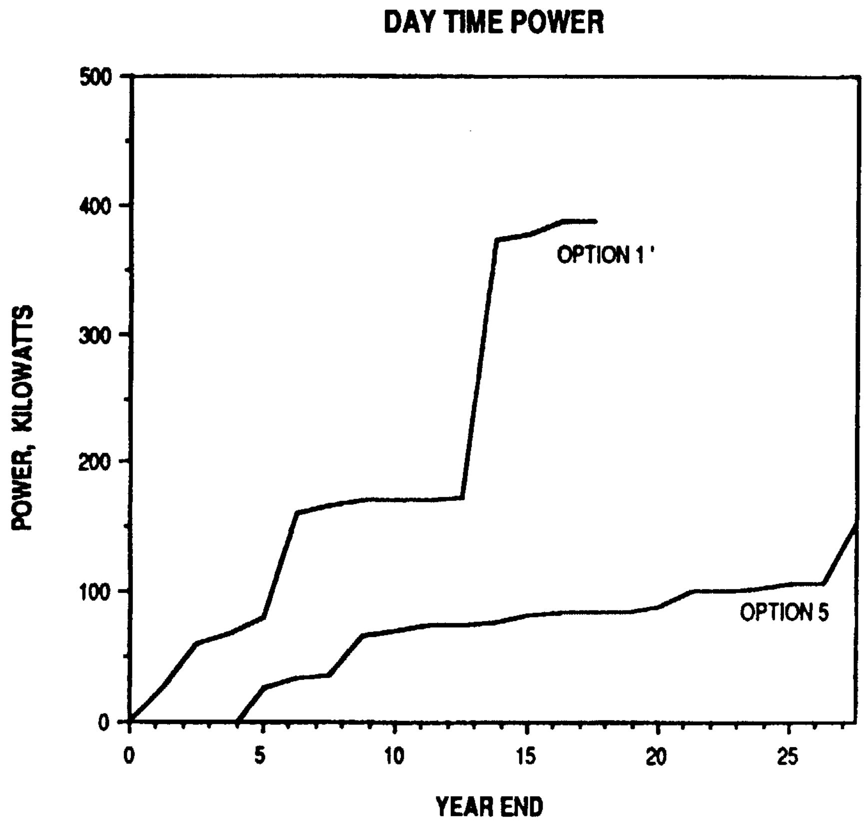
90 DAY STUDY (1990)

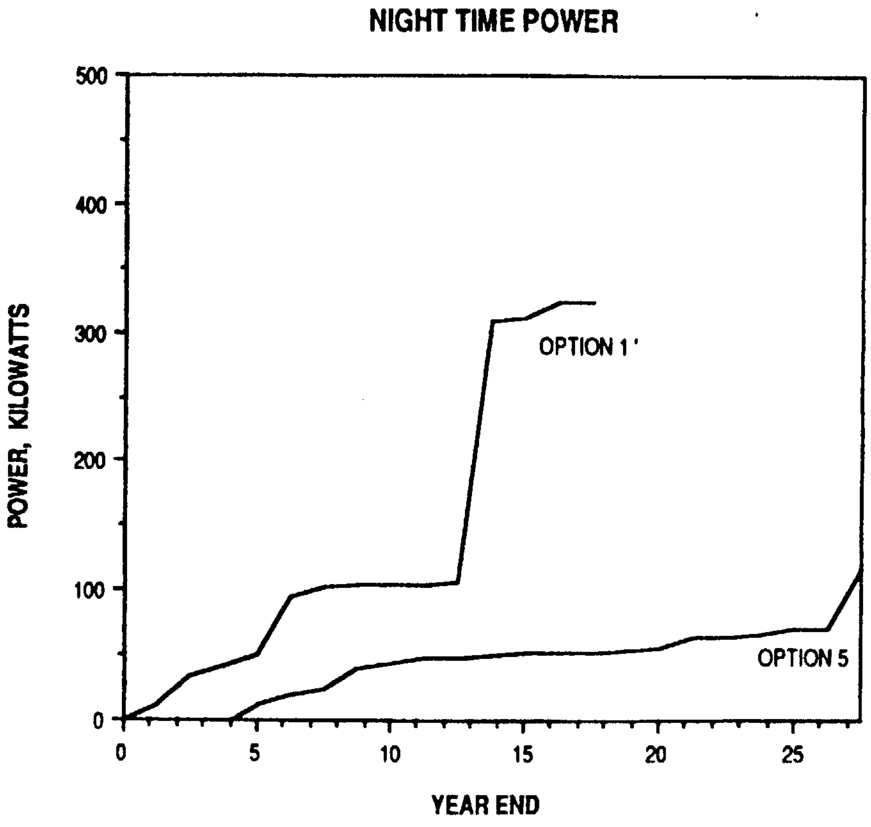
MARS

90 DAY STUDY (1990)

STATIONARY POWER

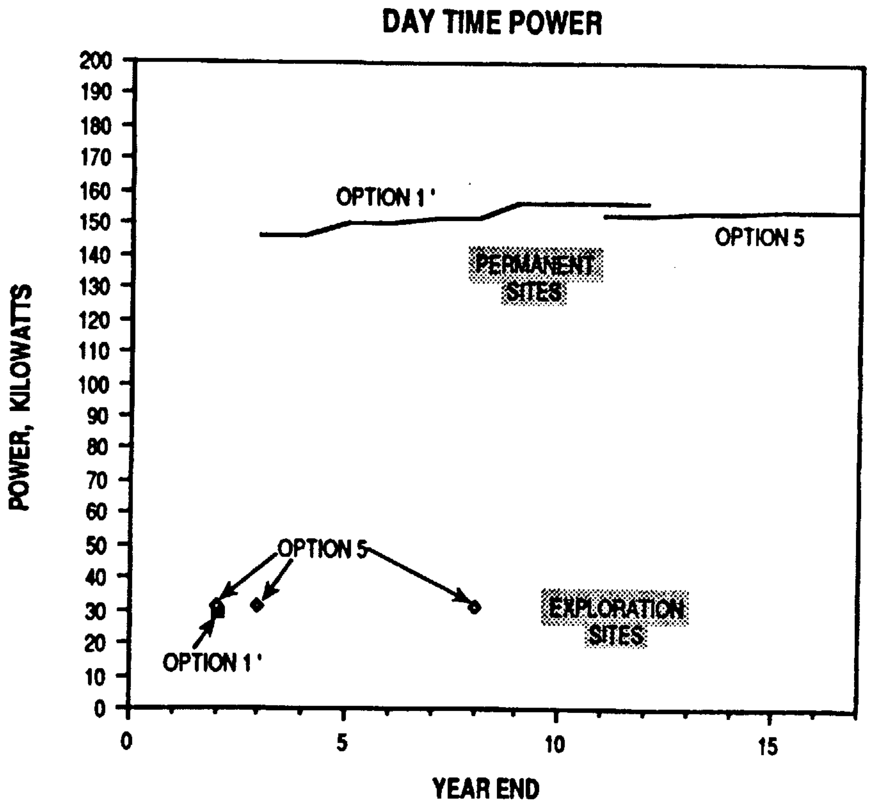
LUNAR STATIONARY POWER REQUIREMENTS

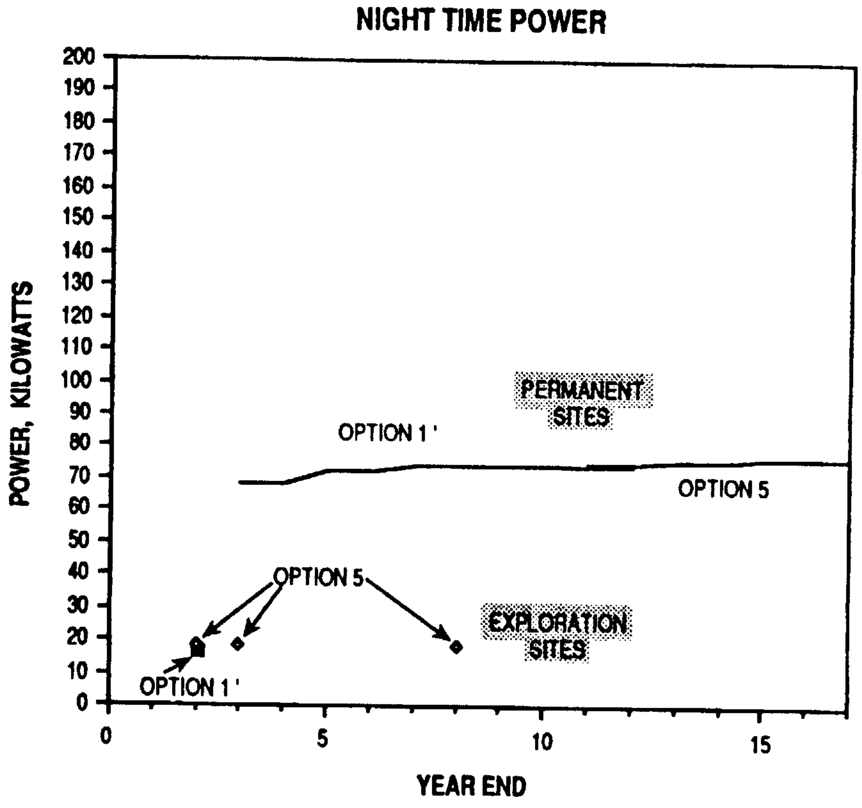




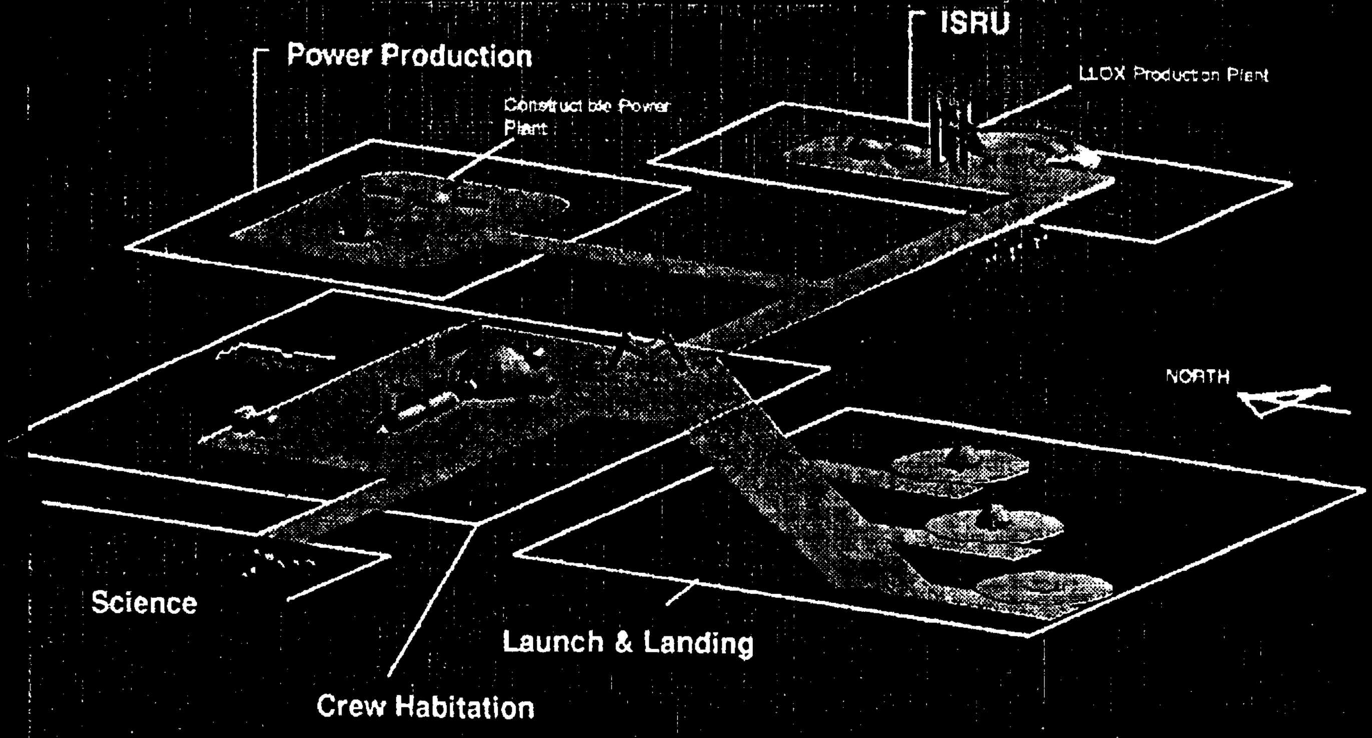
NOTE: 'O' IS 1999

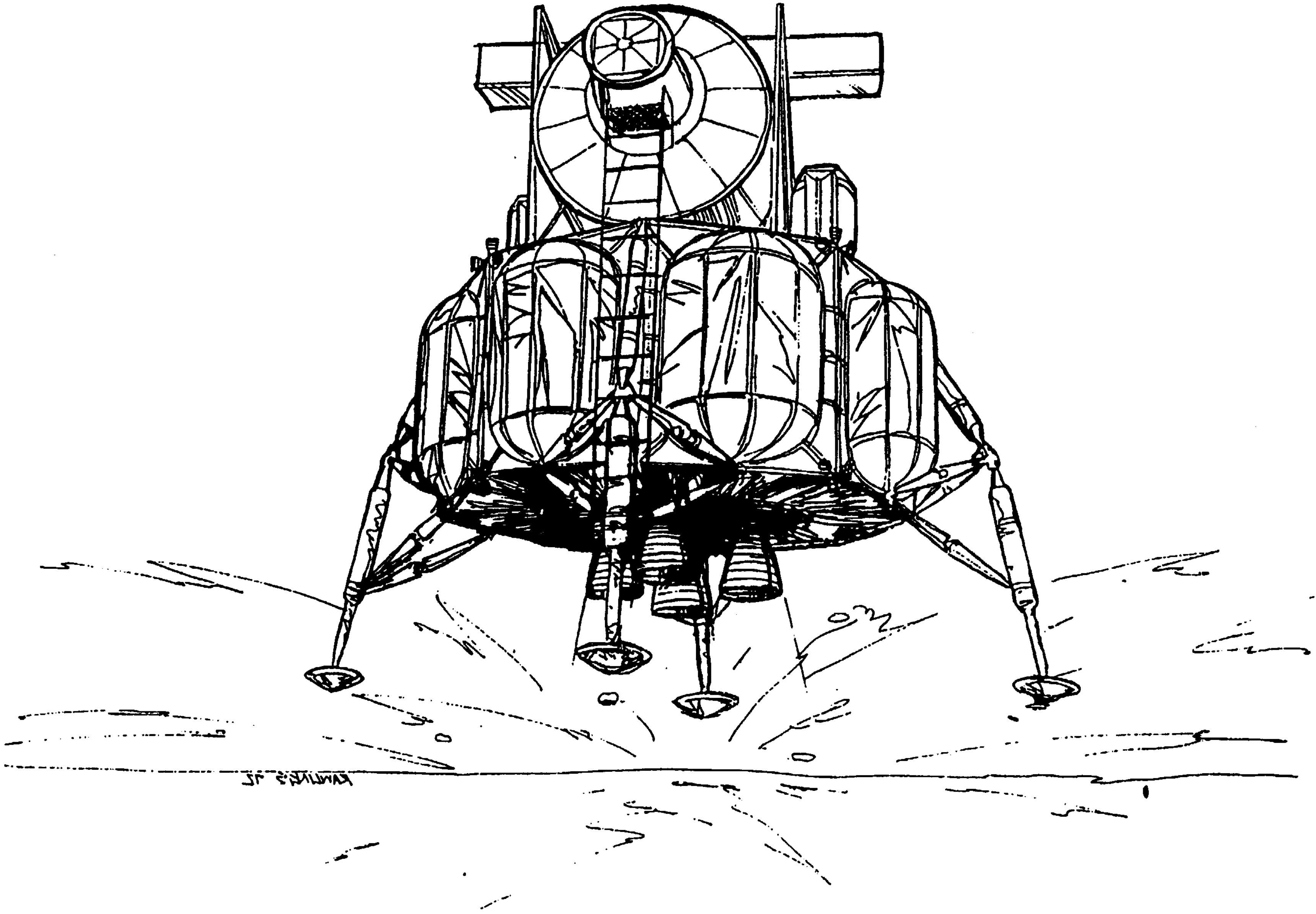
MARTIAN STATIONARY POWER REQUIREMENTS

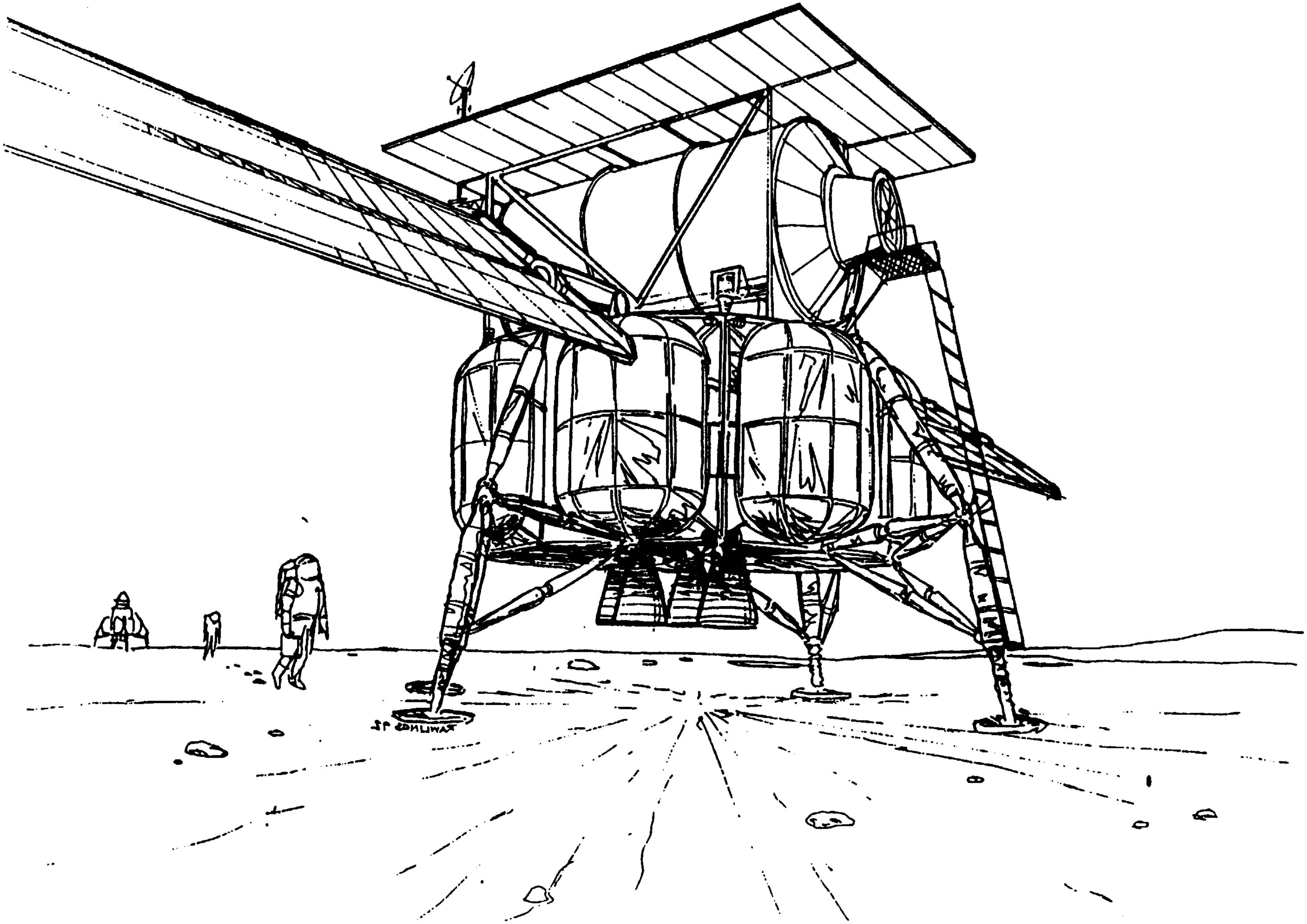




Operations Phase Layout

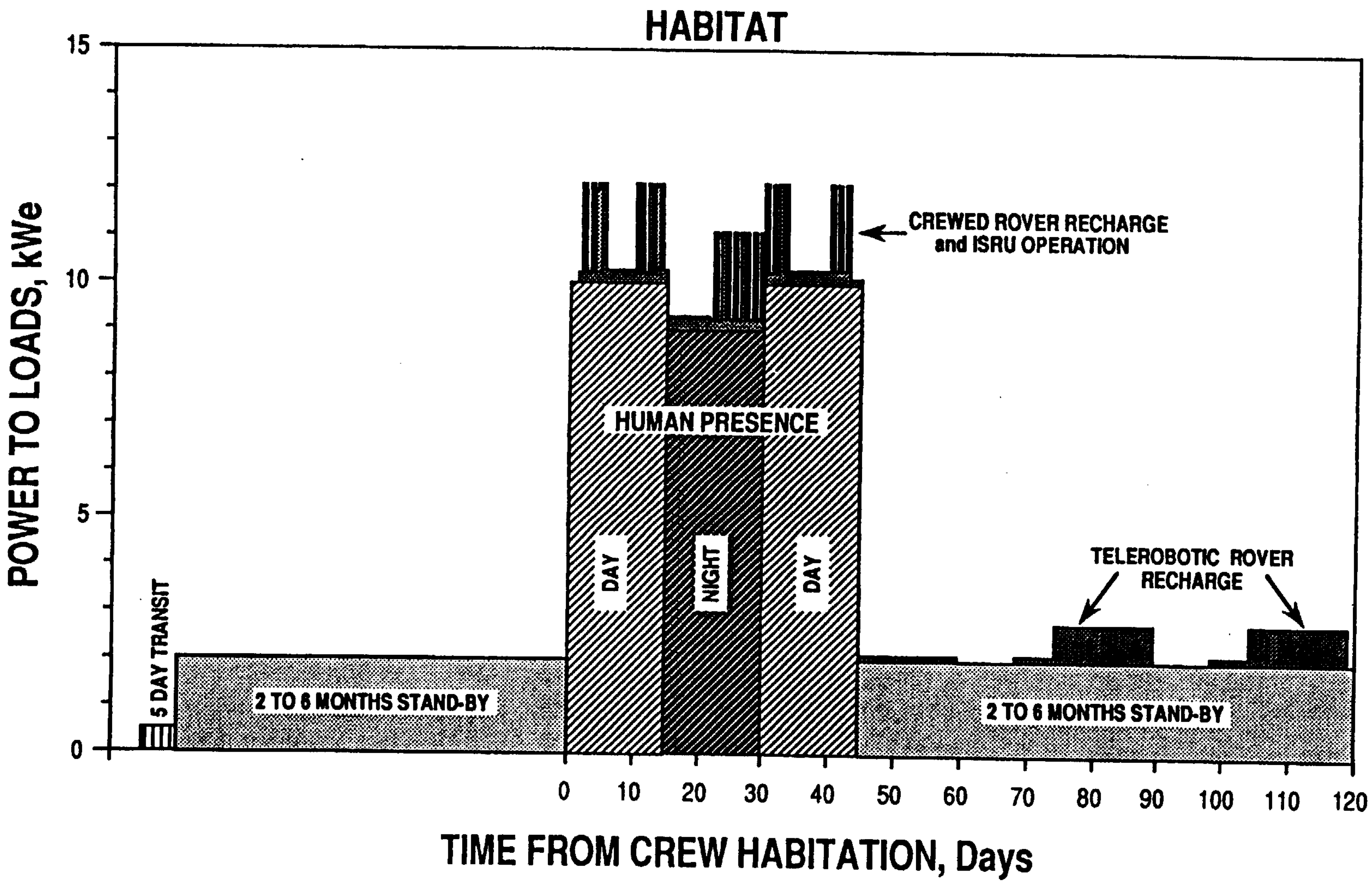






RAWLINGS '92

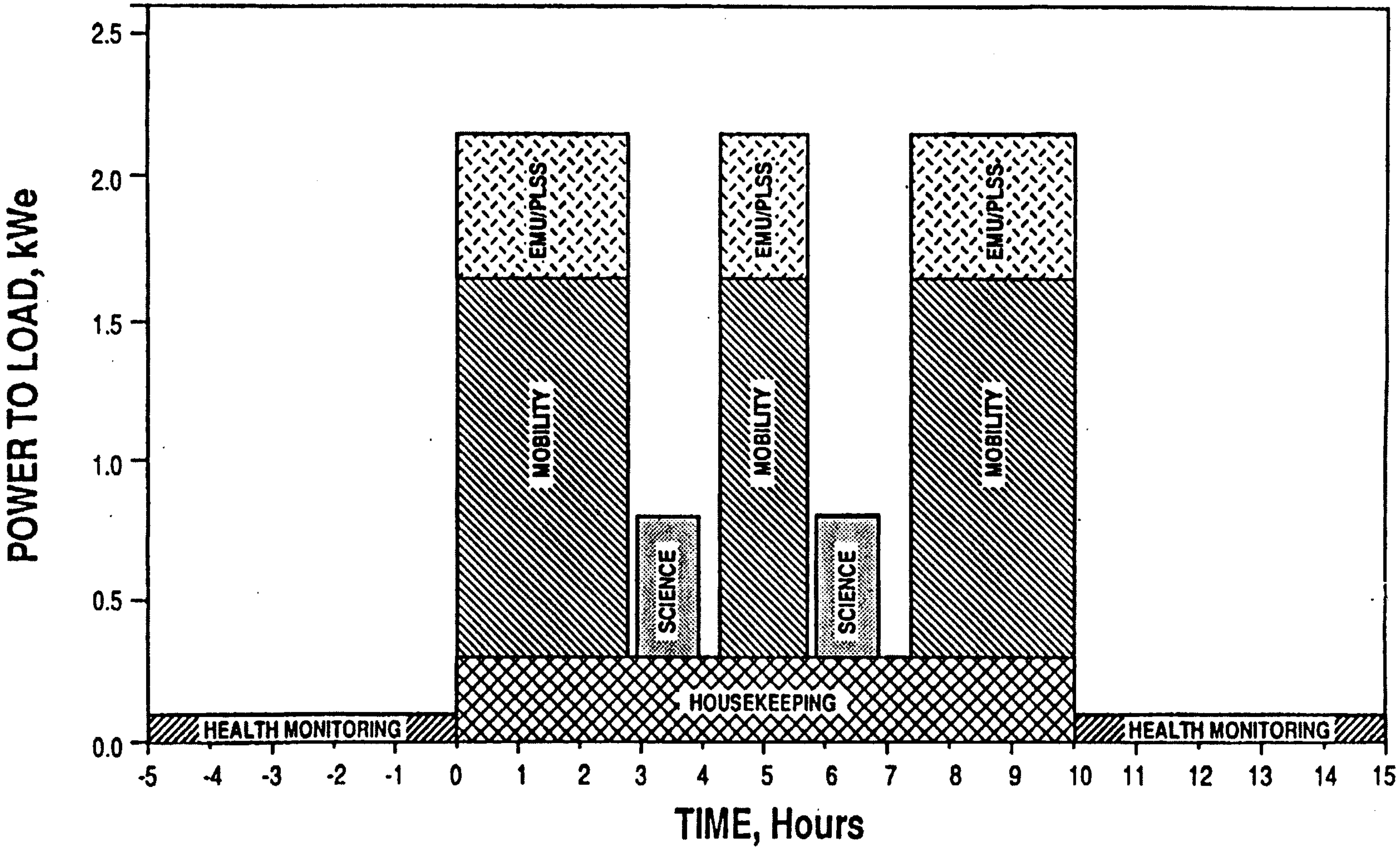
POWER REQUIREMENTS



MOBILE POWER

POWER REQUIREMENTS

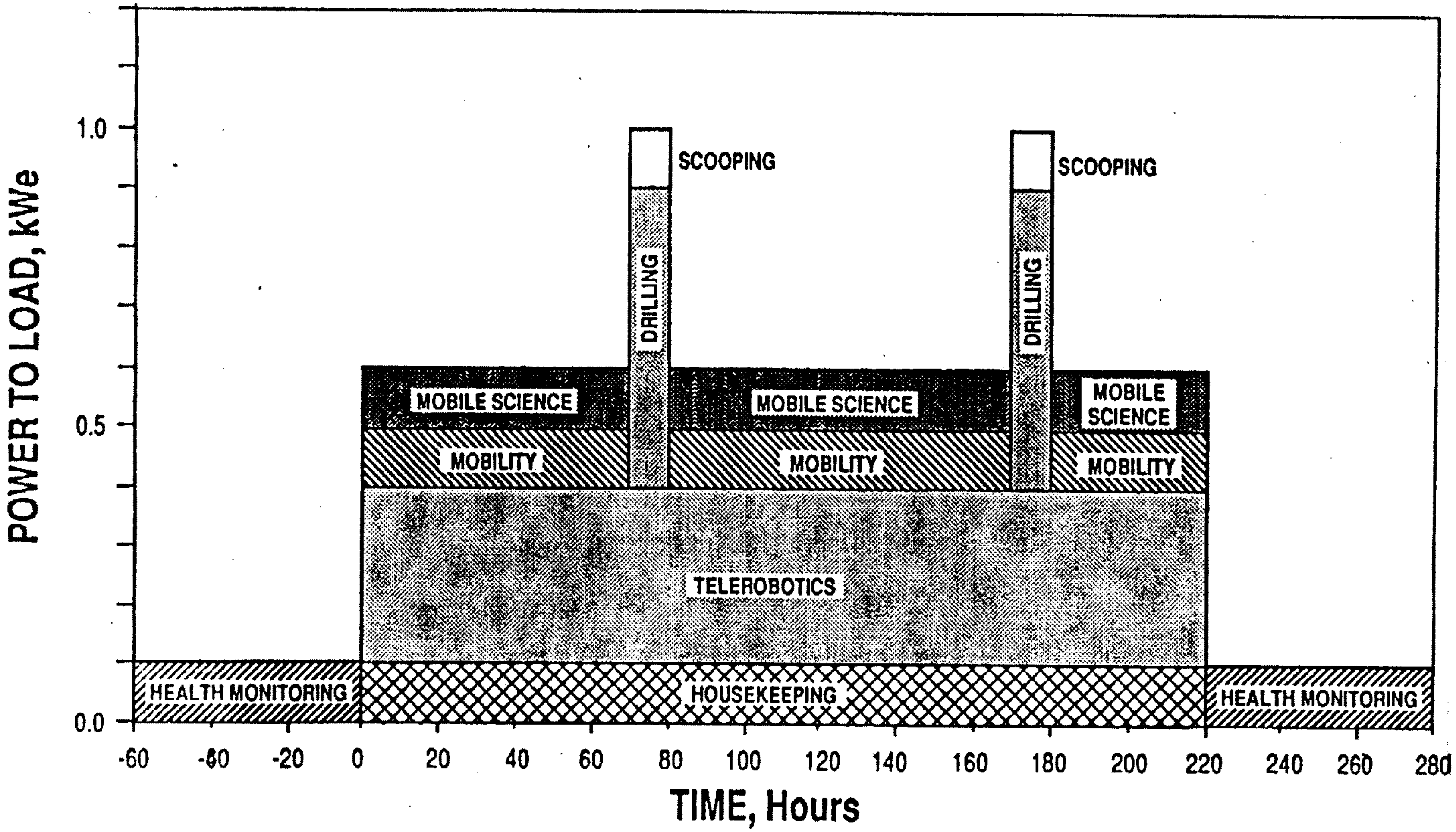
CREWED ROVER



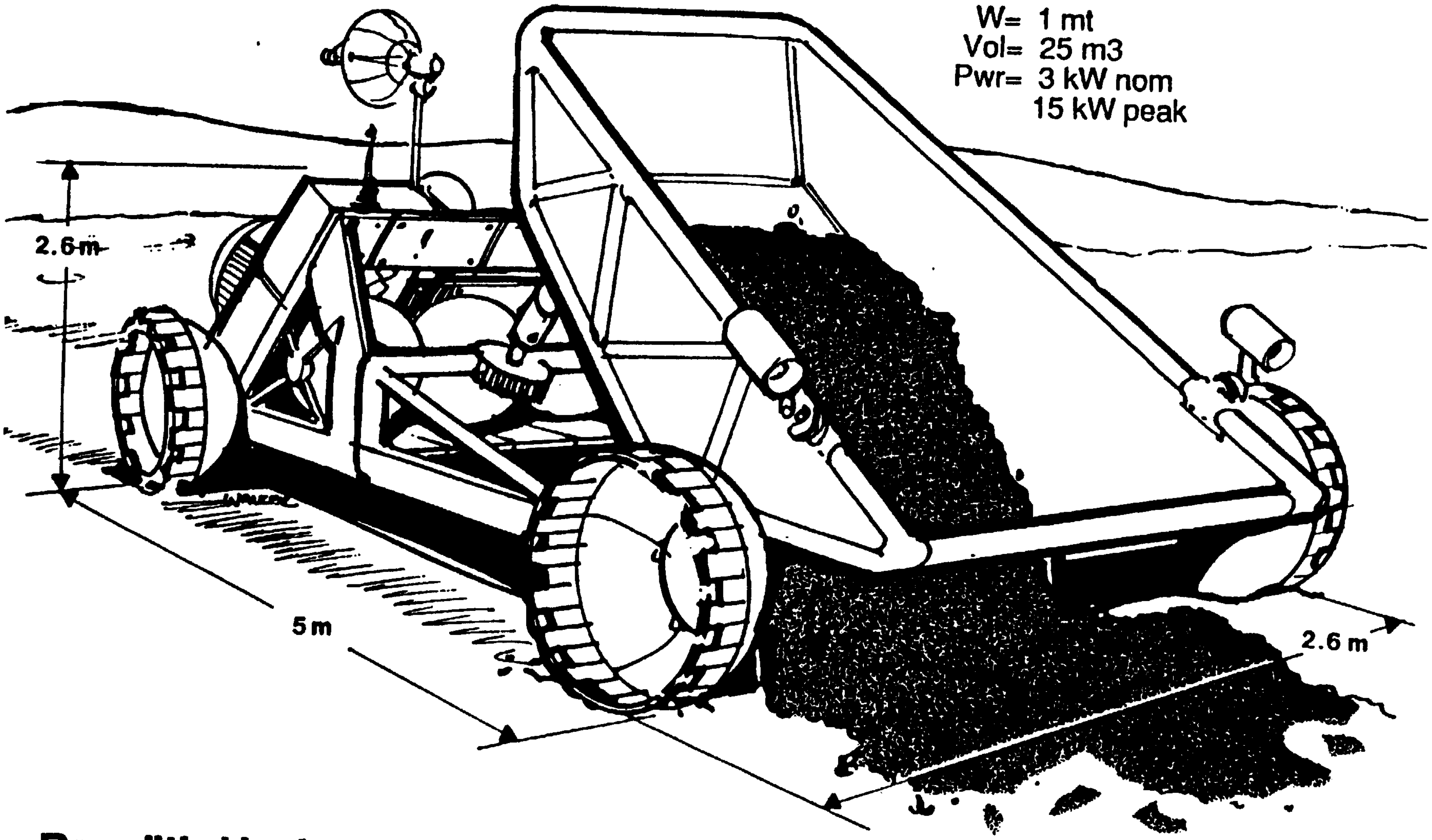
ADVANCED SPACE ANALYSIS OFFICE

POWER REQUIREMENTS

TELEROBOTIC ROVER



ADVANCED SPACE ANALYSIS OFFICE



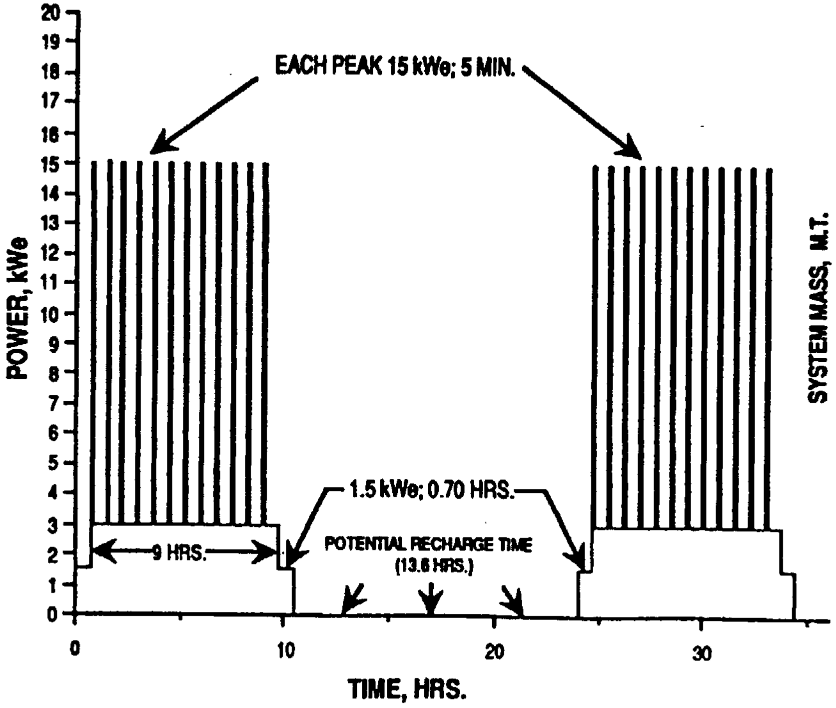
Regolith Hauler

POWER TECHNOLOGY DIVISION

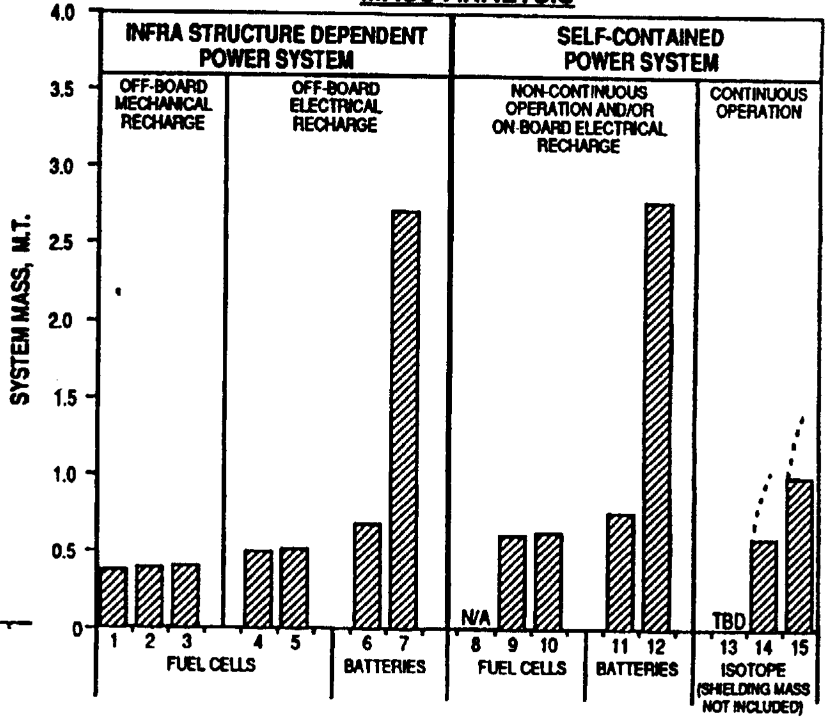
REGOLITH HAULER
(TRUCK)
NO LUNAR NIGHT OPERATIONS

VEHICLE MASS - 1000 kg
HAULING CAPACITY - 750 kg
AVERAGE VELOCITY - 2 m/s
SLOPE CAPABILITY - 6 deg.

POWER PROFILE



MASS ANALYSIS



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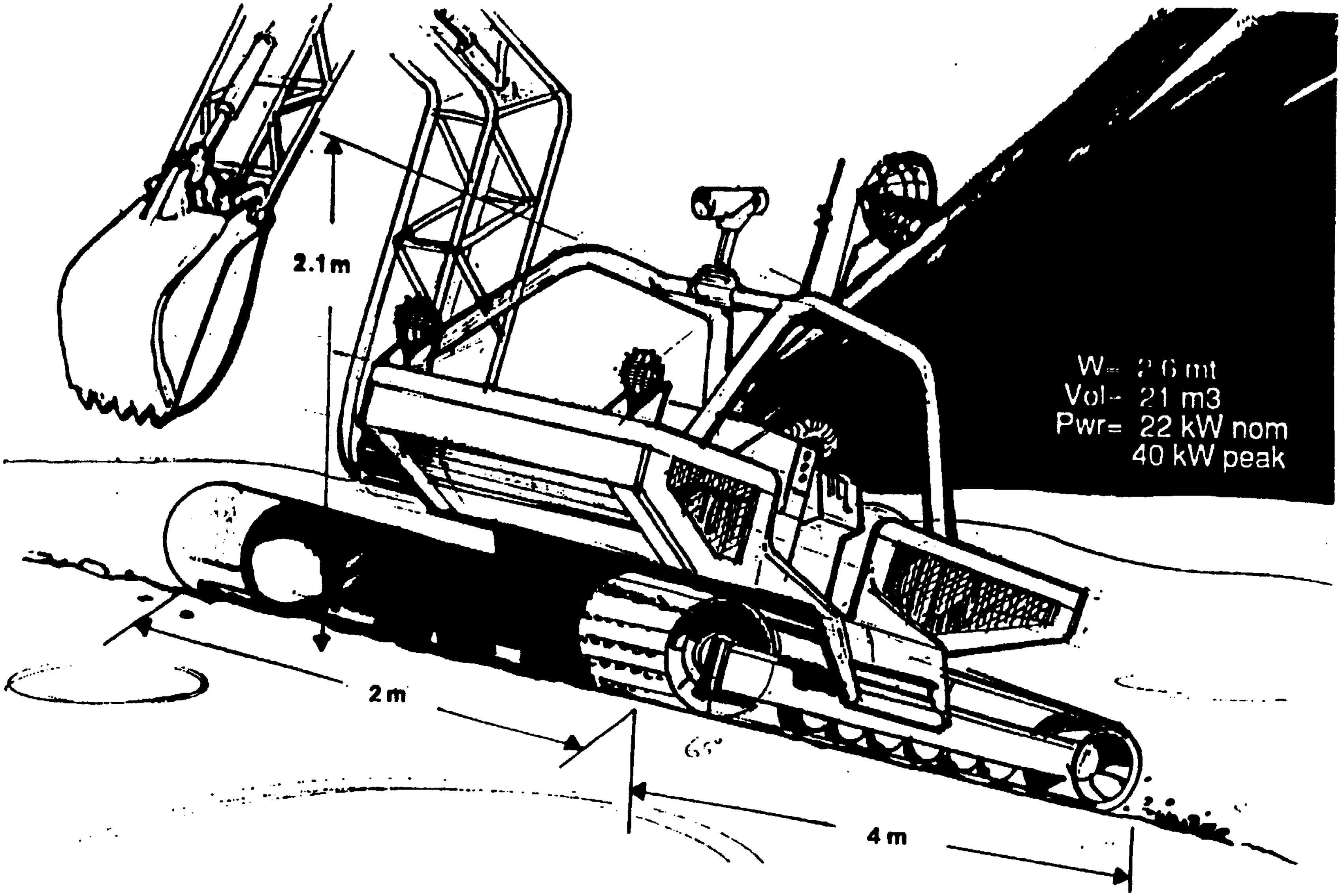


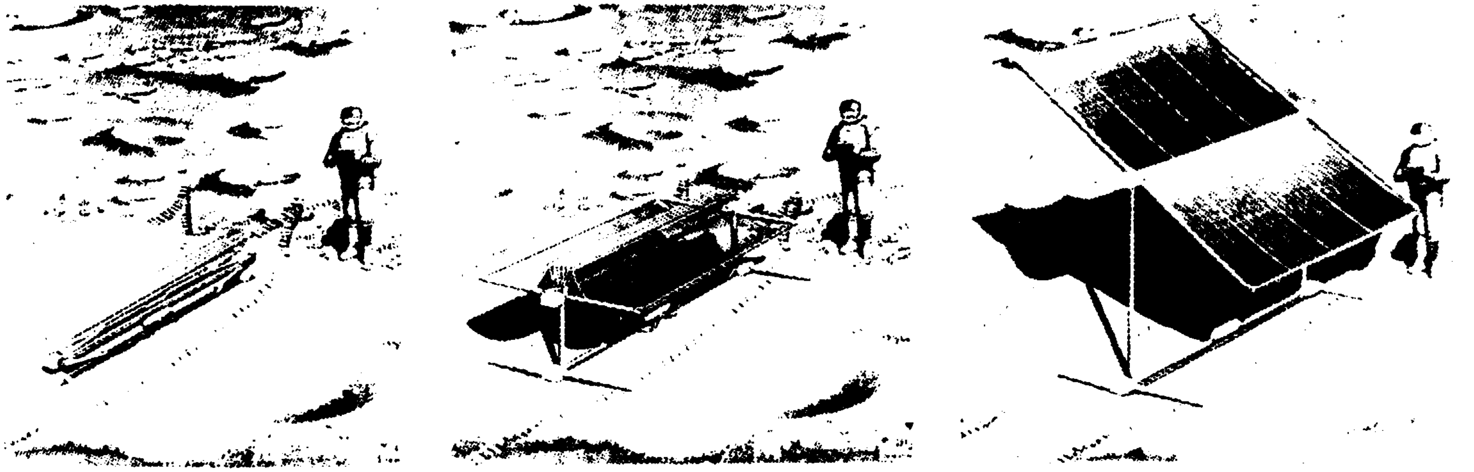
Mining Excavator/Loader

90 Day Lunar/Mars Study

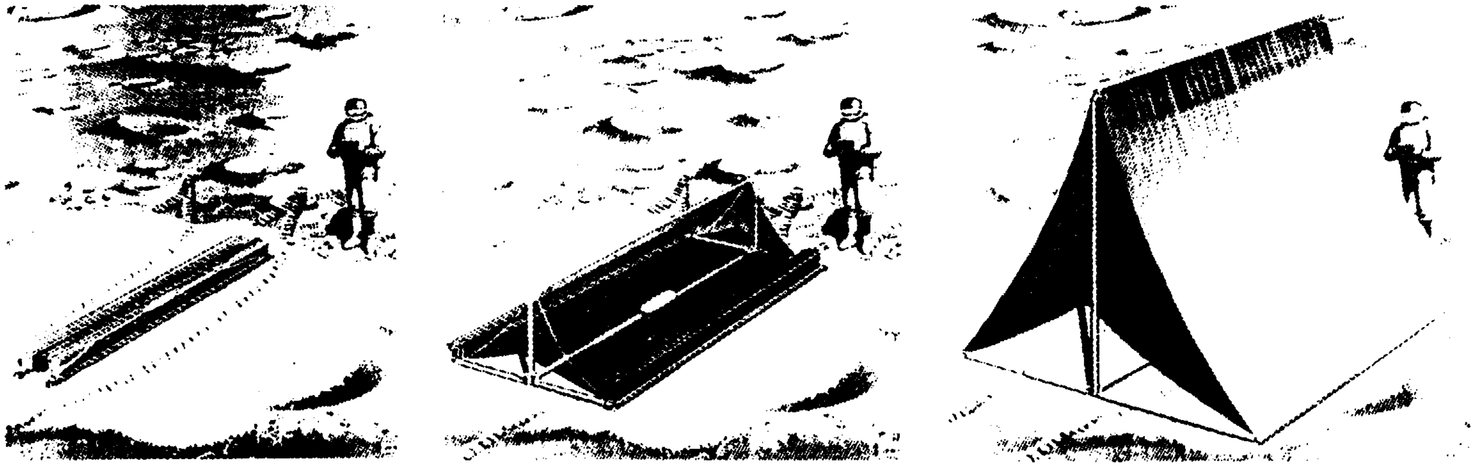
PASSIVE TECHNOLOGY

NASA
C-90-08222

SELF-DEPLOYING PHOTOVOLTAIC ARRAY



SINGLE-AXIS TRACKING

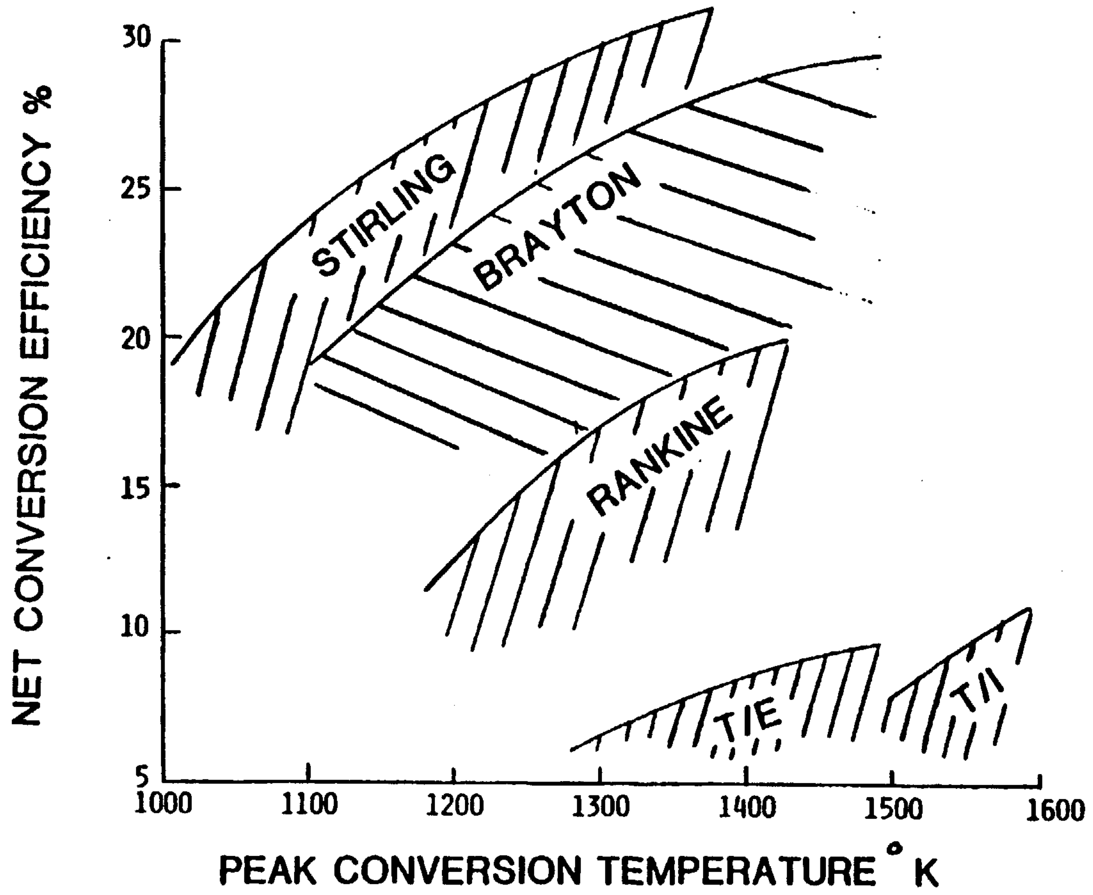


FIXED TENT


USA

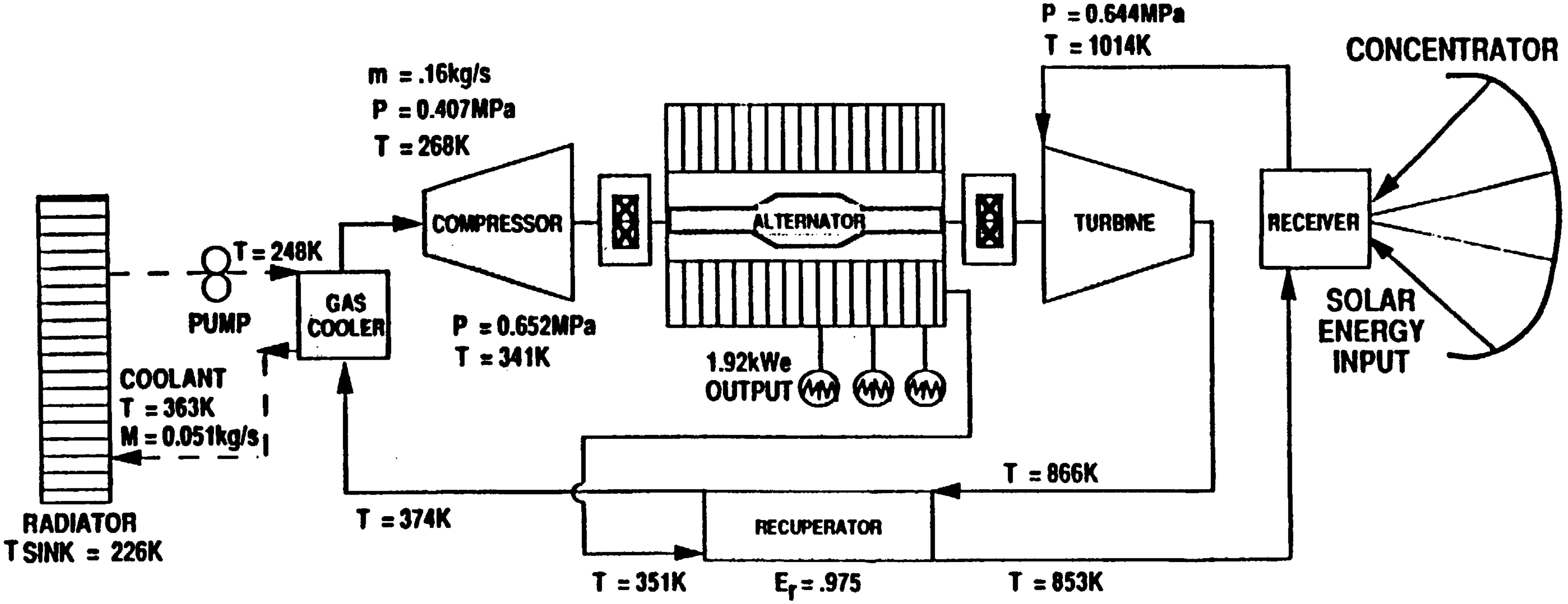
DYNAMIC TECHNOLOGY

COMPARISON OF SPACE POWER CONVERSION SYSTEMS



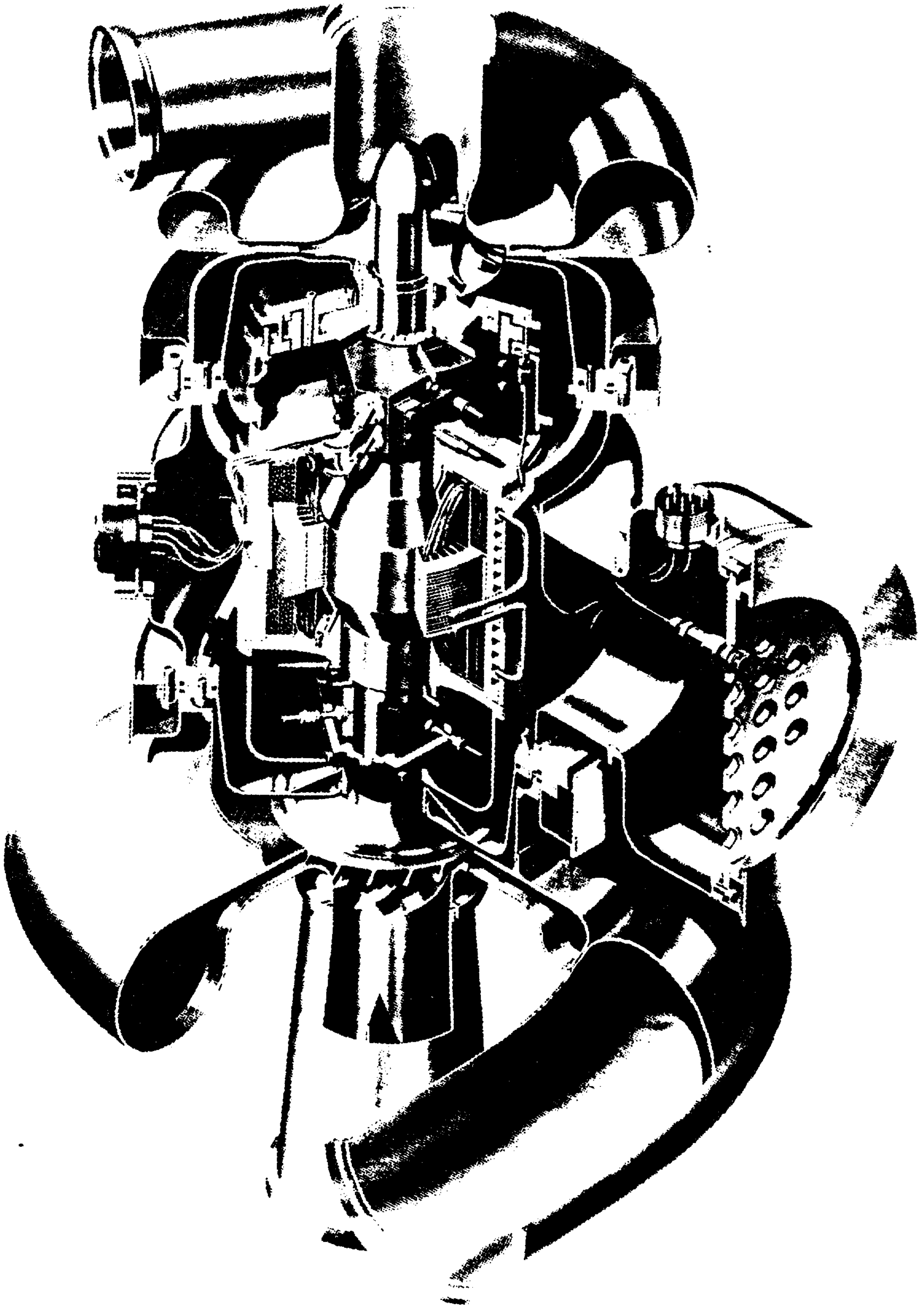
POWER TECHNOLOGY DIVISION

CYCLE STATE-POINTS



NET CYCLE EFFICIENCY = 23 - 25%

(SUN TO ALTERNATOR OUTPUT, DEPENDING ON ORBIT)

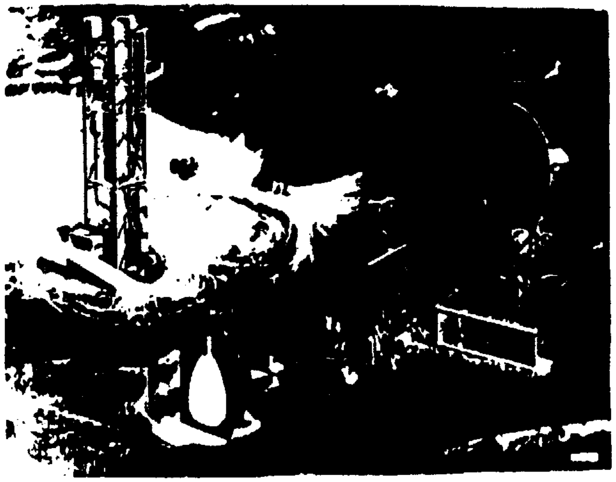


SPACE ENERGY CONVERSION R&T

THERMAL ENERGY CONVERSION

MISSION & BENEFITS
- SURFACE POWER -

LUNAR BASE SD POWER SYSTEM &
OXYGEN PROCESS PLANT

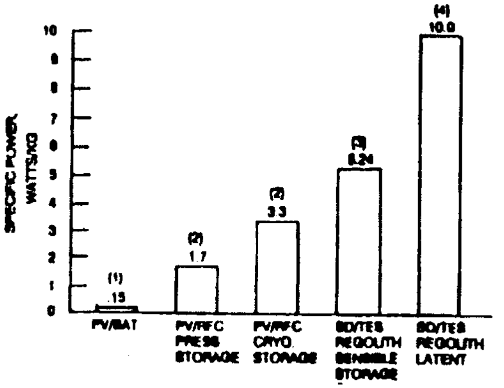


QUALITATIVE BENEFITS

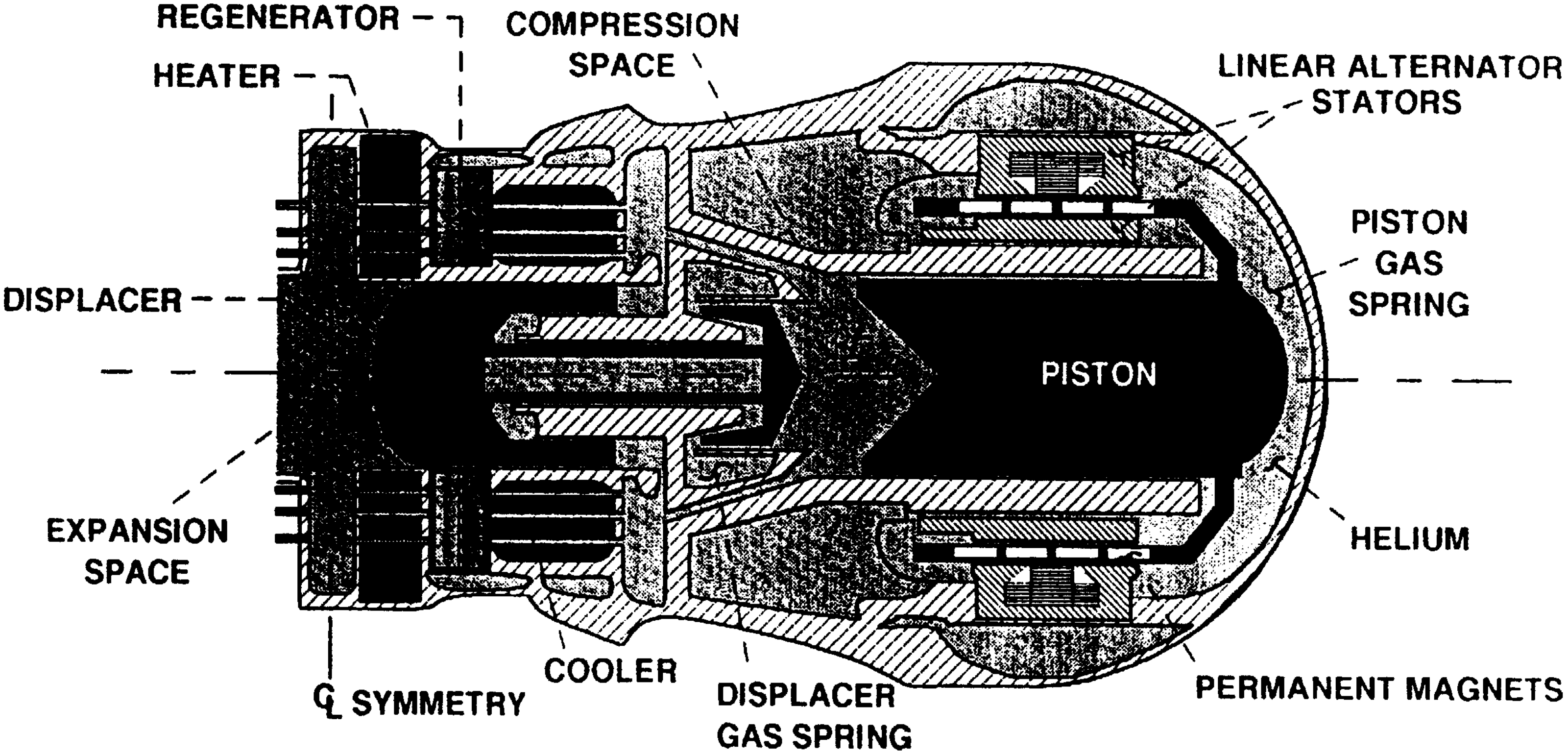
- PROVIDES PROCESS HEAT PLUS ELECTRICAL POWER
- USES IN-SITU MATERIALS FOR TES
- LONG LIFE COMPONENTS

QUANTITATIVE BENEFITS

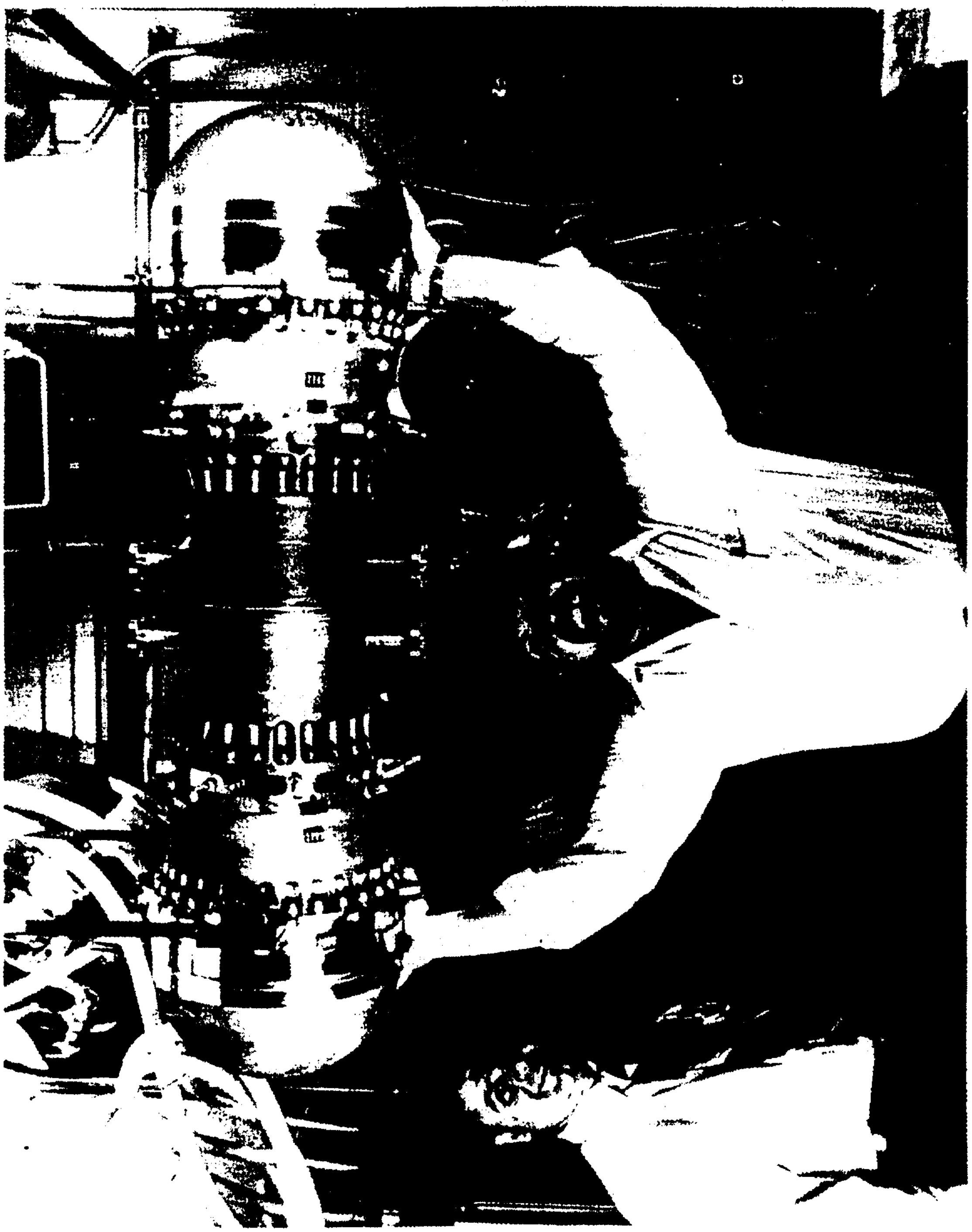
COMPARISON OF ALTERNATE SOLAR
POWER SYSTEMS FOR LUNAR BASE



WHY FREE-PISTON STIRLING ?



- HIGH EFFICIENCY (RELATIVE TO OTHER SYSTEMS)
- POTENTIAL FOR LONG LIFE AND HIGH RELIABILITY



BRAYTON

ADVANTAGES

- HIGHEST DEMONSTRATED SYSTEM PERFORMANCE (29%)
- EASILY SCALABLE TO VERY HIGH POWERS/UNIT
- LOW MASS, COMPACT CONVERSION SYSTEM
- MODULAR
- SINGLE PHASE, INERT WORKING FLUID (He/Xe)
- LOW RISK, HIGH RELIABILITY BASED ON EXTENSIVE SYSTEM AND COMPONENT TECHNOLOGY (1960's) PLUS A MATURE AIRCRAFT GAS TURBINE INDUSTRY
- UNAFFECTED BY ZERO GRAVITY

DISADVANTAGES

- LONG-LIFE SPACE OPERATION NOT PROVEN
- DURABILITY OF HIGH SPEED REFRACTORY WHEELS NOT PROVEN
- HEAT EXCHANGER LOW CYCLE FATIGUE LIFE NOT PROVEN
- CLOSE TOLERANCES REQUIRED FOR HIGH EFFICIENCY
- LARGE RADIATOR TEMPERATURE DIFFERENCE REQUIRES ZONED HEAT PIPE RADIATORS WITH DIFFERENT FLUIDS AND MATERIALS
- LOW TEMPERATURE HEAT REJECTION REQUIRES LARGE RADIATOR

FREE-PISTON STIRLING

ADVANTAGES

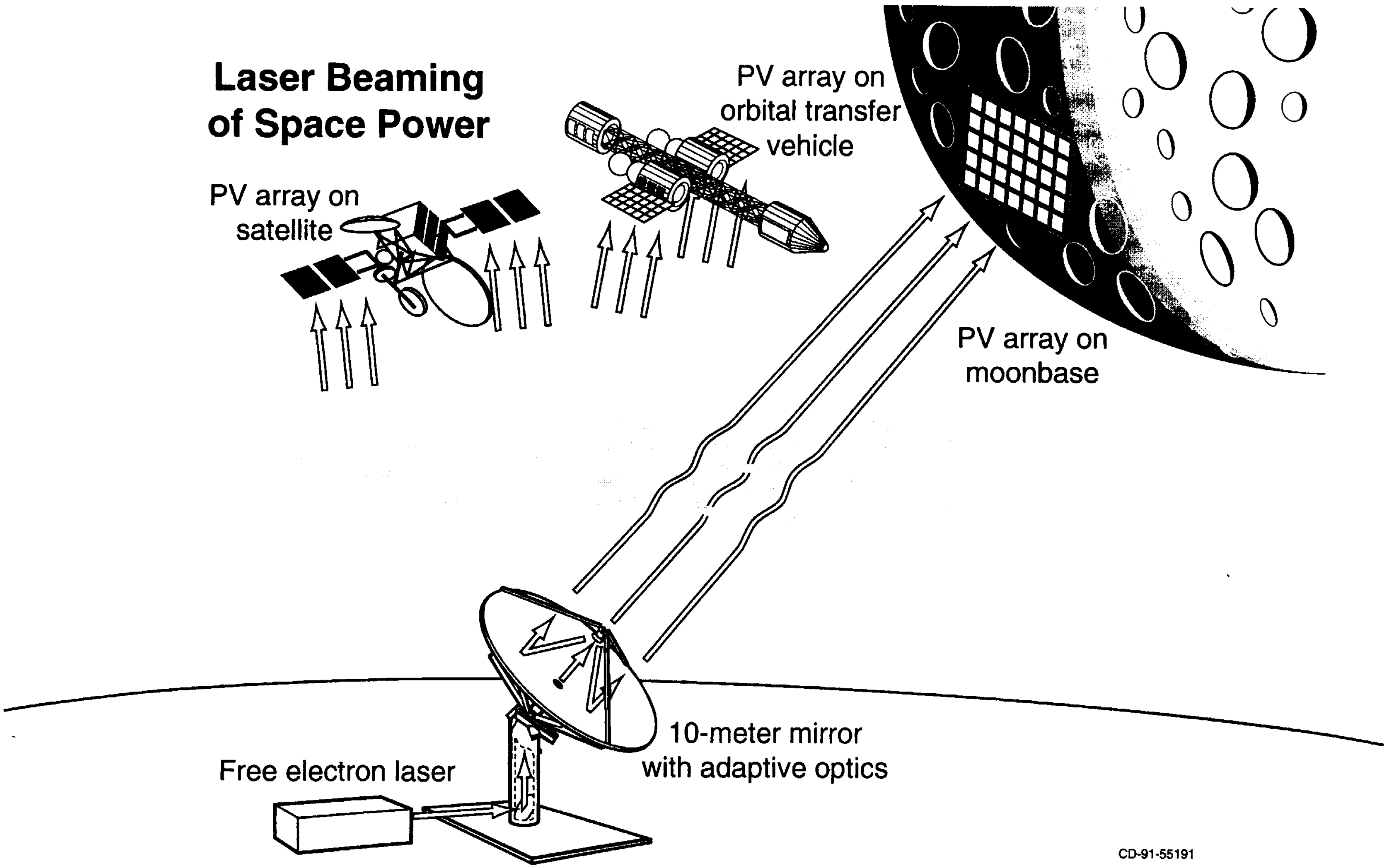
- HIGHEST EFFICIENCY POTENTIAL (35%) @ TEMPERATURE RATIO = 2.0
- COMPACT HEAT TRANSFER ASSEMBLIES
- MODULAR
- ONLY TWO NON-CONTACTING MOVING PARTS
- LONG-LIVED GAS BEARINGS
- ELECTRIC OR HYDRAULIC OUTPUT AVAILABLE
- NO TECHNICAL BARRIERS TO SCALEUP (DEMONSTRATED 3kW TO 25 kW)
- NEARLY CONSTANT TEMPERATURE RADIATOR
- SINGLE PHASE, NON-TOXIC WORKING FLUID (H_E, H_2)
- LOWEST SPECIFIC MASS POTENTIAL (5kg/kW)

DISADVANTAGES

- LACK OF LONG DURATION EXPERIENCE AT LARGE SCALE
- LOW FREQUENCY (60 - 100 Hz) OUTPUT
- CLOSE TOLERANCES REQUIRED
- BERYLLIUM MOVING PARTS
- HIGH PRESSURE (2000 PSI)
- THEORETICAL UNDERSTANDING OF CYCLE LOSS MECHANISMS IS LIMITED
- EXTRAPOLATION OF TECHNOLOGY TO LARGER SIZES (150 kWe +) UNPROVEN
- HEAT PIPE HEAT INPUT REQUIRES START/ RESTART VERIFICATION IN ZERO G
- REFRACTORY/SUPERALLOY ENGINES OPTIMIZE AT 500-600 T_{COLD} - REQUIRE Hg RADIATOR IF HEAT PIPE USED

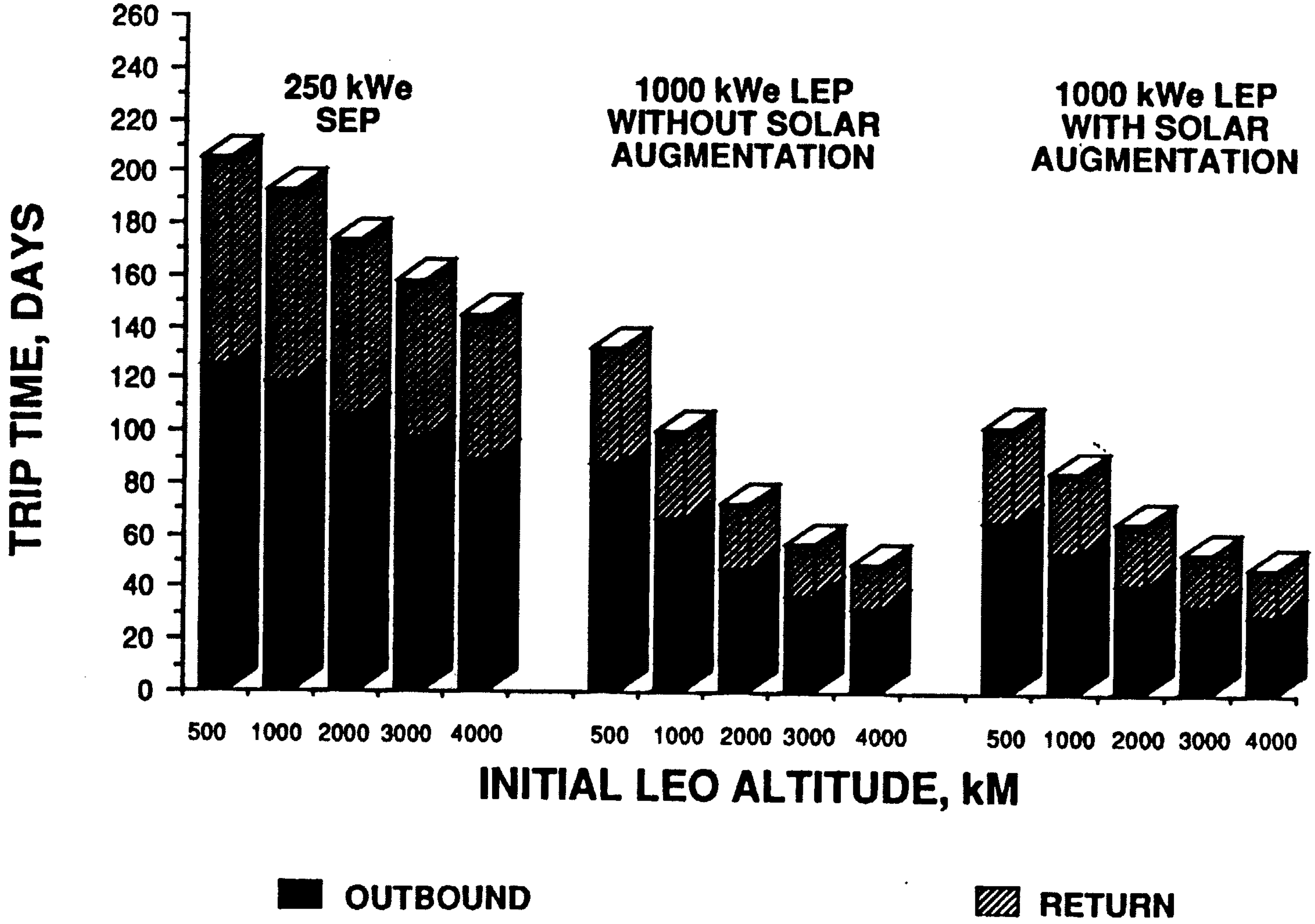
FUTURE TECHNOLOGY

Laser Beaming of Space Power



LEO TO GEO TRIP TIMES FOR OTV TUG

7,000 kg CLASS OTV



SUMMARY

- POWER AND ENERGY REQUIREMENTS CONSTANTLY MOVING UP
- MASS LIMITATIONS CONSTANTLY PUSH TECHNOLOGIES REQUIRING INNOVATION
- LIFE CONSIDERATIONS PUSH RELIABILITY
- UNFORTUNATELY COSTS DRIVE US TO LOW TECH, HEAVY, REPLACEABLE SYSTEMS

WITH A COMPROMISED VISION

PROPULSION REQUIREMENTS FOR SPACE

Jim Dill
Mechanical Technology, Inc.
Latham, New York

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
TURBOPUMP BEARING REQUIREMENTS

- o HIGH SPEED CAPABILITIES
- o ADEQUATE LIFE FOR MISSION (MULTIPLE RUNS EVEN ON ETO SYSTEMS)
- o LOW FRICTION START/STOP
- o ADEQUATE START / STOP CYCLES IN LONG LIFE APPLICATIONS
- o AVOIDANCE / TOLERANCE OF HIGH SPEED RUBS IN LOX
- o SATISFACTORY ROTORDYNAMIC CONTROL
- o ACCOMMODATION OF CENTRIFUGAL GROWTH IN HIGH SPEED PUMPS
- o ACCOMMODATION OF THERMAL DISTORTION AND DIFFERENTIAL EXPANSION PROPERTIES OF COMPONENTS

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
TURBOPUMP BEARING REQUIREMENTS

TURBOPUMP	BEARING SIZE/ SHAFT SPEED/ (DN x 10^6)	TEMPERATURE/ RADIAL LOAD PUMP END BEARING	TEMPERATURE RADIAL LOAD TURBINE END BEARING
SSME OXYGEN	57 mm 29,300 rpm (1.67)	90 K 2600 lb.	120 K 5,000 lb.
SSME HYDROGEN	45 mm 37,000 rpm (1.67)	33 K 1,000 lb.	83 K 1,600 lb.
ALS HYDROGEN	75 mm 28,000 rpm (2.1)	33 K 470 lb.	80 K 800 lb
NTP HYDROGEN	65 mm 30,500 rpm (1.98)	< 30 K ?	< 80 K
CTV HYDROGEN	30 mm 100-200 Krpm (3.0-6.0)	33 K 7 lb.	80 K 50 lb.

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
BEARING OPTIONS

BEARING TYPE	ADVANTAGES	DISADVANTAGES
Rolling Element	o Known Technology o Good Overload Capability o Rubbing Contact Minimized	o Inadequate Life o Low Damping o Wear Changes Properties
Fluid Film	o Not Fatigue or Wear Limited o Good High Speed Capabilities o Good Dynamic Characteristics	o Lift Off Supply o Fluid Dynamics o Start/Stop Wear
Magnetic	o Not Fatigue or Wear Limited o Active Brg Controls Dynamics o Superconductors Improve Performance	o Heavy with Conv. Magnets o Power and Sensors in Cryo o Low Load Capacity

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP

PROPULSION REQUIREMENTS FOR SPACE

BEARING OPTIONS - ROLLING ELEMENT

- o HIGH STIFFNESS SUPPORT - GOOD ROTOR CLEARANCE CONTROL
- o DN LIMITS CAN RESTRICT SHAFT DIAMETERS AND LEAD TO ROTORDYNAMICS PROBLEMS
- o LOW DAMPING OF REB ALONE CAN MAKE DYNAMICS MORE SENSITIVE
- o EXCELLENT OVERLOAD TOLERANCE
- o DN VALUES IN CTV AND NASP TYPE PUMPS ELIMINATE REB
- o WEAR WILL ALWAYS BE PRESENT PARTICULARLY IN LOX LEADING TO PERFORMANCE DEGRADATION AS CLEARANCE INCREASES
- o CERAMIC BALLS AND IMPROVED CAGE MATERIALS CAN SIGNIFICANTLY REDUCE WEAR AND INCREASE TOTAL BEARING LIFE

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE

BEARING OPTIONS - FLUID FILM

- o HIGHER DN LIMITS THAN ROLLING ELEMENT BEARINGS
- o HIGH DAMPING CAN RESULT IN IMPROVED ROTOR STABILITY
- o LOWER STIFFNESS CAN MAKE ROTOR CLEARANCE CONTROL DIFFICULT
- o LESS TOLERANT TO OVERLOADS THAN ROLLING ELEMENT BRGS.
- o HIGH SURFACE SPEED RUBS COULD RESULT IN WEAR PROBLEMS IN LONG LIFE APPLICATIONS
- o FEED ORIFICE EROSION CAN BE A PROBLEM IN HYDROSTATIC DESIGNS
- o WEAR RESISTANT MATERIALS ARE NEEDED TO INCREASE RUB AND START/STOP WEAR TOLERANCE

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE

BEARING OPTIONS - FLUID FILM BEARINGS ISSUES

- o IMPROVED TURBULENCE MODELS
- o BETTER UNDERSTANDING OF POWER LOSS, HEAT GENERATION, TORQUE
- o BEHAVIOR OF COMBINED REYNOLDS NUMBER FLOW
- o TWO PHASE PERFORMANCE OF VARIOUS DESIGNS
- o RELATIVE PERFORMANCE OF DIFFERENT DESIGNS
    - HYDROSTATIC
    - HYDRODYNAMIC
        - o COMPLIANT (FOIL)
        - o RIGID SURFACE
    - HYBRID HYDROSTATIC/HYDRODYNAMIC

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
BEARING OPTIONS -MAGNETIC

ACTIVE:

- o HIGH STIFFNESS AND CONTROLLABLE DAMPING PROVIDE UNIQUE ROTOR CONTROL OPTIONS
- o MAY NEED SUPERCONDUCTING OR HYPERCONDUCTING DESIGNS TO ACHIEVE LOAD CAPACITY REQUIRED FOR TURBOPUMPS
- o HIGH DN LIMITS SIMILAR TO FLUID FILM BEARINGS
- o NEED FOR BACKUP BEARING COULD BE A DISADVANTAGE IN TERMS OF ENVELOP REQUIREMENTS
- o LONG TERM HYDROGEN EXPOSURE OF MATERIALS MAY BE AN ISSUE
- o NEED WEAR RESISTANT SURFACES FOR RUB TOLERANCE

PASSIVE SUPERCONDUCTING:

- o LOW STIFFNESS PRECLUDES USE ALONE IN MOST TURBOPUMP APPLICATIONS
- o CURRENT CRITICAL TEMPERATURES FAVOR USE IN HYDROGEN RATHER THAN OXYGEN
- o LONG TERM EXPOSURE EFFECTS ON MATERIALS

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
BEARING OPTIONS -HYBRID TYPES

o HYDROSTATIC / HYDRODYNAMIC

o HYDROSTATIC / ROLLING ELEMENT

o HYDRODYNAMIC / ROLLING ELEMENT

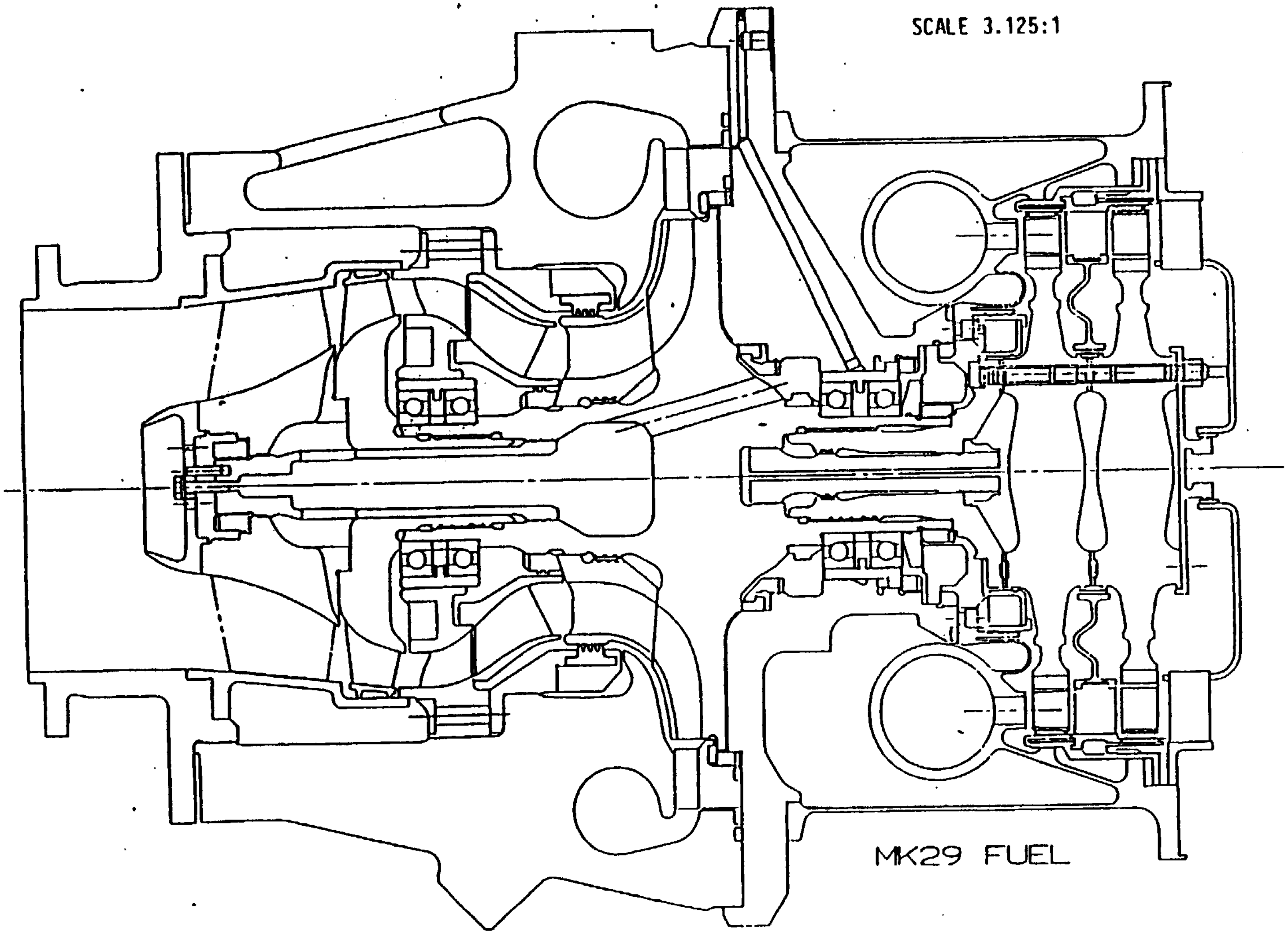
o PASSIVE SUPERCONDUCTING / HYDRODYNAMIC

o ACTIVE MAGNETIC / HYDRODYNAMIC

o ACTIVE MAGNETIC / ROLLING ELEMENT BEARING

TRIBOLOGICAL ISSUES OF THE INDIVIDUAL COMPONENTS ARE BASICALLY THE SAME WHETHER USED INDIVIDUALLY OR AS PART OF A HYBRID PAIR.

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
MK 29 FUEL PUMP CROSS SECTION



NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
MK29F TURBOPUMP DETAILS

PARAMETER	UNITS	REQUIREMENT
TOTAL TIME	SEC.	>5000
START/STOP CYCLES	NUMBER DEMONSTRATED	24
SHAFT SPEED	RPM	30,500
BEARING TYPE		BALL
PUMP BRG. DIAM.	MM	65
TURB. BRG. DIAM.	MM	65
ROTOR WEIGHT	LBF	110
STATIC RADIAL LD.	LBF	0
STATIC THRUST LD.	LBF	1500

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE
NUCLEAR THERMAL PROPULSION

SPECIAL BEARING ISSUES:

SLOW START UP TIME	30 SEC. TO 10 MIN. TO REACH FULL SPEED CONCERN ABOUT RUBBING PRIOR TO LIFT OFF IN FLUID FILM BEARING DESIGNS
LONG COOL DOWN IDLE MODE OPERATION	10 - 100 HR. IDLE SPEED RUNNING REQUIRED FOR REACTOR COOL DOWN AFTER RUNNING
POSSIBLE RADIATION EXPOSURE OF PUMP	0.03-0.5 RAD/HR FOR 1-10 DAYS AFTER SHUTDOWN. POSSIBLY 10-1000 TIMES HIGHER LEVELS DURING OPERATION. SPACE RADIATION DURING MARS MISSION.
LONG TERM HYDROGEN EXPOSURE	OPERATING TIMES AND TOTAL EXPOSURE TIMES MUCH LONGER THAN CURRENT SYSTEMS

NASA SPACE MECHANISMS TECHNOLOGY WORKSHOP
PROPULSION REQUIREMENTS FOR SPACE

TRIBOLOGICAL ISSUES IN NTP

ROLLING ELEMENT BEARINGS	o HIGH DN VALUES (1.98 MILLION DN) WEAR/ HEAT GENERATION o LONG RUNNING TIMES
FLUID FILM BEARINGS	o START / STOP CYCLES o HIGH SPEED RUBS (SURFACE SPEED >20,000 FPM) o CAVITATION EROSION OF ORIFICES IN HYDROSTATIC DESIGNS o RUBBING OR LOW SPEED LIFT OFF DURING LONG START UP AND COOL DOWN IDLE RUNNING
MAGNETIC	o HIGH SPEED RUBS

FIELD ROBOTS FOR THE NEXT CENTURY

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Pittsburgh, Pennsylvania

Introduction

Robotics to date has produced underlying capabilities that enable robots to respond to a variety of task challenges. Robotics is maturing as a discipline, and the investment in prior research has yielded a wealth of technologies for a new generation of competent robots. It is no longer necessary to restrict research to work on testbed robots, since systems that meet performance specifications of end-users can now be developed. Given the existing technology base, robots that were unachievable five years ago now are within reach, provided that performance goals are established and development efforts in the near term are directed to meet them.

With seminal groundwork laid, robotics technology is now evolutionary, not revolutionary. Evolutionary technologies are born of knowledge-based research: efforts aimed at developing a new and better understanding of the application of scientific principles. From failures in early development come the insights that lead to successful future implementations, which show increasing utility and relevance as the technology evolves. Robots that meet new task challenges and exhibit proficiency are feasible, since the knowledge we have gained is allowing us to cross the threshold from pure knowledge-based research to performance-based research.

The Nature of Field Robots

Structured environments, like those found in factory settings, do not challenge robots with the dynamism and uncertainty of unstructured environments. Active and forceful manipulation of objects in unstructured environments requires much more than current industrial robotics can deliver. To work in a field site — say, digging up a gas pipe — a field robot must be able to recognize unknowns and respond to unplanned difficulties. It is paramount that the robot sense events and take responsive actions. Needs of the open work site, like robot intelligence and robustness, drive the agenda for field robotics research.

Robots, in general, fall into three classes, each distinguished by the control procedures available to the robot and its relationship to human supervisors. The first of these classes, programmed robots, perform predictable, invariant tasks according to pre-programmed instructions. Teleoperated robots, the second of these classes, includes machines where all planning, perception, and manipulation is controlled by humans. Cognitive robots, the third class, sense, model, plan, and act to achieve goals without intervention by human supervisors.

Programmed machines are the backbone of manufacturing; preprogramming is extensible to an important class of field work tasks (mostly on the periphery of the field work mainstream, and mostly unenvisioned and untried at this time). Programming commands actions through scripts that are played back by rote with branching of the script occurring at specified times or in response to anticipated events. Such scripts are only useful for predictable and invariant tasks, limiting the general use of preprogrammed robots for field work.

Teleoperated machines, servoed in real-time by human operators who close the strategic control loop, amplify and project the human. Because all perception, planning, high-level control, and liability rest with the human, teleoperation circumvents the most difficult issues that face other robot control modes, including the liability of passing control between machine and human and coping with unanticipated scenarios.

Teleoperation is proven where man does not tread, where demands are superhuman, where tasks are unstructured (by current measure), where liability is high, and where action is inevitable. A downside of teleoperation is that much is lost in translation across this man-machine interface. Robot bodies and senses are not optimal for coupling to man. Similarly, human minds are not optimal for the control of robots because of limitations in input/output bandwidth, memory structures, and numerical processing. The prospect exists for field robots to outperform their human counterparts in many ways.

Cognitive robots sense, model, plan, and act to achieve working goals. Cognitive robots servo themselves to real-time goals and conditions in the manner of teleoperators but without human controllers; they are their own supervisors. Cognitive robots pursue goals rather than play out scripts; they move toward goals and notions rather than to prescriptions and recipes. Although software driven, they are not programmed in the classical sense. Cognitive robots are perceptive and their actions are deliberate; they operate in the face of the vagaries and contingencies of the world. Task performance by a cognitive robot is responsive to the state of the environment and the robot itself.

Hybrid forms of teleoperated and programmed machines are becoming increasingly attractive as robots. For example, because factory processes are becoming more sophisticated as they integrate preprogramming and sensing, supervisory controllers and sensory feedback with teach/playback are becoming new research goals. Hybrid, supervisory, and programmable robots are also evolving from the roots of teleoperation in the nuclear service and decommissioning industries.

However they are classified, the most striking observation of present-day robots is that, with few exceptions, robots lack the ability to perform with any generality, which is the goal of truly capable systems. Even when task directives and methods of procedure are explicit, unforeseen difficulties arise that impede or halt the robot's progress. Autonomous navigation systems, for example, lack the capacity to negotiate traffic or move quickly across unexplored rough terrain. These robots are often debilitated by uncontrollable circumstances, such as bad lighting and inclement weather. Nor can they always cope with conflicting data to resolve ambiguities. Only now are driving robots beginning to distinguish shadows from roads and separate real obstacles from the phantoms caused by spurious sensor readings.

The Use of Field Robots

Factory robots bring the repeatability, productivity, and quality control of automated mechanisms to manufacturing industries. The other historical motivation for using robots is to relieve humans of duty in hazardous environments. The nuclear industry was quick to adopt telerobotics so that human presence can be projected into places where the need for radiation protection hinders manual work or precludes it altogether. Teleoperated manipulators are presently saving thousands of man-rems of exposure in the routine servicing of reactors and associated steam generation equipment; recovery from the Three Mile Island and Chernobyl accidents would not have been possible without robotic worksystems specially commissioned to operate in those scenarios. For their specialized agenda, these nuclear-qualified robots exhibit high competence, owing to the fact that they were built to meet explicit performance goals and design criteria.

The world is now positioned to apply robotic technologies in other commonplace scenarios. Non-factory work sites are ripe, virtually untouched, and inevitable arenas for robotic applications. Labor efficiency on field sites is alarmingly low and the need for improved productivity is evident. Worker time spent idle or doing ineffective work may exceed half the work week, and productivity has generally been in decline for two decades. Thus, industry size, economics, existing inefficiencies, and competition motivate the introduction of robotics to field work. Other motivations include quality assurance and the prospect for better control over the field work site of the future. Further, because field work is often hazardous, concerns for health and safety provide additional impetus for robotic implementations.

In addition to all these motives, certain applications are inevitable because man is not perfectly suited for field work; machines are often better equipped for many applications. Man, for example, is vulnerable to hostilities such as weather, dust, vacuum, submersion, and cave-ins, and limited by a lack of scale or power for activities such as mining, material handling and construction. Man lacks certain sensing modalities, memory structures, and computational abilities that will allow the robots of the future to precisely sense and execute tasks in scaled or measured environments, and optimize automatic material distribution throughout a site. The needs of the field industries drive the development of unstructured robotics just as manufacturing and assembly drove structured robotics and hazardous environments drove teleoperation.

Early applications of robotic arms in manufacturing leveraged on their accuracy, consistency, and repeatability to achieve productivity, performance quantified on the basis of speed and the efficiency of resource investment, particularly the human resource.

Similar increases in productivity are realizable in applications outside the factory. For example, proper characterization of a hazardous waste site requires an enormous amount of data to be taken over a large land area. There are current efforts to automate this process by replacing manual data collection with mobile robots that can acquire and spatially correlate site information. Orders of magnitude increases in the amount of site data, as well as higher precision position estimation, will enable more complete assessments and ultimately reduce the cost of the investigation process.

Excavation is another excellent application to further the evolution of robotics because of its significance in scale and economic importance. It operates on a universal and generic material (soil), and excavation's goal and state can be described adequately by models of geometry and kinetics. Further, excavation is tolerant of imprecision, well-understood as a human driven process, and prototypical of a host of spin-off applications. One motivation for robotic excavation is the hazard in such tasks as blind digging of gas lines, retrieval of unexploded ordnance or removal of hazardous waste from a landfill. Another motivation is the productivity and process control that could be realized in mass earth moving operations. Unmanned excavation will reduce the human injuries and property losses attributed to explosions, decrease operation costs, and increase productivity by lengthening the work day.

Automation of surface mining has the potential to increase safety, decrease cost, and revolutionize control of surface mining operations. Elimination of human operators could circumvent current variables of operator quality and availability and monotony of the task. Further, automation of surface mining is seen as a building block toward general work site automation. Surface mining lends itself well to automation. Driving and haulage are simple actions in comparison with the richness of other robotic tasks like manipulation. Off-road navigation can also be extended to the applications of agriculture and timber harvesting. The environment can be known in advance and rigged to an appropriate level. Because the task is repetitive (the same paths are traversed for years), explicit plans alleviate the need for the robot to explore or learn about its environment. Although it must be able to handle a range of contingencies such as obstacles, an autonomous haulage system is primarily a performer of preplanned actions relegating perceptive sensing to a mechanism of self-survival.

A new generation of robots, grounded in existing robotic technologies, is on the horizon and will find widespread utility.

Robotic navigators are one class of systems that have several applications, including haulage, material delivery, and waste site characterization. Through automation of off-road driving, these tasks can be performed with less direct human involvement, thereby increasing a worker's productivity through simultaneous control of several vehicles and removing his exposure to potential hazards.

Ground vehicles realizable in the near term will navigate under general lighting and weather conditions at productive rates of travel. Some will drive on streets and highways; others will negotiate rough terrain with variable geometry and natural surface characteristics. They will employ multiple sensory modes for guidance; use maps from several sources and of various resolution; detect, recognize and avoid obstacles; and be cognizant of their own dynamics. Future generations of robotic off-road navigators will focus on the design of robust navigational schemes. Obstacle detection and recognition will be extended to accommodate dynamic obstacles like other vehicles so that these robots will ultimately be capable of driving in traffic.

By coupling manipulation to locomotion, a robotic vehicle that can navigate off-road can be complemented with the ability to perform useful work. A terrestrial robot worksystem can be used in construction applications, such girder emplacement, excavation, and brick laying, and hazardous applications like handling of radiological material, waste packaging, and decontamination and decommissioning of nuclear facilities. These tasks share the common denominators that the robot physically engages and manipulates its environment and that the setting for these operations is often very hazardous.

These steps to enhance teleoperation of the worksystem provide the foundation for enhanced performance through increased task autonomy. The worksystem will evolve incrementally, as operations performed under human control in one generation are automated in the next. Interaction between man and machine will become simpler as the robot becomes able to accept higher level commands, and the human's role will transition to supervisor.

Next generation worksystems will perform certain subtasks on their own, while the operator exercises direct control for the more difficult operations, monitors subtask execution, and intervenes as needed. In the case of excavation, subtasks might be the scooping and unloading phases of the digging cycle; for building construction, subtasks might include grasping an I-beam and carrying it to location where a building foundation is being established. These capabilities will develop from the basics of manipulator control and geometric model building of the enhanced teleoperator by adding the capacity to recognize objects and the ability to reason on perceived geometry and force. Future generation worksystems will combine subtasks, automate more difficult aspects of the tasks, and add execution monitoring to achieve a higher degree of autonomy. Alternatively, it might be desirable to pursue execution of a variety of tasks using one worksystem with multiple tools and operating modes to achieve higher utility.

The Evolution of Robotic Technology

Robotics research has reached a threshold where technologies are beginning to find performance niches in which their implementations show comparative advantages over older technology or allow the performance of tasks previously unperformable. We are also witnessing a shift in implementation process from ad hoc integrations to disciplined development of complete systems.

Robotic technology has gained competence in the key areas of sensing, cognition, and control, to the point where new applications are feasible. Early robots had only mechatronic sensing with which they measured directly observable external variables, such as displacement and force, and could perform only simple operations, such as inspection, loading, and other positioning tasks. Increased understanding of vision and other sensory processes has made it possible for robots to make interpretations of their environment. Advanced robots extract and recognize certain features in data, often from multiple sensors, on the basis of pre-stored symbolic representations. This makes them capable of more challenging tasks, for example, manipulating irregularly shaped objects and assessing navigability of roads and paths. A very demanding task, like construction of a building, which requires not only the recognition of features and objects, but understanding of their semantic interplay, is presently beyond robotic technology.

Similarly, robots are able to undertake more challenging tasks as a result of advances in machine cognition. For early robots, planning was algorithmic and often no more than continuous state error correction, as in charting and following a trajectory. It is now feasible for robots to perform tasks like shaping soil and walking over rough terrain, which require automatic planning of significantly greater scope and depth: plans must be decomposed from goal specification into executable actions, and plan formulation has to be done in the face of uncertainty, requiring execution monitoring and use of contingencies. Coordination of multiple, potentially conflicting subgoals to fulfill a single, high-level directive, such as "clear obstacles from the road," remain too ambitious for existing robots.

The evolution of robotic technology is also evident in the increasing physical challenges met by robots. The first robots had kinematic control only, and their task domain spanned only operations that could be expressed by prescriptions of robot position. Better understanding of robot mechanisms and the application of more advanced control theory has enabled tasks that involve dynamic interaction of the robot with its environment, like stable walking and excavation. We are now implementing control at the task level, which goes beyond control theory and includes cognitive functions, such as error detection and fault recovery, so that occurrences, such as an unexpected obstacle, a sudden loss of traction, or a dropped payload, do not prevent completion of a task.

Future Directions

Despite evident need and apparent promise, the evolution of field robotics has not been straightforward. Ancient crafts have been historically slow to embrace new technology. Research investment levels have been insignificant. No precedents in field work industries for development programs of the requisite magnitude exist. Because field problems are difficult, quick fixes or one-time solutions are few, running counter to historical insistence on short-term payoff for investment. Obstacles to the growth of field robotics are compounded by the lack of common ground between the field industries and the robotics research community. The industry cannot yet visualize a programmatic course of action for integrating the growing robotic technology with its own.

At this time, construction, subsea, space, nuclear, mining, and military applications are driving and pacing many field robotics developments. Subsea and space applications, in particular, present unique technical challenges to robots, specialized motivations for field work, and constraints and regulations that discourage the use of human workers. However, the formative integration and drive for field robotics must ultimately come from the field work industry itself. The inevitability of field robotics will drive its evolution despite the immediate immaturity and impotence of the field.

It is likely that all three classes of robots and their hybrids will find sustaining relevance. Experiences are too few and it is too soon to resolve the relative importance of these forms or to discount the potential of any form. The Japanese have embraced teleoperators and programmed machines for field work. Perhaps the early American views of field robotics overestimated the need for sensing, artificial intelligence, and autonomy. Though it now appears that attributes of intelligence, particularly the ability to deliberate performance of tasks, will eventually dominate field robotics, nonetheless, teleoperators and programmed machines have both short- and long-term relevance.

If robots eventually prove themselves infeasible for unstructured environments, our views on what constitutes structure must change. Robots other than teleoperators may be irrevocably synonymous with structure. Our judgment in this matter should not be too clouded by current measures of structure and machine perception. It is common to mistake or overestimate chaos in a task environment simply because form and understanding are not apparent. There is a great prospect for structuring the apparently unstructured either by discovering structure or by imposing it.

The evolution of field robots will distill unique attributes for robots with working goals in unstructured environments. New robotic forms will emerge with the capability and the strategic competence to construct, maintain, and demolish. The evolution of field robotics will no more culminate in a single, ultimate form than did its biological counterpart. Rather, classes of robots will emerge for classes of work within classes of constraints.

Even the robot genus/species formed and proven in other application domains remains untested by field work. No doubt most of the forms evolved for other purposes will find relevance somewhere in field work, if only because field works umbrella is so broad. The discipline of field robotics is embryonic. Its maturation is inevitable, but its mature form is not apparent. Given the uncertainty of what robotic forms may be relevant to field work, we argue that the field should remain open to all possible

The discipline must persevere to distill the unique identity and intellectual content of field robotics. The uniqueness of field robotics appears to lie in the cognitive skills and goals specific to the synthesis of an end product. Much research and many goals in field robotics, however, are generic to unstructured robotics, so field work can benefit from parallel developments in related fields. Little applicability would be lost by changing the domain specificity from field work to nuclear, mining, timbering, or military. It seems that field work will be dragged reluctantly to the opportunities of robotics. Nuclear, military, space, and offshore interests are embracing and driving the ideas now. It is essential that field robotics identify and drive the developments that will distinguish it as a discipline of its own.

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RESPONSES TO OBJECTIVE QUESTIONS

SATELLITES/SPACE PLATFORMS WORKING GROUP I

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JIM GLEESON
WILLIAM ANDERSON
LARRY PINSON

* Group leader

PRIORITIZED LIST OF OBSTACLES

SATELLITES/SPACE PLATFORMS #1

(1) LACK OF KNOWLEDGE OF LONG-LIFE CHARACTERISTICS OF LUBRICANTS
(2) FAILURE CRITERIA UNKNOWN
(3) ENVIRONMENTAL FACTORS EFFECTS UNKNOWN
(4) DEFICIENT TESTING STRATEGIES
(5) INADEQUATE ANALYTICAL MODELS
(6) PRECISE CHARACTERISTICS/CONTROL OF FRICTION VERSUS TIME UNKNOWN
(7) STORAGE EFFECTS DELETERIOUS
(8) EXCHANGE OF DATA NEARLY NON-EXISTENT
(9) LARGE, THIN-SECTION BEARINGS PRESENT PROBLEMS
(10) LUBRICANT REPLENISHMENT A PROBLEM
(11) MECHANISM SUBSTRATE COMPOSITION/QUALITY (IMPURITIES) PRODUCES VARIABILITY IN LIFE AND PERFORMANCE

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

SATELLITES AND SPACE PLATFORMS GROUP #1

OBSTACLE: LONG-LIFE CHARACTERISTICS OF LUBRICANTS

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Limited acceleration techniques/models
- Inadequate knowledge of surface-lube interactions
- Thin film versus Bulk Properties
- Lack of understanding of failure mechanisms
- Application process deficiencies
- lack of correlation between surface conditions and life

CURRENT STATE OF ART

- "Seat-of-the-pants"!
- Good surface analysis/ characterization
- Limited knowledge of lubricant transfer mechanisms (Creep!, et.al.)

APPLICABLE NASA MISSIONS AND NON-NASA MISSIONS

- All

ACTIVE RESEARCH IN THE AREA

● CSCL:	Light effort	Correlation of lube surface status to lifetime
● Honeywell:	Light effort	Lube strategy
● NASA LeRC:	Medium effort	Surface Interactions
● MPB:	Small→Med effort	High-temp vacuum Lube

TECHNOLOGY NEEDS FOR CURRENT OR FUTURE MISSIONS

- Better understanding of Barrier coatings
- Need a lubrication strategy

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

SATELLITES AND SPACE PLATFORMS GROUP #1

OBSTACLE: FAILURE CRITERIA

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Monitoring/sensing (telemetry)
- Definition of failure
- Accuracy/sensitivity of test equipment
- Correlation of testing with application
- Inadequate data base

CURRENT STATE OF ART

- Performance oriented versus diagnostic
- Limited data channels/rates
- Remedies limited
- Fragmented data bases

APPLICABLE NASA MISSIONS AND NON-NASA MISSIONS

- All

ACTIVE RESEARCH IN THE AREA

● MPB:	Small→Med effort	Lubricant Breakdown
● NRL,Draper:	Small effort	Lubricant breakdown detection
● MMC	Small effort	Surface integrity
● Honeywell	"Medium" effort	Fluid Lubricant failure criteria

TECHNOLOGY NEEDS FOR CURRENT OR FUTURE MISSIONS

- Assessment/survey of existing effort/data
- Coordination of existing activities

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

SATELLITES AND SPACE PLATFORMS GROUP #1

OBSTACLE: ENVIRONMENTAL FACTORS

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Accurate Characterization
  - Pressure
  - Radiation
  - Temperature
  - vibration
  - EMC/EMI
  - AO
  - Orbital debris
  - Zero-G
- Obsolete Data
- Lack of information exchange

CURRENT STATE OF ART

- Partial simulation - Lack of combined environments
- "Crude" Estimates
- Limited Test Capability

APPLICABLE NASA MISSIONS AND NON-NASA MISSIONS

- Mission Specific - Earth orbit versus interplanetary, etc.

ACTIVE RESEARCH IN THE AREA

- LDEF
- Numerous scientific studies - LANL, NASA, SDIO, etc.

TECHNOLOGY NEEDS FOR CURRENT OR FUTURE MISSIONS

- Develop methods and facilities for combined testing
- Better modeling of environment and effects

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

SATELLITES AND SPACE PLATFORMS GROUP #1

OBSTACLE: TESTING STRATEGIES

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Inadequate Accelerated testing methods
- Inadequate simulation - Environment, load, motion, geometry
- Inadequate failure criteria

CURRENT STATE OF ART

- Real-time life testing
- Screening versus component-subsystem
- Good analytical capability

APPLICABLE NASA MISSIONS AND NON-NASA MISSIONS

- All

ACTIVE RESEARCH IN THE AREA

- Limited!

TECHNOLOGY NEEDS FOR CURRENT AND FUTURE MISSIONS

- Fund/develop qualitative discrimination technique
- Survey of existing capabilities

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

SATELLITES AND SPACE PLATFORMS GROUP #1

OBSTACLE: ANALYTICAL MODELS

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Little/no connection from component to system!
- Limited verification - Experiment and Test!!
- Lack of life prediction techniques.

CURRENT STATE OF ART

- Static models not bad at the component level.
- Limited dynamic component level models available.

APPLICABLE NASA MISSIONS AND NON-NASA MISSIONS

- All

ACTIVE RESEARCH IN THE AREA

- Not known

TECHNOLOGY NEEDS FOR CURRENT MISSIONS

- Complete tribological models (Mechano-materials)
- Valid testing procedures
- Model connectivity (Interaction)

CONCERNS

- Leading or Following model (Expt./test/applic)
- Misuse of model

PRIORITIZED LIST OF TECHNOLOGY NEEDS

SATELLITES/SPACE PLATFORMS #1

(1) ACCELERATED TECHNIQUES AND MODELS

(2) UNDERSTANDING OF FAILURE MODES

(3) LUBRICANT/SUBSTRATE/ENVIRONMENT INTERACTIONS

(4) COMBINED ENVIRONMENT SIMULATION

(5) ANALYTICAL MODEL CONNECTIVITY - LATERAL AND VERTICAL

INFORMATION TO BE INCLUDED IN A SPACE MECHANISMS DESIGN GUIDELINES HANDBOOK

(SATELLITES/SPACE PLATFORMS #1)

(1) QUALIFICATION OF LIMITATIONS
(2) CASE STUDIES (HISTORIES)
(3) ENVIRONMENTAL FACTORS
(4) SPECIFICATION OF LIMITS
(5) LIVING DOCUMENT - CONTINUOUS REVIEW (SUPPLEMENTS)
(6) FAILURE CRITERIA
(7) PROVISION FOR REPORTING SUCCESS AND FAILURE
(8) POINTS OF CONTACT - EXPERIENCE BASE
(9) VOLUNTARY SOURCE LIST BY EXPERTISE
(8 AND 9 ARE FILTERS FOR PROPRIETARY)
(10) GENERIC DESCRIPTIONS OF TYPICAL MECHANISMS
(11) LISTING OF ANALYTICAL TOOLS (MODELS)
(12) MODEL DESIGN PROCESS - GENERIC FLOW CHART

WHAT CAN BE DONE TO IMPROVE TECHNOLOGY DEVELOPMENT AND DISSEMINATION OF INFORMATION

(SATELLITES/SPACE PLATFORMS #1)

(1) GOVERNMENT AND INDUSTRY IS DOING WORK THAT DOES NOT GET PUBLISHED
  - -- COULD WE PAY TO OPEN UP FILES?
  - -- PROPRIETARY RIGHTS ISSUES

(2) EXCHANGE EACH OTHERS REFERENCES, WHAT WE'VE DONE (ONLY SOCIETY-TYPE PAPERS APPEAR IN LITERATURE SEARCH)

(3) DECLASSIFICATION OF TECHNICAL INFORMATION

(4) LONG-TERM FUNDING COMMITMENT (>5 YEARS)

(5) ENHANCE COMMUNICATION, INFORMATION EXCHANGE

(6) IMPROVE THE MEANS OF PUBLICATION (SPEED AND ACCESS)

(7) ESTABLISH CENTRAL REPOSITORY

OTHER ISSUES

(SATELLITES/SPACE PLATFORMS #1)

(1) CONTINUED FUNDING "AIRCRAFT INDUSTRY MODEL"
  -- NEED MECHANISM VISIBILITY TO LEO
  -- LEO'S LOBBY @ NASA - HQ, CONGRESS

(2) FOREIGN INVOLVEMENT??

(3) HANDBOOK IS MULTI-YEAR, LARGE-TEAM, BIG BUCKS

(4) REGULATORY ISSUES (CONSTRAINTS)

(5) COHESIVE LONG-TERM PLAN (POLICY)

(6) MILITARY-CIVILIAN COOPERATION

(7) DEVELOP/STRENGTHEN TECHNOLOGY BASE BEYOND NEAR TERM

(8) ENCOURAGE CAREER DEVELOPMENT - ATTRACT NEW BLOOD

WHAT NEXT?

(SATELLITES/SPACE PLATFORMS #1)

(1) PERMANENT COMMITTEE OR WORKING GROUP
  -- TO EXCHANGE INFORMATION

(2) COOPERATIVE PROGRAMS

(3) REGULAR MEETINGS

(4) CATALOG OF CAPABILITIES (VERY NEAR TERM)
  -- PERSONNEL
  -- FACILITIES

(5) ESTABLISH SCHEDULE FOR FOLLOW-UP (ACTION PLAN)

RESPONSES TO OBJECTIVE QUESTIONS

SATELLITES/SPACE PLATFORMS WORKING GROUP II

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* Group leader

PRIORITIZED LIST OF OBSTACLES

SATELLITES/SPACE PLATFORMS #2

(1) LACK OF CONSISTENT, LONG TERM FUNDING (TO OVERCOME THE WORKING GROUP OBSTACLES) -- 100% AGREEMENT

(2) LACK OF COMMUNICATIONS AND TECHNOLOGY TRANSFER

- -- LESSONS LEARNED AND CASE HISTORY <u>DATABASE</u>
    - -- FROM GOVERNMENT AND INDUSTRY
- -- TECHNOLOGY TRANSFER
    - -- COMPANY-TO-CUSTOMER
    - -- WITH FOREIGN COUNTRIES
    - -- THROUGH WORKING GROUP MEETINGS

(3) LACK OF TEST METHODS & TEST DATA

- -- INSUFFICIENT OR WRONG TYPE OF TRIBOLOGY TEST DATA
- -- LACK OF REPORTING AND TEST METHOD STANDARDIZATION
- -- NEED FOR ACCELERATED LIFE TEST METHODS
- -- POOR CORRELATION BETWEEN BENCH TESTING AND FULL SCALE TESTING
- -- LONG TERM TECHNOLOGY RESEARCH TO DEVELOP NEW MATERIALS AND COMPONENTS FOR FUTURE APPLICATIONS
- -- FUNDAMENTAL CAUSE & EFFECT OF LUBRICATION PROCESSES

PRIORITIZED LIST OF OBSTACLES

SATELLITES/SPACE PLATFORMS #2

(4) LACK OF ADEQUATE MECHANICAL DESIGN
- GUIDELINES NEEDED FOR GOOD DESIGN PRACTICES (LIVING DOCUMENT)
- ANALYTICAL METHODS (BEARING/LUBE MODELS FOR SERVOS) LACKING
- LACK OF KNOWLEDGE AND USE OF ADVANCED MECHANISM STRUCTURAL MATERIALS
- LACK OF AN INTERDISCIPLINARY APPROACH TO DESIGN
- LACK OF UTILIZING OF NEW TECHNOLOGY INTO OPERATIONAL AND NEW SYSTEMS
- LACK OF ROBUST DESIGNS

(5) QUALITY CONTROL
- LACK OF PROCESS CONTROL FOR NEW MATERIALS - e.g. NEW SOLID LUBRICANTS AND CERAMIC BEARINGS
- QUALITY CONTROL SHOULD BE PART OF DESIGN/PROGRAM
- MAINTAIN QUALITY CONTROL EVEN WHEN COST AND SCHEDULE REDUCTIONS ARE IMPOSED

PRIORITIZED LIST OF TECHNOLOGY NEEDS

SATELLITES/SPACE PLATFORMS #2

(1) IMPROVE ACCELERATED TEST METHODS AND ESTABLISH A TEST DATA BASE

(2) DEVELOP THE CAUSE AND EFFECT RELATIONSHIP BETWEEN LUBRICANT SYSTEM LIFE AND DEGRADED LUBRICANT AND BEARING MATERIALS

(3) RESEARCH INTO NEW MATERIALS AND LUBRICANT SYSTEMS TO ANSWER ALL QUESTIONS FOR INTRODUCTION OF THE LUBRICANT SYSTEM INTO AND OPERATIONAL SATELLITE

INFORMATION TO BE INCLUDED IN A SPACE MECHANISMS DESIGN GUIDELINES HANDBOOK

(SATELLITES/SPACE PLATFORMS #2)

---

(1) INCLUDE ALL INFORMATION DISCUSSED IN THIS WORKING GROUP

(2) REGISTER OF ADVISORY EXPERT ADVISE AND TEST CAPABILITY FOR LUBRICATED MECHANISMS

WHAT CAN BE DONE TO IMPROVE TECHNOLOGY DEVELOPMENT AND DISSEMINATION OF INFORMATION

(SATELLITES/SPACE PLATFORMS #2)

(1) COMMUNICATION IMPROVEMENTS

- ESTABLISH A NASA LEAD CENTER
- WRITE A NASA SPACE MECHANISM HANDBOOK
- ESTABLISH ANNUAL MEETINGS
- INSTITUTE CASE HISTORY AND LESSONS LEARNED DATA BASES

OTHER ISSUES

(SATELLITES/SPACE PLATFORMS #2)

(1) INVITE SPACE MECHANISM PARTICIPATION FROM COMMERCIAL SATELLITE COMPANIES AND MILITARY SATELLITE COMPANIES

(2) SEND LETTERS OF SUPPORT FROM PRIVATE INDUSTRY COMPANIES TO BOB FUSARO/LeRC, TO SUPPORT SPACE MECHANISMS ACTIVITIES

(3) FORM AN ADVISORY BOARD FROM INDUSTRY TO PROVIDE NASA HEADQUARTERS GUIDANCE

WHAT NEXT?

(SATELLITES/SPACE PLATFORMS #2)

(1) SPACE MECHANISMS HANDBOOK
  - -- INCLUDE ALL WORKING GROUP TOPICS
  - -- PAY WORKING GROUP MEMBERS TO WRITE HANDBOOK
  - -- COLLECT LUBRICATION CDR PRESENTATION AND LUBRICATION LIST AS BACKGROUND

(2) ESTABLISH LeRC AS LEAD CENTER FOR SPACE MECHANISMS

(3) MEET 1 OR 2 TIMES A YEAR TO ASSURE THE WORKING GROUP OBJECTIVES ARE ACCOMPLISHED

(4) FOLLOW THE ESA EXAMPLE

RESPONSES TO OBJECTIVE QUESTIONS

PLANETARY SURFACE OPERATIONS WORKING GROUP

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SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

PLANETARY SURFACE OPERATIONS GROUP

OBSTACLE: MATERIALS FOR PLANETARY COMPONENTS

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Lack of flexible materials for use at high/cold temperatures
- Unknown property changes in materials exposed to the environment (vacuum, dust, radiation, temperature, abrasion, corrosion)
- Unknown storage and non-operational effects on mechanism materials
- Don't know the types of materials to use!

CURRENT STATE OF ART

- SOA is for short life, low-use mechanisms
- Space qualified materials are for Earth orbit only.

APPLICABLE NASA MISSIONS AND NON-NASA MISSIONS

- MESUR
- ARTEMIS
- Robotic - Precursor
- Discovery Missions

ACTIVE RESEARCH IN THE AREA

- LeRC - Radiator Materials
- Powered solid Research (MTI)

TECHNOLOGY NEEDS FOR FUTURE MISSIONS

- Flexible materials (e.g. belts, cloth, coatings, seals, etc.)
- Improved wear resistant materials
- Definition of performance of materials (stress corrosion, embrittlement)

CONCERNS

- New and/or advanced materials as needed will not be developed when needed

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

PLANETARY SURFACE OPERATIONS GROUP

OBSTACLE: INADEQUATE LUBRICATION

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- No test data for choosing lubricants to use on planetary surfaces
- Lack of low vapor pressure liquid lubricants for planetary surface use
- Lack of adequate lubricants for ceramics and advanced materials
- Lack of low temperature liquid lubricants
- Lack of solid lubricants for air/vacuum, low/high temperature use
- Lack of understanding on what types of seals will be needed to protect lubricants
- Lack of lubricants that can operate in combined environments (lunar, martian)
- Lack of accelerated testing methods

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

PLANETARY SURFACE OPERATIONS GROUP

OBSTACLE: INADEQUATE DESIGN PROCESS

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Lack of integrated and structured design tools
- Lack of understanding of requirements
- Lack of standard techniques
- Lack of Earth based test-beds for demonstration
- Prejudiced against advanced technology and unwillingness to invest
- Lack NASA/Industry dissemination of data
- Lack of experience in young engineers
- Lack of adequate analytical models for mechanisms design
- Lack of a design manual
- Lack of interdisciplinary efforts in the design phase of mechanisms
- Perception that mechanism development is considered cheap (Better estimates needed)
- Designing for Reliability and lifetime limitation is difficult
- No system to promote utilization or development of Earth Applications
- No Repair or replacement plans
- A need for low cost standardized components (off the shelf) for design and building of mechanisms (cheaper, quicker)
- Lack of commonality among design for moon and Mars
- Limitations on available power could be a problem
- Designs for sealing an unknown
- Lack of drive train component design
- A need to look at non-traditional components and design of components

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

PLANETARY SURFACE OPERATIONS GROUP

OBSTACLE: INADEQUATE DESIGN PROCESS

CURRENT STATE OF ART

- Evolving but inadequate for mechanism designs

ACTIVE RESEARCH IN THE AREA

● LeRC	-Seal Design/analysis tool
● MSFC	-Rolling Element D/A tool
● Lockheed	-Computer int. eng. manufacturing
● EPSAT	-Environmental power system design

TECHNOLOGY NEEDS FOR CURRENT OR FUTURE MISSIONS

- Common NASA Engineering and Analysis data base
- Effective means of data transmission
- Tools for synthesis, constraint, propagation, documentation, process and analysis)

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

PLANETARY SURFACE OPERATIONS GROUP

OBSTACLE: LACK OF ENVIRONMENTAL UNDERSTANDING AND AFFECTS

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Lack of definition of the working environment
- Lack of mechanisms that can operate in an abrasive environment
- Lack of information on material/lubricant interaction effects due to moon and Mars environment
- No prior knowledge of dust mitigation techniques
- Lack of understanding of dust impacts for static versus moving parts
- Lack of engineering based precursor missions
- Unknown electrostatic effects of lunar dust
- Unknown tribological effects of high vacuum and dusty environment in non-lubricated rubbing contact
- Unknown environmental tribological effects on lubricated contacts
- No definitions of operating environments are available
- Lack of system generated environmental data

CURRENT STATE OF ART

- Knowledge of LRV, Apollo, etc.

SPACE MECHANISMS CURRENT OR PERCEIVED OBSTACLES.

PLANETARY SURFACE OPERATIONS GROUP

OBSTACLE: LACK OF ADEQUATE TESTING METHODS

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- Lack of existing test facilities that adequately simulate the lunar environmental conditions
- Lack of test requirements
- Lack of a theory on which to validate test results
- No validity of 1-G testing to predict successful operation on the moon and Mars
- Lack of demonstration missions to detect problems in mechanism operation
- No known test beds
- lack of planned tribology flight experiments

OBSTACLE: LACK OF HISTORICAL MECHANISM DATA FOR PLANETARY SURFACE APPLICATION

TECHNOLOGY DEFICIENCIES (KNOWN OR PERCEIVED)

- No guidelines or handbooks for planetary surface mechanism design
- No guidelines or handbooks for planetary surface lubricant selection
- Data from previous missions hard to obtain
- Lack of low cost, standardized components for design and building of mechanisms (leads to expensive mechanisms)
- Lack of configuration and performance metrics for mechanisms

INFORMATION TO BE INCLUDED IN A SPACE MECHANISMS DESIGN GUIDELINES HANDBOOK

PLANETARY SURFACE OPERATIONS

(1) STATISTICAL DATA

(2) HISTORICAL DATA

(3) PAPERS AND SYMPOSIUM PROCEEDINGS

(4) LESSONS LEARNED

(5) WORKING CONDITION DATA
-- ENVIRONMENT (LUNAR, MARS)

(6) PRECEDENT COMPONENT INFORMATION

WHAT IS NEEDED TO IMPROVE THE RELIABILITY OF MECHANISMS

PLANETARY SURFACE OPERATIONS

(1) DEFINE SPECIFIC PROBLEM AREAS THAT ARE RELATED TO MECHANISM LIFETIME

(2) HEALTH MONITORING
-- CAPABILITY TO MONITOR AND REPAIR POTENTIAL FAILURES

(3) INCORPORATION OF EMBEDDED SENSORS IN MECHANISMS

OTHER ISSUES

PLANETARY SURFACE OPERATIONS

(1) NEED FOR ESTABLISHING A DATABASE OF INFORMATION CONSISTING OF:
-- LESSONS LEARNED ON PREVIOUS SPACE MISSIONS
-- TECHNICAL PAPERS

(2) SCOPE STUDY TO DETERMINE EXTENT OF EFFORT IN ESTABLISHING A DATABASE

(3) EMPHASIZE COMMON USE OF VARIOUS COMPONENTS (FAMILY OF PRE-QUALIFIED STANDARDIZED COMPONENTS (FOLLOWS IDEA OF CHEAPER, FASTER)

(4) ATTEMPT TO "PIGGY-BACK" ON OTHER EXPERIMENTS TO GAIN MECHANISM DATA

WHAT NEXT?

PLANETARY SURFACE OPERATIONS

(1) EVALUATE SUMMARIES OF WORKSHOP AND ALLOW PARTICIPANTS TO REVIEW AND RETURN PRIOR TO FINAL CONFERENCE PROCEEDINGS

(2) ESTABLISHMENT OF AN ADVISORY COMMITTEE TO SERVE AS A VOICE FOR THE CONCERNS OF INDUSTRY/NASA/OTHER GOVERNMENT/UNIVERSITY

(3) MECHANISM NEWSLETTER

(4) SELECT BEST CANDIDATES FOR FUNDING A BUILD A CASE FOR PROCUREMENT

(5) FUTURE WORKSHOP IN CONJUNCTION WITH AEROSPACE MECHANISMS SYMPOSIUM

PRIORITIZED LIST OF OBSTACLES

PLANETARY SURFACE OPERATIONS

(1) BETTER UNDERSTANDING OF MATERIALS ARE NEEDED FOR PLANETARY SURFACE APPLICATIONS

(2) INADEQUATE DESIGN PROCESS

(3) INADEQUATE LUBRICATION

(4) LACK OF UNDERSTANDING OF ENVIRONMENT AND EFFECTS

(5) LACK OF ADEQUATE TESTING METHODS

(6) LACK OF HISTORICAL MECHANISM DATA FOR PLANETARY SURFACE APPLICATION

RESPONSES TO OBJECTIVE QUESTIONS

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NONPRIORITIZED LIST OF OBSTACLES

POWER/PROPULSION

- TURBOPUMP TECHNOLOGY IS LIMITED
  - -- POWER DENSITY OF TURBOMACHINERY IS NEAR A PEAK
  - -- CANNOT EXTRAPOLATE AND INCREASE POWER DENSITY ANOTHER 4 TIMES (PROBABLY)
  - -- LIFE IS ALSO LIMITED
- NUCLEAR THERMAL PROPULSION (ALSO NUCLEAR ELECTRIC PROPULSION)
  - -- HIGHLY RADIOACTIVE
  - -- ENGINE GIMBAL MECHANISMS, PUMPS
  - -- ION ENGINES - NEUTRALIZING BEAMS
  - -- THESE ENGINES NEED LONG LIFE (2 OR YEARS)
  - -- SOVIET TECHNOLOGY CAN BE USED (TEST, BUT NOT TAKEN APART)
- SOLAR ELECTRIC PROPULSION (SEP)
  - -- NEED LARGE ARRAYS
  - -- HOW TO KEEP CLEAN ON PLANETS (DUST COLLECTS ON PANELS)
  - -- DEPLOYABLE MECHANISMS
  - -- RETRACTION PROBLEMS OF ARRAYS
  - -- CONTAMINATION FROM ORBITER--LANDING VEHICLES

NONPRIORITIZED LIST OF OBSTACLES

POWER/PROPULSION

- BRAYTON AND STIRLING CYCLE ENGINES
  - -- BRAYTON HAS OPERATED 5 YEARS AT LeRC WITH TILTED PAD BEARINGS
  - -- LONGEST STIRLING HAS RUN 2 YEARS
  - -- PROBLEM WITH "DYNAMIC SYSTEMS"IS PERCEIVED -- DON'T TRUST ITEMS WITH MOVING PARTS
  - -- LIMITED TEST DATA TO DETERMINE LIFE - WHAT KIND OF TESTING IS REQUIRED
  - -- HOW IS NTP LAUNCHED
  - -- DISTANCE ISOLATION
- PROPULSION SYSTEMS
  - -- NEED FOR LUBRICATION METHODS FOR ALL SYSTEMS
  - -- HOW TO HANDLE LUBRICANT CONTAMINATION
  - -- MECHANISM OPERATION UNDER FLUCTUATING TEMPS
- TESTING, QUALIFICATION OF SYSTEMS
  - -- ANALYSIS AND PROOF TESTING MAY USE UP MOST OF USEFUL LIFE
  - -- STABILITY OF LUBED MECHANISMS. ATMOSPHERE ON EARTH MAY DAMAGE SPACE LUBRICANTS

NONPRIORITIZED LIST OF OBSTACLES

POWER/PROPULSION

- SEALING OF BEARINGS TO PREVENT CONTAMINATION
  - -- EFFECT OF TEMPERATURE ON GREASE
  - -- ELECTRICAL MOTORS
  - -- LUBRICATION OF INTERNAL COMBUSTION ENGINES
  - -- DAMPING EQUIPMENT, SHOCK ABSORBERS, TRANSMISSION DEVICES, ETC. NEED TO BE DESIGNED DIFFERENT
- EMBRITTLEMENT OF MATERIALS
- STERILIZATION OF COMPONENTS FOR TRIPS TO MARS
- SPACE ENVIRONMENT
  - -- ATOMIC OXYGEN, UV, ELECTRONS, PROTONS, ETC.
  - -- OUTGASSING REQUIREMENTS (VACUUM CONDENSABLE MATERIALS)
- STORABLES -- HYDRAZINE, SOLIDS, NOZZLE PROBLEMS
- ARC JET FOR STATION KEEPING
  - -- ALL HAVE CONTROL VALVES

PRIORITIZED LIST OF TECHNOLOGY NEEDS

POWER/PROPULSION

(1) PUMPS (COMPRESSOR)
  -- FOR PROPULSION (BEARING, SEAL, DYNAMICS, GEARS BLADES, DESIGNS)
  -- FOR H_2 AND O_2
  -- FOR WET O_2
  -- MOLTEN LI, NaK, ETC.

(2) ROTATING MACHINERY (SYSTEMS INTEGRATION FOR RECIPROCATING, ROTATING, STERLING, BRAYTON)
  -- BEARINGS: HYDRODYNAMIC, MAGNETIC HYDROSTATIC
  -- DESIGN EFFICIENCY TRADEOFFS (e.g.: STERLING MUST BE LOOKED AT AS A SYSTEM)
  -- COMPONENT CHANGE OUT AFTER SERVICE LIFE

(3) SOLAR ELECTRIC POWER
  -- DEPENDENT ON MISSION (ORBIT, MOON, MARS)
  -- DEPLOYMENT OF ARRAYS
  -- SUPPORT STRUCTURE ARTICULATION IN ORBIT
  -- SHUTTLE DOCKING
  -- MECHANISM RETRACTION

PRIORITIZED LIST OF TECHNOLOGY NEEDS

POWER/PROPULSION

(4) NUCLEAR ELECTRIC POWER
  -- PERCEIVED DANGER IN LAUNCHING
  -- SPACE START ONLY
(5) NDE AND ACCELERATED LIFE TESTING INCLUDING ENVIRONMENT
  -- HOW TO DETERMINE X YEARS OF LIFE IN A SHORT TIME
  -- WHAT ARE FAILURE MECHANISMS
  -- HEALTH MONITORING (STORAGE AND TESTING)
(6) LUBRICATION SYSTEMS
  -- DESIGN OF BEARINGS
  -- CONTAMINATION, EFFECT OF TEMPERATURE, PRESSURE, RESUPPLY
  -- WHAT IS BEARING FOR WHEELS, ETC.
  -- GIMBALS FOR NOZZLES
(7) TRANSMISSION DEVICES (POWER TRAINS, BELTS, CHAINS, ARTICULATED DEVICES U-JOINTS)
(8) ADDRESS DESIGN ISSUES UP FRONT FOR TRIBOLOGY CONSIDERATIONS
  -- DESIGN OF BOTH WITH THE TURBOMACHINERY CFD's
  -- CONCURRENT ENGINEERING

PRIORITIZED LIST OF TECHNOLOGY NEEDS

POWER/PROPULSION

(9) MATERIALS SELECTIONS
  -- FABRICATION VS LUBRICANT SELECTION
  -- NEED FOR CONSIDERATION OF BOTH AS TRIBOLOGY PART
  -- FOCUS ON HOW TO CONSTRUCT THE DATA BASE
  -- LIGHT VERSUS HEAVY CONTACTS, LEAD COATINGS (OLD AND SIMPLE MAY BE BEST)
  -- ACCURATE REPRODUCIBLE MOTION
  -- USEFUL HANDBOOK OF MATERIALS, LUBRICANTS, GUIDES
(10) BIG DUMB BOOSTERS
  -- ROBUSTNESS AND RELIABILITY, SOLID AND LIQUIDS

TECHNOLOGY NEEDS CLASSIFIED INTO 3 AREAS

POWER/PROPULSION

(1) TECHNOLOGY BASE

- MATERIALS/FABRICATION
  - CONSIDERATION OF TRIBOLOGICAL PAIRS AND OPERATING ENVIRONMENT
  - HOW DO YOU CONSTRUCT THE INTERFACE (FUNCTIONALLY GRADED MATERIALS, COATINGS, ETC.)
  - LIGHT VERSUS HEAVILY LOADED CONTACTS
- NDE/HEALTH MONITORING/SMART COMPONENTS
  - ACCEL. LIFE TESTING WITH NEURAL NETS, FUZZY LOGIC EXPERT SYSTEMS
  - "TRAINING" OF SMART COMPONENTS
  - BUILDING DATA BASES FOR 20-30 YEAR RELIABILITY
  - IDENTIFICATION OF FAILURE MECHANISMS
- LUBRICATION SYSTEMS
  - NEED CLEAN SHEET APPROACH VS (ADD OR UPGRADE)
  - PARAMETERS ISSUES: TEMPERATURE, PRESSURE, VACUUM, CONTAMINATION, RESUPPLY, MATERIALS, ENGINEERING THE INTERFACE

TECHNOLOGY NEEDS CLASSIFIED INTO 3 AREAS

POWER/PROPULSION

(2) FOCUSED TECHNOLOGY

- PUMPS: TURBO, COMPRESSORS, GENERIC
    - -- COMPONENT TYPES: BEARINGS, SEALS, GEARS, LUBE-SYSTEMS, BLADE DESIGNS, ETC.
    - -- HIGH POWER DENSITY FOR SSME PUMPS
    - -- FUEL COMPATIBILITY ISSUES FOR: SLUSH FLUIDS, H-O STEAM ENGINE (CRYO TO HOT GAS), WET O_2 (O_2 + STEAM + OTHER GASES), LIQUID METALS (Li, NaK, ETC.)
    - -- SMART SYSTEMS NEEDED
- ROTATING MACHINERY SYSTEMS
    - -- SYSTEMS INTEGRATION APPROACH, TARGET CYCLE & MISSION (e.g. NASP ENGINE/AIRFRAME)
    - -- RECIPROCATING/ROTATING (STIRLING/BRAYTON)
    - -- SUSPENSION FOR BEARINGS: MAGNETIC, HYDRODYNAMIC, FOIL (-STATIC, AND -FILM)
- POWER TRANSMISSIONS, POWER TRAINS DEVICES
    - -- ARTICULATING JOINTS
    - -- COMPONENT TYPES: GEARS, BELTS, CHAINS, SCREWS, TRACTION DRIVES, μ-ELECTRONICS/SENSORS, AND FEEDBACK LOOPS

TECHNOLOGY NEEDS CLASSIFIED INTO 3 AREAS

POWER/PROPULSION

(2) FOCUSED TECHNOLOGY (CONTINUED)
- UPFRONT ADDRESS OF DESIGN ISSUES
  - -- INVOLVE CONTRACTOR/EE DIRECTLY WITH TRIBOLOGIST
  - -- NEED FOR HANDBOOK OF MATERIALS FOR DESIGNERS
  - -- PROCEEDINGS FOR DESIGNERS VS RESEARCHERS
- TRIBO-DEVICES
- NEURAL NETS, FUZZY LOGIC INTERFACE CONTROLLERS

(3) APPLIED TECHNOLOGY
- SOLAR ARRAY
  - -- MISSION DEPENDENT (REQUIREMENTS/LIMITATIONS)
    - -- POWER/PROPULSION
  - -- SUPPORT DEPLOYMENT, RETRACTION, STORAGE OF ARRAYS
  - -- ARTICULATED JOINTS (e.g., ALPHA, BETA ON SPACE STATION)

TECHNOLOGY NEEDS CLASSIFIED INTO 3 AREAS

POWER/PROPULSION

(3) APPLIED TECHNOLOGY (CONTINUED)

- NUCLEAR POWER (NTP, NEP)
  - -- COUPLINGS FOR RADIATORS, ARRAYS
  - -- SAFE SPACE ORBITAL START ONLY
  - -- MECHANISMS RELIABILITY OF X-YEARS
  - -- WASTE DISPOSAL
  - -- TETHERING AND SHIELDING OF REACTOR
  - -- ROBOTICS ISSUES
- BIG DUMB BOOSTERS
  - -- LOWER TECHNOLOGY MAY BE BETTER (OFF SHELF, NO DEVELOPMENT, LOW COST)
  - -- ROBUST, RELIABLE, CHEAP
  - -- JOINTS AN ISSUE HOW TO ASSEMBLE
- NEURAL NETS, FUZZY LOGIC INTERFACES/CONTROL
  - -- LIFE, CONTROL, LEARNING, TEACHING, DATA BASES, μ-SENSORS, μ-CIRCUITRY (ALSO MAY BE FOCUSED TECHNOLOGY)

WHAT IS NEEDED TO IMPROVE THE RELIABILITY OF MECHANISMS

POWER/PROPULSION

(1) BRING SPECIALISTS UP FRONT (i.e. DURING THE CONCEPTIONAL DESIGN)
(2) RIGOROUS CHECKS AND BALANCES (HELP NOT ROAD BLOCKS)
(3) INTERACTIONS AND REVIEW BY TECHNICALLY COMPETENT ENGINEERS
(4) MAINTAIN IN HOUSE (NASA) CAPABILITY
(5) REALISTIC TESTING AND SIMULATION (THEORY AND EXPERIMENTAL)
(6) FEEDBACK
(7) LONG TERM TESTING TO ASSURE DATA BASE
(8) CONCLUSION! STABILITY OF PROGRAMS
(9) RETURN TO APOLLO PHILOSOPHY!

INFORMATION TO BE INCLUDED IN A SPACE MECHANISMS DESIGN GUIDELINES HANDBOOK

POWER/PROPULSION

(1) TECHNOLOGY ITEMS
    -- MATERIALS/FABRICATIONS
    -- NDE (ACCELERATED TESTING)
    -- MONITORING TECHNIQUES
    -- OUTGASSING DOCUMENTATION
(2) LIST OF EXPERTS (DIRECTORY)
(3) DISCUSSION OF PITFALLS OF SPACE ENVIRONMENT
(4) LIST OF SUGGESTED MATERIALS/DATA
(5) EASILY AVAILABLE TO THE MASSES (FLOPPY, VIDEO, CD-ROM)
(6) DO's AND DON'TS (HANDBOOK, VIDEO, ETC.)
(7) TWO VOLUMES (COMPONENTS AND TRIBOLOGY)
(8) CONSIDER BUYING PROPRIETARY DATA
(9) OBTAIN BLACK PROGRAM DATA BASE
(10) HANDBOOK THAT IS FUNCTIONAL AND KEPT CURRENT

WHAT CAN BE DONE TO IMPROVE TECHNOLOGY DEVELOPMENT AND DISSEMINATION OF INFORMATION

POWER/PROPULSION

(1) CENTRALIZED CENTER FOR MECHANISMS/TRIBOLOGY (i.e. EUROPEANS)
(2) ANNUAL WORKSHOPS/MEETINGS
(3) CONSISTENT FUNDING (SUPPORT) FOR TECHNOLOGY ALLOW FOR BETTER PLANNING
(4) INTERNAL PRESENTATIONS SUCH AS ONR
(5) LINKING UP MECHANISMS TESTING DONE BY
  - TECHNOLOGY TESTING (GENERIC)
  - FOCUSED TESTING (COMPONENT)
  - APPLIED TESTING (MISSION, DIRECT APPLICATION)
(6) PEER REVIEW OF TECHNOLOGY PROGRAM

OTHER ISSUES

POWER/PROPULSION

- BASIC RESEARCH NEEDED FOR NEW PROPULSION SYSTEMS
- CUT RED-TAPE COSTS
- DISCUSSION ON HOW TO PRIORITIZE
    - MUST AIM AT A SPECIFIC MISSION (e.e., LUNAR LANDING MISSION)
    - LED TO SPLITTING TECH DEVELOPMENT INTO 3 GROUPS
        - TECHNOLOGY BASE (GENERIC)
        - FOCUSED TECHNOLOGY (COMPONENTS)
        - APPLIED TECHNOLOGY (MISSIONS)
- NEED FOR HEALTH MONITORING, NEURAL NETS, FUZZY LOGIC SMART SYSTEMS, EXPERT SYSTEMS, ACCELERATED TESTING FOR NDE
- ENGINEERING THE INTERFACE IS "BAND AID"
- RATHER FAIL TRYING THAN TALKING ABOUT IT
- THEME "NEED TO PUT IT WHERE YOU WANT IT WHEN YOU WANT TO, RELIABLY"

WHAT NEXT?

POWER/PROPULSION

(1) ON GOING CONFERENCE (ANNUAL)
(2) FLOPPY VIDEO HANDBOOKS
(3) QUARTERLY VIDEO CONFERENCES (NASA'S)
(4) IMPLEMENT RESEARCH IN:
  -- SMART SYSTEMS AND DATA BASE
  -- 2 PHASE FLOW
  -- WET O_2 PUMPING
  -- LIQUID METAL - SEALS AND BEARINGS
  -- DEMONSTRATE HARDWARE (PUMPS, ETC.)
(5) 20 YEAR TECHNOLOGY LEAD TIME MANDATES THAT WE START NOW TO ACHIEVE NASA's MARS/MOON MISSIONS

The responses to each objective question (discussed by the four working groups) were tabulated and prioritized according to the number of groups that thought it was an important issue. The following includes tables illustrating those responses and some written comments on each objective question.

CURRENT SPACE MECHANISMS OBSTACLES

The two obstacles mentioned by each of the four working groups were (1) deficient testing methods and (2) deficient lubrication technology for mechanisms. These appear to be the two major needs areas.

The problem with testing is that mechanisms are very systems dependent, if one test parameter is changed, one can not verify that a mechanism will operate as reliably or efficiently under the new condition. Thus, one has to ascertain that all possible operational parameters (that the mechanism will encounter) are evaluated. In addition, it is very hard to simulate a space condition in ground based testing. For example, simulating a zero-g, high vacuum environment or a dusty, wide temperature spectrum, high vacuum environment (as will be the case on the moon) is quite difficult.

Since testing involves tribological effects, the effect of atmosphere type is very important. Tests in air should not be performed unless one is absolutely certain this environment will create no unwanted additional effects. When liquid lubrication is involved there are currently no methods for accelerating the testing because the lubrication mechanism is speed dependent. Testing also must take into account vibrational effects caused during the launch of the mechanism and effects due to storage of the mechanism.

Lubrication technology for space applications has not advanced markedly in the last 20 years. The concern is that currently satellites are being put into orbit with the expectation that they will last for longer periods of time and demanding minimal contamination by outgassing of lubricants. Solid lubricants would be ideal, but generally they have limited life. In addition, those that work well in a vacuum usually do not function well in an air environment, and vice versa. New liquid lubricants have been developed with very low vapor pressures, but they have a tendency to break-down under boundary lubrication conditions and thus their life is unreliable. There are other liquid lubricant candidates for space applications, but the problem is that minimal testing has been done for space qualification or the information on them is proprietary. In the propulsion area, lubrication and testing in LOX has been a problem. And for planetary surfaces, we have no experience in operating mechanical equipment in very cold, dusty, high vacuum, or corrosive environments.

The next most mentioned area was a lack of communication or lack of data sharing. Three of the four groups mentioned this. The Aerospace Mechanisms Symposium is held every year by NASA, but it was felt that this symposium dealt more with design issues than with technology issues and was not much benefit in disseminating technology information. Three of the four groups also mentioned mechanism design methods. It was felt that new or innovative methods need to be developed. It remains to be seen how to accomplish this?

Two of the four groups mentioned quality control methods, space environmental effects and mechanisms materials as being obstacles. The current state of tribology is such that the performance of many lubricants is dependent more on how they are applied than on what is applied. Similarly with producing quality bearings, gears, etc. for space applications. It is important that these parts are produced according to specifications, thus good quality control practices are required. It is becoming more difficult to find good suppliers. Not many materials are space qualified for mechanisms applications. Because materials are qualified for structural applications, designers often choose such materials, even though tribologically speaking they are poor choices, they are selected only because they are "space qualified". Space environmental effects on mechanisms and lubricants are, for the most part, indeterminate, especially on the moon or Mars.

The other deficient areas mentioned at least once by one of the groups, were: analytical models, storage methods, unknown failure mechanisms, and consistent funding. Basically there are very few analytical models to predict a mechanisms performance or how long it will operate. There is a lack of information on how storage will affect the performance or endurance of mechanisms. We do not know how many mechanisms fail when tribology problems occur. And finally, it was felt that the key to improving the operation of space mechanisms was to have consistent funding from NASA Headquarters in this area.

SPACE MECHANISMS TECHNOLOGY NEEDS

The technology needs that were discussed for the most part parallel the obstacles listed, however, the technology need responses tended desirable specific areas that were not mentioned in the obstacle discussions. Improved lubricating systems and accelerated testing techniques were listed by all groups. Improved component materials was listed by 3 groups although only 2 groups mentioned materials as an obstacle. Two groups mentioned better design processes, knowledge of failure modes and environmental simulation as technology needs. Analytical models, historical data, testing methods, rotating machinery, pumps, solar and nuclear electric, transmissions, and boosters were mentioned by at least one group.

HOW DO WE IMPROVE THE RELIABILITY OF MECHANISMS

The power and propulsion group was the only group that had sufficient time to address the reliability of mechanisms issue, however their responses are very applicable to the other discipline areas. They felt that: (1) a specialist in mechanical components and lubrication should be involved during the conceptual design phase of any project NASA should supply these specialists or have a list of approved specialists. (2) A system incorporating a rigorous systems of checks and balances should be established. (3) All plans should be reviewed by technically competent engineers. (4) NASA needs to maintain a strong in-house capability to guide and direct contractors as well as to develop needed technology. (5) Realistic testing and simulation of the hardware should be conducted. (6) Long term testing is needed to establish and assure a data base. (7) While NASA's overall missions may change, research and technology in key technological disciplines (such as mechanisms) which are important to many programs should be maintained and stabilized. (8) Finally it was felt that we should return to the "Apollo Philosophy".

WHAT SORT OF INFORMATION SHOULD BE IN A SPACE MECHANISMS GUIDELINES HANDBOOK

All the groups felt a space mechanisms guidelines handbook was a good idea. It was also felt that this document should be a "living" document, being continuously updated as new technology and techniques are developed. A large number of items were listed by each group as to the type of information that should be included in this manual. The responses varied somewhat depending upon the discipline and background of the group participants, but everyone agreed that points of contacts or experts in various disciplines was one of the most important items that should be included. The next most important item concerned environmental effects that should be taken into account. Two of the groups suggested that some case histories should be included. The rest of the items mentioned by the groups are listed in the enclosed table.

HOW CAN TECHNOLOGY DEVELOPMENT AND THE DISSEMINATION OF INFORMATION BE IMPROVED

The number one suggestion for improving technology development and the dissemination of information was to establish a lead or central repository. An important consideration that came out of this workshop was that mechanisms technology is very generic. Technology developed for the satellite industry can also be applied to planetary surface operations as well as to power and propulsion problems. It would be beneficial to have one center correlate all the mechanisms work which would apply to all the agency needs. This would reduce costs as well as reduce the duplication of research. It was also felt that regular meetings such as this workshop need to be conducted to foster the exchange of information. It may be possible to have seminars or sessions at engineering conferences that deal with space mechanisms. A number of other items were discussed and they are listed in the enclosed table.

OTHER ISSUES

The groups were also asked to list other issues that they perceived to be important but were not covered in the objective questions given to the groups. Each group tended to have its own issues. The only issue mentioned by two groups was that better military-civilian cooperation is needed in the satellites area. Various areas were discussed ranging from how to advocate a space mechanisms program to very specific technology issues such as the need for smart systems. The issues listed by the groups can be reviewed in the enclosed table.

WHAT NEXT

All four working groups indicated that the first task that should be done in the space mechanisms area is to initiate a space mechanisms handbook. (Note: the production of that handbook is currently underway, being sponsored by Code Q at NASA Headquarters.) The next task that all of the groups agreed upon was that some forum which would permit regular discussions should be established. Three of the groups stated that regular meetings should take place and three said that a permanent advisory committee or working group should be formed. Other items that should be considered include: have cooperative programs, catalog capabilities (personnel and facilities), establish a lead center, have video conferences, develop a newsletter, etc. The table on "What's Next" includes all the items mentioned by the groups.

The Workshop ended with Professor Theo Keith of the OAI outlining a possible plan whereby industry, government and universities could network though OAI to develop educational courses, handbooks, computer databases, etc. (see accompanying figure). Professor Keith also outlined a plan whereby the workshop could lead to a steering group and then to a space mechanisms advisory group to help advocate a program, to form coalitions, form agendas and improve communication between industry, government and universities (see attached figure).

COMPILATION OF OBSTACLES LISTED BY SPACE MECHANISMS WORKING GROUPS

OBSTACLES (DEFICIENT AREAS)	SATELLITES #1	SATELLITES #2	POWER/ PROPULSION	PLANETARY SURFACES	TOTALS
TESTING METHODS	X	X	X	X	4
LUBRICATION TECHNOLOGY	X	X	X	X	4
DATA SHARING (LACK OF COMMUNICATION)	X	X		X	3
MECHANISMS DESIGN MECHANISMS	X	X		X	3
MECHANISMS MATERIALS		X		X	2
QUALITY CONTROL METHODS		X	X		2
SPACE ENVIRONMENTAL EFFECTS	X			X	2
ANALYTICAL MODELS	X				1
STORAGE METHODS	X				1
CONSISTENT FUNDING		X			1
UNKNOWN FAILURE MECHANISMS	X				1

COMPILATION OF TECHNOLOGY NEEDS LISTED BY SPACE MECHANISMS WORKING GROUPS

TECHNOLOGY NEEDS	SATELLITES #1	SATELLITES #2	POWER/ PROPULSION	PLANETARY SURFACES	TOTALS
IMPROVED LUBRICATING SYSTEMS	X	X	X	X	4
ACCELERATED TESTING TECHNIQUES AND NDE	X	X	X	X	4
IMPROVED COMPONENT MATERIALS		X	X	X	3
BETTER DESIGN PROCESSES	X			X	2
ENVIRONMENTAL SIMULATION	X			X	2
KNOWLEDGE OF FAILURE MODES	X			X	2
ANALYTICAL MODELS	X				1
HISTORICAL DATA				X	1
TESTING METHODS				X	1
ROTATING MACHINERY	X				1
PUMPS	X				1
SOLAR AND NUCLEAR ELECTRIC	X				1
TRANSMISSIONS	X				1
BOOSTERS	X				1

COMPILATION OF ITEMS MENTIONED BY THE SPACE MECHANISMS WORKING GROUPS THAT SHOULD BE IN A HANDBOOK

HANDBOOK ITEM	SATELLITES #1	SATELLITES #2	POWER/ PROPULSION	PLANETARY SURFACES	TOTALS
POINTS OF CONTACT (EXPERTS)	X	X	X	X	4
ENVIRONMENTAL EFFECTS FACTORS	X		X	X	3
SHOULD BE A "LIVING" DOCUMENT	X		X		2
VOLUNTARY SOURCE LIST	X	X			2
CASE STUDIES OF HISTORIES	X			X	2
QUALIFICATION OF LIMITATIONS	X				1
EASILY ACCESSIBLE (FLOPPY, VIDEO, CD ROM)			X		1
SPECIFICATIONS OF LIMITS	X				1
FAILURE CRITERIA	X				1
PROVISION FOR REPORTING SUCCESSES/FAILURES	X				1
GENERIC DESCRIPTIONS	X				1
ANALYTICAL TOOLS (MODELS)	X				1
MODEL DESIGN PROCESS	X				1
CURRENT TESTING CAPABILITY		X			1
MATERIALS/SPECIFICATIONS			X		1
MONITORING TECHNIQUES			X		1
OUTGASSING INFORMATION			X		1
ACCELERATED TESTING METHODS			X		1
DO'S AND DON'TS			X		1
PAPER REFERENCES				X	1
LESSON LEARNED STUDY				X	1
STATISTICAL DATA				X	1
COLLECTION OF WORKING DATA				X	1
COMPONENT INFORMATION				X	1

COMPILATION OF ITEMS LISTED BY THE SPACE MECHANISMS WORKING GROUPS THAT WOULD IMPROVE TECHNOLOGY DEVELOPMENT AND THE DISSEMINATION OF INFORMATION

ITEM	SATELLITES #1	SATELLITES #2	POWER/ PROPULSION	PLANETARY SURFACES	TOTALS
ESTABLISH A LEAD CENTER OR CENTRAL REPOSITORY	X	X	X	*	3
LONG TERM FUNDING COMMITMENT	X		X		2
ENHANCE INFORMATION EXCHANGE	X	X			2
HOLD REGULAR MEETINGS		X	X		2
DECLASSIFY TECHNICAL INFORMATION	X				1
OPEN UP PROPRIETARY FILES	X				1
EXCHANGE EACH OTHERS REFERENCES	X				1
IMPROVE SPEED AND ACCESS OF PUBLICATIONS	X				1
DEVELOP A HANDBOOK		X			1
CASE HISTORY/LESSONS LEARNED STUDY		X			1
INTERNAL PRESENTATIONS			X		1
LINK UP TECHNOLOGY, FOCUSED AND APPLIED MECHANISMS TESTINGS			X		1
PEER REVIEW THE TECHNOLOGY			X		1

* Planetary Surfaces group did not have time to address this questions.

COMPILATION OF IDEAS ON HOW TO IMPROVE THE RELIABILITY SPACE MECHANISMS

IDEA	SATELLITES #1	SATELLITES #2	POWER/ PROPULSION	PLANETARY SURFACES
BRING SPECIALIST IN DURING CONCEPTUAL DESIGN PHASE	*	*	X	*
RIGOROUS CHECKS AND BALANCES			X	
INTERACTIONS AND REVIEW BY TECHNICALLY COMPETENT ENGINEERS			X	
MAINTAIN AN IN HOUSE (NASA) CAPABILITY			X	
REALISTIC TESTING AND SIMULATION (THEORY AND DESIGN)			X	
LONG TERM TESTING TO ASSURE DATA BASE			X	
STABILITY OF PROGRAMS!			X	
RETURN TO APOLLO PHILOSOPHY!			X	

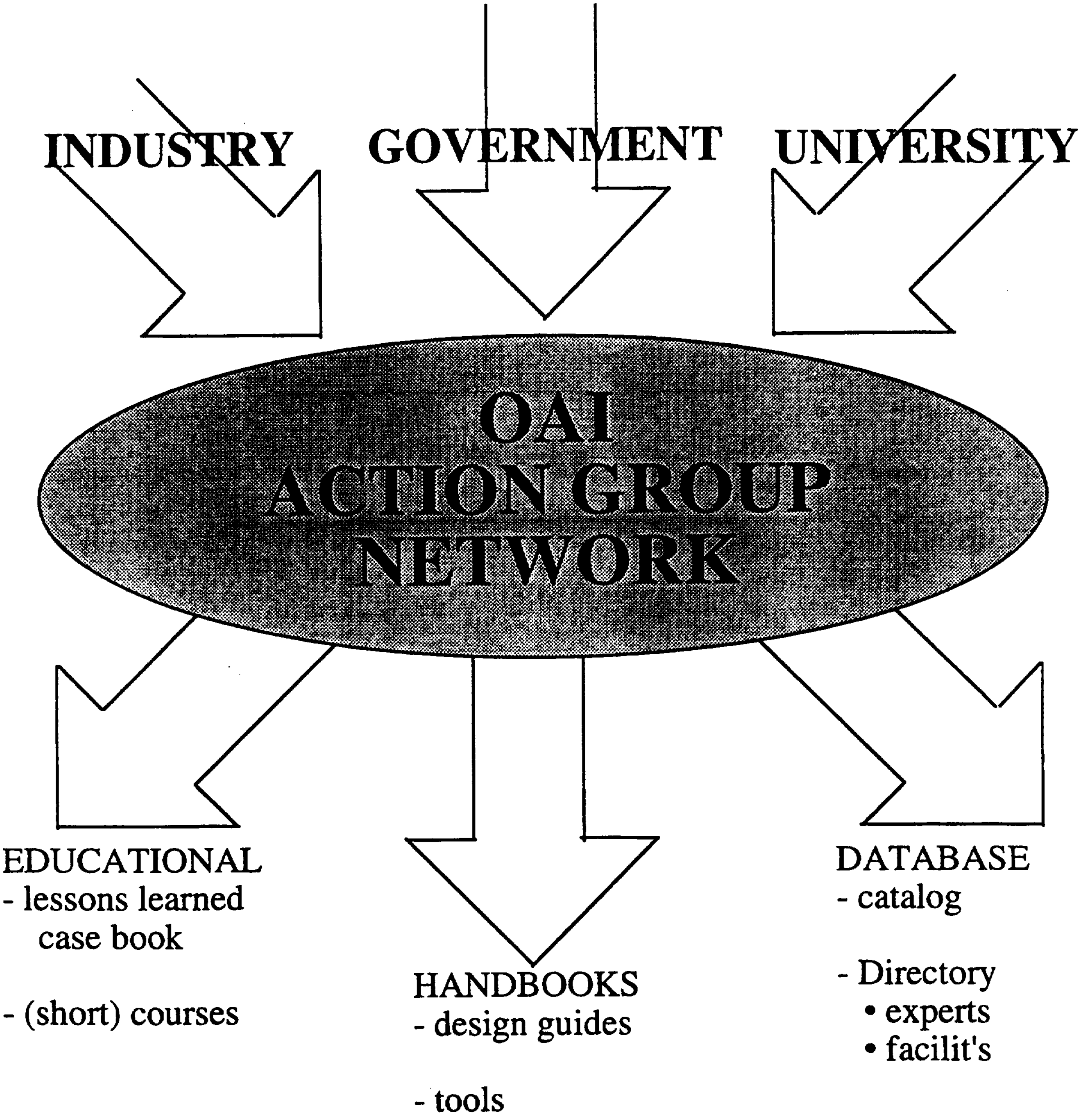
* THESE GROUPS DID NOT HAVE TIME TO ADDRESS THIS QUESTION

COMPILATION OF ISSUES LISTED BY SPACE MECHANISMS WORKING GROUPS

ISSUE	SATELLITES #1	SATELLITES #2	POWER/ PROPULSION	PLANETARY SURFACES	TOTALS
MILITARY-CIVILIAN COOPERATION	X	X			2
AIRCRAFT INDUSTRY MODEL FOR FUNDING	X				1
BIG BUCKS NEEDED FOR HANDBOOK	X				1
REGULATORY ISSUES (CONSTRAINTS)	X				1
COHESIVE LONG TERM PLAN NEEDED	X				1
ENCOURAGE CAREER DEVELOPMENT	X				1
LONG TERM TECH BASE SHOULD BE DEVELOPED	X				1
GET SUPPORT LETTERS FROM INDUSTRY		X			1
FORM AN INDUSTRY ADVISORY BOARD		X			1
BASIC RESEARCH NEEDED FOR NEW PROPULSION SYSTEMS			X		1
CUT RED TAPE COSTS			X		1
MUST AIM AT SPECIFIC MISSIONS			X		1
NEED FOR SMART SYSTEMS			X		1
RATHER FAIL TRYING THAN TALKING ABOUT IT			X		1
ENGINEERING INTERFACE IS A BANDAID			X		1
ESTABLISH A PLANETARY DATA BASE OF INFORMATION				X	1
DEVELOP A COMMON USE OF COMPONENTS				X	1
PIGGY BACK TECHNOLOGY EXPERIMENTS ON SCIENCE MISSIONS				X	1

COMPILATION OF ITEMS THAT SPACE MECHANISMS WORKING GROUPS STATED SHOULD BE DONE NEXT

WHAT NEXT? ITEM	SATELLITES #1	SATELLITES #2	POWER/ PROPULSION	PLANETARY SURFACES	TOTALS
SPACE MECHANISM HANDBOOK	X	X	X	X	4
PERMANENT ADVISORY COMMITTEE OR WORKING GROUP	X	X		X	3
REGULAR MEETINGS	X		X	X	3
COOPERATIVE PROGRAMS	X				1
CATALOG OF CAPABILITIES (PERSONNEL & FACILITIES)	X				1
DEVELOP A FOLLOW UP PLAN SCHEDULE	X				1
ESTABLISH A LEAD CENTER		X			1
FOLLOW THE EUROPEAN SPACE AGENCY EXAMPLE		X			1
VIDEO CONFERENCES			X		1
IMPLEMENT RESEARCH			X		1
A NEED TO START NOW--20 YEAR LEAD TIME			X		1
DEVELOP A NEWSLETTER				X	1
SELECT BEST CANDIDATE AND BUILD A CASE FOR FUNDING				X	1



INDUSTRY **GOVERNMENT** **UNIVERSITY**

OAI ACTION GROUP NETWORK

EDUCATIONAL
- lessons learned
  case book

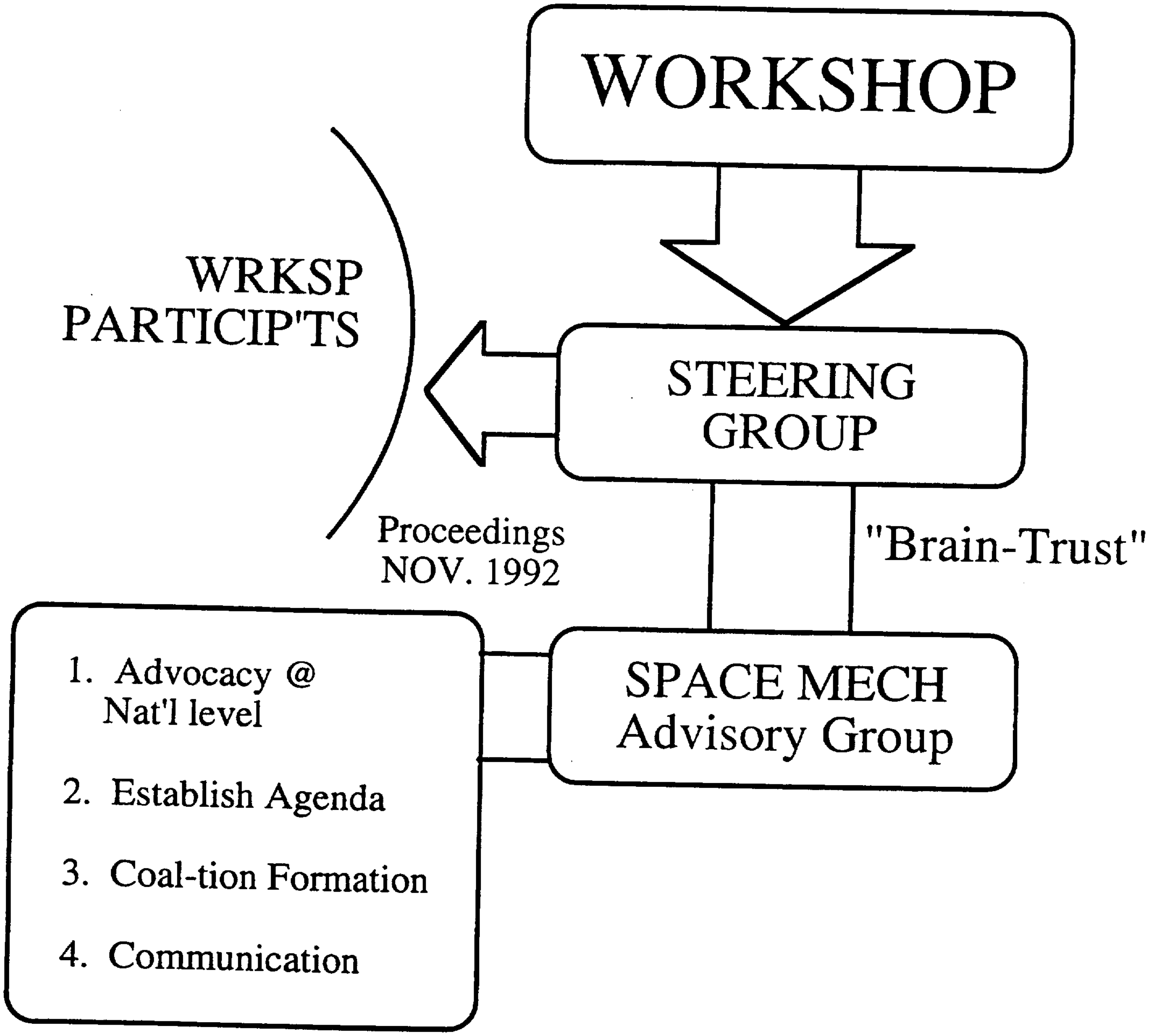
- (short) courses

HANDBOOKS
- design guides

- tools

DATABASE
- catalog

- Directory
  • experts
  • facilit's



WORKSHOP

WRKSP
PARTICIP'TS

STEERING
GROUP

Proceedings
NOV. 1992

"Brain-Trust"

SPACE MECH
Advisory Group

1. Advocacy @
   Nat'l level
2. Establish Agenda
3. Coal-tion Formation
4. Communication

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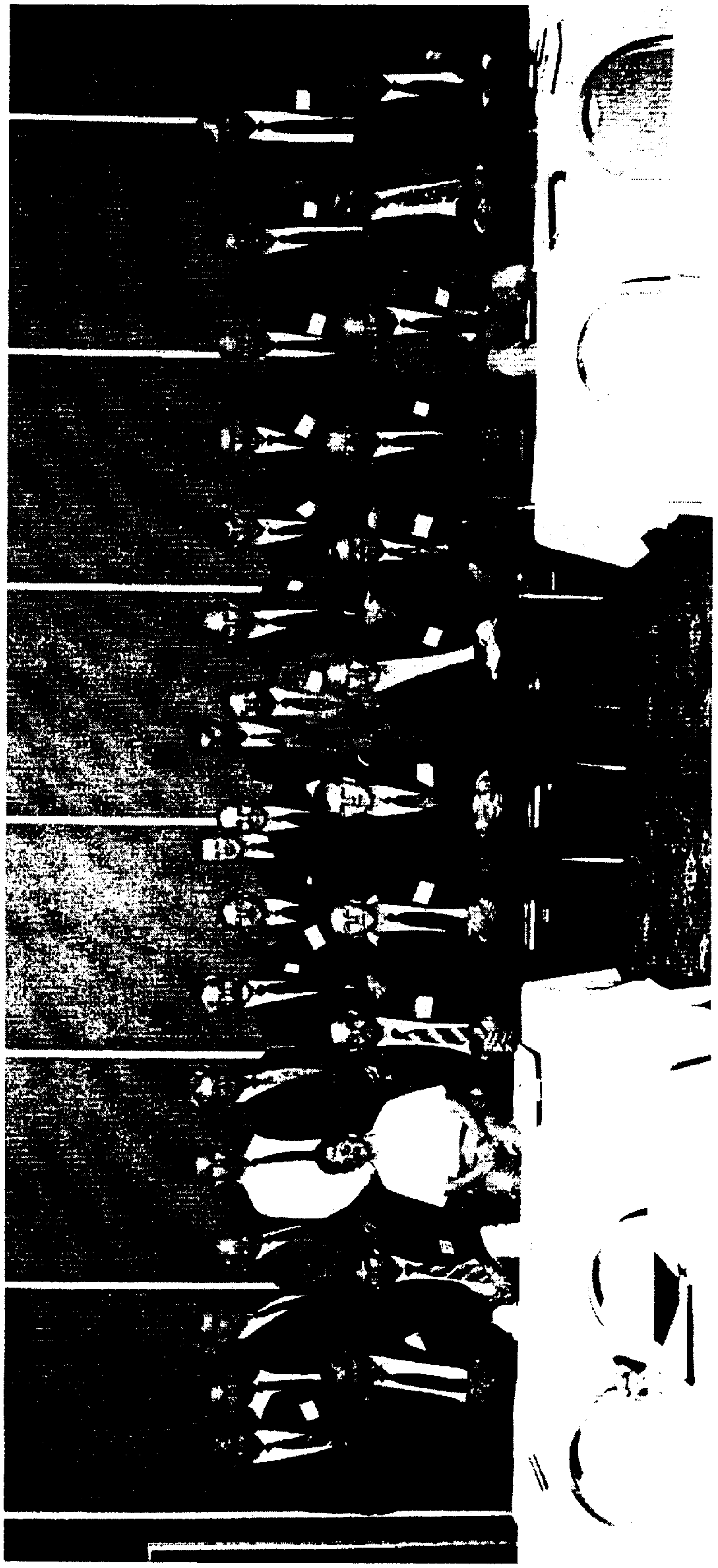

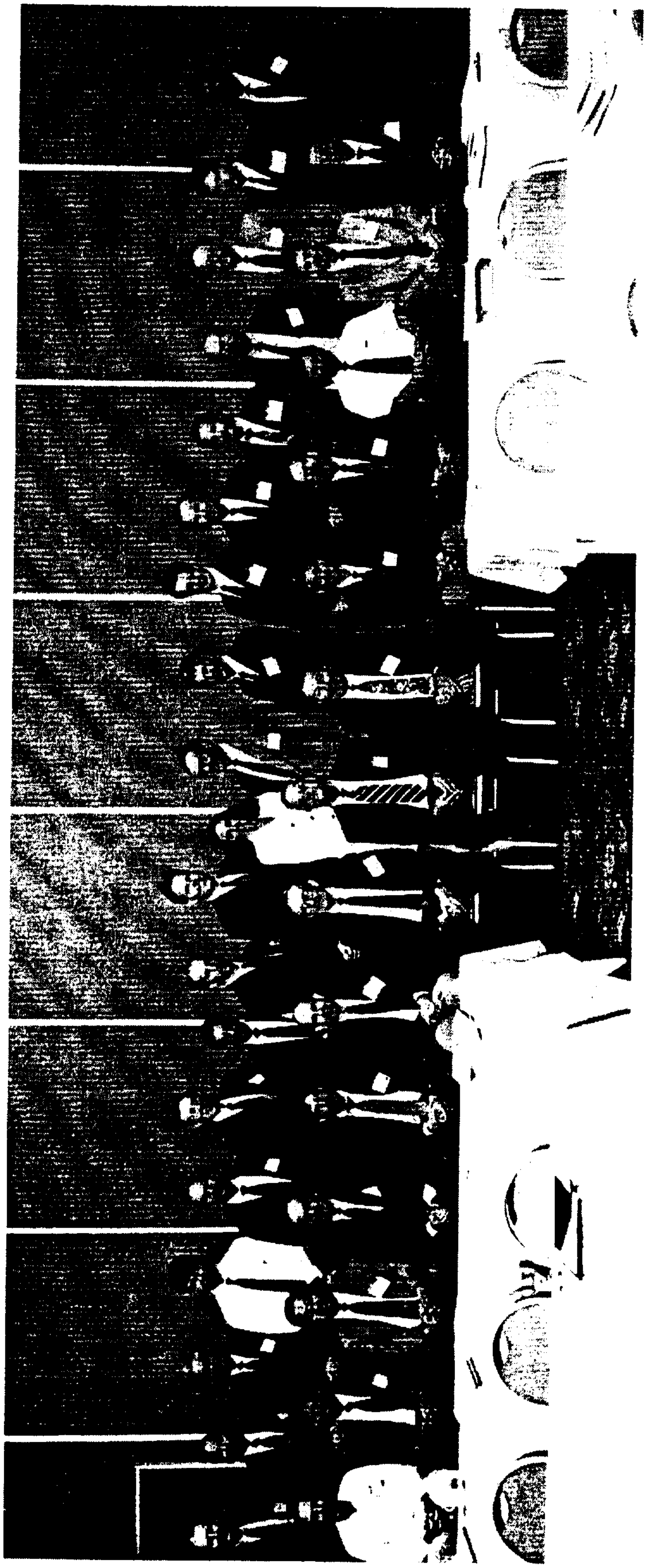

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13. ABSTRACT ***(Maximum 200 words)***

Over the years, NASA has experienced a number of troublesome mechanism anomalies. Because of this, the NASA Office of Safety and Mission Assurance initiated a workshop to evaluate the current space mechanism state-of-the-art and to determine the obstacles that will have to be met in order to achieve NASA's future missions goals. The workshop was co-sponsored by NASA/Lewis Research Center and the Ohio Aerospace Institute (OAI) and was held at the Holiday Inn in Westlake, Ohio. Seventy experts in the field attend the workshop. The experts identified current and perceived future space mechanisms obstacles. For each obstacle, the participants identified technology deficiencies, the current state-of-the-art, and applicable NASA, DOD, and industry missions. In addition, the participants at the workshop looked at technology needs for current missions, technology needs for future missions, what new technology is needed to improve the reliability of mechanisms, what can be done to improve technology development and the dissemination of information, and what do we do next.

14. SUBJECT TERMS

Mechanisms; Systems; Problems; Space; Mechanical components; Tribology; Lubrication; Deployables

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