NASA Conference Publication 3361

1997 Spacecraft Contamination and Coatings Workshop

Organized by
Philip T. Chen
Steve M. Benner
NASA Goddard Space Flight Center
Greenbelt, Maryland

Sponsored by
National Aeronautics and Space Administration,
Office of Space Science,
Space Environments and Effects Program

National Aeronautics
and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

1997

RELEASE FORM FOR PUBLICATION MATERIALS

I hereby grant my permission to publish my presentation materials in the 1997 Spacecraft Contamination & Coatings Workshop Proceedings. The title of my presentation is "Advanced Conductive Thermal Control Material Systems".

Mr. Mike Deshpande
ITT Research Institute
10 West 35th Street
Chicago, IL 60616

Date: 9/30/97

RELEASE FORM FOR PUBLICATION MATERIALS

I hereby grant my permission to publish my presentation materials in the 1997 Spacecraft Contamination & Coatings Workshop Proceedings. The title of my presentation is "AO and VUV Resistant TOR and COR Polymers for Space Applications".

Dr. Allan Shepp
Triton Systems, Inc.
114 Turnpike Road
Chelmsford, MA 01824

Date: Oct 6, 1997

This publication is available from the NASA Center for AeroSpace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934, (301) 621-0390.

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PREFACE

The workshop was a two-day meeting sponsored by the Space Environments and Effects (SEE) Program. The SEE program is a major activity under the Advanced Technology and Missions Studies Division of the NASA Office of Space Science. The objective of the workshop is to provide a forum for exchanging new developments in spacecraft contamination and coatings.

The workshop was attended by representatives from NASA, JPL, DoD, industry, and universities concerned with the spacecraft contamination engineering and thermal control coatings. Approximately 130 people attended the Workshop and participated in technical sessions and round table discussion.

The workshop was organized by Drs. Philip Chen and Steve Benner of the Thermal Engineering Branch at the Goddard Space Flight Center (GSFC). Four technical sessions were chaired by Ms. Eve Wooldridge, Ms. Sharon Straka, Mr. Randy Hedgeland, and Mr. Lon Kauder of GSFC. Administrative and logistics support was provided by Ms. Jessica Katz of GSFC and Ms. Sharland Norris of Jorge Scientific Corporation.

Single copies of this document can be obtained by writing to

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1997 SPACECRAFT CONTAMINATION AND COATINGS WORKSHOP

July 9, 1997

7:30 - 8:30	Badging	
8:30 - 8:45	Welcome and Administrative Items	Dennis Hewitt/Steve Benner *NASA/GSFC*
8:45 - 9:00	Opening Remarks	Peter Ulrich *NASA/HQ/S*

SPACECRAFT CONTAMINATION ENGINEERING

Chairperson: Eve Wooldridge

9:00 - 9:30	NASA Space Environments and Effects Program Overview	Stuart Clifton *NASA/MSFC*
9:30 - 10:00	Current and Future Spacecraft Contamination Control Engineering	Philip Chen *NASA/GSFC*
10:00 - 10:30	Effects of Contamination on Optical Performance in the EUV	Ritva Keski-Kuha *NASA/GSFC*
10:30 - 10:45	Break	
10:45 - 11:15	Active Contamination Control	Charles Stein *Phillips Laboratory*
11:15 - 11:45	Contamination Research at Aerospace Corporation	David Hall/Graham Arnold *Aerospace Corporation*
11:45 - 1:00	Lunch	
		Chairperson: Sharon Straka
1:00 - 1:30	Space Technology Research Vehicle 2 Contamination Control	Ranty Liang/James Kenny *NASA/JPL* John Stubstad *BMDO*
1:30 - 2:00	MSX Mission Flight Data	Manual Uy *JHU/APL*
2:00 - 2:30	LDEF Materials/Contamination	Gary Pippin *Boeing Defense & Space Group*
2:30 - 3:00	Contamination and Thermal Control Coating Activities for the International Space Station at MDA	Hank Babel *McDonnell Douglas*
3:00 - 3:15	Break	
3:15 - 3:45	Current Modeling Tools and Applications	Shaun Thomson *NASA/GSFC*
3:45 - 4:15	Contamination Edition of the Environment WorkBench	Barbara Gardner/Gary Jongeward *Maxwell Technologies*
4:15 - 4:45	MSFC Contamination Control Overview	DeWitt Burns *NASA/MSFC*

1997 SPACECRAFT CONTAMINATION AND COATINGS WORKSHOP

July 10, 1997

8:00 - 8:30	Badging	Chairperson: Randy Hedgeland
8:30 - 9:00	Contamination Control for Interplanetary Spacecraft	Jack Barengoltz *NASA/JPL*
9:00 - 9:30	Space Environmental and Contamination Effects on Optical Surfaces - Both Cryogenic and Warm	Bob Wood *Arnold Air Force Base/Micro Craft Technology*
9:30 - 10:00	Application of ASTM E 1559 for Material Characterization	Jeff Garrett *Lockheed Martin Missiles & Space*
10:00 - 10:30	A Pragmatic Approach to Contamination Control, Program Management and Development	Barry Greenberg *ManTech Systems Engineering Corporation*
10:30 - 10:45	Break	

THERMAL CONTROL COATINGS

		Chairperson: Lon Kauder
10:45 - 11:15	The GSFC Solar Wind and Calorimetric Facility	Lon Kauder *NASA/GSFC*
11:15 - 11:45	Degradation of HST External Multi-layer Insulation Material	Yuke Yoshikawa *Lockheed Martin Missiles & Space* Jack Triolo *Swales Aerospace* Patricia Hansen *NASA/GSFC*
11:45 - 1:00	Lunch	
1:00 - 1:30	Thermal Control Coatings Development at the GSFC	Wanda Peters/George Harris *NASA/GSFC*
1:30 - 2:00	Electrochromic Coatings	Stuart Cogan *EIC Laboratories Inc*
2:00 - 2:30	New Thermal Control Coatings from AZ Technology	Donald Wilkes/Richard Mell/ Randell Thompson/*AZ Technology*
2:30 - 3:00	IITRI Thermal Control Coatings	Mike Deshpande *IIT Research Institute*
3:00 - 3:30	AO and VUV Resistant Films and Coatings for MLIs and Inflatables	Ross Haghighat/Allan Shepp/ John Lennhoff/Peter Schuler *Triton Systems, Inc.*
3:30 - 3:45	Break	
3:45 - 5:00	Round Table Discussion	*All*
5:00	Adjourn	

GSFC
Thermal Engineering Branch
-Code 724-

Overview Presentation to Spacecraft Contamination and Coatings Workshop

7/9/97

D. Hewitt/Branch Head

T. Swanson/Assistant Branch Head

GSFC
Thermal Engineering Branch
-Continued-

- **Staff;**
  - 46 Civil Servants; 42 engineers/analysisists, 3 technicians, 1 clerical
  - approximately 20 on-site contractors
- **Facilities - approx. 10,000 sq ft lab space**
  - Properties measurements
  - Coatings applications
  - Contamination measurements
  - Technology development

GSFC
Thermal Engineering Branch
-Overview-

- **Single point of Thermal Support for virtually all flight projects at GSFC.**
  - Conceptual design studies, design, detailed analysis, supervision of fab and I&T, launch/initial flight operations support.
- **Single point for Contamination Support at GSFC**
  - Requirements definition, contamination plan, analysis, supervision of plan implementation, hands-on support, monitoring/certification of flight worthiness.
- **Significant advanced technology development effort**
  - Definition, testing, flight experiments

Technology Development in the New NASA

1997 Spacecraft Contamination & Coatings Workshop
Annapolis, MD
July 9, 1997

Peter B. Ulrich
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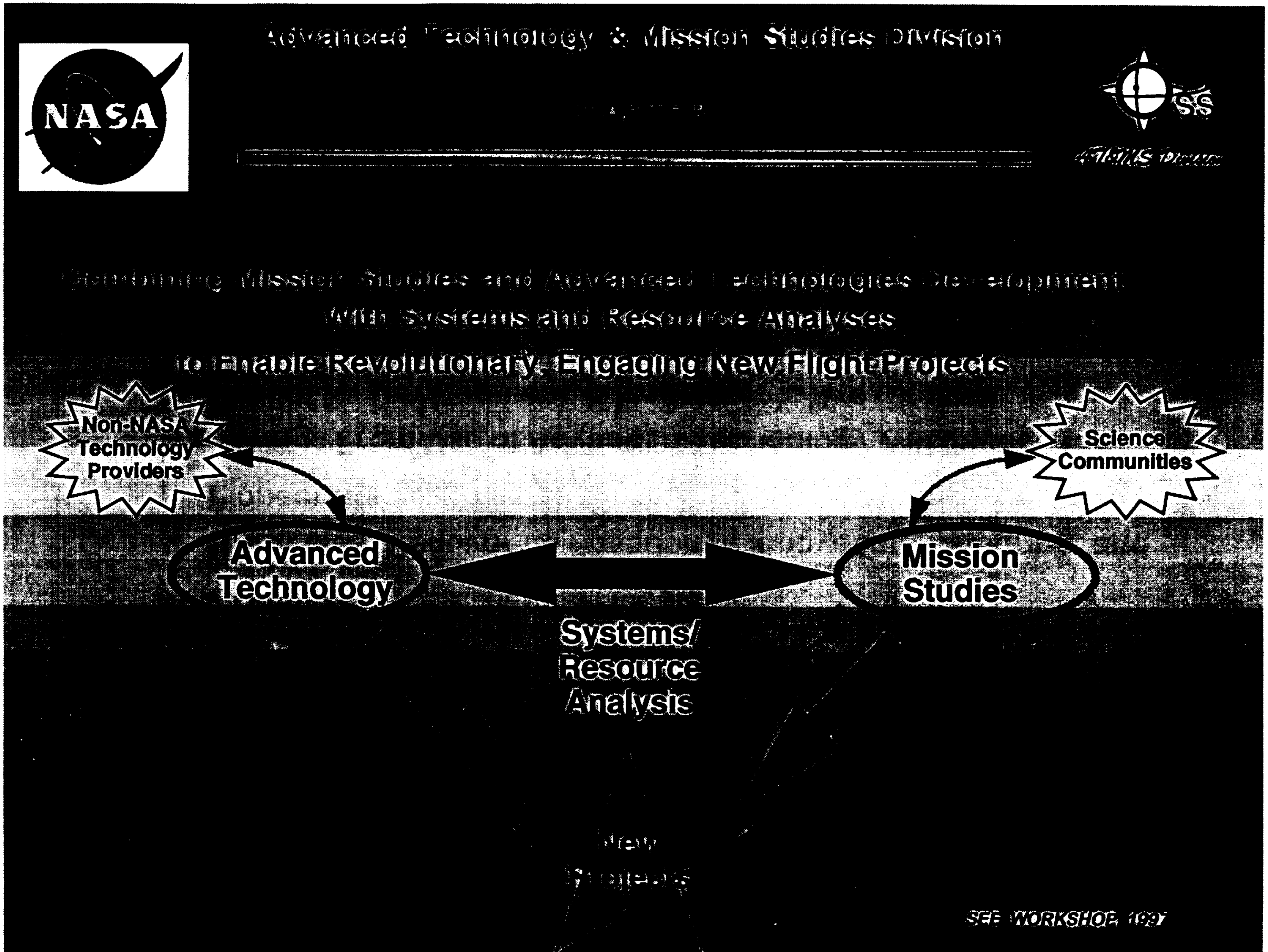
Advanced Technology & Mission Studies Division
Combining Mission Studies and Advanced Technologies Development
With Systems and Resource Analyses
to Enable Revolutionary, Engaging New Flight Projects
Non-NASA Technology Providers
Science Communities
Advanced Technology
Mission Studies
Systems/ Resource Analysis
New Projects
SEE WORKSHOP 1997

Technology Will Enable Low Cost Missions

AT&MS Division

- Low Cost Missions Are Vital to the Survival of Space Science and to the Nurturing of a Vital Space Science Community
- New Technology Is Essential Because:
  - NASA Must Recover Its Function of Innovating, Exploring, and Pioneering
  - Savings From Use of Advanced Technology Will Exceed the Cost of Its Development, If Investments Are Chosen Judiciously
    - Example: New, Low-Power VLSI Permits Mass Savings Which Can Then be Allocated to Risk Reduction (Such As Radiation Shielding or Added Redundancy)

NEW ROLE OF TECHNOLOGY DEVELOPMENT

(Chief Technologist, 1/97)

ATOMS Division

- Elevates Technology from "Problem Solver" to "Driver"

- ENTERPRISES Will *Develop and Integrate* Technology for their MIssions
  - *Balance* Near, Mid, and Long Term Needs
  - Conduct *Advanced Concept* Studies
  - Adopt *Revolutionary* Architectures and Systems
- Common Cross-cutting Technologies Maintained by OSS (Code SM)
  - Requirement: *Strong Core Capability Across Enterprises*
- Broad-based *Industry Benefit* From Long-range NASA Investment
  - NASA: >3 years; Industry: 1-3 years
- Office of the Chief Technologist Established to Provide *Integrated "Corporate" Leadership*

SEE WORKSHOP, 1997

New Vision for Implementing Space Science Missions

ATEMS Division

CHARACTERISTICS OF CURRENT MISSIONS	REVOLUTIONARY EXPANDING VISION
Planetery Remote Observation	Virtual Presence
Planetary Reconnaissance	Detailed *In Situ* Exploration
Only Single S/C Missions	S/C Constellations
Heavy, Complex S/C	Small Modular *Science*craft
Data Collection	Information Products
Technology to Enhance Performance	Technology to Enable Imaginative Missions
Contracting	Partnerships
Labor-intensive Ground Control	Autonomous Spacecraft Control
Risk Avoidance	Risk Management
Conservative Designs	Rapid Infusion of New Technology

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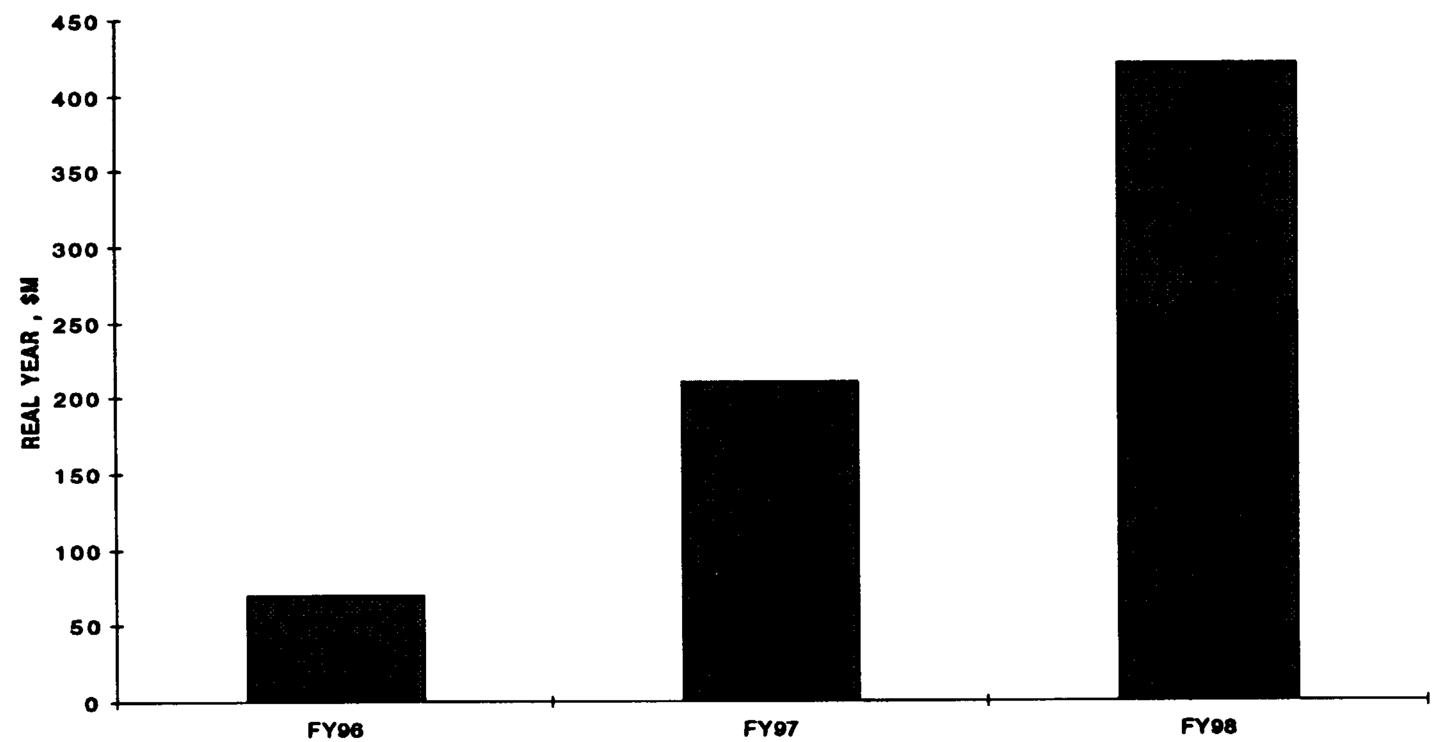
Technology Development Shows Dramatic Growth

AT&MS Division

AT&MS DIVISION BUDGET GROWTH



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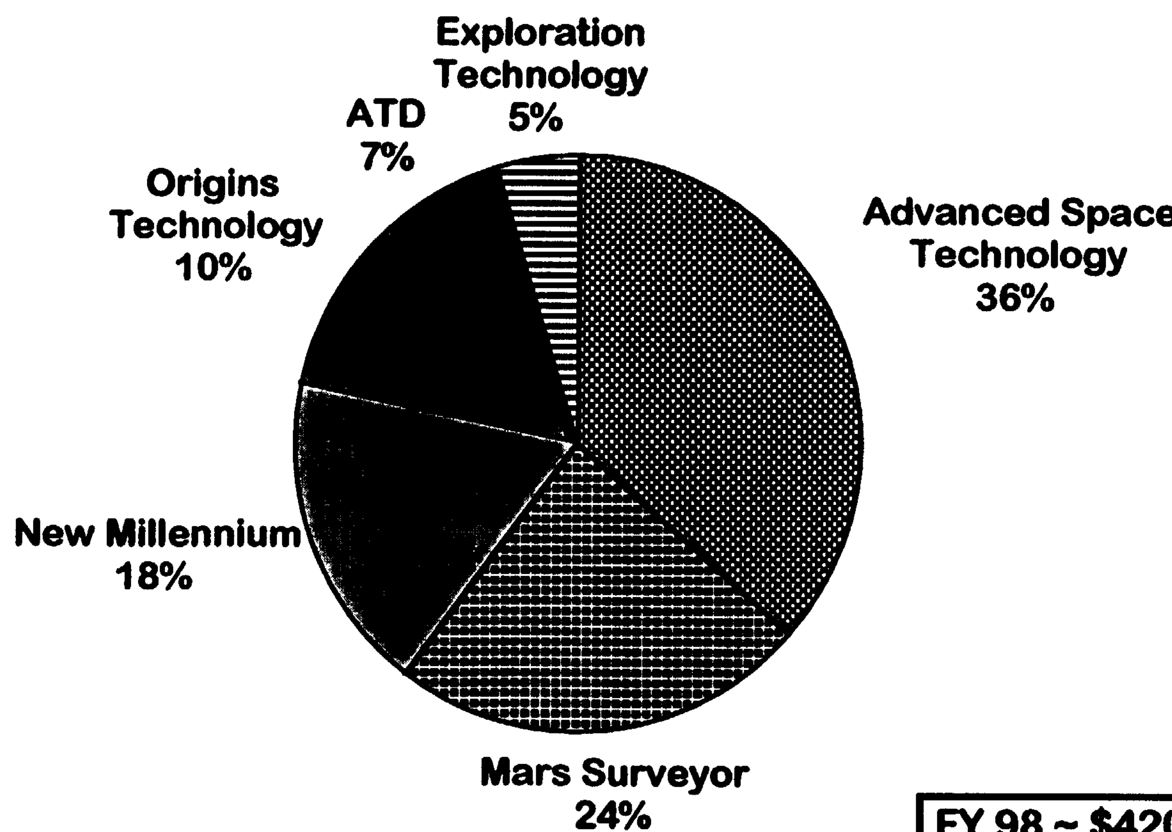
Advanced Technology & Mission Studies
FY1998 Budget

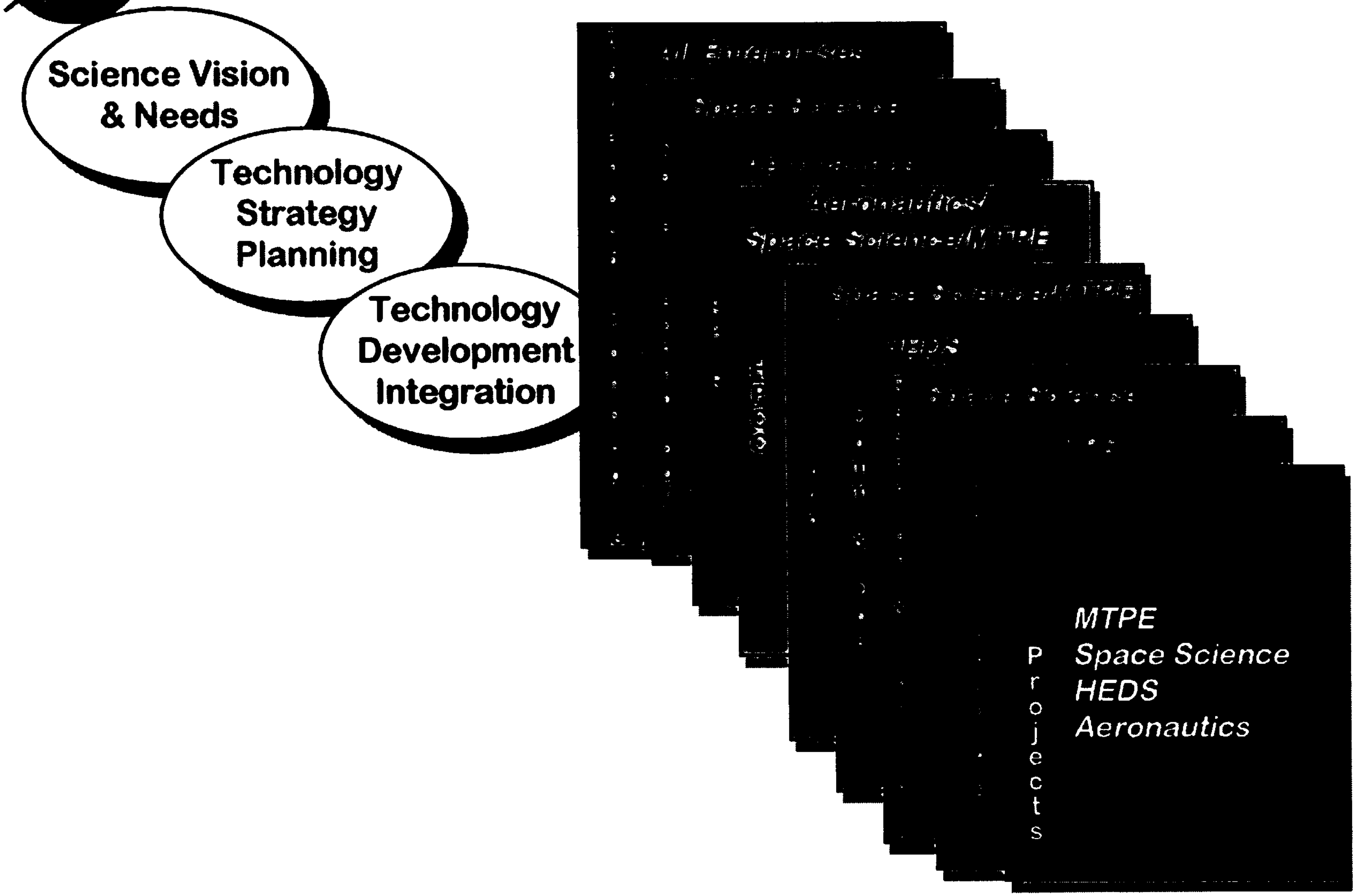
ATBMS Division



FY 98 ~ $420M

NASA Technology is Widely Distributed Among Enterprises

AT&MS Division



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Context for the NASA *Crosscutting* Technology Program

AT&MS Division

MAXIMIZE INVESTMENT PAYOFF
BY AVOIDING DUPLICATION
THROUGH COOPERATION,
LEVERAGING, PARTNERSHIPS

Billions	International (Japan, Europe, Russia, Canada, etc)
Billions	Industry (Info Tech, Comm, Robotics, Avionics, etc.
Billions	Industry IR&D
Billions	Non DoD Agencies (NSF, DOE, etc)
Billions	DoD Classified R&D
Billions	Other DoD (DARPA, Projects, etc.
~$350M	DoD Space Technology (Laboratories)
~$100M	NASA Reimbursable Technology Development
$850M	Relevant NASA Aeronautics Technology (RLV, Base, etc)
$110M	HPCC
$125M	SBIR
~$250M	Code SD Projects (Incl. NMP)
~$200M	Code SR grants (~$25M Technology?)
$150M	**Code SM (was Code XS)**

Code SM areas:
- Instruments
- Spacecraft Systems
- Communications
- Autonomy & Information Mgmt
- Telerobotics

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Strategy for *Concurrent & Distributed* Management

AT&MS Division

HORIZONTAL

(Cross-Enterprise)

- Joint Enterprise Strategy Team (JEST)
  - Chaired by Director of Code SM
  - Membership: Technology Lead from Each HQ Enterprise Office (S,Y,M,U,R) and Directors of Center Technology Offices
  - Charter: Policy, Coordination, Oversight, Conflict Resolution

VERTICAL

(HQ - Centers: Mission Requirements & TechnologyDevelopment)

- Joint Planning Teams (JPT's)
  - Vertically Integrate HQ and Center Functions - all "Levels" have a role
  - One JPT for Each Technology Element (e.g. Telerobotics, Communications, Autonomy, S/C Systems, Instruments/Sensors)
  - Match Mission Requirements and Technology Assets
    - i.e., Organize Execution of Mission Studies; Assure Availability of Enabling Technology

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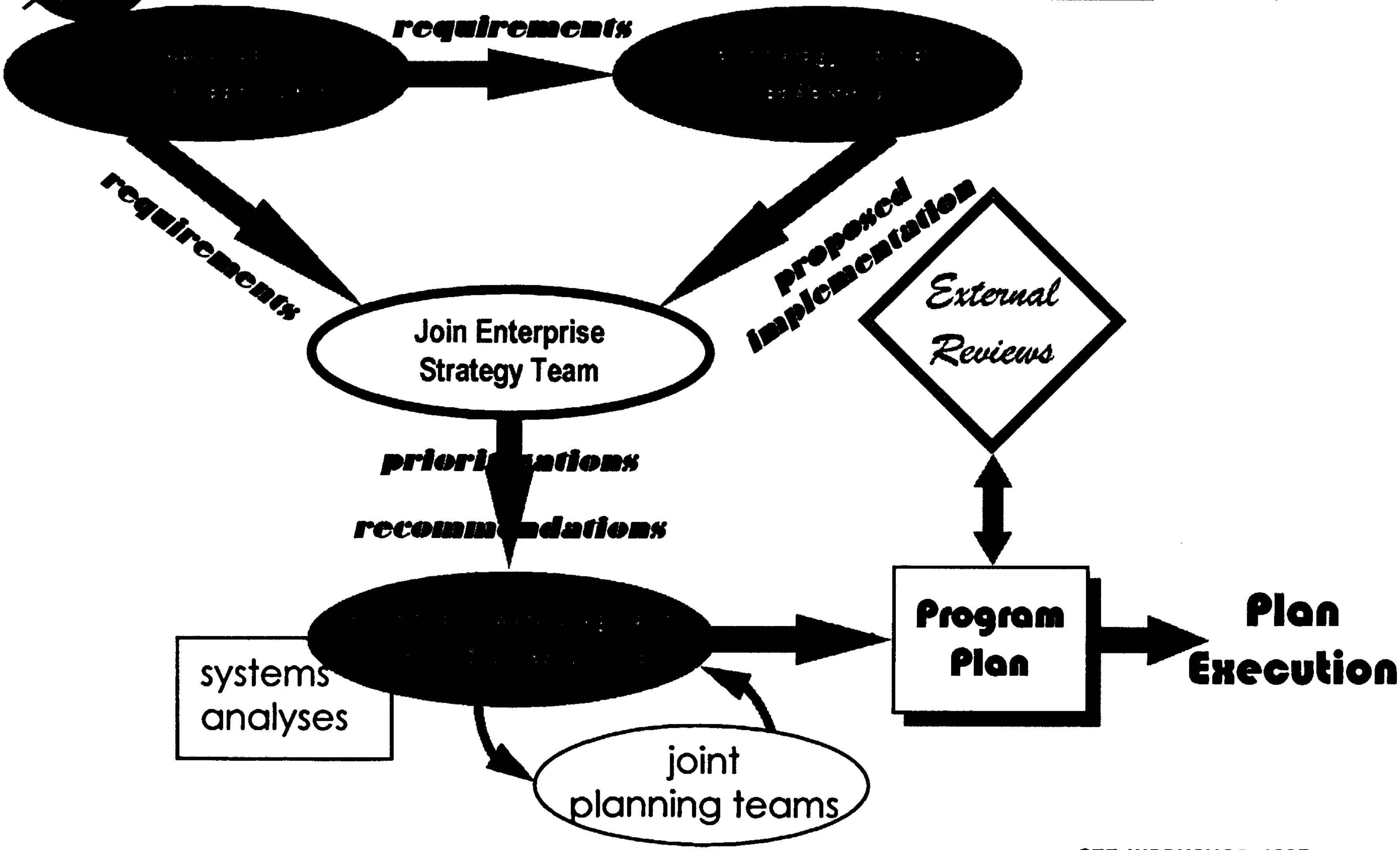
Core Technology is Managed Through a CROSS-ENTERPRISE PROCESS

ATBMS Division



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Technology Management in the NEW NASA
CONCLUSIONS

AT&MS Division

- OSS Is Responsible for Both the Core Cross-Cutting Technology Development Program for the Agency and for Code S Unique Needs
  - We Support All Enterprise Technology Needs That Are Not Unique To a Single Enterprise
- A Concurrent and Distributed Management Approach Is Used That Incorporates Functions and Expertise At All Levels Within the Agency
  - THIS IS WHERE "FAR-OUT" TECHNOLOGY PROPOSALS GET A FIRST HEARING
- Synergism With Other NASA and Non-NASA Programs Is Essential
- Far-Term, More Speculative Technology Will Be Supported at a Significant Level (~25-30%)
- The NASA–Wide Technology Inventory Is Being Developed
  - Will Be Linked to DOD and Other Technology Data Bases
  - To Be Made Available on the Web Late Summer/Early Autumn 1997
- The OSS Strategic Plan, The MTPE Biennial Review and The HEDS Technology Plan (in preparation) Form the Basis For Technology Requirements Upon Which Our Program Is Built
- Detailed, Mission-Connected Technology Roadmaps Are Being Developed By Each Enterprise and Integrated to Form An Agency-Wide Plan to be Completed Later This Year

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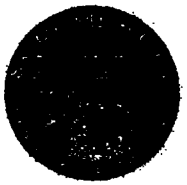

Space Environments and Effects Program

NASA
Space Environments and Effects (SEE) Program

Overview

Sponsored by: NASA's Advanced Technology and Mission Studies Division
Coordinated by: NASA's Marshall Space Flight Center

SEE Program Disciplines

Space Environments and Effects Program

- ELECTROMAGNETIC EFFECTS (EME)
  - Supports developments associated with EME research, and the design and operations implementation for earth orbiting spacecraft
- IONIZING RADIATION
  - Explores techniques to improve the accuracy of models representing radiation in the upper earth atmosphere
- METEOROIDS & ORBITAL DEBRIS (M/OD)
  - Develops and integrates activities associated with M/OD research and transfers this new technology to spacecraft design
- PLASMA AND FIELDS, THERMOSPHERE, THERMAL, AND SOLAR ACTIVITY
  - Seeks to understand, model, and predict the effects of interactions between spacecraft and plasma, the thermosphere (neutral gases), and solar electromagnetic energy for incorporation into spacecraft systems design
- NEUTRAL EXTERNAL CONTAMINATION
  - Studies, models, and counteracts the effects of induced molecular or particulate matter in the vicinity of spacecraft or on spacecraft surfaces
- MATERIALS AND PROCESSES
  - Seeks to predict materials' behavior in space and to develop longer-life materials for use with orbiting spacecraft and spacecraft systems

SEE Program Mission

Space Environments and Effects Program

- Research, develop, verify and transfer SEE-related technologies
  - To facilitate the design, manufacture, and operation of cost-effective spacecraft that will reduce the cost of access to space
    - ⇒ By providing engineering tools to help accommodate or mitigate effects due to the space environment
    - ⇒ By providing help early in the design and operations planning phases
  - To help maintain U.S. preeminence in space
  - To promote continued U.S. economic competitiveness in the global market place

SEE Program Goals and Strategies

Space Environments and Effects Program

- ◆ **Advocate technology development, flight experiments, and databases by developing and maintaining:**
  - Environments Definitions and Handbooks
  - Engineering Design Guidelines and Handbooks
  - Integrated Engineering Assessment Models
  - Environments and Materials Databases
  - Flight/Ground Simulation/Technology Assessment Data
- ◆ **Maintain cutting-edge expertise in SEE-related technologies**
  - Collaboration of NASA and Non-NASA technical experts/specialists
  - Sustained awareness of state-of-the-art SEE technologies
- ◆ **Heighten the awareness of SEE and SEE-related activities**
  - SEE Newsletter, Web Site, Brochure, Publications, and Displays
  - SEE Workshops

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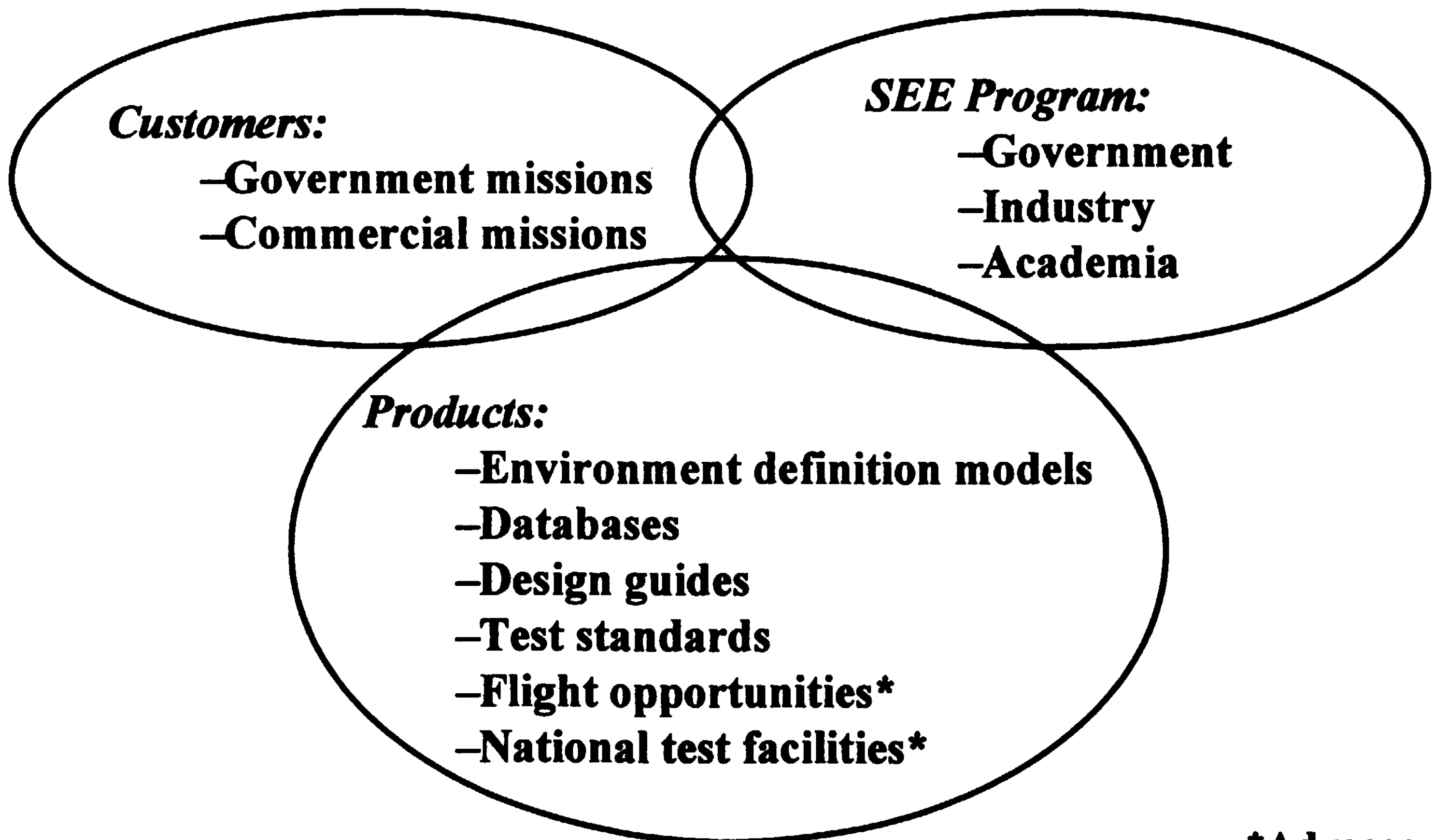
SEE Program Philosophy

Space Environments and Effects Program

◆ ***Customer-Driven <u>AND</u> Product-Oriented***



*Advocacy

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Components of SEE Program

Space Environments and Effects Program

Scientific Research of the Space Environment

Research Data
into technology programs

Technology development and Demonstration programs:
Update models, databases, design guidelines, flight experiments
for technology demonstration & development

New Technology
into design programs

Design and Operations Programs: Implement accurate environment effects accommodations into spacecraft design and operations (NASA, DoD, Commercial)

Key: SEE Program Focus

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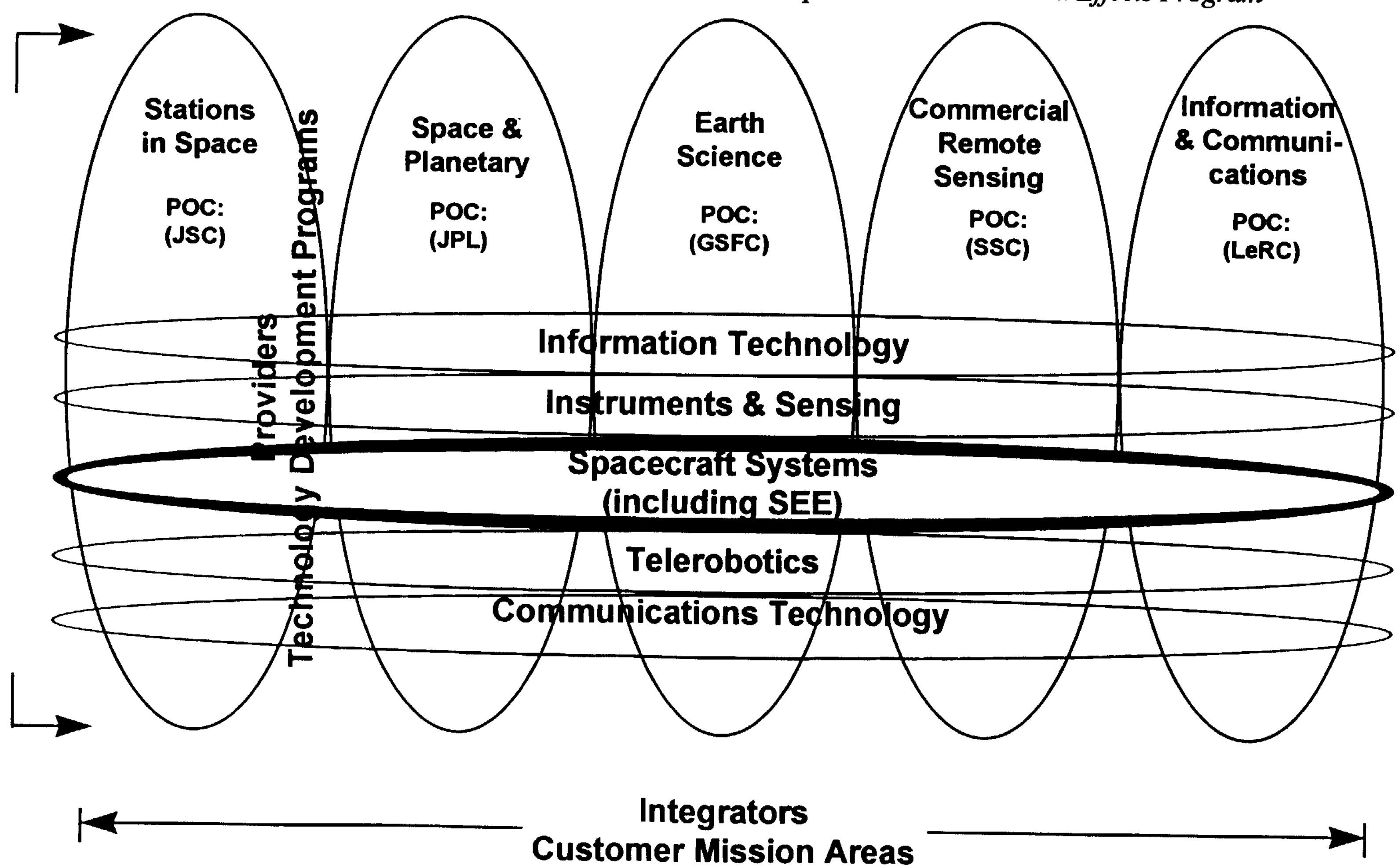
Integrators: Customer Mission Areas
Providers: Technology Development Programs

Space Environments and Effects Program



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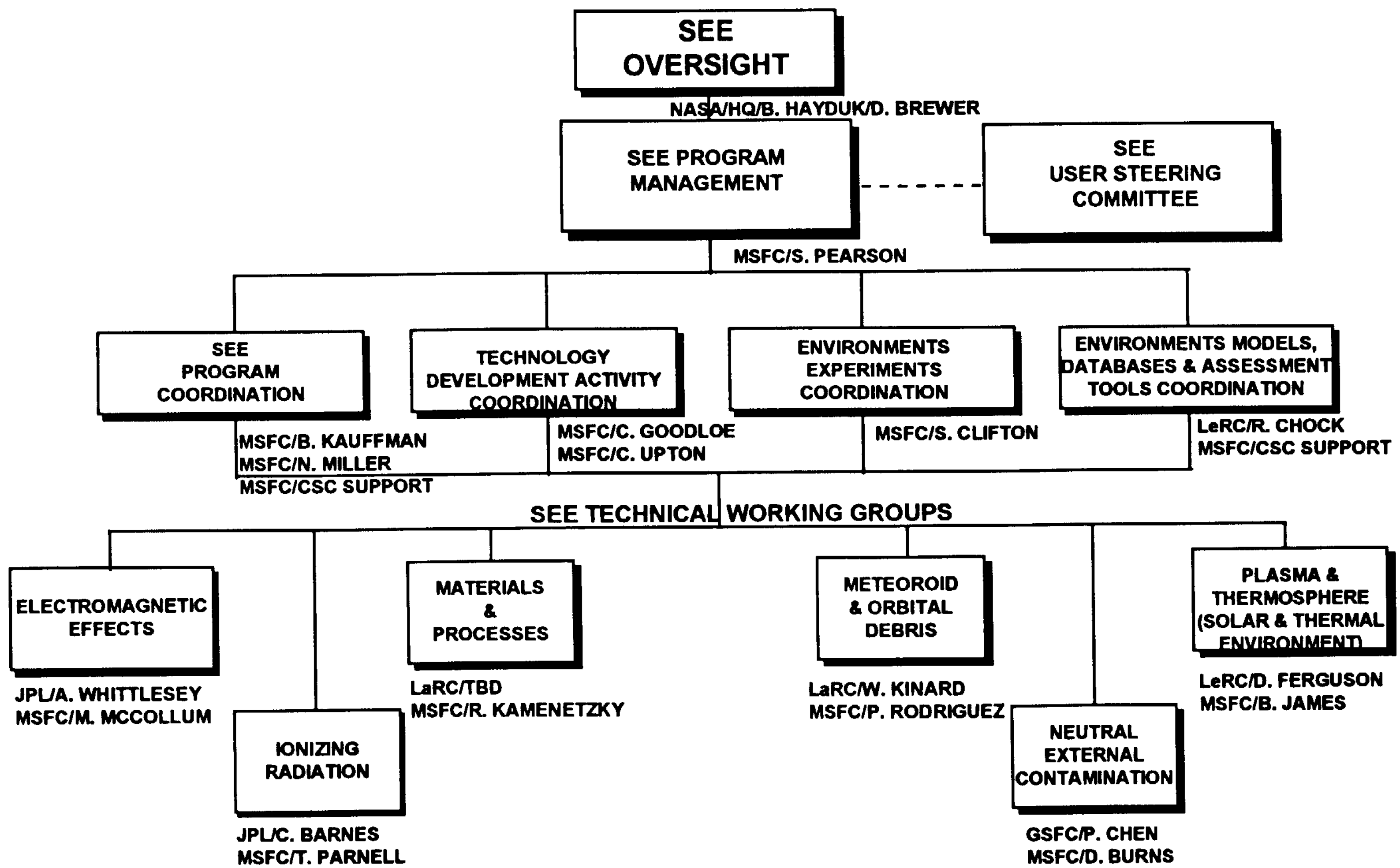
SEE Program Organization

Space Environments and Effects Program



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SEE Oversight and Management

Space Environments and Effects Program

- SEE Oversight
  - Provides headquarters involvement for program oversight
  - Provides liaison and advocacy with other NASA headquarters activity
- SEE Program Management
  - Manage overall SEE activity with all program participants
  - Allocate roles and responsibilities

SEE Coordination Activities

Space Environments and Effects Program

- ♦ **Program Coordination**
  - Overall coordination of SEE Program
    - ⇒ Technical Work Groups & SEE Community
    - ⇒ Customer Mission Areas & User Steering Community
    - ⇒ Principle Investigators
- ♦ **Technology Development Activity Coordination**
  - Serves as a focal point to coordinate technology development activities in order to meet the technology needs of the customers
  - Development of SEE Technology "Roadmaps"
- ♦ **Environments Experiments Coordination**
  - Serves as a focal point to coordinate experiment developments with flight opportunities in order to meet the technology needs of the customers
  - Advocates SEE- related technology flight experiments
  - Serves as point of contact for information exchange between experiment developers and program managers/coordinators
- ♦ **Environments Models, Databases and Assessment Tools Coordination**
  - Coordination of efficient utilization of environments models, databases and assessment tools
  - Dissemination and distribution of ISS environments and SEE experiments data

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SEE User Steering Committee

Space Environments and Effects Program

- Customer oriented
- Supports SEE Program Management
- Provides leadership in identifying, coordinating, evaluating, integrating, and prioritizing SEE research areas
- Evaluates research results
- Membership represents industry, government, and academia

SEE Technical Working Groups
"General Functions"

Space Environments and Effects Program

- Activities and responsibilities for all SEE Program technical working groups include:
  - Ensuring communication with working group members
  - Coordinating development, evaluation and maintenance of working group technical content and research areas
  - Coordinating research and development of new technologies and design issues that impact their respective space environmental areas
  - Coordinating development and use of engineering tools, models and database
  - Coordinating development of spacecraft design and test techniques and methodologies for accommodating or mitigating space environments effects

SEE Program Technical Working Groups - Specific Functions (cont'd)

Space Environments and Effects Program

- **Neutral External Contamination Working Group**
  - Concerned with the effects of neutral external contamination (presence of molecular or particulate matter on spacecraft surfaces) that may detrimentally impact planned mission operation
  - Support the development and integration of technical activities, technology transfer, design and operations implementation for spacecraft operating in low Earth and geosynchronous orbits
- **Materials and Processes Working Group**
  - Concerned with space environment effects on spacecraft materials and associated processes
  - Provide national level coordination, review and support of material activities to identify customer defined requirements and to meet these requirements for present and future space mission

Technical Working Group: Contamination Working Group Members

Space Environments and Effects Program

Co-Chairpersons:

◆ Philip Chen	NASA/GSFC
◆ DeWitt Burns	NASA/MSFC

Members:

◆ Arnold Graham	Aerospace Corporation
◆ Henry Babel	McDonnell Douglas Aerospace
◆ Jack Barengoltz	NASA/JPL
◆ Donald Bartelson	Brown & Root Services Corporation
◆ Gene Borson	
◆ Ralph Carruth	NASA/MSFC
◆ Richard Fedors	Rome Laboratory/OPC
◆ Peter Glassford	Lockheed Martin Missiles & Space
◆ Bryon Green	Physical Sciences, Inc.
◆ Gale Harvey	NASA/LaRC
◆ James Kenny	NASA/JPL
◆ Carl Maag	T&M Engineering
◆ Ron Mikatarian	Rockwell Aerospace
◆ Ray Rantanen	ROR Enterprises
◆ John Scialdone	NASA/GSFC
◆ David Silver	Johns Hopkins University/APL
◆ Edward Silverman	TRW
◆ Charles Stein	Phillips Laboratory/VTV
◆ Randy Thompson	AZ Technology
◆ Manuel Uy	Johns Hopkins University/APL
◆ Bob Wood	Sverdrup Technology, Inc
◆ James Zwiener	NASA/MSFC

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SEE Technology Development Activities
Current Status

Space Environments and Effects Program

- Technology development tasks were solicited through a NASA Research Announcement released in May 1994
- 18 contracts were awarded, utilizing peer review, from 176 proposals submitted
- Technical Disciplines Represented - electromagnetic effects; ionizing radiation; materials and processes; meteoroid and orbital debris; neutral external contamination; plasma and fields; thermosphere, thermal and solar activity
- Organizations Selected - GB Tech, Tec-Masters, NRL, SAIC, IIT Research Institute, McDonnell Douglas, ERIL Research, POD Associates, Boeing, Lockheed, Rockwell, TRW, University of Michigan, MIT, GSFC, MSFC

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SEE Technology Development Activities
Neutral External Contamination Working Group

Space Environments and Effects Program

- Contract Title: ***Comparison of Spacecraft Contamination Models with Well Defined Flight Experiments***
  - Organization: Boeing Defense & Space Group
  - Principal Investigator: Gary Pippin
  - Objective: Define the deposition of molecular contamination on the Long Duration Exposure Facility including geometry, orientation, and environmental exposure, and compare these results to existing contamination models such as MOLFLUX and ISEM.
- Contract Title: ***Vehicle-Atmosphere Interaction Glows: FUV-IR***
  - Organization: Lockheed Research and Development
  - Principal Investigator: Gary R. Swenson
  - Objective: The development of computer models to predict spacecraft glow in the far ultraviolet to infrared spectral regions (0.14 to 40 micron wavelengths).

SEE Technology Development Activities
Neutral External Contamination Working Group (cont'd)

Space Environments and Effects Program

- Product Title: ***Contamination Control Engineering Design Guidelines for the Aerospace Community***
  - Organization: Rockwell International Space Systems Division
  - Principal Investigator: Alan C. Tribble
  - Objective: Develop a Contamination Control Engineering Handbook. Develop a Contamination Control Plan. Develop an interactive expert knowledge system, for both the handbook and plan.

- Contract Title: ***Contamination Effects on EIUV Optics***
  - Organization: NASA Goddard Space Flight Center
  - Principal Investigator: June L. Tveekrem
  - Objective: To perform in-vacuum measurements of the specular reflectance and BRDF of deliberately contaminated optical surfaces at EUV/FUV wavelengths. To quantify the effect of photopolymerization on optical scattering, and to determine the UV intensity needed to initiate the photopolymerization process. To compare the laboratory results with predictions from models based on Mie scattering theory. To make the data available for incorporation into standard optical design software.

NASA Research Announcement Schedule

Space Environments and Effects Program

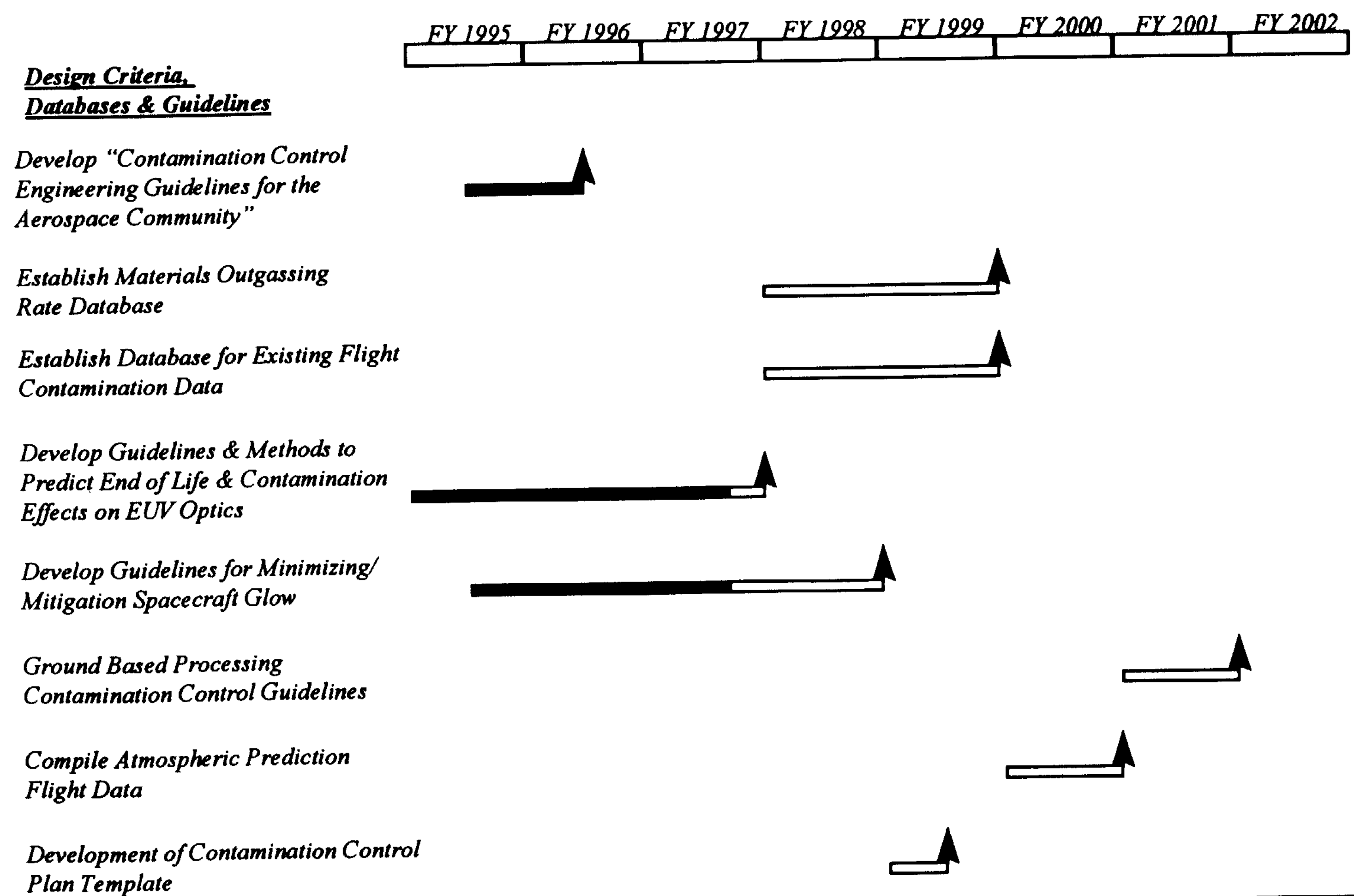
◆ Technical Working Groups Develop Roadmaps/Potential NRA Tasks	April 30, 1997
◆ User Steering Committee Evaluation and Prioritization	June 1, 1997
◆ NRA Released	July 1, 1997
◆ Proposal Deadline	October 1, 1997
◆ Evaluation of Proposals Completed	November 1, 1997
◆ Selection Committee Report	December 1, 1997
◆ Procurement Deliberations Complete	March 1, 1998

Details as they Develop at the SEE Web Site: http://see@msfc.nasa.gov

Contact Cindy Upton for particular questions: cindy.upton@msfc.nasa.gov

Space Environments & Effects
"Neutral External Contamination"

Space Environments and Effects Program



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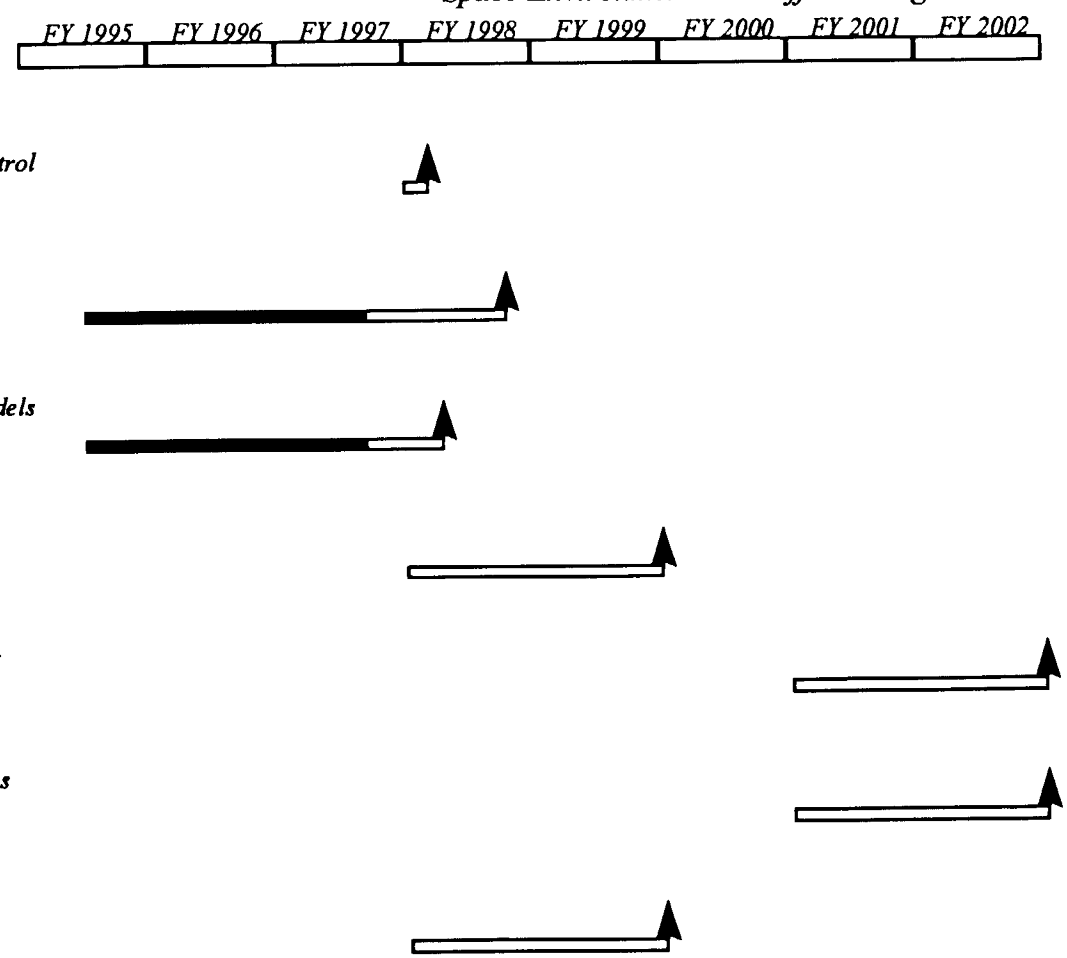
Space Environments & Effects
"Neutral External Contamination"

Space Environments and Effects Program



Models

Enhancements to Contamination Control Expert System Tool

Develop Engineering Models of Spacecraft Glow Environment

Validate Existing Contamination Models Against Silicone Contamination from LDEF

In-flight Particulate Contamination Effects

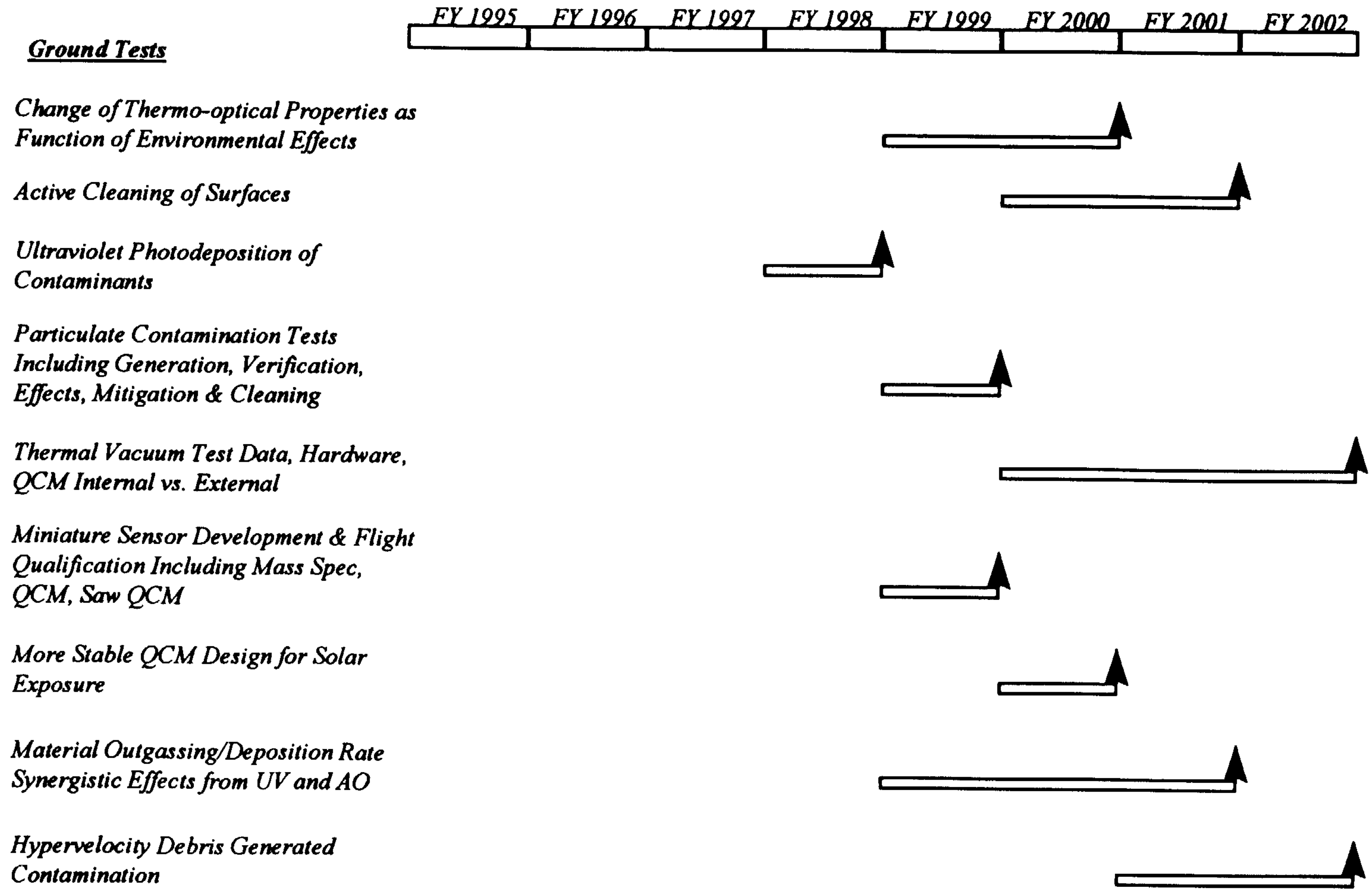
Particulate Contamination Effects of Debris Wake

Ionizing of Neutral Molecular Species Especially GEO

Molecular Contamination Effects Modeling

Space Environments & Effects
"Neutral External Contamination"

Space Environments and Effects Program



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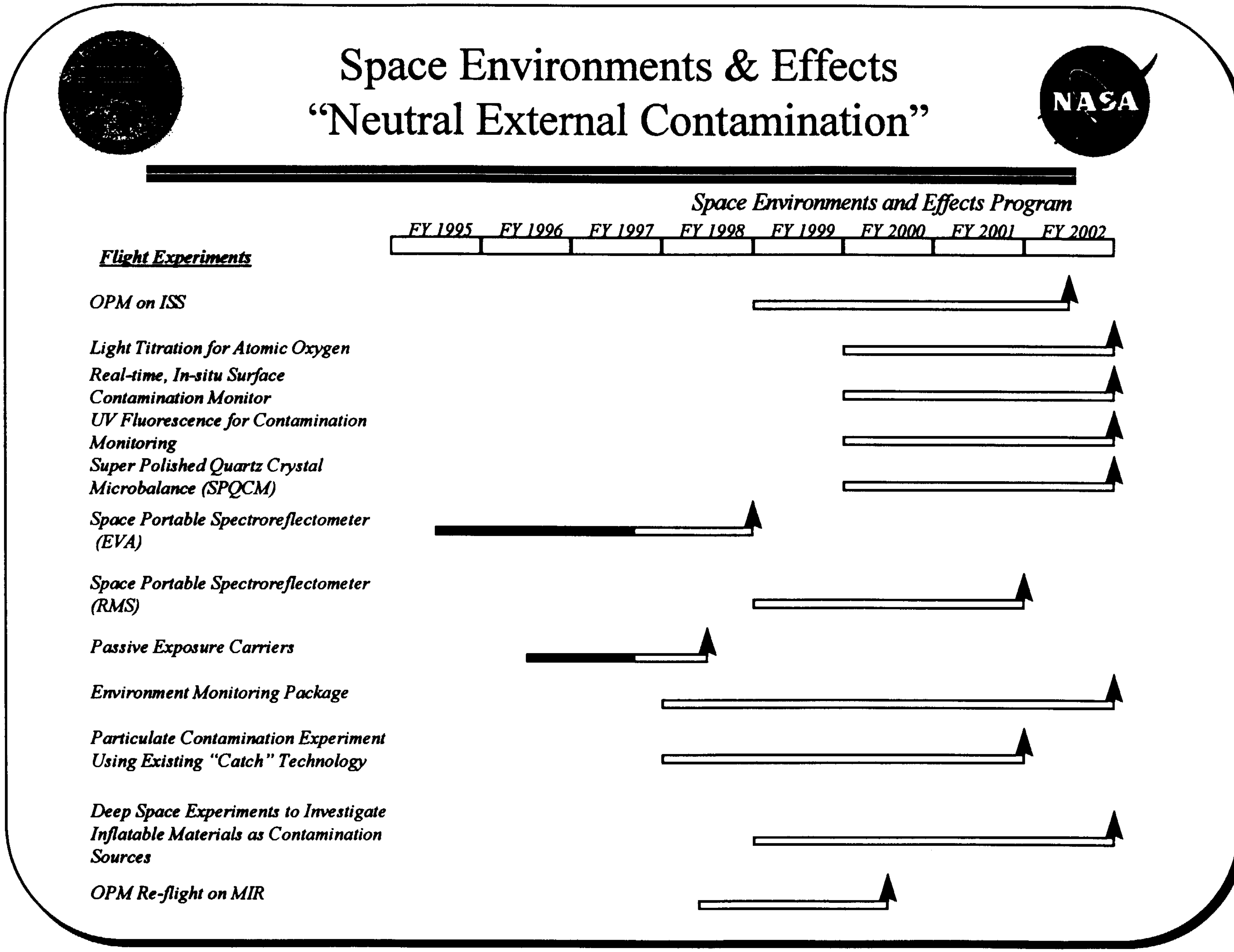

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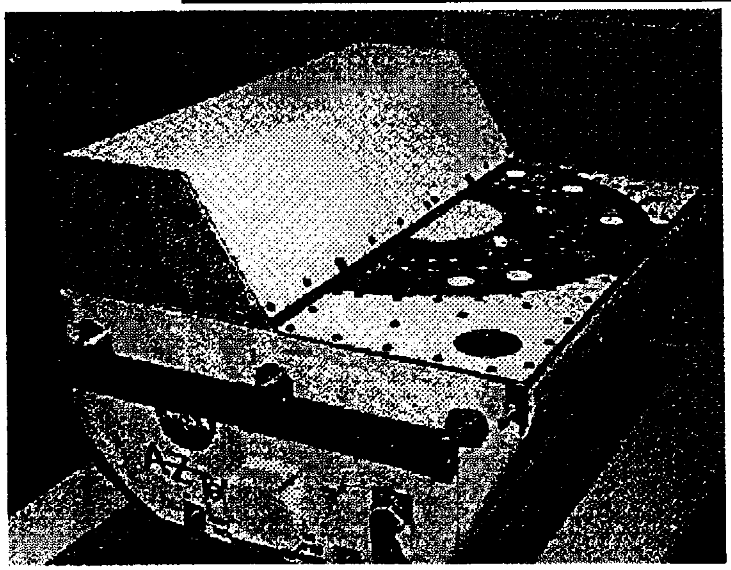
SEE Advocated Flight Experiments Current Status

Space Environments and Effects Program

- Risk mitigation Experiments
  - *Mir* Photo Survey: STS-63, -71, -74, -76, -79, -81
  - Trapped Ions in Space (TRIS): STS-74
  - Real-Time Radiation Monitor Detector (RRMD): STS-74, -84
  - Plume Impingement Contamination (PIC): STS-76
  - Micrometeroid/Orbital Debris Collector: Deployed STS-76; Retrieved STS-86
  - *Mir* Electric Field Characterization: STS-76, -81
  - Polished Plate Experiment: Deployed STS-76; Retrieved STS-86
  - Optical Properties Monitor (OPM): Deployed STS-81; Retrieved STS-89
  - Space Portable Spectro-Reflectometer (SPSR): STS-86
  - Cosmic Ray Effects Activation Monitor: STS-81
  - Passive Optical Sample Assembly 1 (POSA 1): Deployed STS-76; Retrieved STS-86
  - Passive Optical Sample Assembly 2 (POSA 2): Deployed STS-76; Retrieved STS-86

Optical Properties Monitor (OPM)

Space Environments and Effects Program



Objectives:
- To study the natural and induced effects of the space environment on optical and thermal control surfaces
  - measure the total hemispherical reflectance of test materials
  - monitor surface damage and contamination of optical and thermal control surfaces caused by the space environment
  - measure the specular reflectance and transmittance of test samples at selected wavelengths in the vacuum ultraviolet
- To monitor the MIR environment
  - molecular contamination
  - atomic oxygen fluence
  - solar and terrestrial irradiance

Instrumentation:
- Integrating Sphere Reflectometer
- Total Integrated Scatter (TIS) Instrument Coblentz Sphere
- Vacuum Ultraviolet (VUV) Spectrometer
- Temperature-Controlled Quartz Crystal Microbalance (TQCM) Sensors
- Atomic Oxygen Sensor
- Radiometers

Operation:
- Rotating Carousel with materials samples
- Over 100 samples submitted by industry, government, and academia
- Measurements made weekly

Status:

•Initial sample selection	April 1996
•Launched aboard STS-81	December 1996
•Deployed for operation	April 29, 1997
•To be retrieved on STS-86	January 1998

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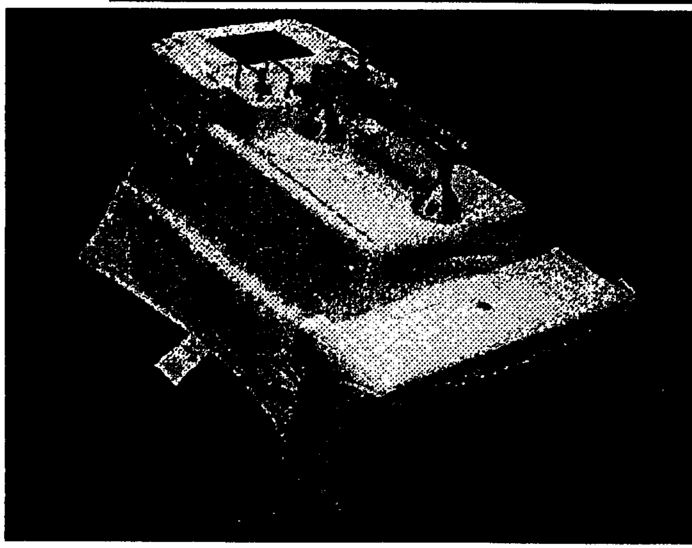
Space Portable Spectro-Reflectometer



Space Environments and Effects Program

Instrumentation:
- •Hand-held EVA carriage
- •Total hemispherical reflectometer
- •Internal data Storage
- •Battery Pack

Operation:
- •During EVA, take reflectance measurements of MIR's external surfaces and video the activity
- •Transfer reflectance data to MIPS laptop; downlink to ground

Status:

•Planned Launch (STS-86)	September 1997
•Planned EVA/Deployment	December 1997
•Planned Retrieval (STS-89)	January 1998

Objectives:
- •Determine effects and damage mechanisms of the MIR space environment on materials
- •Develop a portable handheld EVA instrument to measure the solar absorptance (alpha) of spacecraft surfaces in orbit
  - •total hemispherical reflectance from 250-2500 nm
  - •reusable flight instrument
  - •joint U.S./Russian Experiment
- •Provide data to validate ground test facilities and prediction models for materials behavior in space

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Environment Monitoring Package

Objectives:
- Verify the ISS environment is consistent with Space Station contamination control/payload design requirements
  - Plasma
  - Atomic Oxygen, solar UV, radiation
  - Induced Molecular
  - Particulates
  - Electromagnetic Environment
- Provide quantitative environmental measurement data to verify the ISS environment models
- Provide near real-time monitoring of environment constituents for system and payload operations

Space Environments and Effects Program

Potential Instrumentation:
- Temperature-controlled Quartz Crystal Microbalance (TQCM) Sensors
- Mass Spectrometer
- Cold Cathode Pressure Gauge
- Langmuir probe/V-Body Probe
- Other instruments depending upon user requirements

Operation:
- Utilized Express Pallet payload carrier/facility
- Operable at S3 attached payload site
- Interfaces with Special Purpose Dexterous Manipulator (SPDM)
- Periodically removed for remote measurements
  - Coverage of U.S. Lab nadir window
  - Remote Locations
- Five-year missions

Status:

•Phase 1 Definition Phase started	April 1997
•Phase 2 Development phase to begin	March 1998
•Launch (UF-4)	Jan 2002

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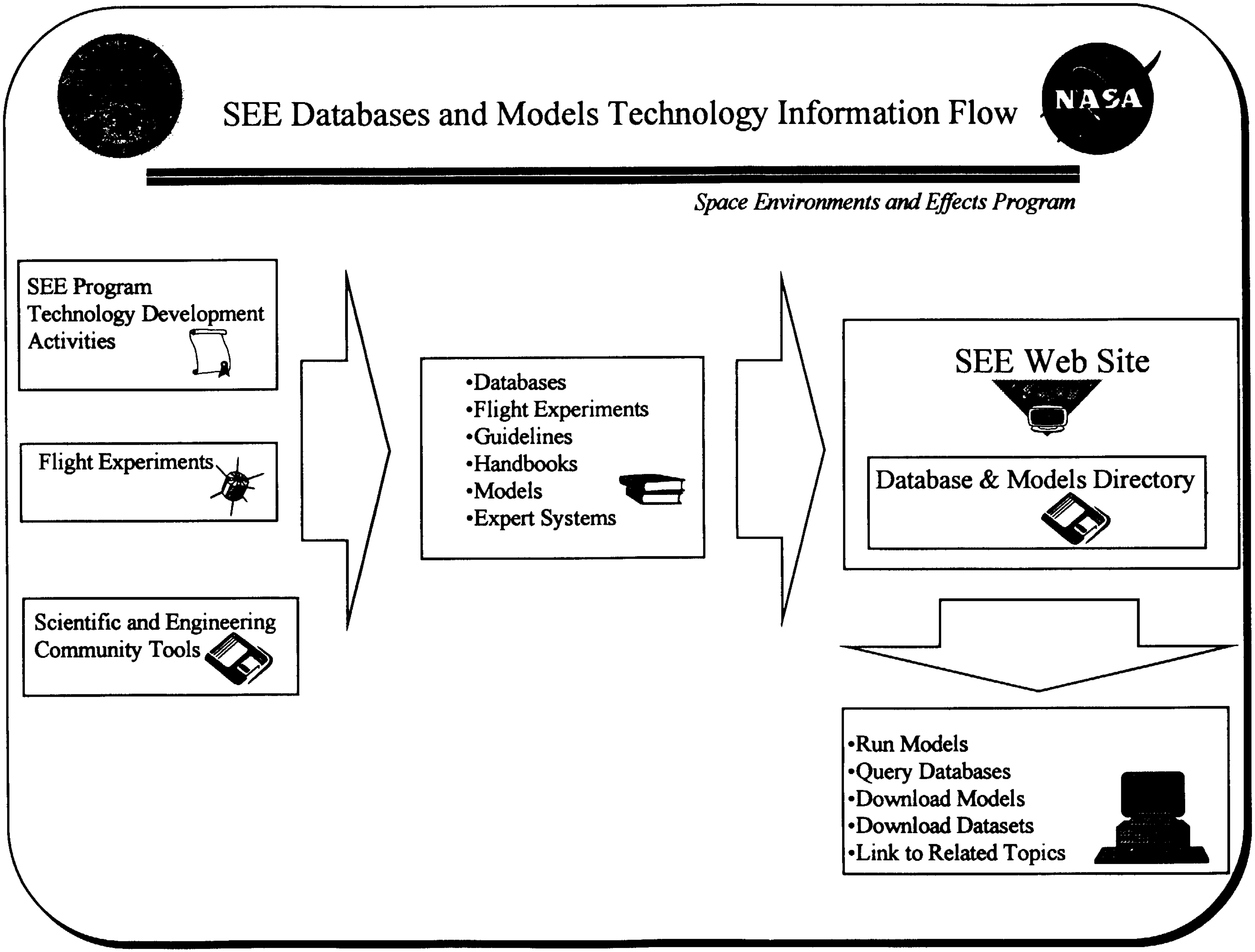

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Contact Information

Space Environments and Effects Program

For more information contact Billy Kauffman at:

billy.kauffman@msfc.nasa.gov

or

visit our Website at:

http://see.msfc.nasa.gov

Closing Remarks

Space Environments and Effects Program

- This is a NASA technology development program which is customer - driven AND product-oriented
- There is a great interest in coordinating our activities with the entire Space Environments and Effects (SEE) community (i.e., other Gov't agencies, industries, and universities) to make maximum usage of new and existing SEE technologies
- Our Future role deals with inserting these new technologies into NASA and commercial programs

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Current and Future Spacecraft Contamination Control Engineering

Philip Chen
National Aeronautics and Space Administration
Goddard Space Flight Center
Thermal Engineering Branch

1997 Spacecraft Contamination and Coatings Workshop
Annapolis, Maryland
July 9, 1997

Contamination Engineering Outlook

- Recognized as a significant factor for a successful mission.
- Improved knowledge of contamination effects on spacecraft systems.
- Increased complexity and sensitivity of spacecraft, instruments, and launch environments.
- Requirements are more demanding in system performance.
- New advanced instruments and applications, NGST, small satellites, constellation high-power laser.
- Challenging New Environments from LEO, GEO, to Space Station, Unique Orbits, Interplanetary Missions.

Development of Spacecraft Contamination Engineering

- Early development stage in 1970s
  - The contamination engineering used a "Best Effort" approach.
  - The contamination engineering effort was limited to understanding the problems and providing problem solving.

- Significant advancement in 1980-90
  - Spacecraft contamination engineering becomes a systematic approach as part of the mission.
  - Involvement of contamination engineers is through all phases of a mission.
  - Applying acquired knowledge including modeling techniques. contamination engineers provide significant influence in the design phase.
  - Heavy involvement in the I&T phase with established approaches and procedures.

Development of Spacecraft Contamination Engineering (continued)

- Significant advancement beyond 2000
  - Optimize current contamination engineering process.
  - Standardize the contamination engineering program.
  - Through contamination engineering, further improve schedule and save cost in order to enhance mission performance.

Significant Advancements in 1980-90

- Missions and Flight experiments
- Ground Operations
- Instrumentation
- Analytical Modeling
- Research/New technologies
- Information Exchange
- Lessons learned

Missions and Flight Experiments

- **Through accomplished missions and lessons learned, the contamination related effects and problems have been understood.**
- **Contamination related flight Experiments have been flown to study on-orbit phenomena.**
  - **SCATHA (1979) to study contamination build-up on thermal control surfaces.**
  - **Early STS missions (STS-3 in 1982, STS-8 in 1983, STS-11 in 1984) for AO study.**
  - **QCMs on NOAA-7 (1982) to measure spacecraft outgassing/venting.**
  - **Solar Maximum Repair Mission (SMRM) (1984) for returned hardware.**
  - **The Interim Operational Contamination Monitor (IOCM) STS-51C (1985), STS-28 (1989), STS-32 (1990), and STS-44 (1991) to study Shuttle Bay environments.**
  - **The Ascent Particle Monitor STS-28 (1989) for particle generation during ascent phase .**
  - **LDEF (launch in 1984 and retrieved in 1990) for an extensive long-term AO/materials/contamination study.**

Missions and Flight Experiments (continued)

- Environmental Verification experiment for the EUVE Explorer Platform (EVEEP) (1992) for spacecraft outgassing study.
- REFLEX experiment (1996) for backscattering effect study.
- MSX experiment (1996), a dedicated contamination experiment.
- Contamination Environmental Package (CEP), HST-SM2 (1997) to monitor Shuttle bay and EVAs.
- MIR, OPM experiments for materials and environmental effects study.

Summary: ***Significant knowledge has been obtained through missions and flight experiments***

Ground Operations

- **The concept of using a contamination control plan as governing document has been well accepted.**
- **Federal, Military, and NASA standard documents delineating contamination are available. Other documents such as contamination guidelines, CCP, and databases are also obtainable.**
- **Contamination control implementation has been performed following developed procedures.**
- **New cleanroom operation**
- **Purge concept**
- **Contamination generation, characterization, cleaning, and verification have been developed**

Ground Operations

- **More involvement with international partners, ESA, Japan, Russia, South America. Adopt the approach of the ISO standard in the future.**

Summary: ***Better ground procedures have been established.***

Instrumentation

- **Molecular Contamination Measurement**
  - Black/white light inspections
  - Cold Finger/Plate
  - Hardware NVR witness sample
  - Real-time NVR monitor
  - Hydrocarbon monitors
  - FTIR, GC/MS, RGA, TQCM, Saw QCM

Instrumentation

- **Particulate Contamination Measurement**
  - **Visual Observation (White Light Black Light)**
  - **Tapelifts**
  - **Particle counter**
  - **Fallout plates**
  - **Optical Monitors**
  - **Real-time fallout monitors**
  - **Surface particle detectors: Image analysis, BRDF/BSDF, reflectance, ESCA, SEM/EDX**

Summary: ***Better instrumentation allows much improved characterization of contamination.***

Analytical Modeling

- **Validate Design**
- **Establish requirements**
- **Verify requirements**
- **Assess performance degradation for EOL**
- **Design Impact**

Summary: ***<u>Change the philosophy of analytical modeling in contamination engineering.</u>***

Research/New Technologies

- **Category 1: Design Criteria , Databases And Guidelines**
  - **Develop "Contamination Control Engineering Guidelines for the Aerospace Community"**
  - **Establish Materials Outgassing Rate Database**
  - **Establish Database for Existing Flight Contamination Data**
  - **Develop Guidelines & Methods to Predict End Of Life & Contamination Effects On EUV Optics**
  - **Develop Guidelines for Minimizing/ Mitigation of Spacecraft Glow**
  - **Ground Based Processing Contamination Control Guidelines**
  - **Compile Atmospheric Prediction Flight Data**
  - **Development of Contamination Control Plan Template**

Research/New Technologies (continued)

- Category 2: Models
  - ISS Contamination Environment Model
  - MIR Contamination Environment Model
  - Enhancements to Contamination Control Expert System Tool
  - Develop Engineering Models Of Spacecraft Glow Environment
  - Validate Existing Contamination Models Against Silicone Contamination From LDEF
  - In-flight Particulate Contamination Effects
  - Particulate Contamination Effects of Debris Wake
  - Ionizing Of Neutral Molecular Species Especially GEO
  - Molecular Contamination Effects Modeling

Research/New Technologies (continued)

- **Category 3: Flight Experiments**
  - OPM on ISS
  - Light Titration For Atomic Oxygen
  - Real-time, In-situ Surface Contamination Monitor
  - UV Fluorescence For Contamination Monitoring
  - Super Polished Quartz Crystal Microbalance (SPQCM)
  - Space Portable Spectroreflectometer (EVA)
  - Space Portable Spectroreflectometer (RMS)
  - Passive Exposure Carriers
  - Environmental Monitoring Package
  - Particulate Contamination Experiment Using Existing "Catch" Technology
  - Deep Space Experiments to Investigate Inflatable Materials as Contamination Sources
  - OPM Re-flight on MIR

Research/New Technologies (continued)

- Category 4: Ground Tests
  - Change of Thermo-optical Properties as Function of Environmental Effects
  - Active Cleaning of Surfaces
  - Ultraviolet Photodeposition of Contamination
  - Particulate Contamination Tests Including Generation, Verification, Effects, Mitigation, & Cleaning
  - Thermal Vacuum Test Data, hardware, QCM Internal vs. External
  - Miniature Sensor Development & Flight Qualification Including Mass Spec, QCM, Saw QCM
  - More Stable QCM Design For Solar Exposure
  - Material Outgassing / Deposition Rate Synergistic Effects From UV and AO
  - Molecular Outgassing Mitigation With Zeolite Coatings (Adsorbent)
  - Hypervelocity Debris Generated Contamination
  - Evaluation of Inflatable Materials as Contamination Sources

Research/New Technologies (continued)

Summary: ***Technologies have been initiated in response to the contamination engineering need. Significant technologies have been developed.***

Information Exchange

- **Professional organizations: SPIE, IES, AIAA, ASTM, SEE**
- **Working Group Meetings: NASA, DoD, ESA, International**
- **De-classification of DoD documents**
- **The knowledge explosion: World-Wide-Web**

Summary: ***<u>The information exchange has become more efficient.</u>***

Changing Practices

- Cost driving and mission specific

- How to achieve this goal?

  - Best utilize the well-established current knowledge including lessons learned.
  - Establish reasonable and optimum requirements
  - Develop creative approaches
  - Develop and apply new technologies

Summary

- Early development stage (before 1980)
- Exploding field (1980-2000)
- Challenging future (2000 and beyond)

Effects of Contamination on Optical Performance in the EUV

Presented by Ritva A. Keski-Kuha
NASA/GSFC

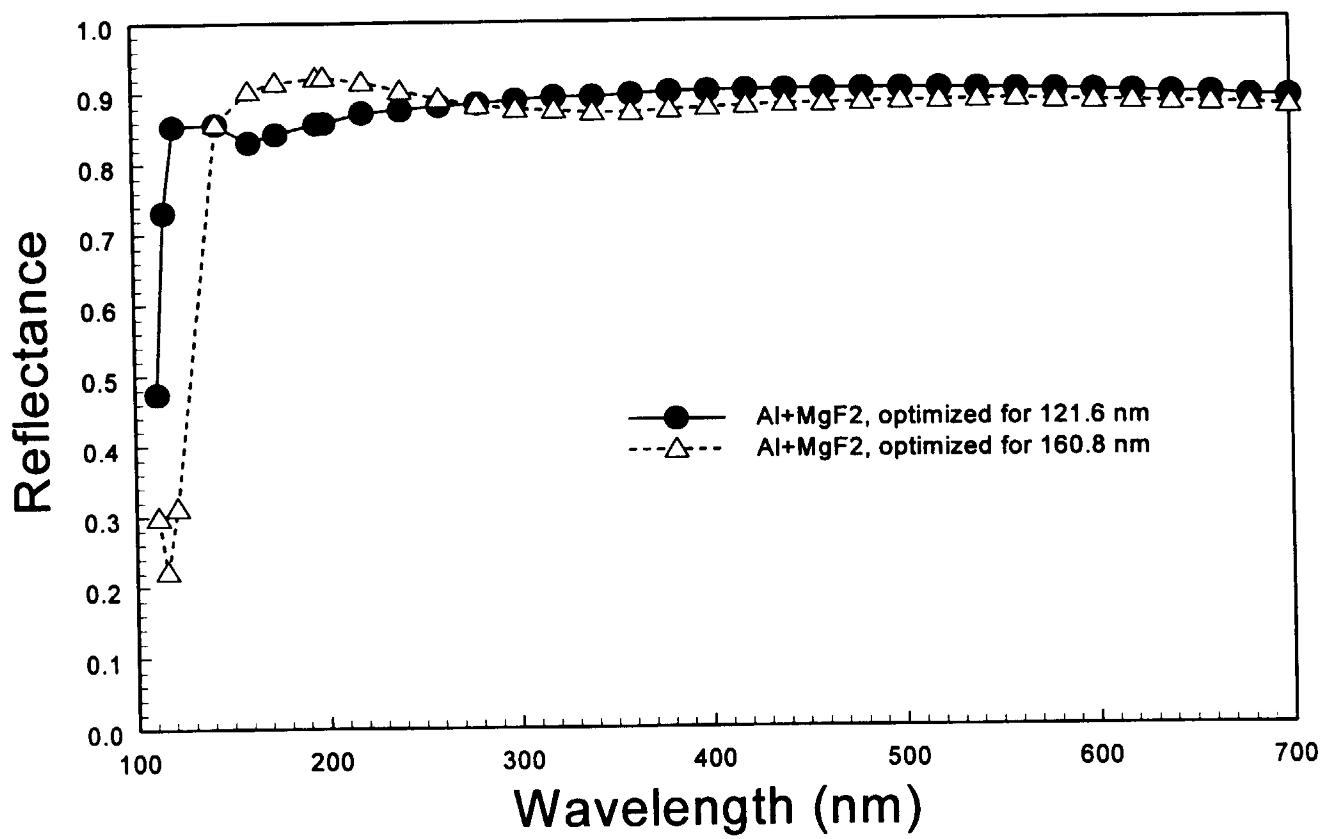
Outline

- Review optical coatings for the extreme and far ultraviolet wavelength regions.
- Discuss contamination and cleaning.
- Discuss effects of space exposure on UV coatings.

Magnesium Fluoride Protected Aluminum (Al+MgF2)

- the most commonly used coating for the spectral region above 110nm
- the thickness of MgF2 is selected to eliminate oxidation of the Al film while maintaining its excellent ultraviolet reflectance
- highly reliable coating

COSTAR and STIS Coatings
Nominal Measured Reflectance



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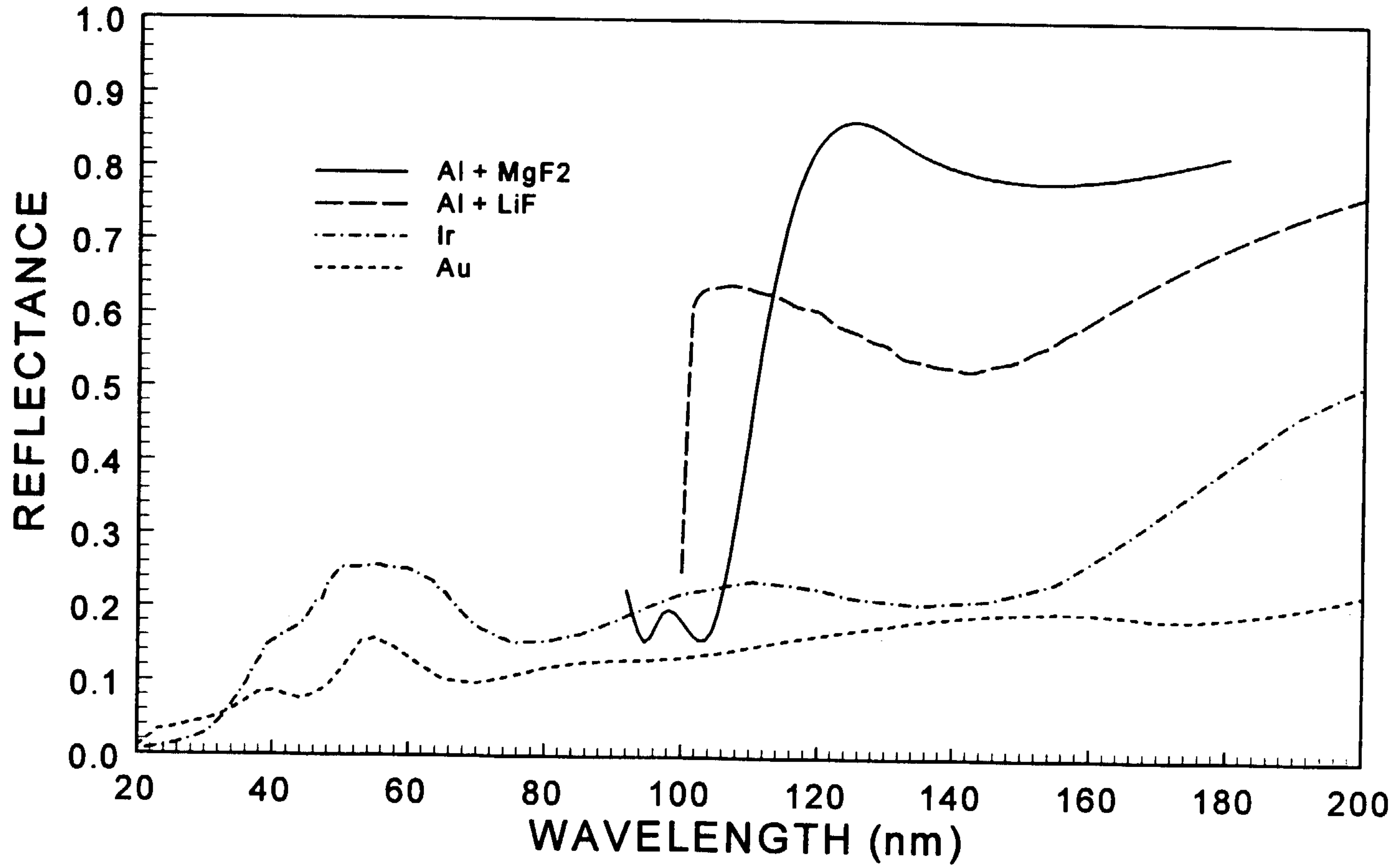
Reflectance of Various UV Coatings



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Importance of CVD SiC as an Extreme Ultraviolet Optical Material

- best known broadband reflectance (>40 %) across the extreme ultraviolet
- highly polishable providing low scatter optical surface
- good thermal and mechanical properties

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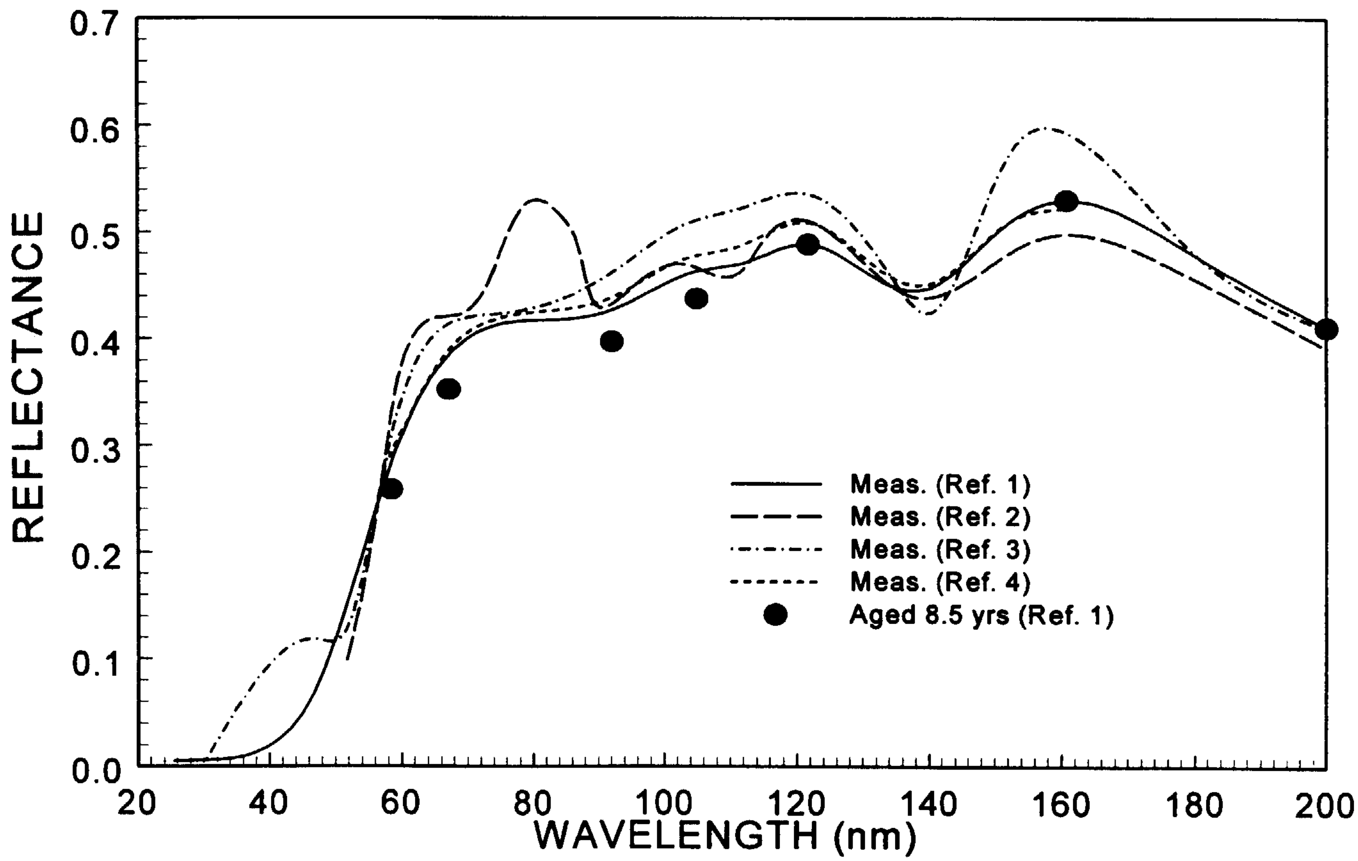
Normal Incidence Reflectance of CVD-SiC



1) R.A.M. Keski-Kuha. etal, Appl. Opt. V. 27, 2815 (1988)
2) W.J. Choyke, etal, Appl. Opt. V. 16, 2013 (1977)
3) Morton International, polished by General Optics
4) Sample provided by B. Bach, Hyperfine Inc.

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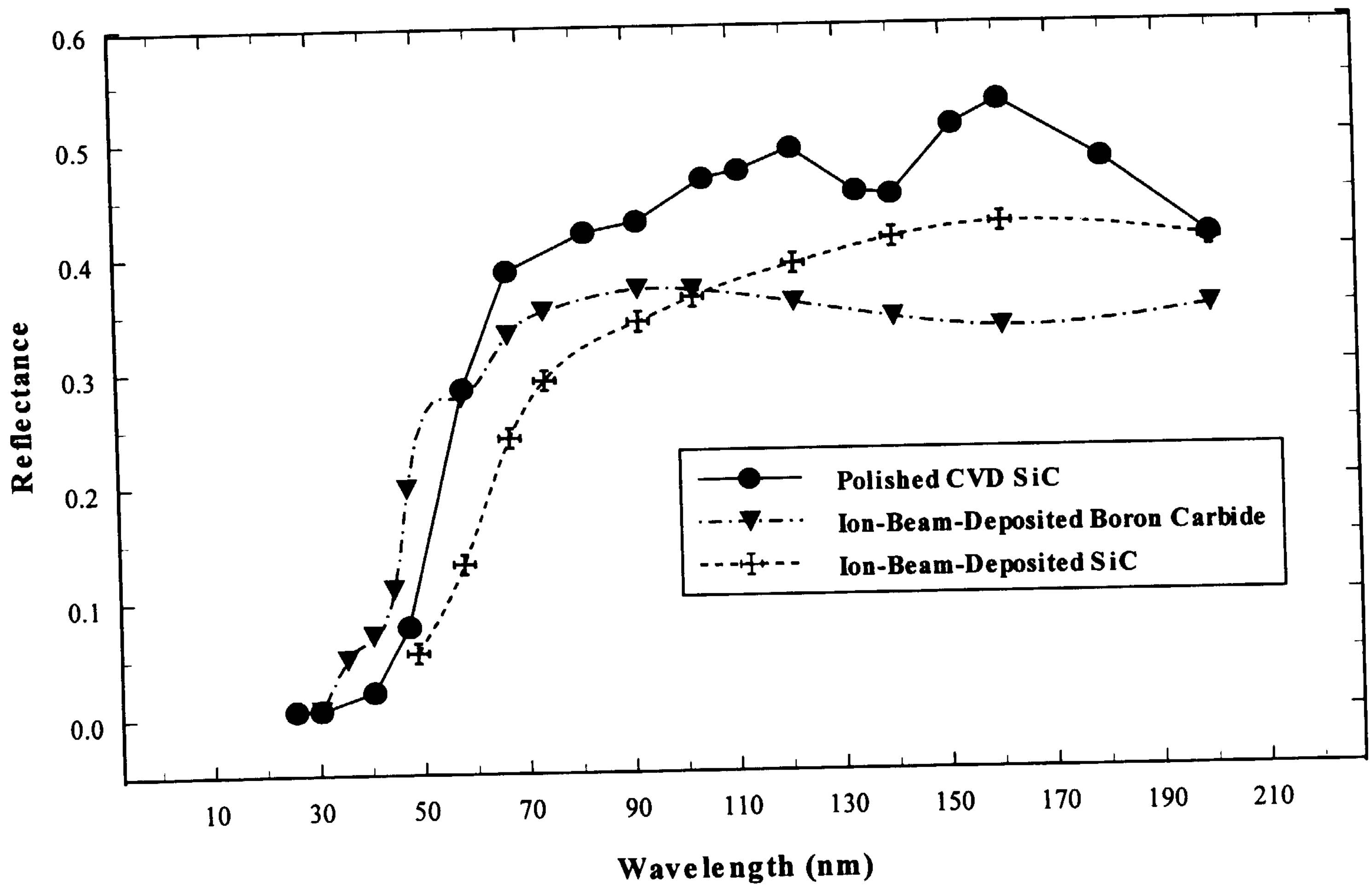
Normal Incidence Reflectance of Silicon Carbide and Boron Carbide



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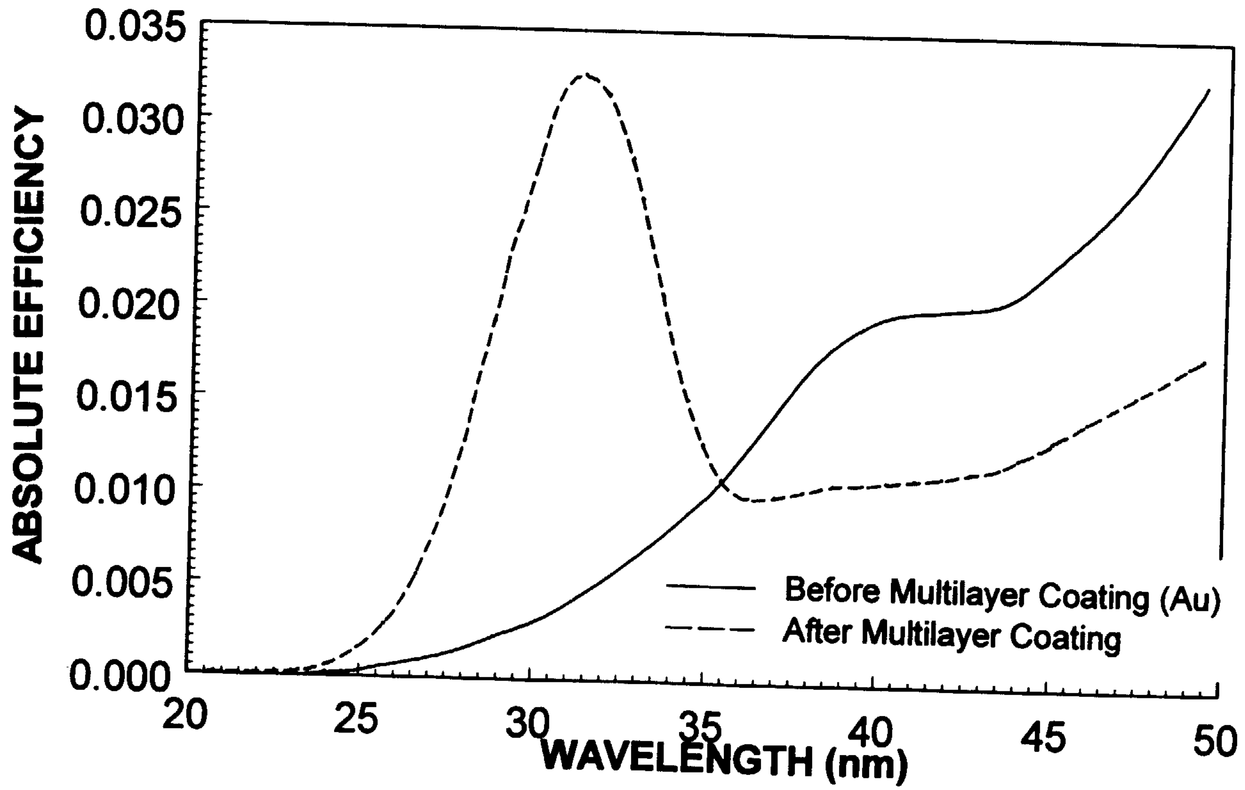
Absolute Efficiency of SERTS Diffraction Grating



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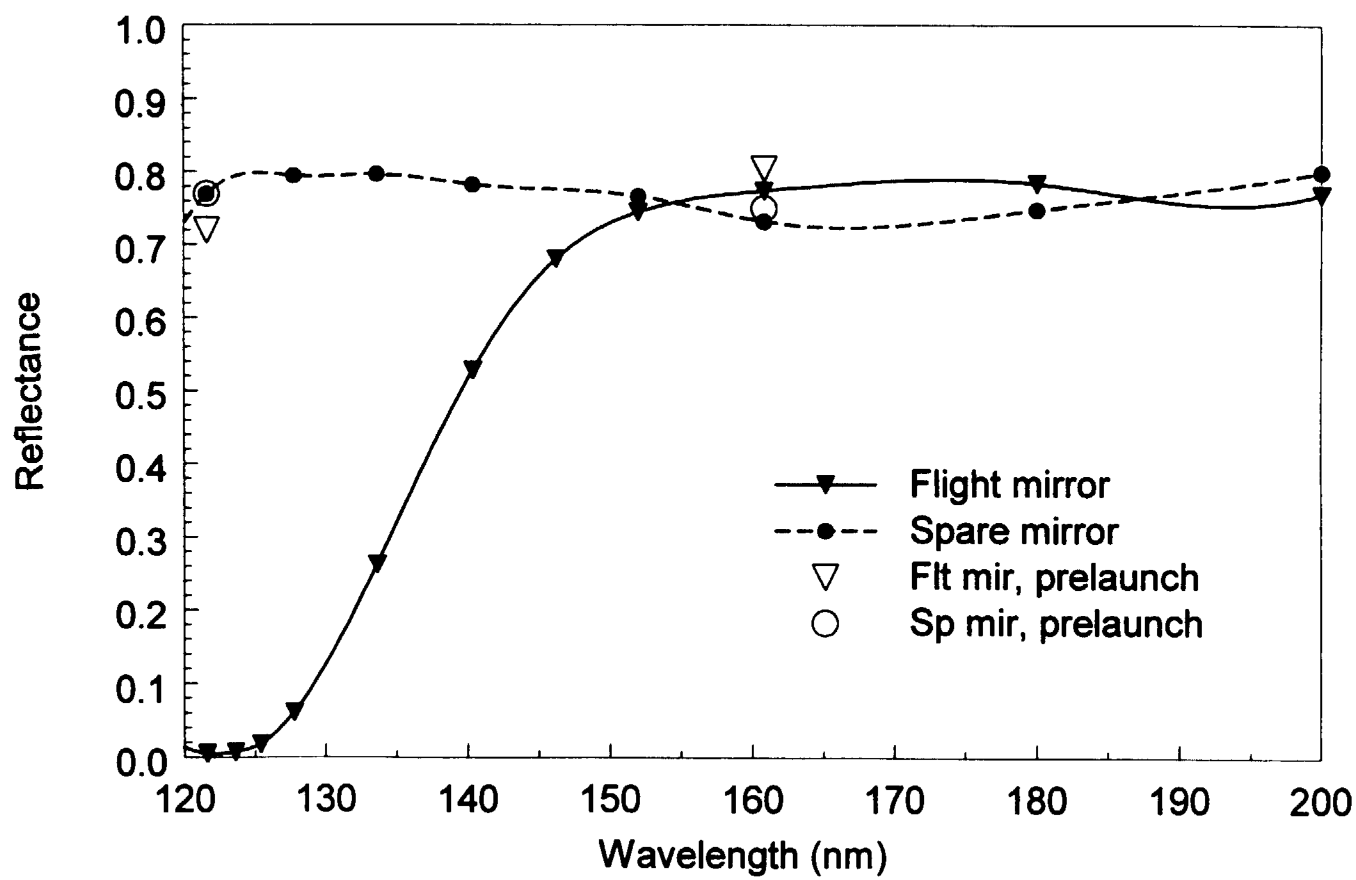
HST WF/PC-1 Returned Hardware

- The optical surfaces facing the central "hub" region of the HST Optical telescope Assembly (OTA) were studied to understand the effects of space exposure on HST hardware.
- WF/PC-1 pickoff mirror showed a blue haze consisting of numerous droplet-like features 1 to 2 microns in diameter.
- To evaluate the impact of the contaminant on performance reflectance of the pickoff mirror and the transmittance of the WF/PC-1 aperture window were measured in the 92 nm to 650 nm wavelength range.

UV Reflectance at Normal Incidence Flight and Spare Pickoff Mirrors



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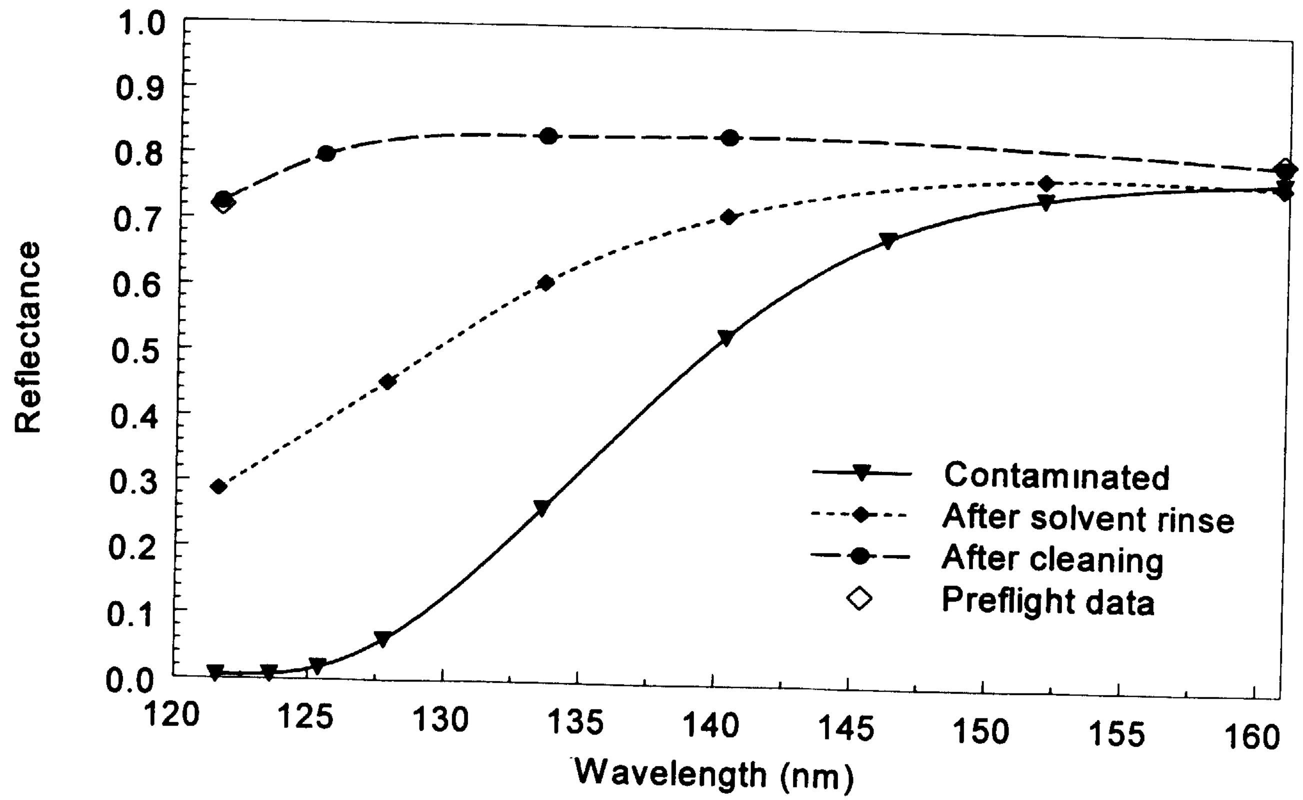
HST WF/PC-1 Returned Hardware Results

- Surface chemistry analyses were performed to determine the composition of the contaminant.
- Pickoff mirror heavily contaminated with hydrocarbons, esters, and silicones.
- Thickness of the contaminant layer approximately 45 nm on the pickoff mirror and approximately 15 nm on the aperture window and HSP filters.
- Contamination mechanism is believed to be photopolymerization of outgassed contaminants from FGS and OTA by earth albedo UV.
- Cleaning restored the UV reflectivity of the pickoff mirror indicating that reflectance degradation was caused by contamination, not optical coating damage.

WF/PC-1 Pickoff Mirror Reflectance Restoration

Normal Incidence



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SOHO/SUMER SiC Telescope Mirror Efficiency

- Mirror S/N 2
  - expected full aperture efficiency >44% at 123.6 nm, measured after ion figuring 31.2%.
  - subaperture efficiencies varied across the surface from 26.4% to 40.5% in five locations after ion figuring.
  - degradation caused by carbon contamination, based on witness sample characterization.
  - restored by flow polishing to 44.6%, full aperture.
- Mirror S/N 3
  - full aperture efficiency after thermal vac 38.2 %
  - restored to 45.4% by cleaning.

Contamination

- UV coatings and materials sensitive to highly absorbing contaminants
- causes reflectance degradation, increased scatter
- exposure to UV light causes the contaminant to photopolymerize
- in Al+MgF2 irradiation induced reflectance loss is due to surface contamination not changes in the MgF2 film

Laboratory Investigations

- Designed and built a small EUV scatterometer. In process of building a larger one in the DGEF.
- Contaminated an Al + MgF2 mirror to Level 500 with room dust .
- Measured BRDF of sample at 633, 325, 121.6, and 74.0 nm and compared with predictions from OPALS model.
- Results showed good agreement between model and data except at 121.6 nm where the data were above the OPALS curve.
- Refurbished the Contamination-Irradiation Facility (CIRF). Initial data runs involving depositing molecular contaminants on an Al + MgF2 sample in progress.
- Extend molecular contamination work to a greater variety of mirror coating types and contaminant materials.

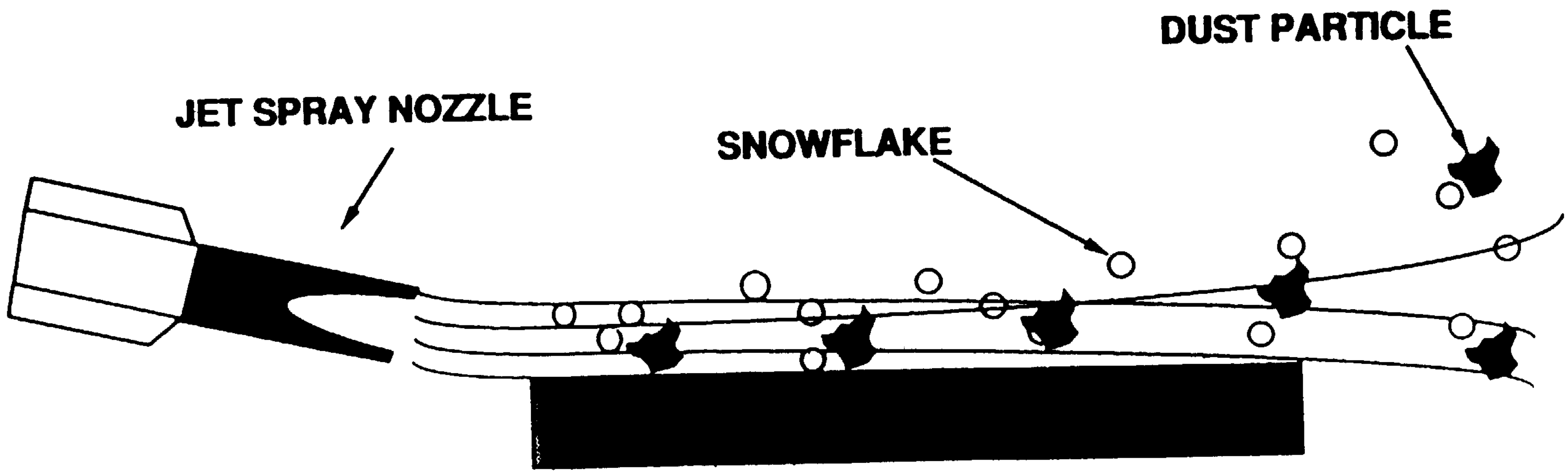
Cleaning Techniques

- solvent flush
- rubbing with Alconox and water solution followed by flushing with acetone has been used for cleaning Al+MgF2 mirrors and CVD-SiC
- photopolymerized contamination:
  - mild abrasive cleaning with calcium carbonate
  - ion beam cleaning

Evaluation of Cleaning Procedures for COSTAR Mirrors

- Solvent flushing results mixed
  - some indication of sleeks and increased scatter
- Gaseous nitrogen ineffective for small particles
  - only method used on flight mirrors
- High pressure carbon dioxide snow (jet spray)
  - damage to Al+MgF2 coatings
  - increased pinholes
- Low pressure carbon dioxide snow (jet spray)
  - qualified for Al + MgF_2

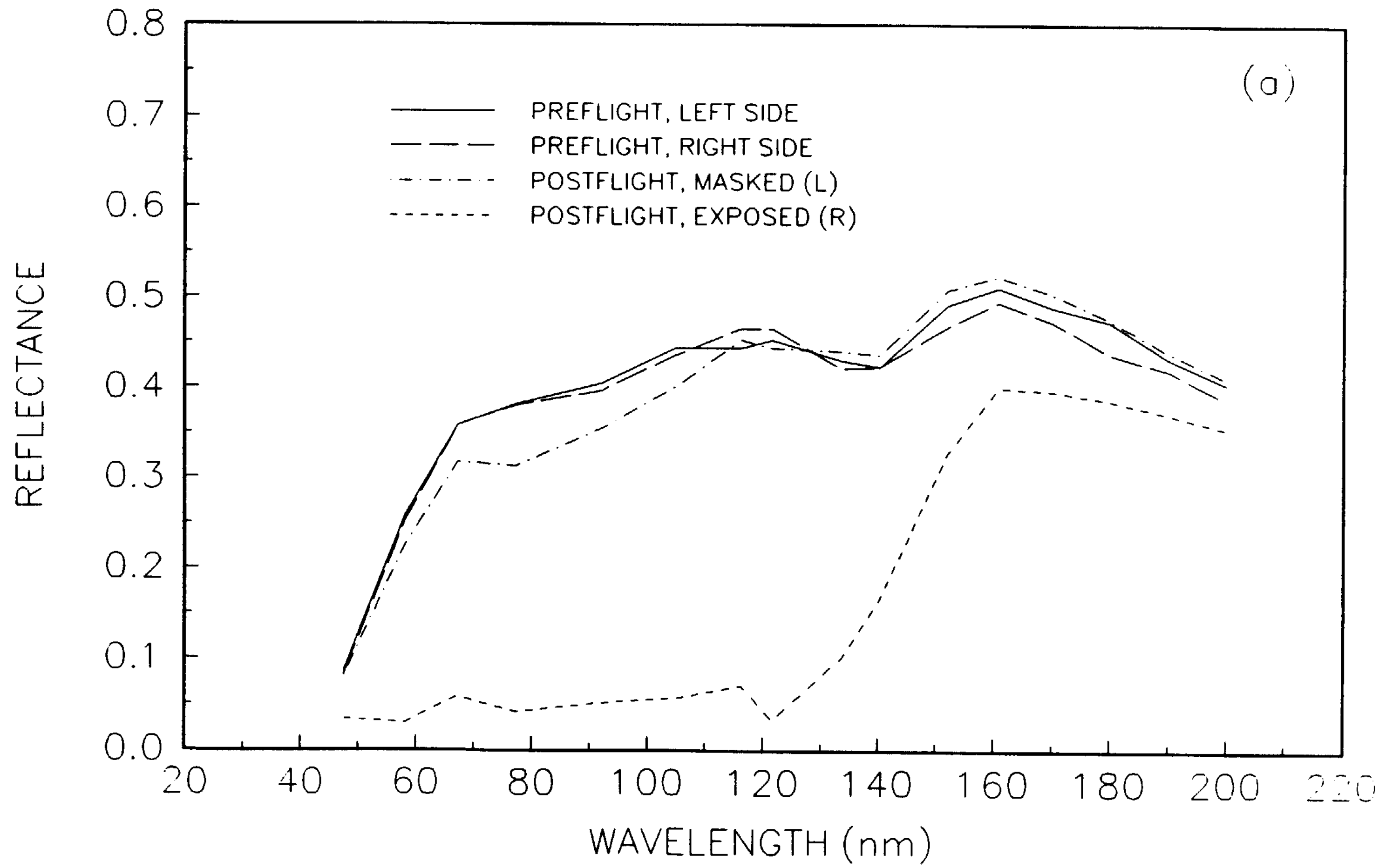
Jet Spray Cleaning Procedure



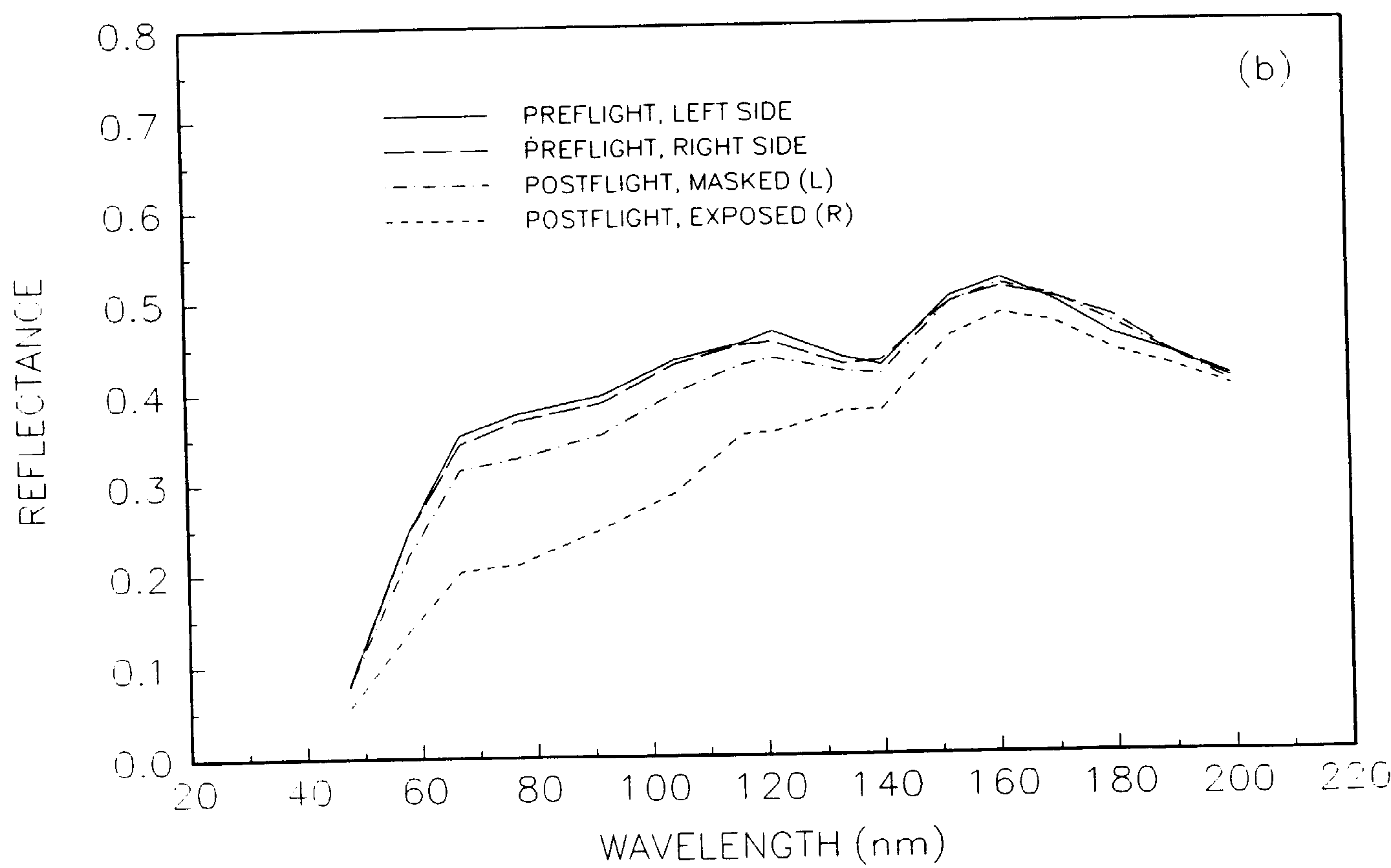
LDEF

- Eight optical coating materials Al, Au, Ir, Os, Pt, Al+MgF2, Al+SiOx, and CVD- SiC representing reflective optical applications from vacuum ultraviolet through visible wavelength region were included.
- Exposure time 10 months.
- The results suggest the need for protecting optical surfaces against external low-earth-orbit environment, particularly ram direction effects.
- Reinforced the short term space exposure results obtained from EOIM experiment.

Reflectance for LDEF CVD-SiC Sample Leading Edge



Reflectance for LDEF CVD-SiC Sample Trailing Edge



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SESAM Experiment

- Surface Effects Sample Monitor (SESAM) experiment was developed to study the effects of space exposure at the low earth orbits on optical materials.
- PI Dr. Dirk-Roger Schmitt from DLR in Germany.
- Flown 3 times on ORFEUS-SPAS and CRISTA-SPAS shuttle missions.
- Allows exposure of three different sets of samples during a shuttle mission; launch, on orbit and landing.
- Samples sealed before and after exposure.
- We have studied effects of on orbit environment on ion beam deposited SiC and boron carbide.

Optical Properties Monitor (OPM) Experiment

- The objective is to study effects of space environment on optical, thermal control and other materials.
- PI Dr. Donald R. Wilkes of AZ Technology, Inc.
- OPM is being flown on Mir Space Station.
- Experiment includes on-board optical instruments to measure space exposure effects.

Optical Properties Monitor (OPM) Experiment (continued)

- The VUV sample portion of the sample carousel includes optical coating, window and baffle samples that have application in the VUV wavelength region.
- GSFC supplied samples include Al+MgF2, Ir, SiC and boron carbide films, CVD-SiC and CVD diamond on the VUV portion, and Ir/Si multilayer on the passive portion of the carousel.
- Goal is to study effects of the environment around a large space platform including contamination, atomic oxygen and solar and earth UV irradiance.

Conclusions

- Improvements in optical coatings and materials technology have made possible the development of instruments with substantially improved efficiency in the EUV spectral region.
- Contamination severly degrades performance in the EUV by causing reflectance degradation and increased scatter.
- EUV optical coatings and materials need to be protected against contamination on the ground and on orbit, and the external low-earth orbit environment, particularly ram direction effects.

1997 Spacecraft Contamination & Coating Workshop

Active Contamination Control

Tom King and Charles Stein

Air Force Phillips Laboratory

Albuquerque, NM

USA

and

James Baird

Department of Chemistry, University of Alabama

at Huntsville

USA

Research Team Members

	Name	Affiliation	Discipline
1.	Dr Warren Wilson	PL	Experimental Physicist
2.	Dr Thomas King	PL / NRC	Theoretical Physicist
3.	Capt Stephen Davis	PL	Experimentalist
4.	Mr Robert Robertson	Contractor	Data Acquisition
5.	Dr Jon Shively	Cal State U.	Materials Scientist/Shock Physicist
6.	Dr. Pawel Tlomak	Contractor	Ultraviolet Radiation/ Hypervelocity Debris
7.	Dr. James Baird	U. of Alabama	Theoretical Chemistry
8.	Mr. Charles Miglionico	PL	Electron Microscopist
9.	Dr. Charles Stein	PL	Materials Scientist
10.	Dr. Craig Outten	PL	Experimental Physicist

Space Environment Interaction Studies

Projects

Hypervelocity Debris

1. Debris Generated Contamination
2. Debris Generated Damage
3. Shock Physics

   a) Non Equilibrium Chemistry

   b) Laser vs Debris Generated Chemistry

Interactive Chemistry

1. Outgassing/Contamination
2. Accelerated Testing
3. Synergistic Photon/Particle Chemistry

   a) AO + e

   b) AO + uυ

   c) AO + uυ + e

   d) AO + uυ + e + Debris

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Space Environment Interaction Facility

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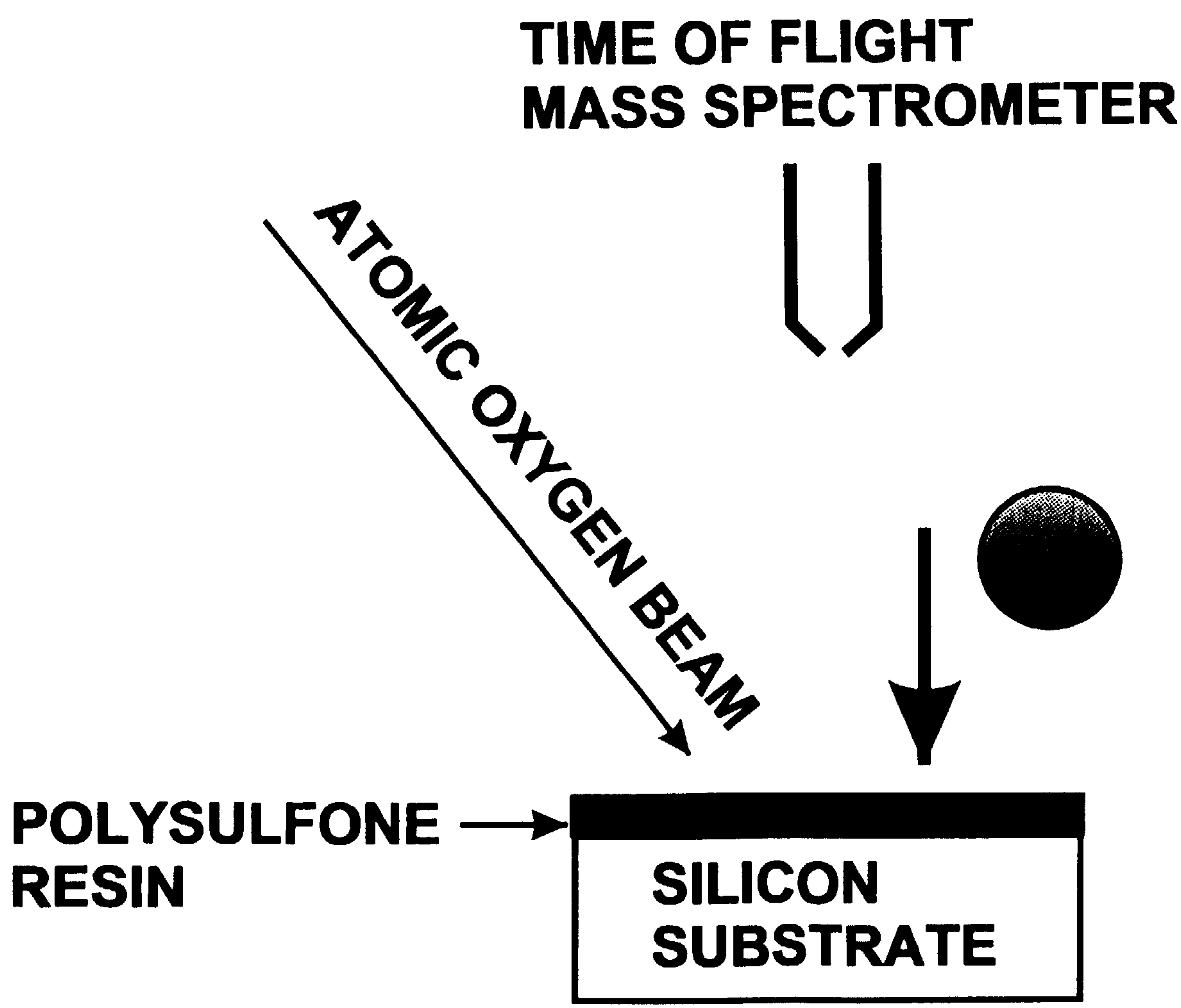

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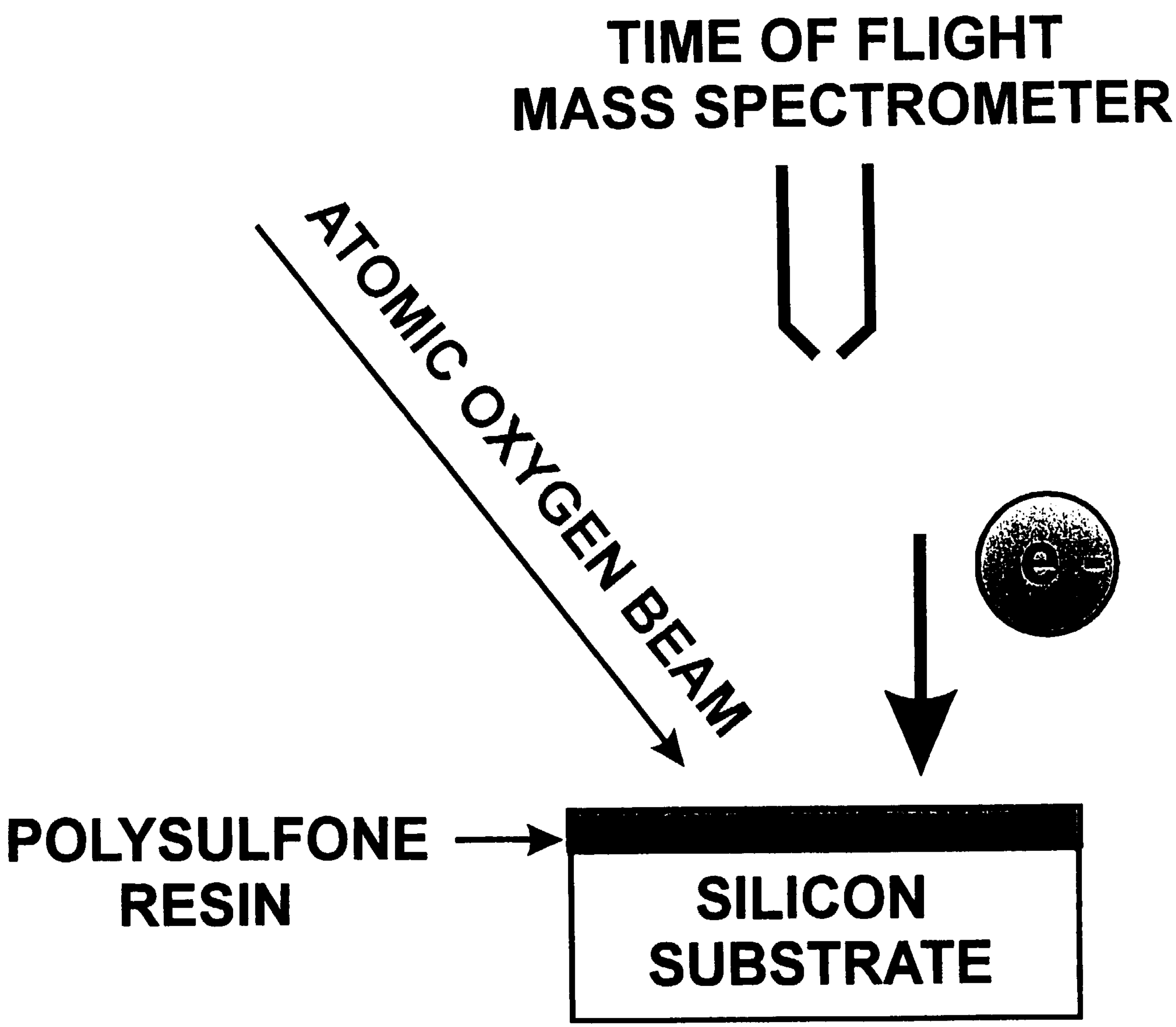
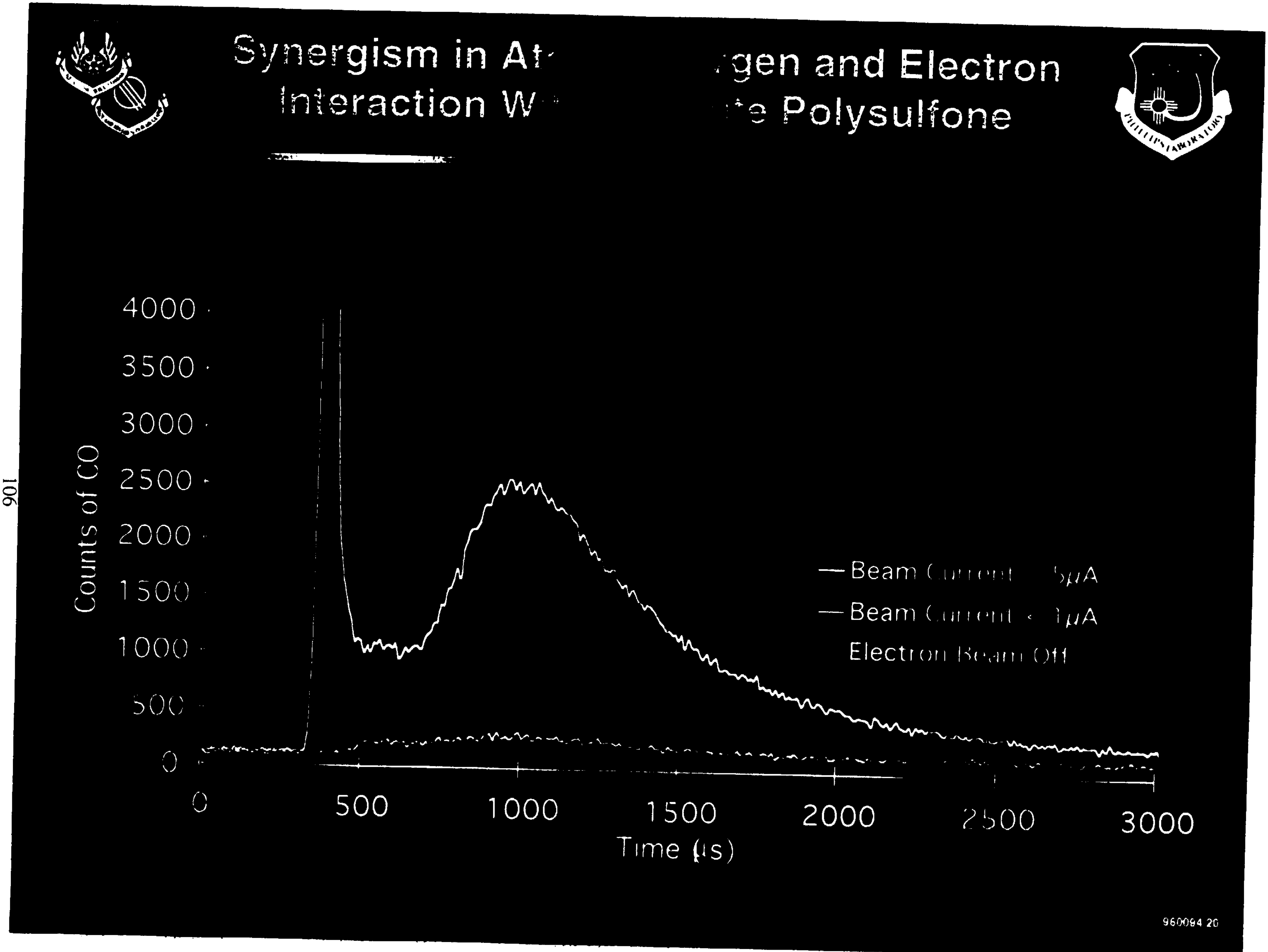
EXPERIMENTAL SETUP




Synergism in At gen and Electron
Interaction W Polysulfone
Counts of CO
4000
3500
3000
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
Time (µs)
Beam Current
Beam Current
Electron Beam Off
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POSSIBLE ELECTRON / OXYGEN INTERACTIONS

(1) ENERGETIC ELECTRONS CAN HELP SUPPLY THE REQUIRED ACTIVATION ENERGY OF 0.4 eV FOR THE HYDROGEN EXTRACTION PROCESS:

$$R + O^{o} + e^{-} \rightarrow R\bullet + OH^{-}.$$

(2) ENERGETIC ELECTRONS CAN EXCITE THE GROUND STATE OF ATOMIC OXYGEN WHICH THEN ATTACKS THE LONG CHAIN MOLECULE AT AN INCREASED RATE:

$O^{o} + e^{-} \rightarrow O^{*}$ (O^{-} or $O^{1}D$); then:

$$R + O^{*} \rightarrow R\bullet + OH^{-}.$$

(3) ENERGETIC ELECTRONS CAN DIRECTLY EXCITE ATOMS ON THE LONG CHAIN HYDROCARBON, WHICH THEN INTERACTS WITH ATOMIC ENERGY AT A HIGHER RATE:

$R + e^{-} \rightarrow R^{*}$; then:

$$R^{*} + O^{o} \rightarrow R\bullet + OH$$

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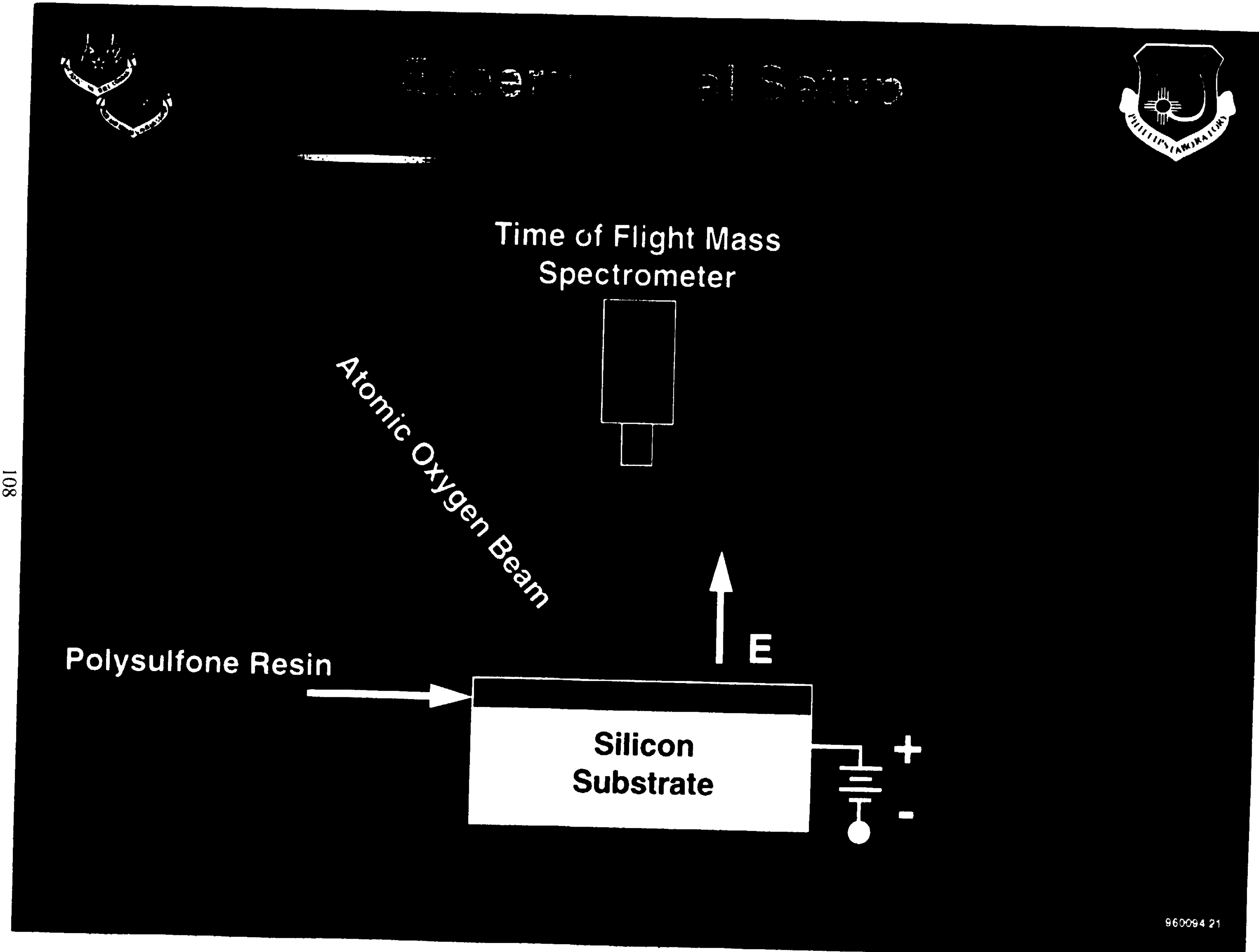
Time of Flight Mass
Spectrometer
Atomic Oxygen Beam
E
Polysulfone Resin
Silicon
Substrate
+
-
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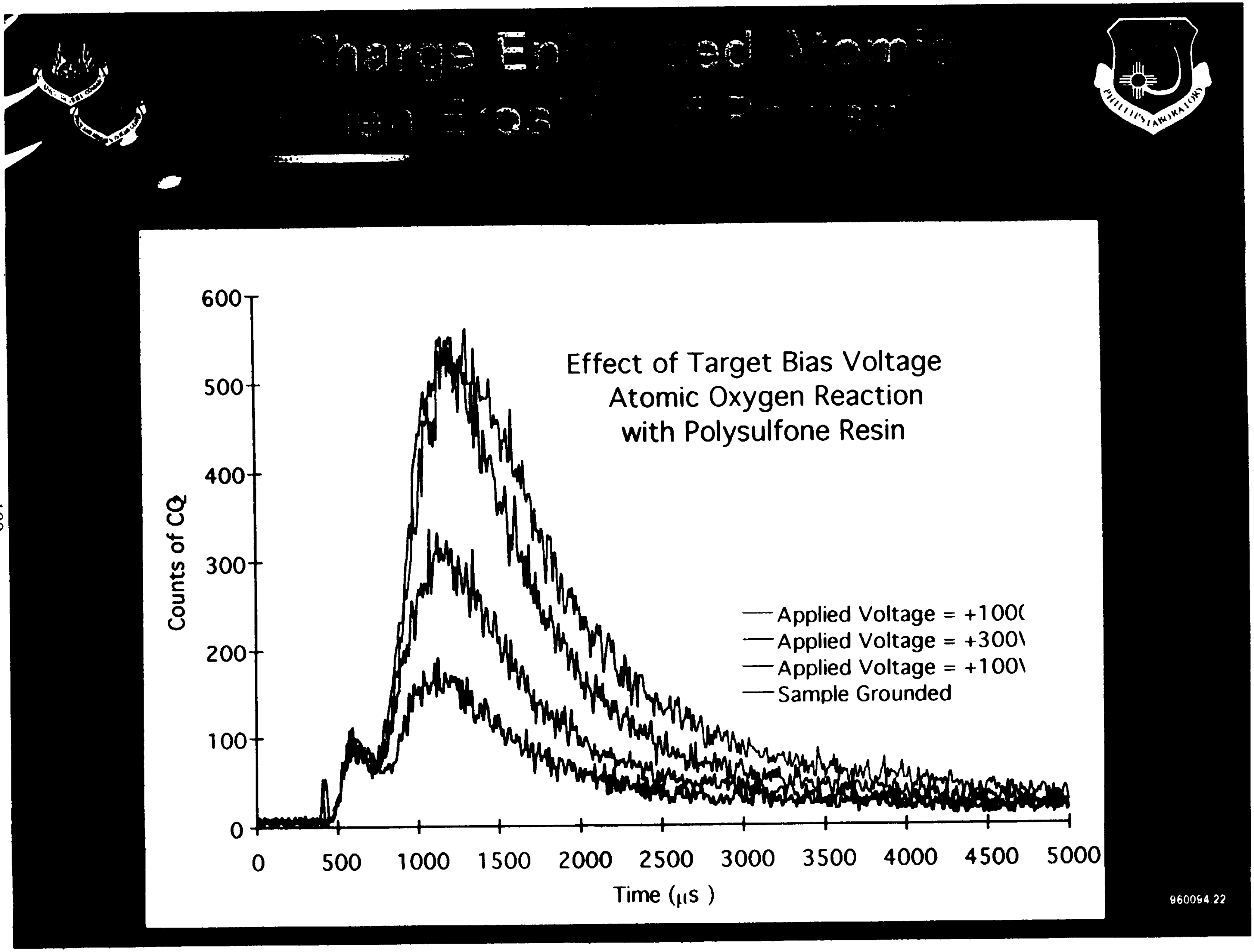
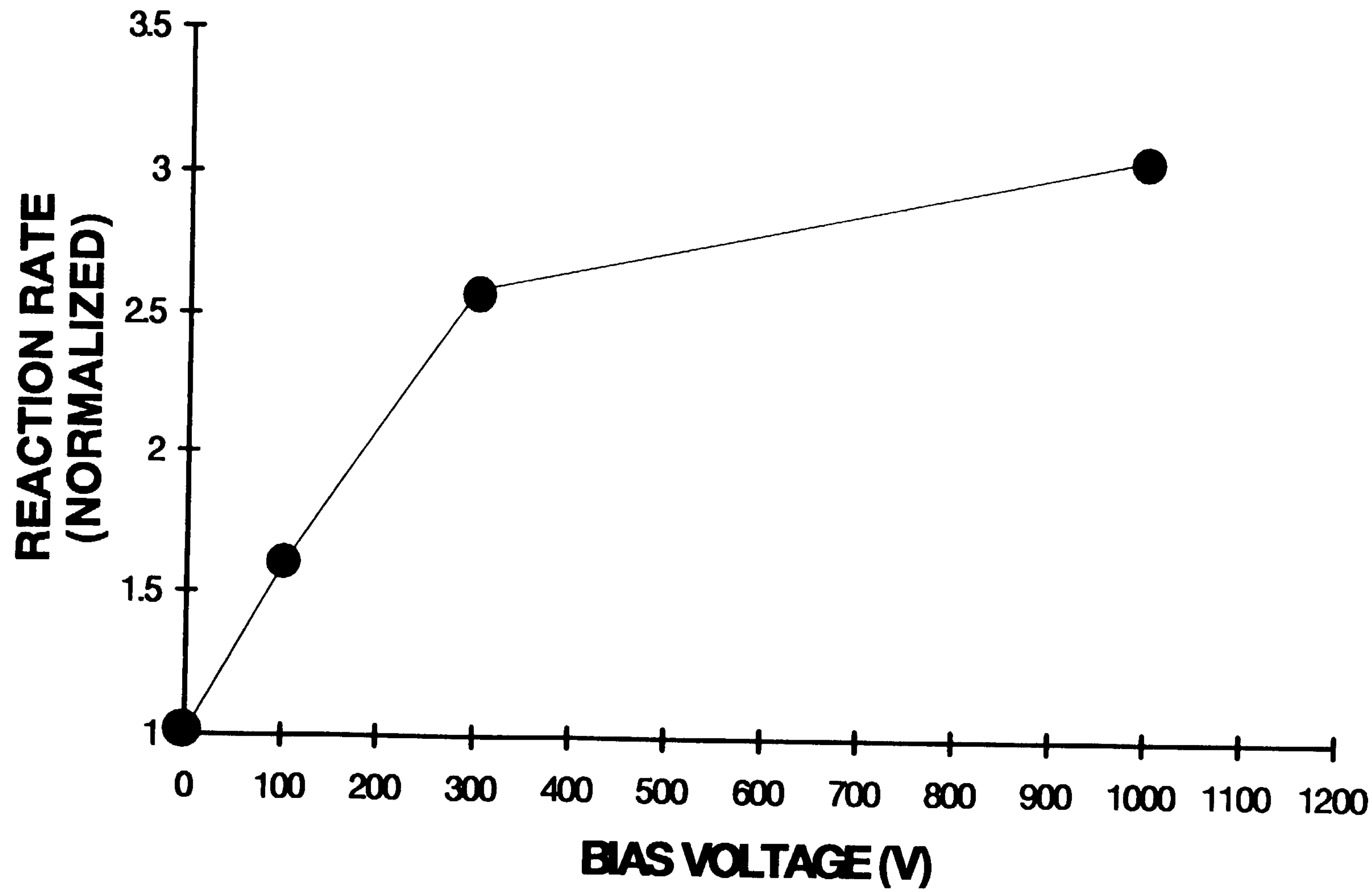


Effect of Target Bias Voltage
Atomic Oxygen Reaction
with Polysulfone Resin
Applied Voltage = +100(
Applied Voltage = +300\
Applied Voltage = +100\
Sample Grounded
Counts of CQ
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (μs)
960094.22

REACTION RATES VERSUS BIAS VOLTAGE



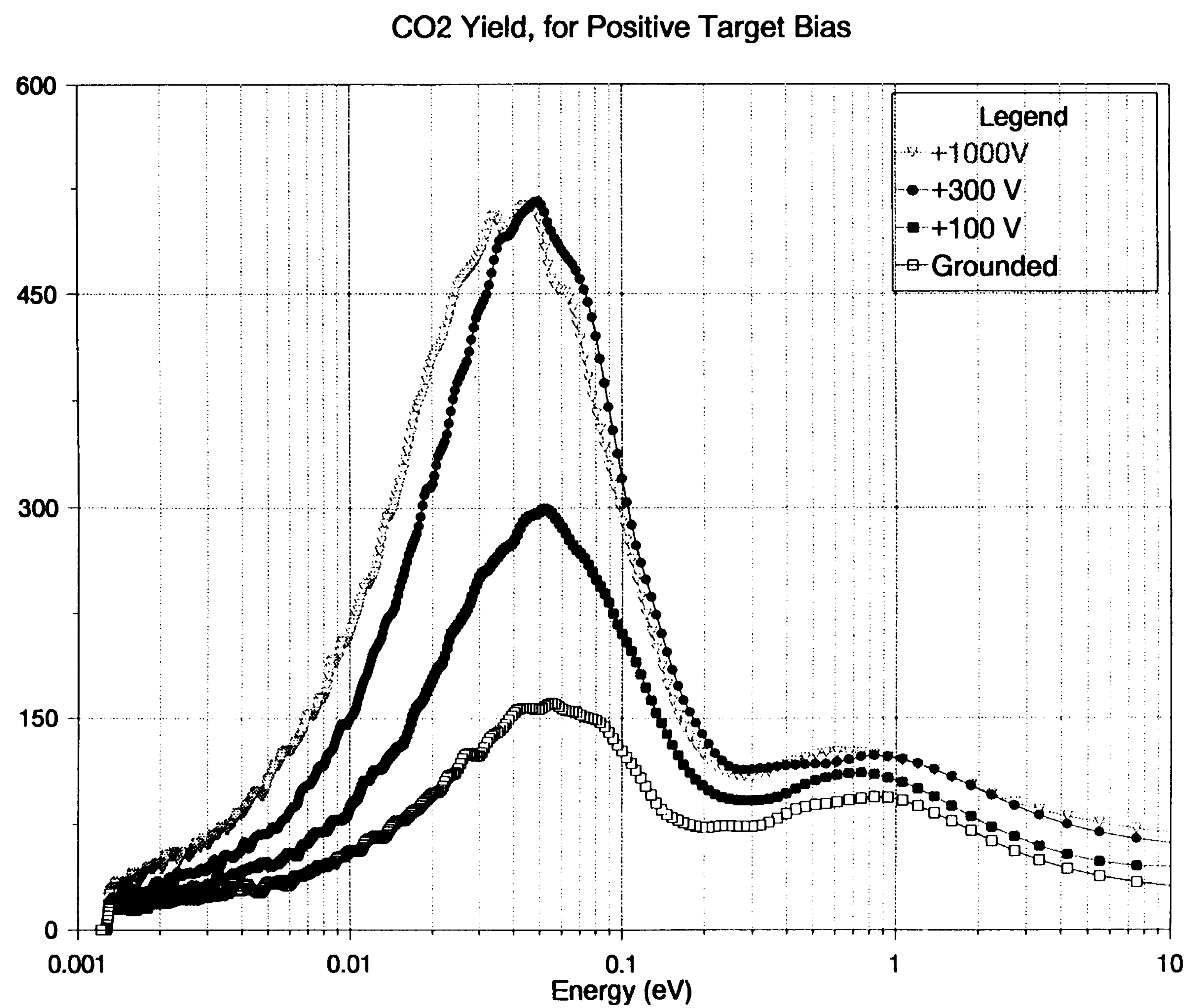


Fig. 7. CO2 Yield for positive target bias. Bottom curve is for target grounded.

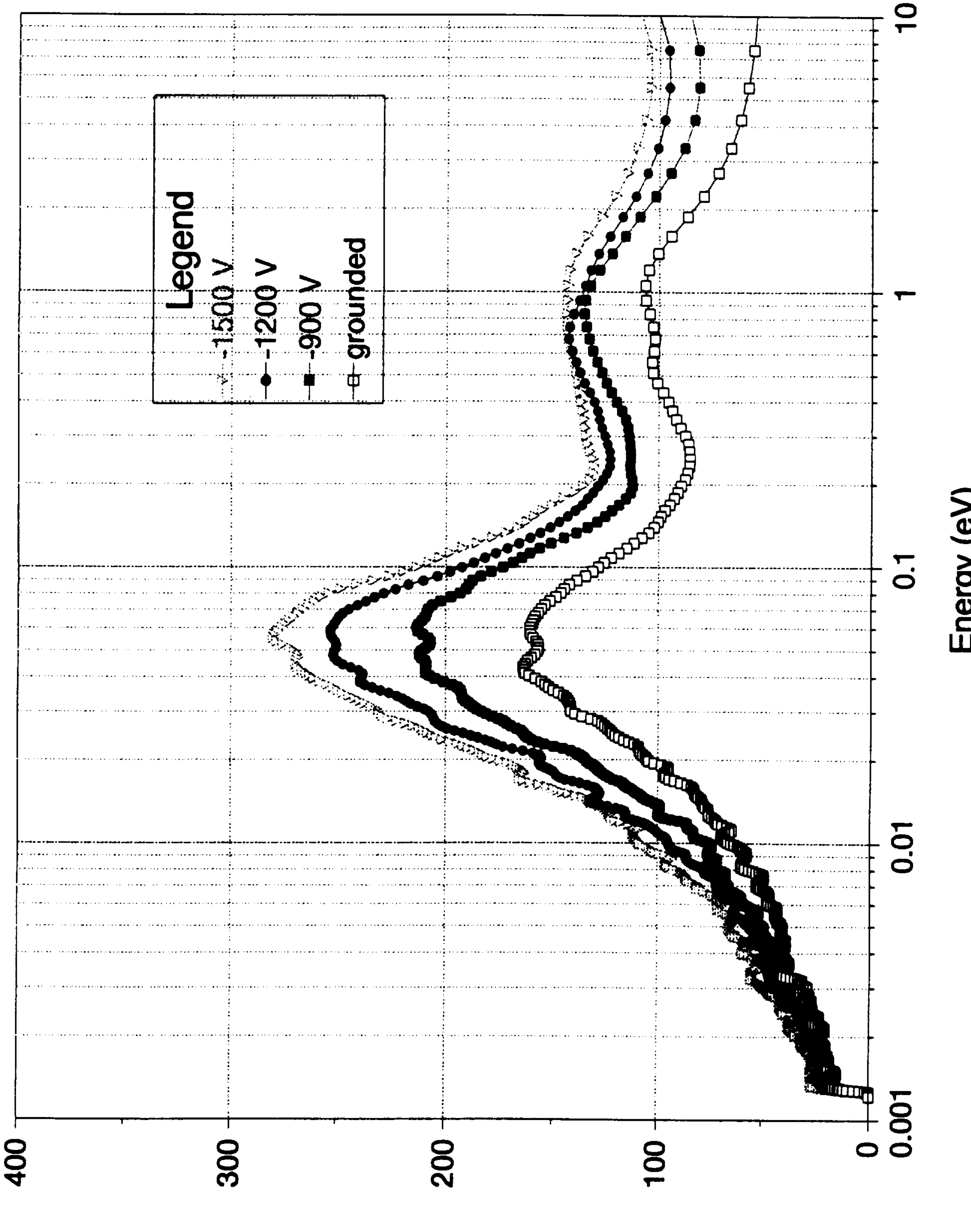
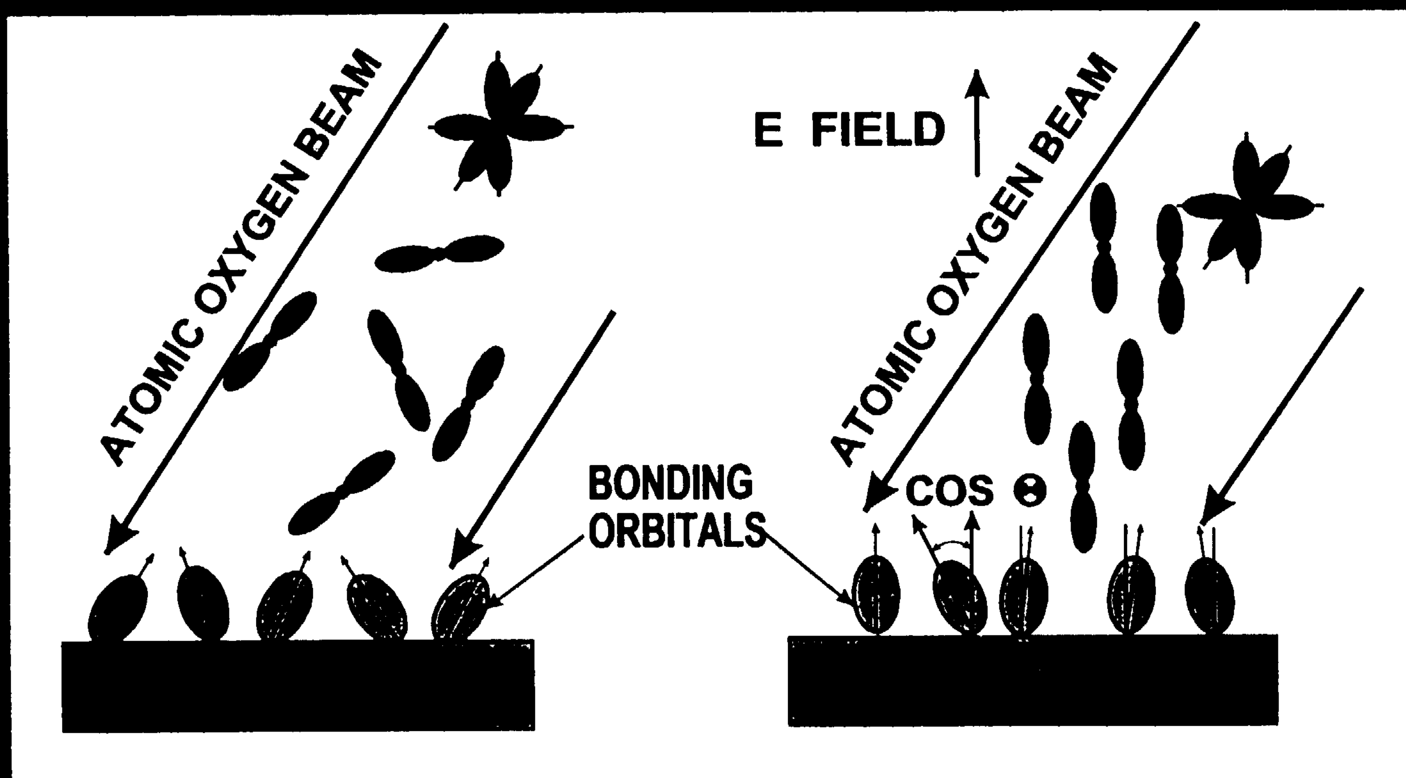


Fig. 8. Effect of negative bias on CO_2 yield.

Interaction of Atomic Oxygen and Electric Field

JUL297.PPT



BALLISTIC
MISSILE
DEFENSE
ORGANIZATION

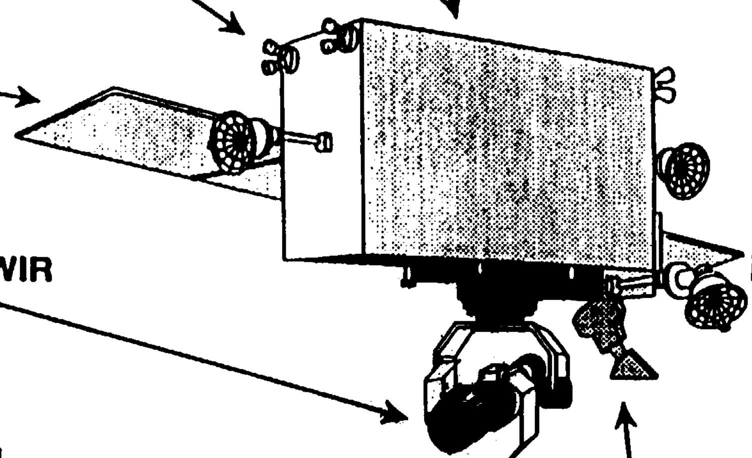
SMTS (BE) TECHNOLOGIES

Reaction Control
- Monopropellant N_2H_4

Structure
- Aluminum Honeycomb (Gr / TP, Metal Matrix)

Communications
- 60 GHz Solid-state Cross-links
- 44 / 20 GHz Up / Downlinks
- Gimballed Antennas (Phased Array)

Electrical Power
- GaAs / Ge-Solar Arrays
- NIH_2 CPV Batteries



Signal / Data Processing
- Rad 6000 (RH 3000) (RH-32)
- 1Mbit SRAMs (256K SRAMs)
- 12 Bit ADC
- 256K NVRAM
- 60K - 90K Gate Arrays

Staring Sensors
- HgCdTe SWIR / MWIR / M-LWIR
- HgCdTe LWIR
- Si CCD Visible
- Be Optics (SiC)
- 1-Stage And 2-Stage Stirling Cryocoolers (Turbo Brayton, Pulse Tube)

GN&C
- CMG (Reaction Wheels)
- GPS
- Ring Laser Gyro
- Star Tracker
- Earth Horizon Sensors
- Magnetometers
- Torquer Rods

Thermal Control
- Radiators
- Phase Change Materials
- Variable Conductance Heatpipes
- Multilayer Insulation

Scanning Sensors
- HgCdTe SWIR
- Be Optics
- Si Correctors

( ) Technology Options

pj-43149 / 042904

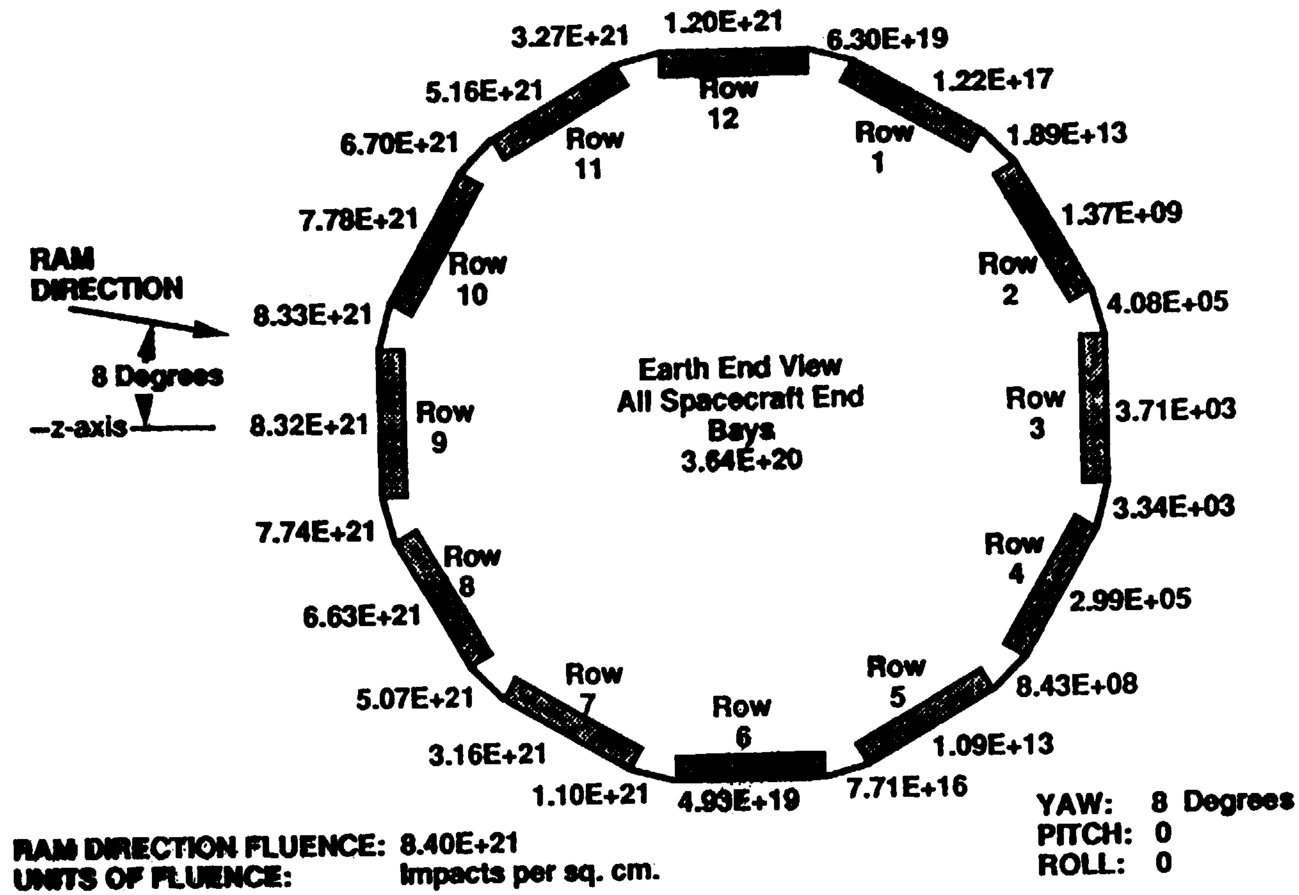
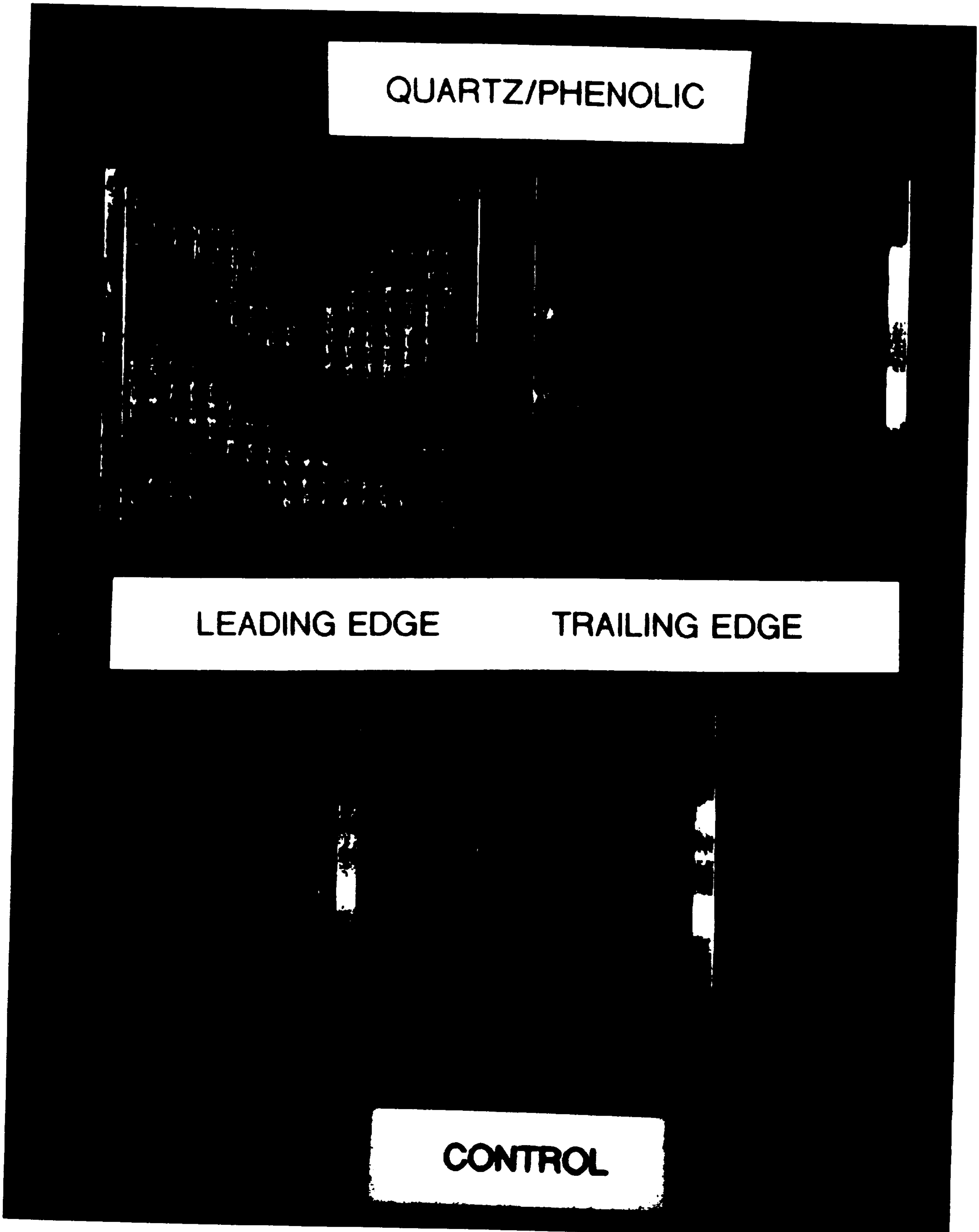


Figure 38.
Atomic oxygen fluences at end of mission for each tray location.


QUARTZ/PHENOLIC
LEADING EDGE
TRAILING EDGE
CONTROL

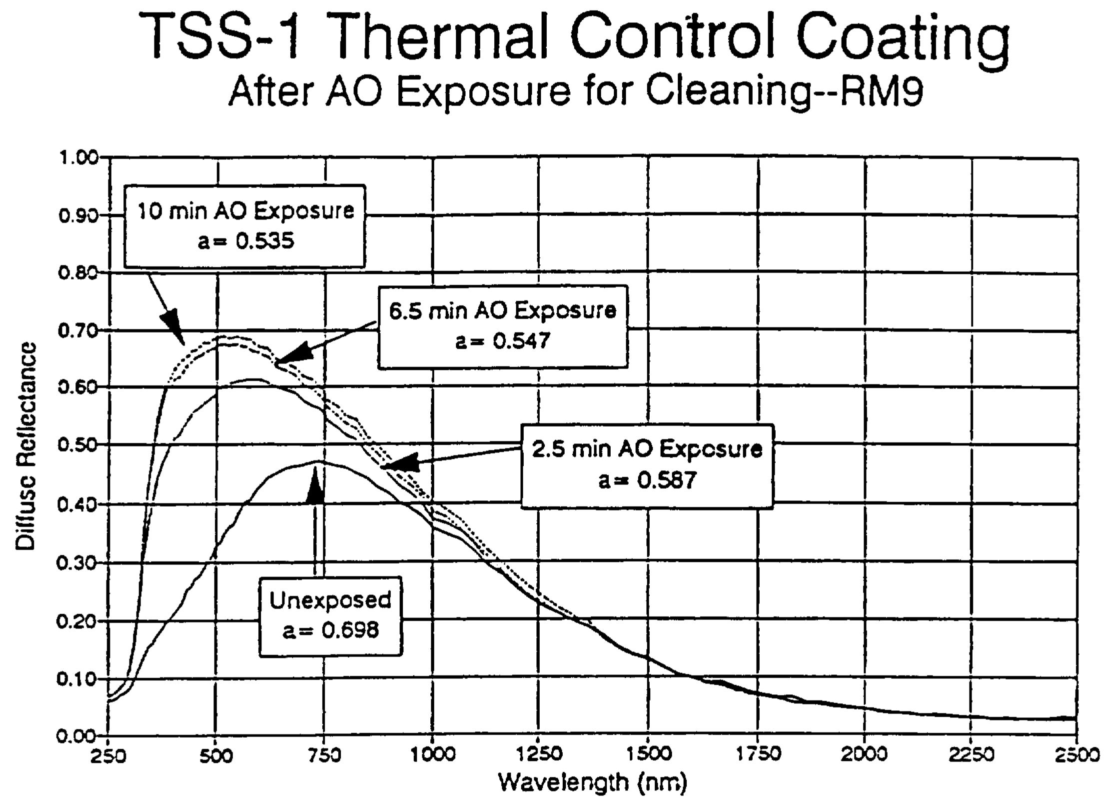


Figure 9. Typical diffuse reflectance curves for AO cleaning of RM400.

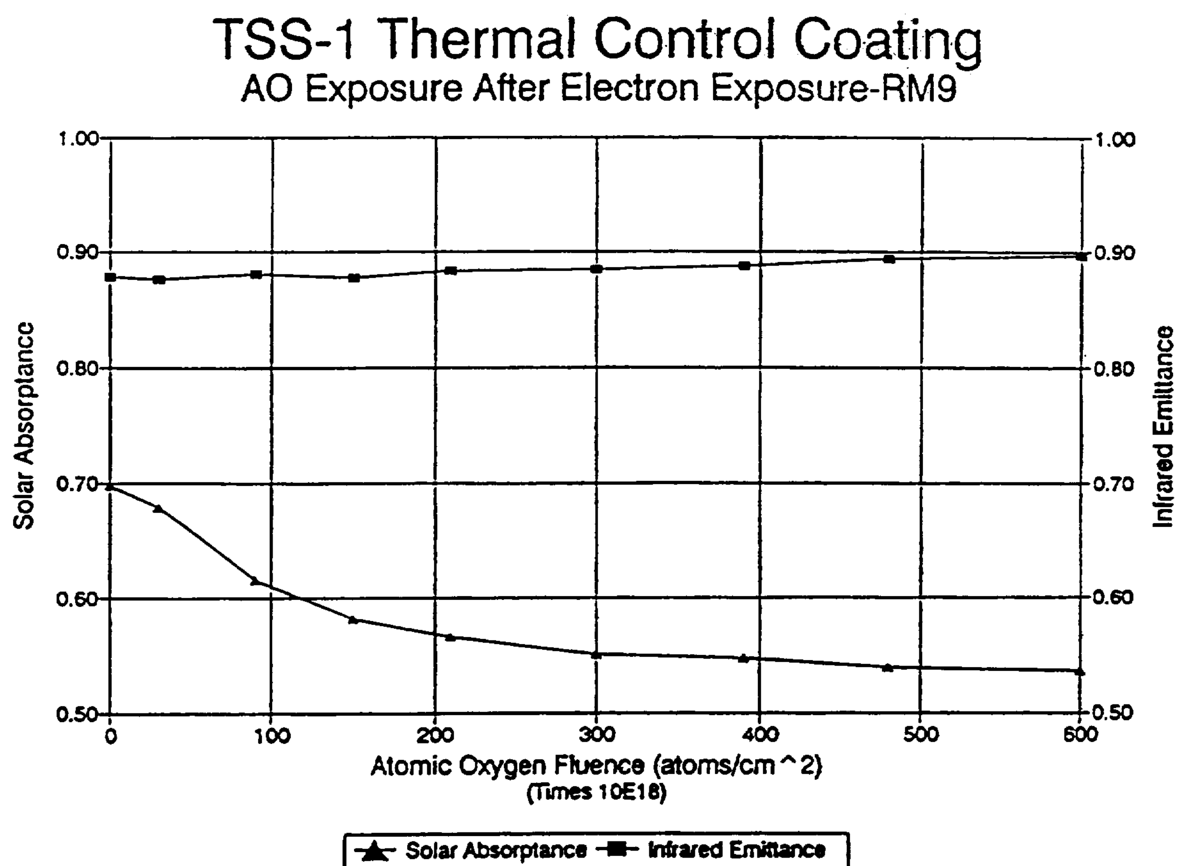


Figure 10. Solar absorptance and infrared emittance data for AO cleaning of RM 400.

FEASIBILITY OF USING ATOMIC OXYGEN FOR ACTIVE CONTAMINATION CONTROL OF SATELLITES*

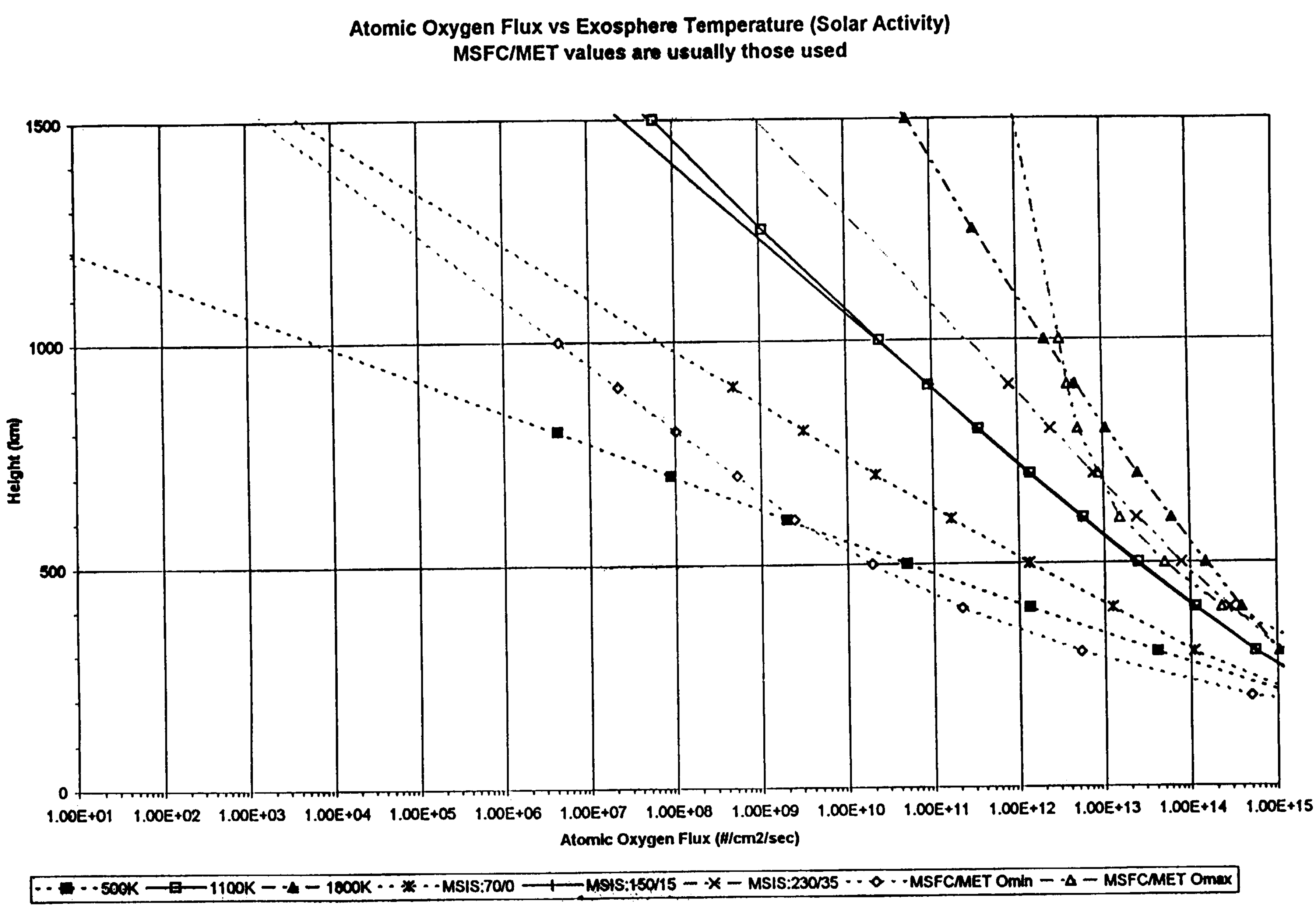
CONTAMINATION RATE(1)	5×10^{-17} gm/cm²/sec
ATOMIC OXYGEN EROSION RATE(2)*	9×10^{-14} gm/cm²/sec

* Calculations do not include the enhancement of AO erosion by charging the substrate

1) Calculated using the measured MXS outgassing 3.4×10^{-11} gm/cm²/sec and a return ratio of 1.5×10^{-6} gm/cm²/sec. (The MSX altitude is 904 km)

2) Calculated using an atomic oxygen flux at 1,000 km of 3×10^{10} AO/cm²/sec and a Reaction efficiency measured for polysulfone of: $R_e = 2.4 \times 10^{-24}$ cm³/AO and a density for polysulfone of 1.24.

CNSTEBNACTIVE.CON


Atomic Oxygen Flux vs Exosphere Temperature (Solar Activity)
MSFC/MET values are usually those used
Height (km)
1500
1000
500
0
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07
1.00E+08
1.00E+09
1.00E+10
1.00E+11
1.00E+12
1.00E+13
1.00E+14
1.00E+15
Atomic Oxygen Flux (#/cm2/sec)
500K
1100K
1800K
MSIS:70/0
MSIS:150/15
MSIS:230/35
MSFC/MET Omin
MSFC/MET Omax

Contamination Research at The Aerospace Corporation

Graham Arnold

Graham.S.Arnold@aero.org; 310 336-1935

David F. Hall

David.F.Hall@aero.org; 310 336-5896

MECHANICS AND MATERIALS TECHNOLOGY CENTER

THE AEROSPACE CORPORATION

Outline

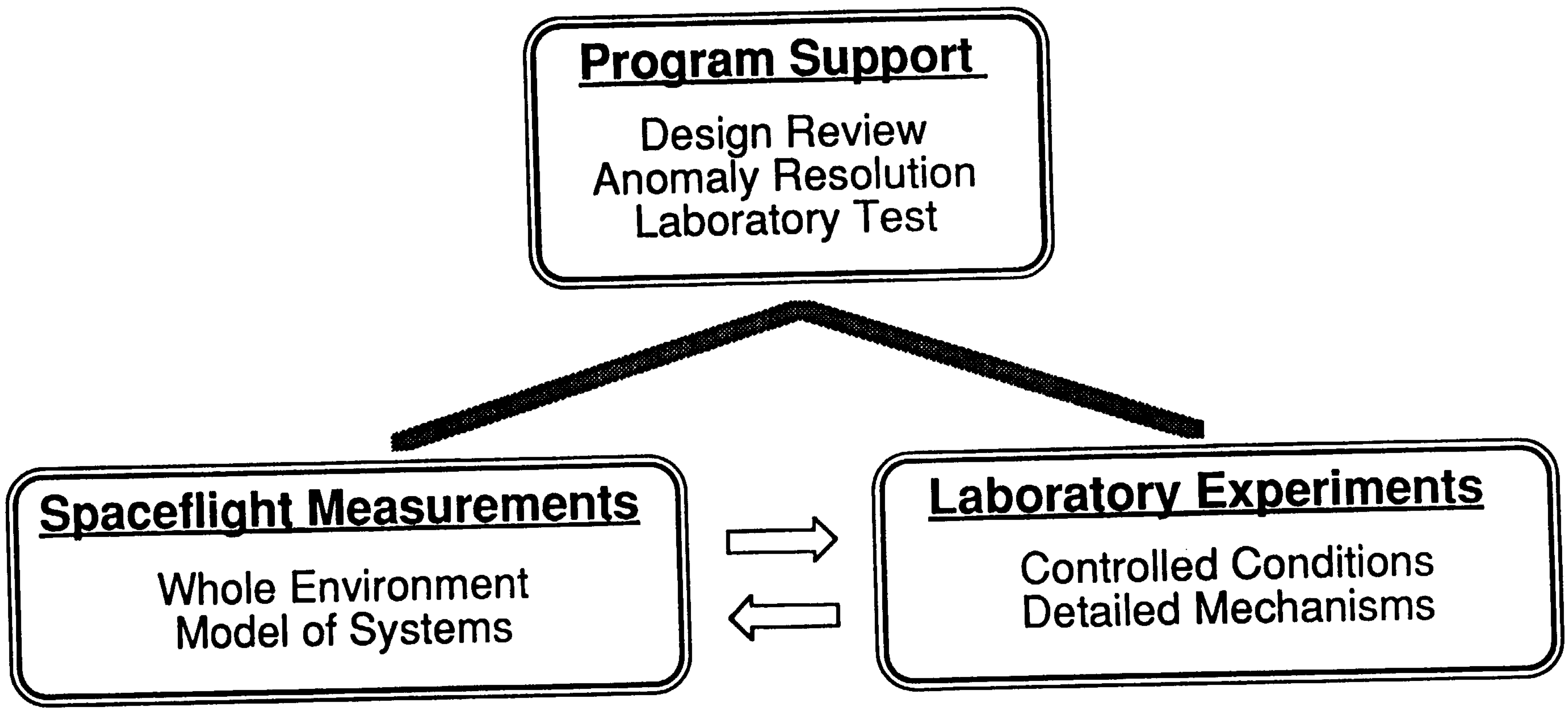
- Roles and Goals
- Current Laboratory Research
  - NVR Test Solvent Replacement
  - Photochemical Contaminant Deposition
- Current Flight Research
  - Diagnostic Instrumentation Package
  - MSX Contamination Experiment Team Member
- Future Flights
  - GPS Block IIA S/N 38 Calorimeters
  - SAMMES on STRV 2 on TSX 5

Spacecraft Phenomena Section

- G. S. Arnold (Surface Science Dept. Mgr.)
- E. N. Borson (retired -- "casual" employee)
- D. J. Coleman
- D. F. Hall
- K. T. Luey
- J. C. Uht

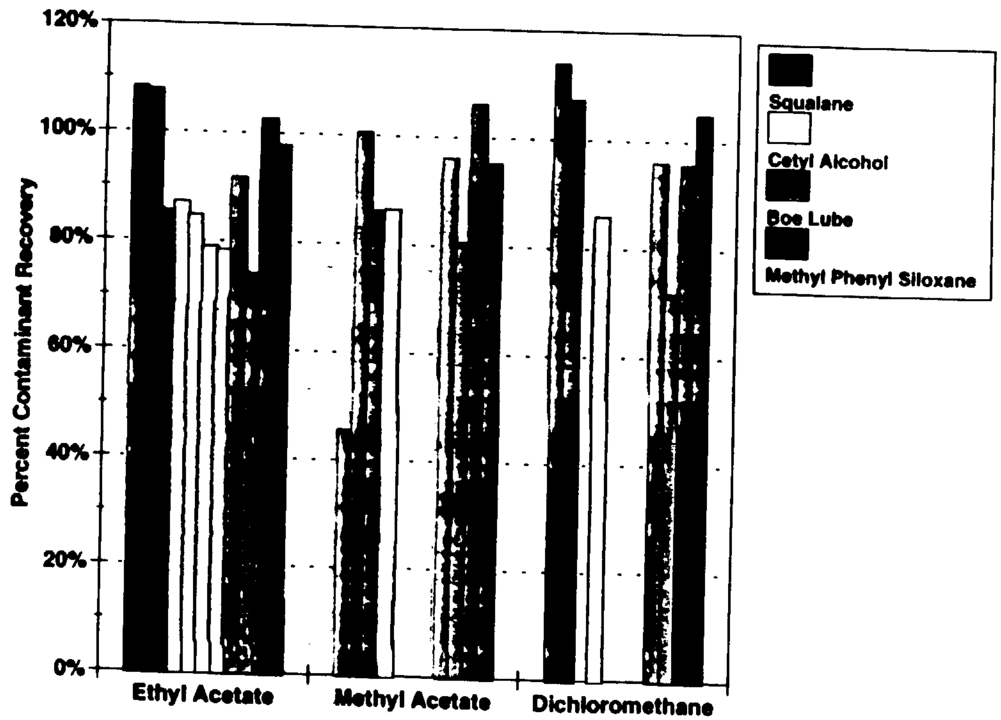
Spacecraft Environmental Phenomena

Approach



Contamination Diagnosis/Cleaning

Non-Volatile Residue Test Solvent Replacement



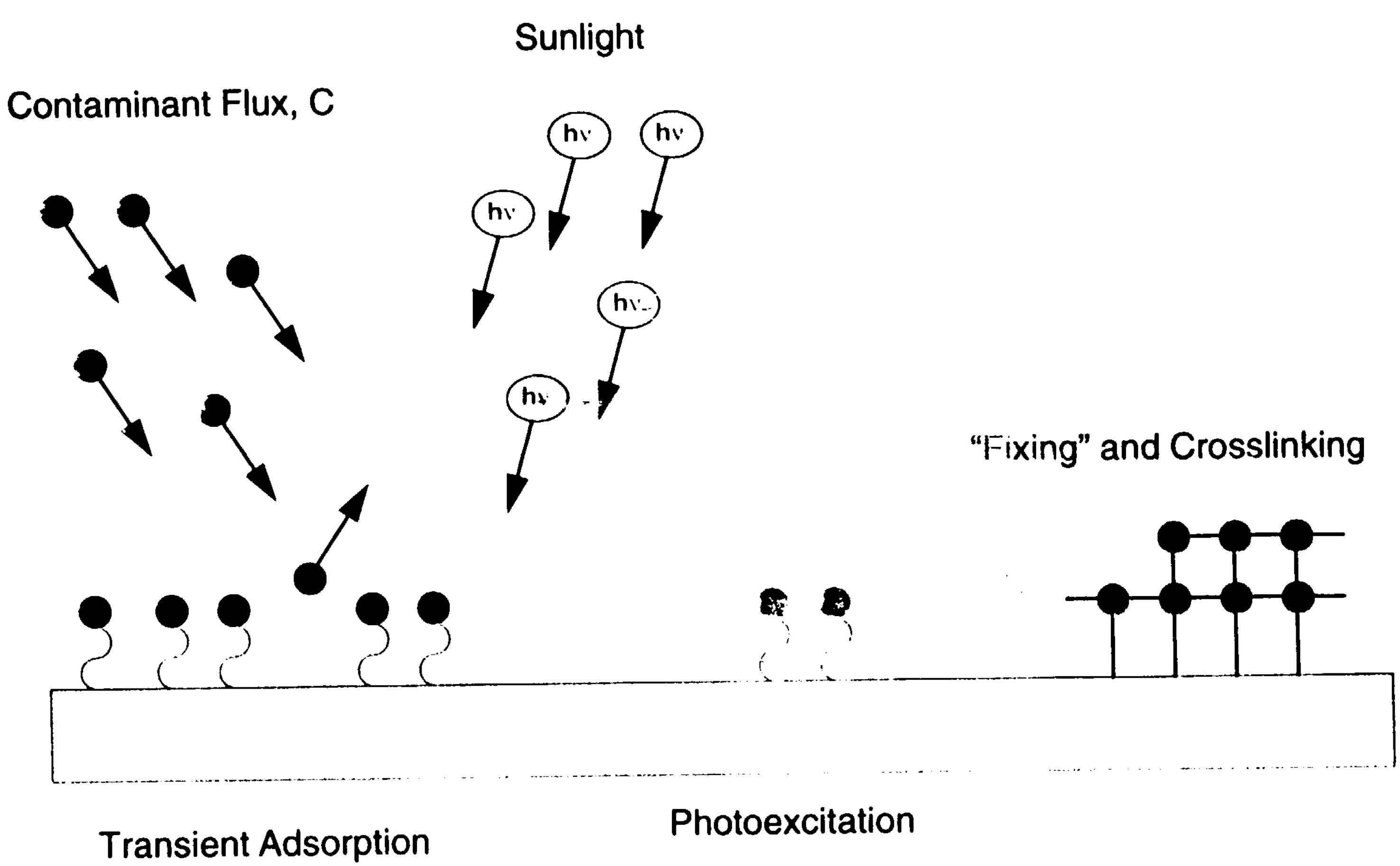
- Gravimetric "NVR" analysis verifies spacecraft & launch vehicle cleanliness.
- Existing test methods use *Class 1 ODC's*
- Laboratory tests have identified Ethyl Acetate as a good replacement
- Ongoing research for Freon replacement for launch site GN_2 system validation

MECHANICS AND MATERIALS TECHNOLOGY CENTER

THE AEROSPACE CORPORATION

Photochemical Contaminant Deposition

Mechanism



MECHANICS AND MATERIALS TECHNOLOGY CENTER

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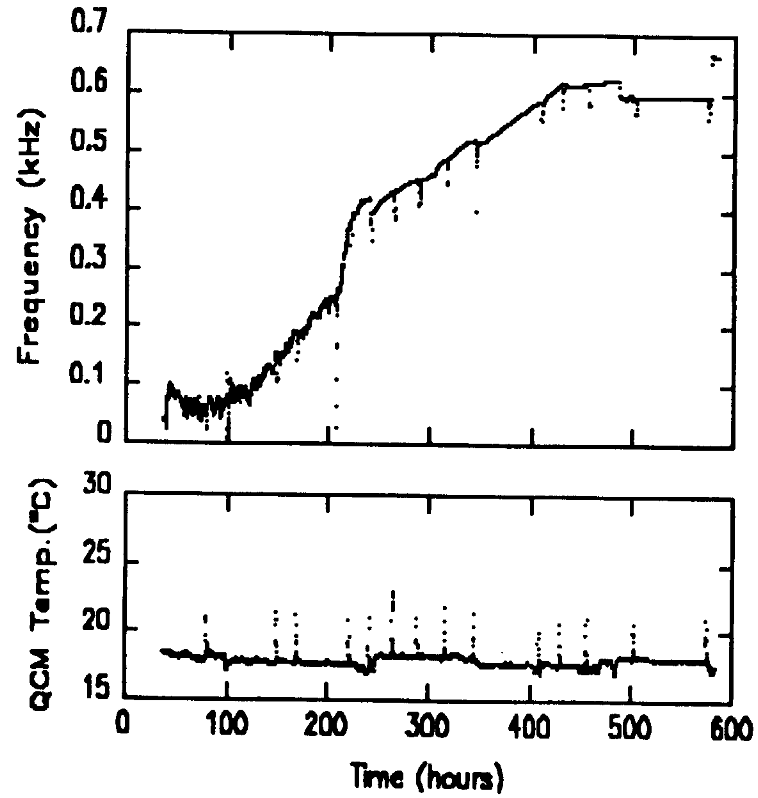
Deposition Results Summary

Model Contaminants



- **Deposition at ~0.04-0.08 nm/hr**
  - **Phthalates** (dioctyl phthalate, DEHP)
  - **Phenols** (bisphenol-a)
  - **Aromatic Amines** (4-tetradecylanaline)
  - **Silicones** (DC 704)
  - **Alkenes** (Squalene)
- **No observable Photodeposition**
  - **Aromatic Hydrocarbons** (bibenzyl, dodecahydrotriphenylene)
  - **Aliphatic Carbonyls** (10 nonadecanone)

MECHANICS AND MATERIALS TECHNOLOGY CENTER

THE AEROSPACE CORPORATION

Computed Contaminant Film Effects

Summary

Computed increase in integrated solar absorptance (α_s) per micrometer of contaminant film

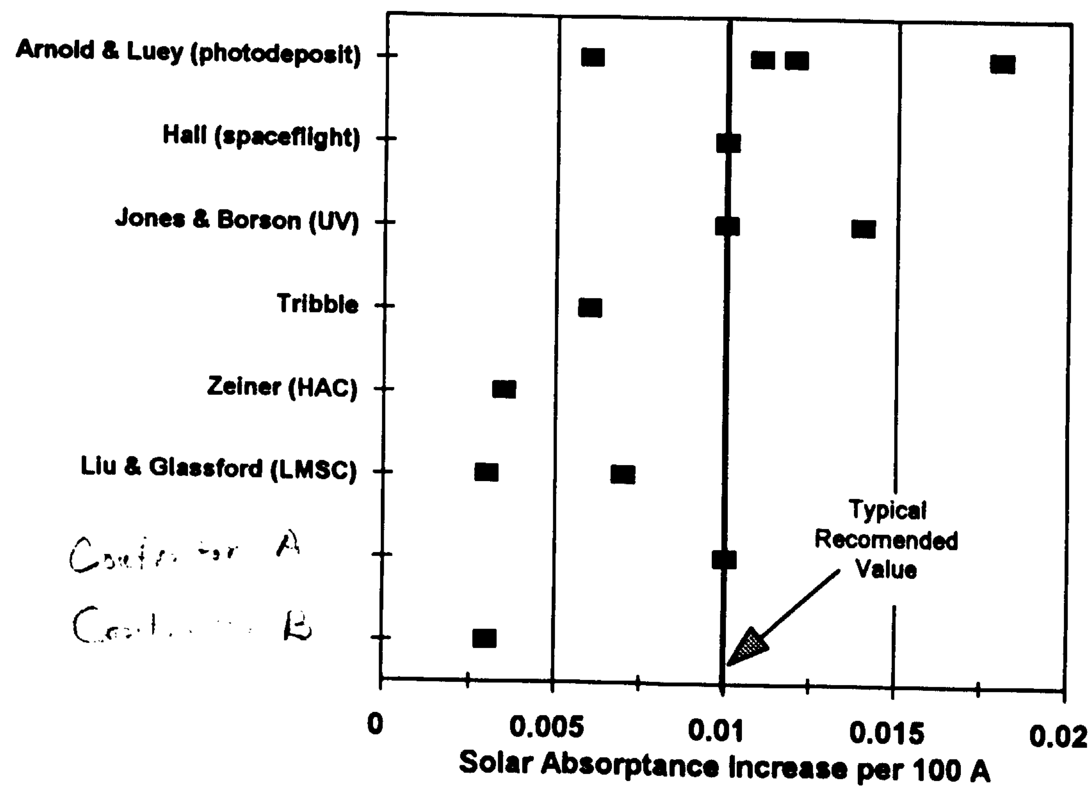
Contaminant	OSR		YB71-P		S13G/LO-1P		Z93-P	
	min	max	min	max	min	max	min	max
Squalene	1.8	2.6	1.8	2.5	1.5	2.2	1.6	2.3
DC704	1.2	1.6	1.2	1.6	0.9	1.3	0.9	1.4
DEHP	1.1	1.8	1.1	1.8	0.9	1.5	0.9	1.6
Bisphenol	0.6	0.8	0.6	0.8	0.4	0.6	0.5	0.6

MECHANICS AND MATERIALS TECHNOLOGY CENTER

THE AEROSPACE CORPORATION

Contamination Effects

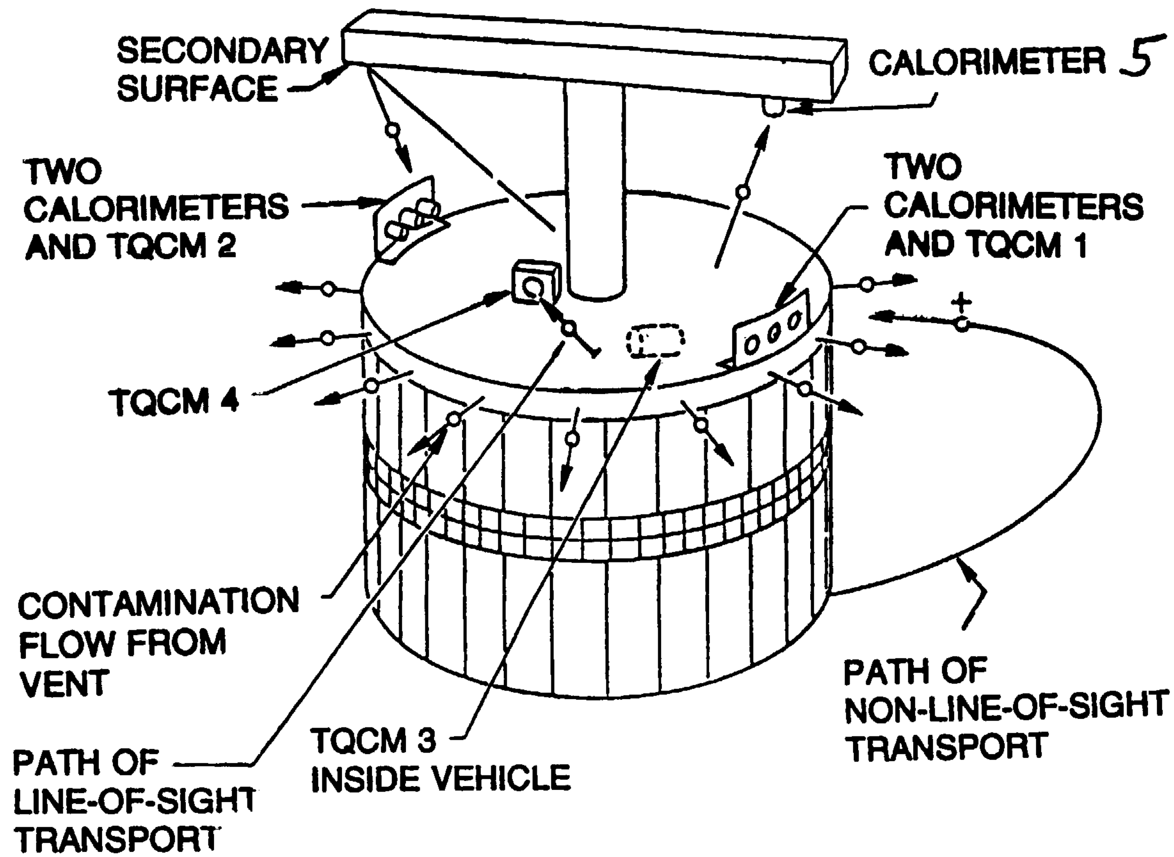
Solar Absorptance Effects Estimates

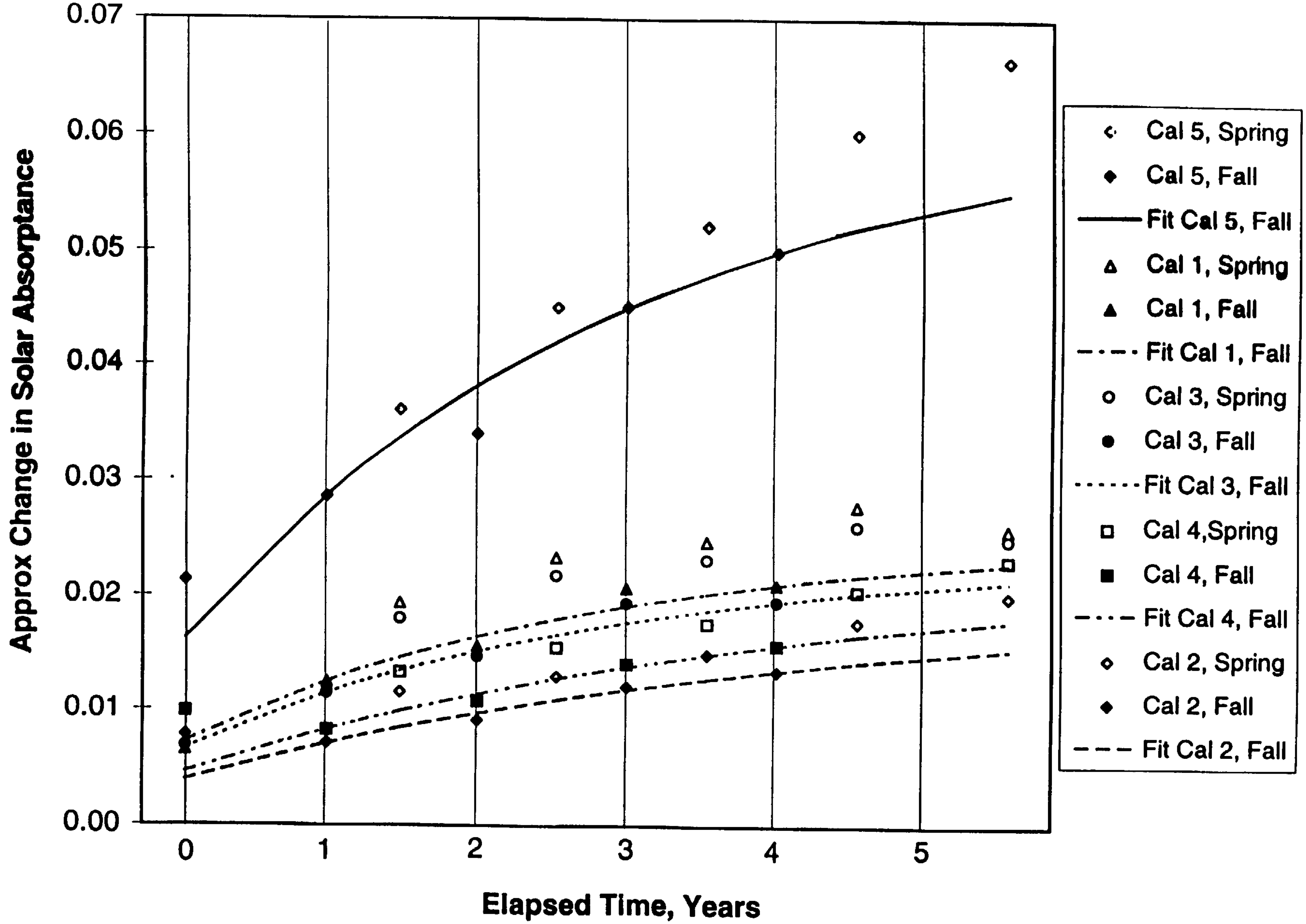


MECHANICS AND MATERIALS TECHNOLOGY CENTER

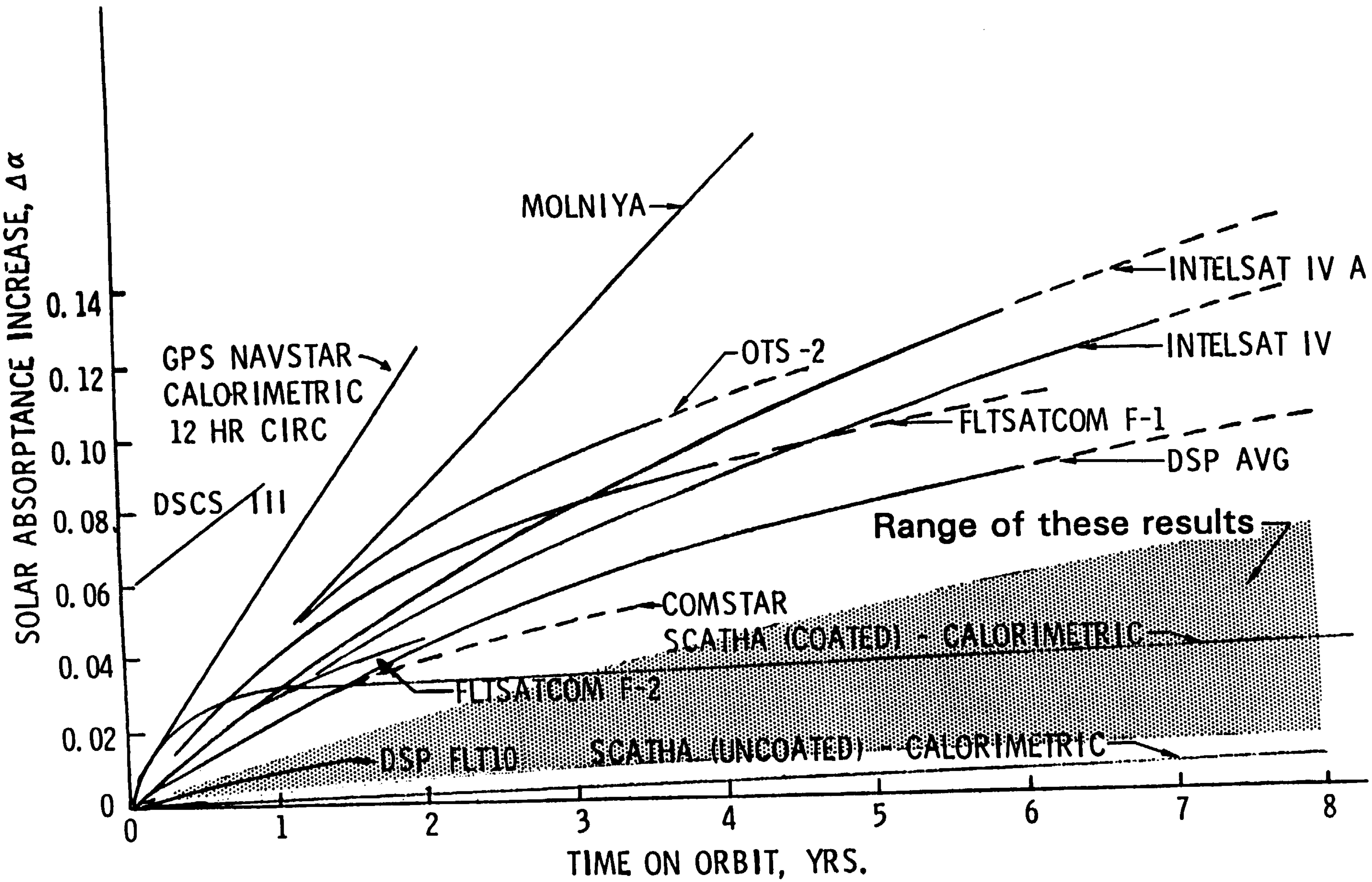
THE AEROSPACE CORPORATION

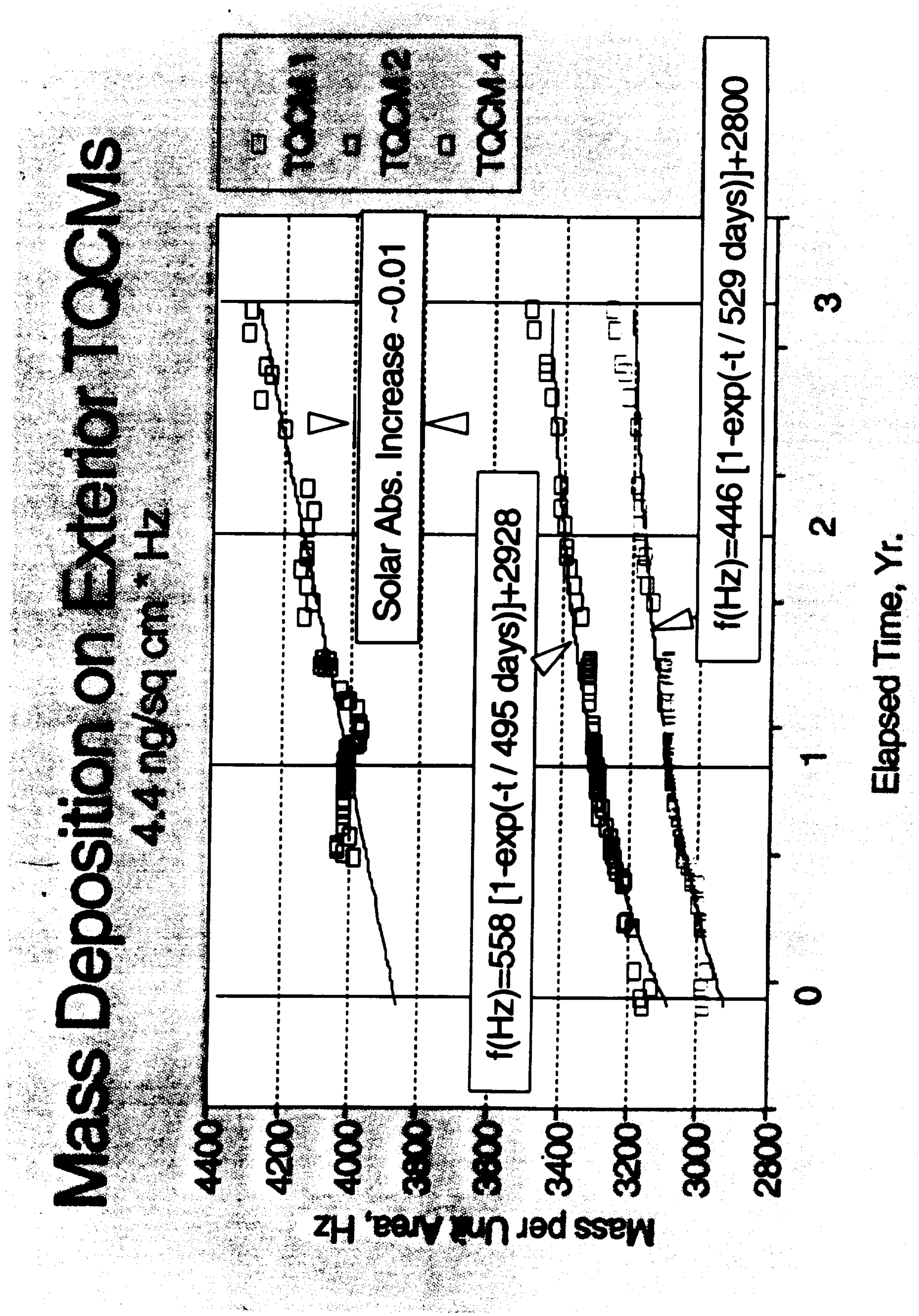
Transport Classes & Instrument Locations




Approx Change in Solar Absorptance
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
1
2
3
4
5
Elapsed Time, Years
Cal 5, Spring
Cal 5, Fall
Fit Cal 5, Fall
Cal 1, Spring
Cal 1, Fall
Fit Cal 1, Fall
Cal 3, Spring
Cal 3, Fall
Fit Cal 3, Fall
Cal 4,Spring
Cal 4, Fall
Fit Cal 4, Fall
Cal 2, Spring
Cal 2, Fall
Fit Cal 2, Fall

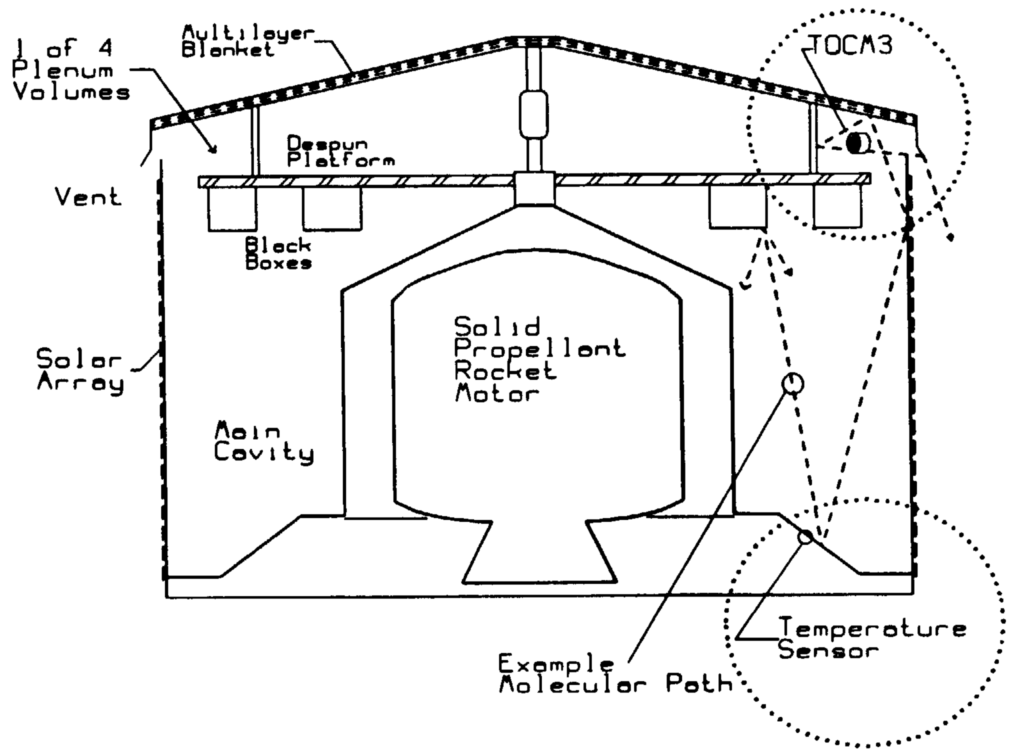
SILVERIZED FUSED SILICA MIRROR DEGRADATION





Mass Deposition on Exterior TQCMs
4.4 ng/sq cm * Hz
TQCM 1
TQCM 2
TQCM 4
Solar Abs. Increase ~0.01
f(Hz)=558 [1-exp(-t / 495 days)]+2928
f(Hz)=446 [1-exp(-t / 529 days)]+2800
Mass per Unit Area, Hz
4400
4200
4000
3800
3600
3400
3200
3000
2800
0
1
2
3
Elapsed Time, Yr.

Diagnostic Instrumentation Package



- Spacecraft instrumented with QCM's and Calorimeters
- Contamination Processes:
  - Production
  - Transport
  - Deposition
  - Effects
- One qcm *inside* spacecraft

MECHANICS AND MATERIALS TECHNOLOGY CENTER

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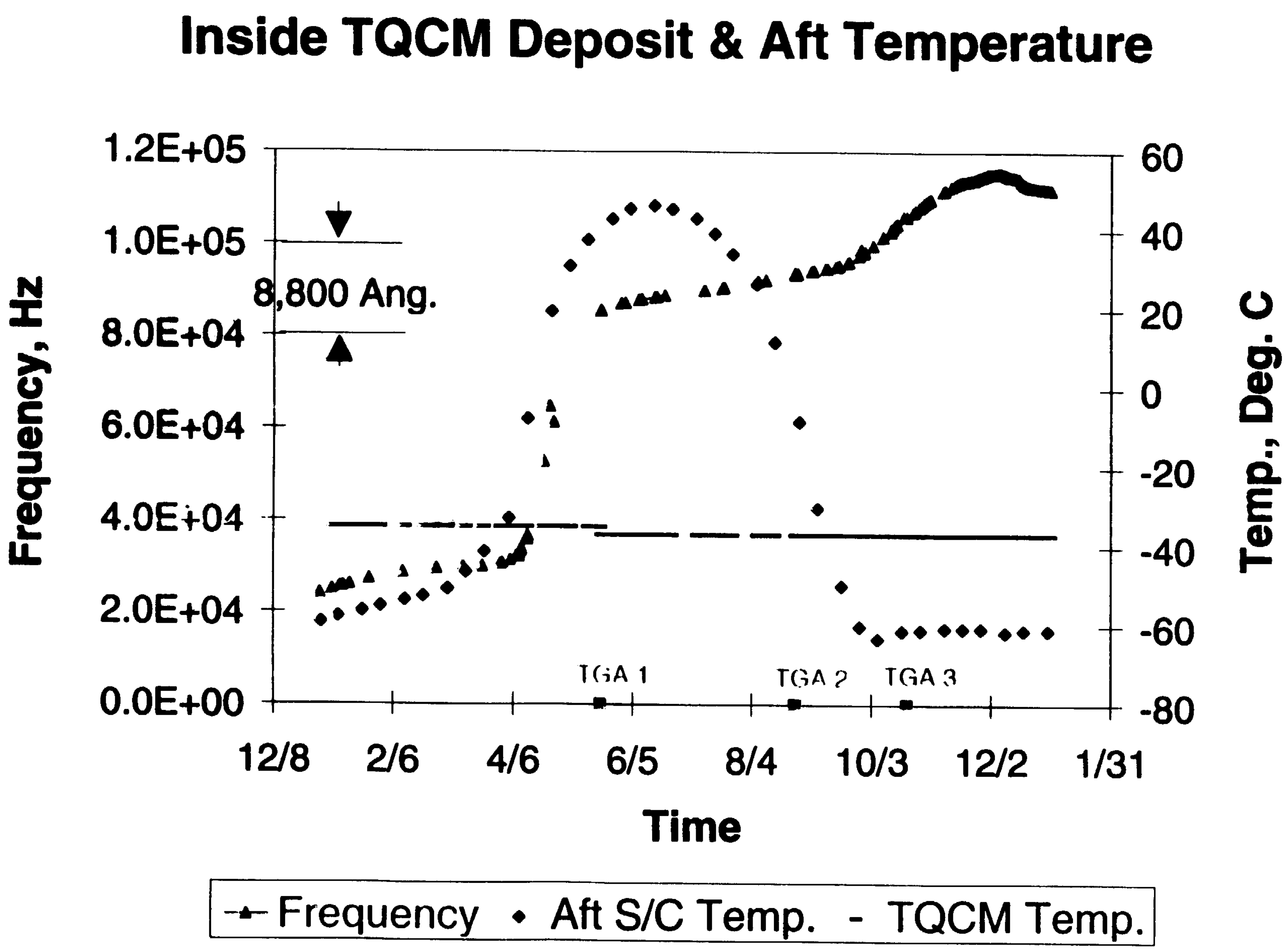


Inside TQCM Deposit & Aft Temperature
1.2E+05
1.0E+05
8.0E+04
6.0E+04
4.0E+04
2.0E+04
0.0E+00
Frequency, Hz
8,800 Ang.
TGA 1
TGA 2
TGA 3
60
40
20
0
-20
-40
-60
-80
Temp., Deg. C
12/8
2/6
4/6
6/5
8/4
10/3
12/2
1/31
Time
Frequency
Aft S/C Temp.
TQCM Temp.

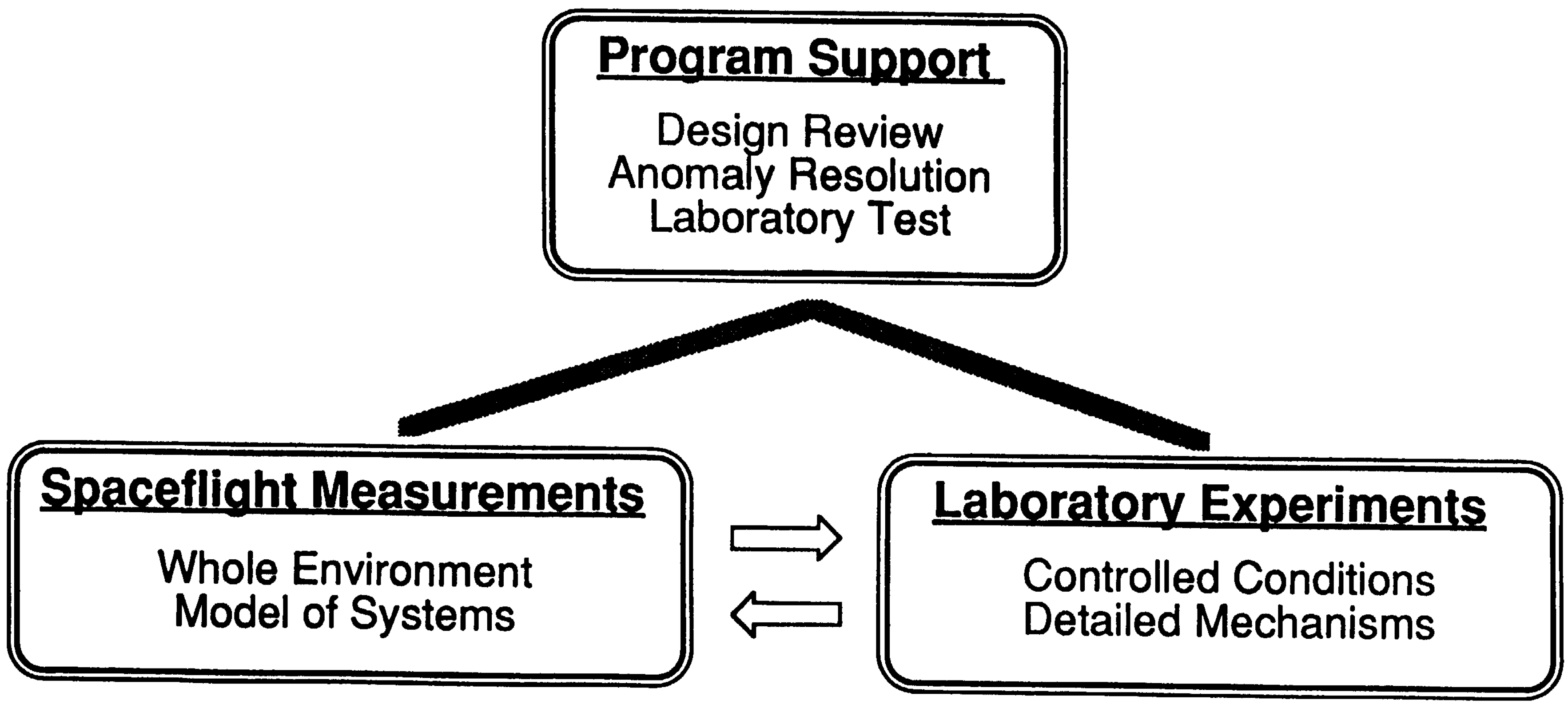
Midcourse Space Experiment

Contamination Experiments

- MSX spacecraft instrumented with multiple contamination sensors
  - Quartz crystal microbalances, external
  - Quartz crystal microbalance, inside SPIRIT III
  - Total gauge
  - Ion and neutral mass spectrometers
  - Flash lamp for particle, water illumination and detection
- Multi-member team led by Principal Investigator O.M. Uy, JHUAPL
- Bibliography and binder of published papers (SPIE, AIAA, etc.) in preparation for SBIR library

Spacecraft Environmental Phenomena

Approach



CONTAMINATION CONTROL
FOR
LOW COST PAYLOAD
WITH
SENSITIVE OPTICAL INSTRUMENTS

James T. Kenny
Jet Propulsion Laboratory
California Institute of Technology

Midcourse Space Experiment (MSX) Mission Flight Data

1997 Spacecraft Contamination & Coatings Workshop
Sponsored by
NASA Goddard Space Flight Center and Space Environments and Effects Program
Historic Inns of Annapolis, MD
Annapolis, MD, July 9-10, 1997

O. Manuel Uy, R. C. Benson, R. E. Erlandson, M. T. Boies, R. P. Cain, J. C. Lesho and D. M. Silver,

Johns Hopkins University Applied Physics Laboratory;

G.E. Galica and B. D. Green, Physical Sciences Incorporated;

J. D. Dyer, Space Dynamics Laboratory, Utah State University;

B. E. Wood, Sverdrup, Arnold Air Force Base; and

D. E. Hall, Aerospace Corporation

Outline

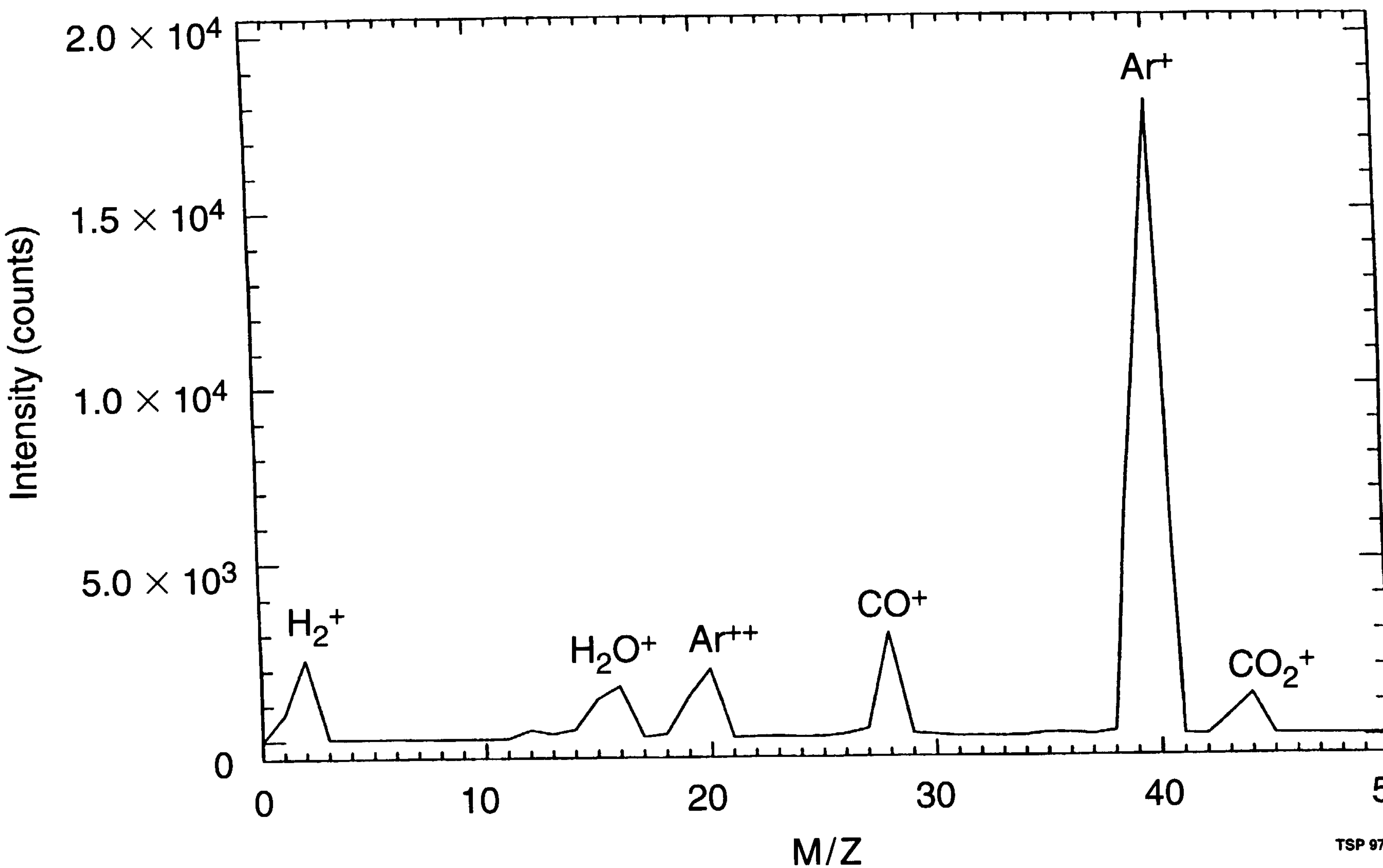
- Introduction
- Approach
- Charts Used for Rapid Evaluation during Early Operations
- In-orbit Measurements During Cryogen Phase
- Summary

Contamination Experiment

Approach:

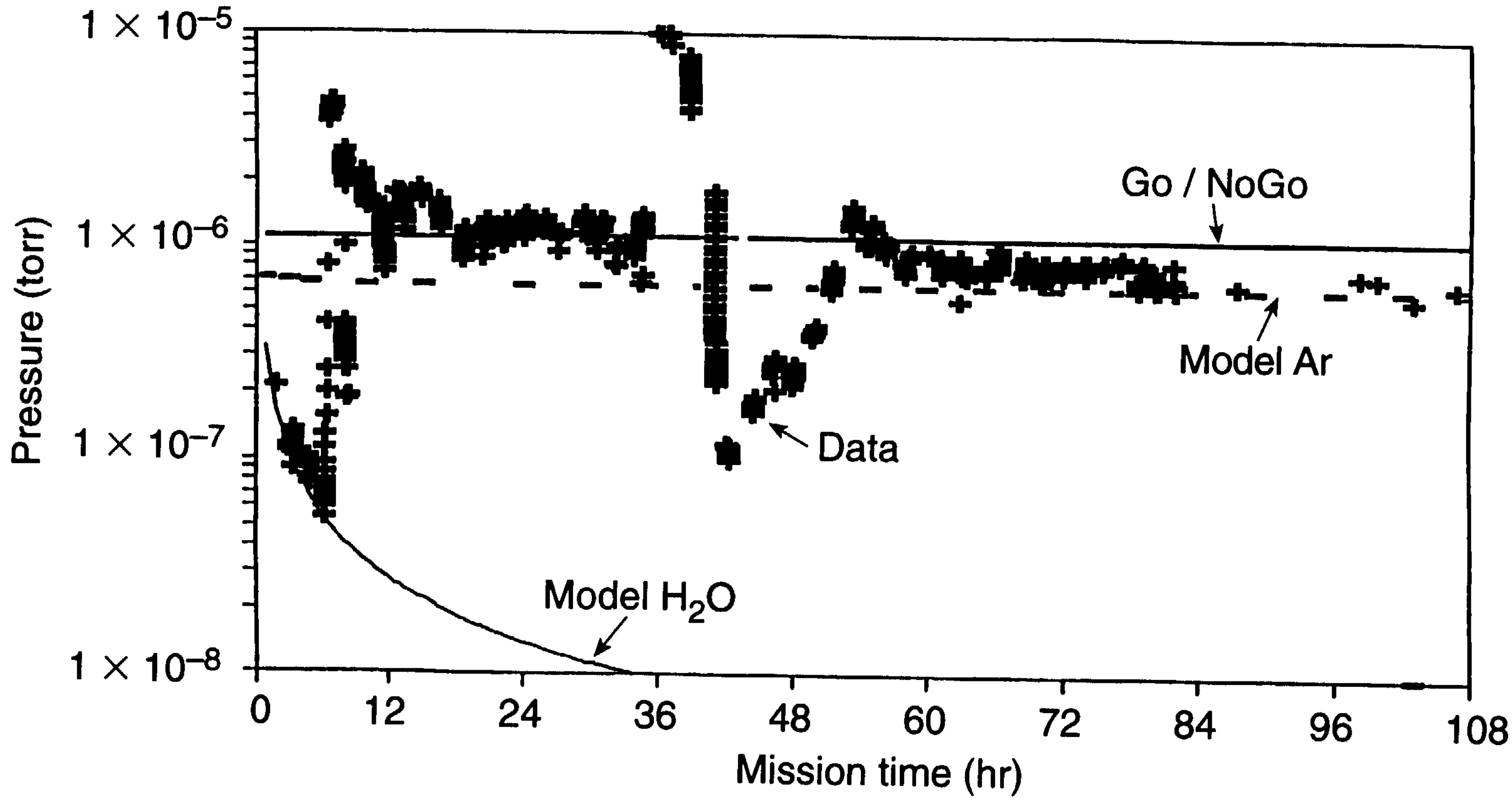
- Start with a Contamination Control Plan
  - Identify materials used by PDR and give input to designers
  - Based on preliminary models, give input to S/C designs on placement of vents, optical instruments, electronics
  - Conduct outgassing tests on selected materials as input to model
- Construct Contamination Model before launch
- Select Contamination Instruments
- Perform in-orbit measurements and compare with model predictions
- Refine Contamination Model
  - Report to MSX Program by end FY97.

Early Operations Mass Spectrum of the Atmosphere Above MSX



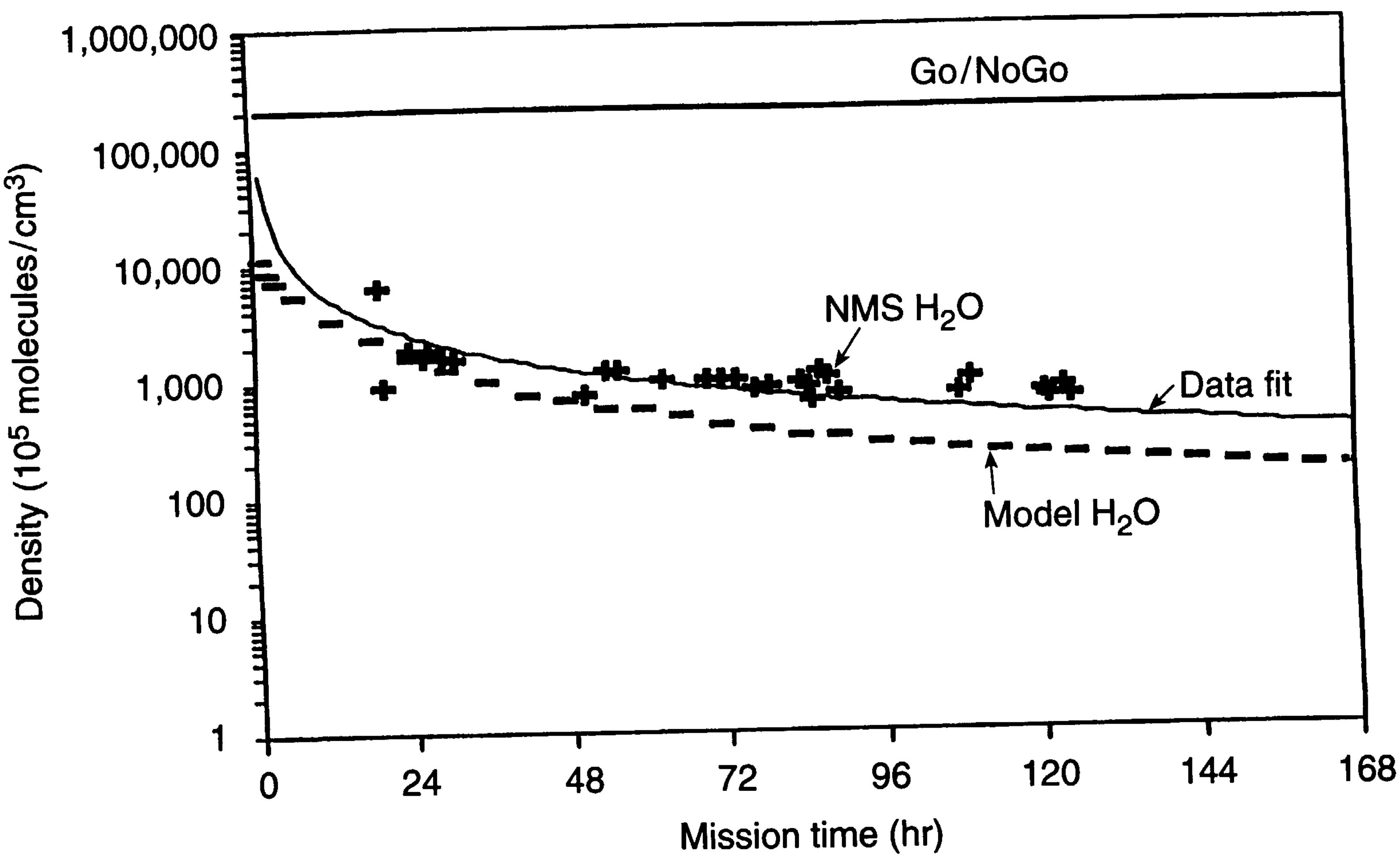
TSP 97-7362- 2

Early Operations Chart for Total Pressure Sensor



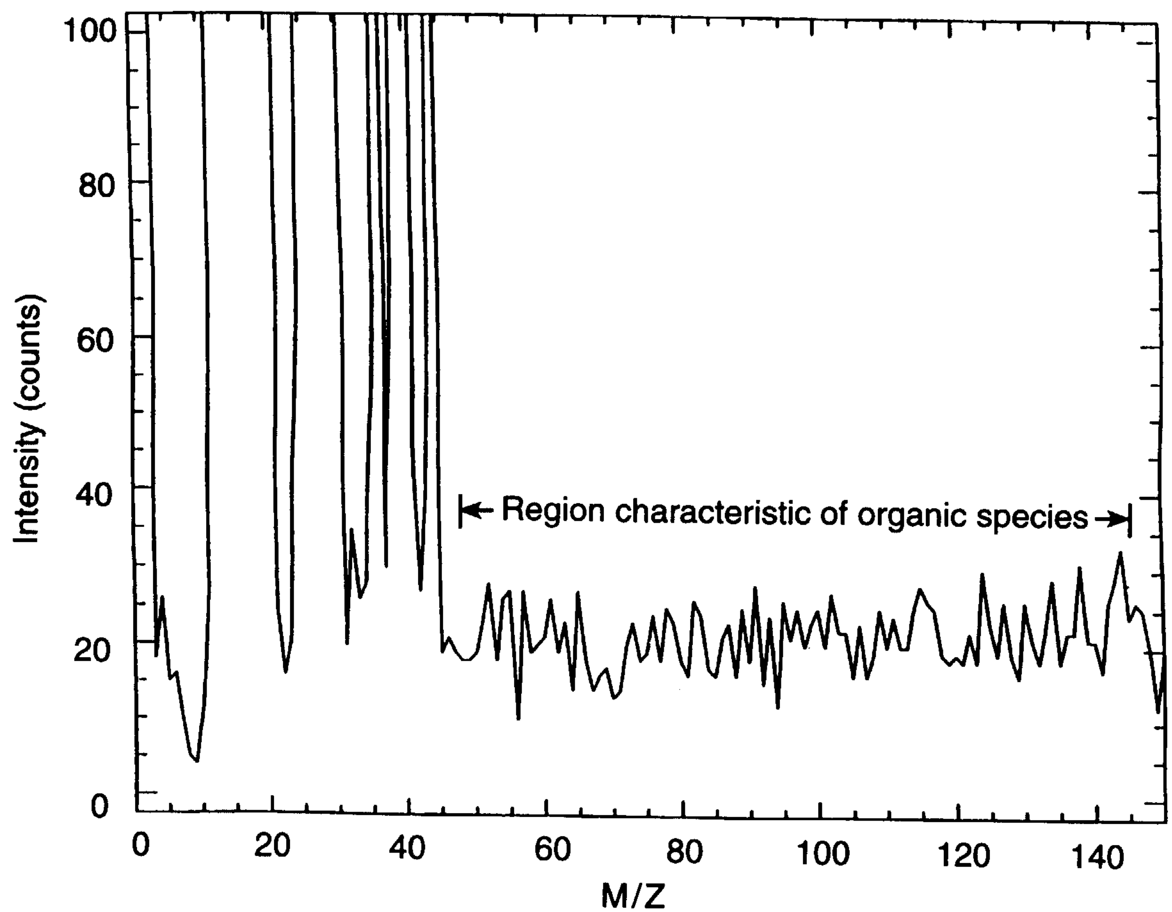
TSP 97-7362- 1

Early Operations Water Vapor Measurements with the NMS



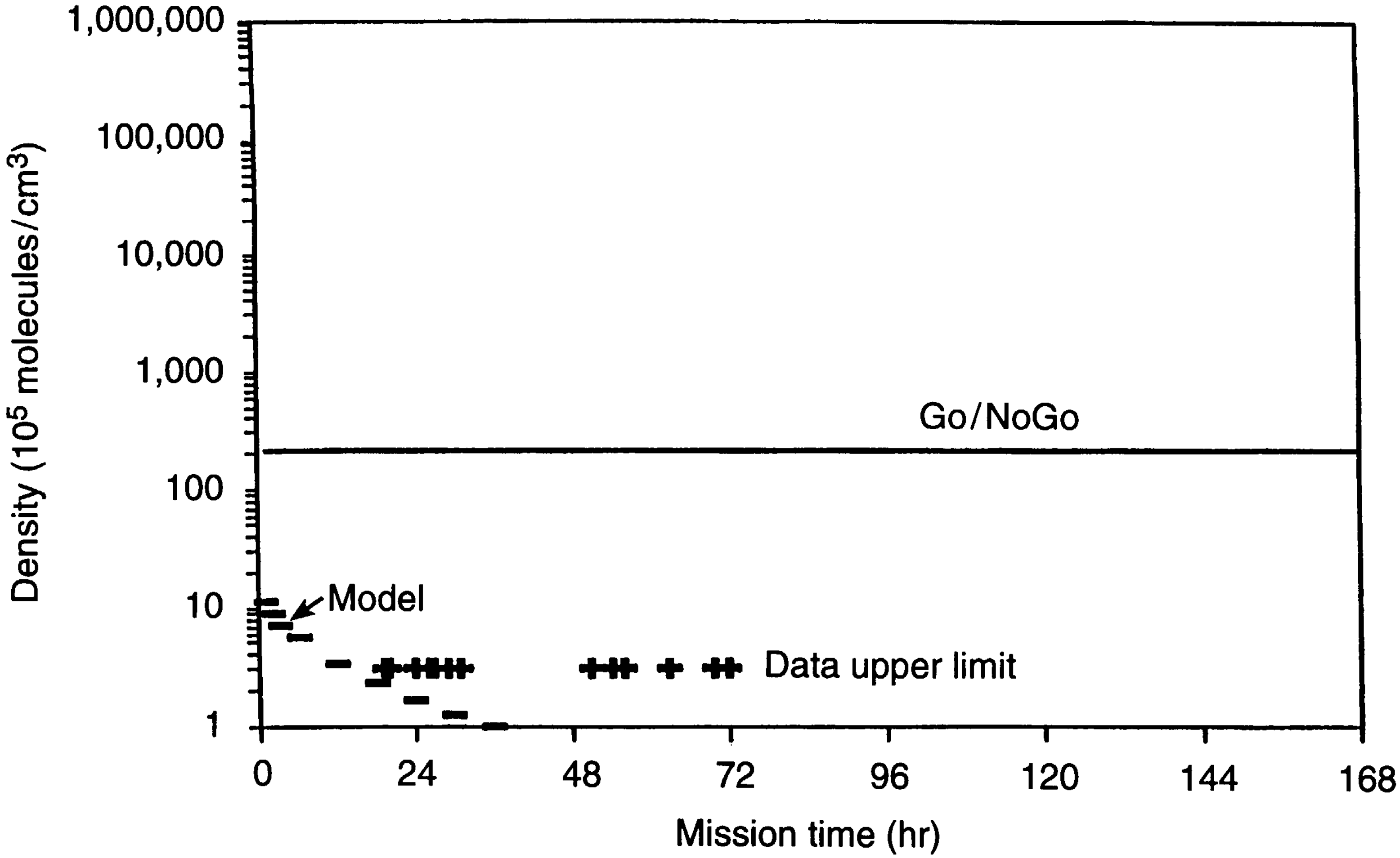
TSP 97-7362- 3

Mass Spectrum Showing Lack of Higher Masses Above 45



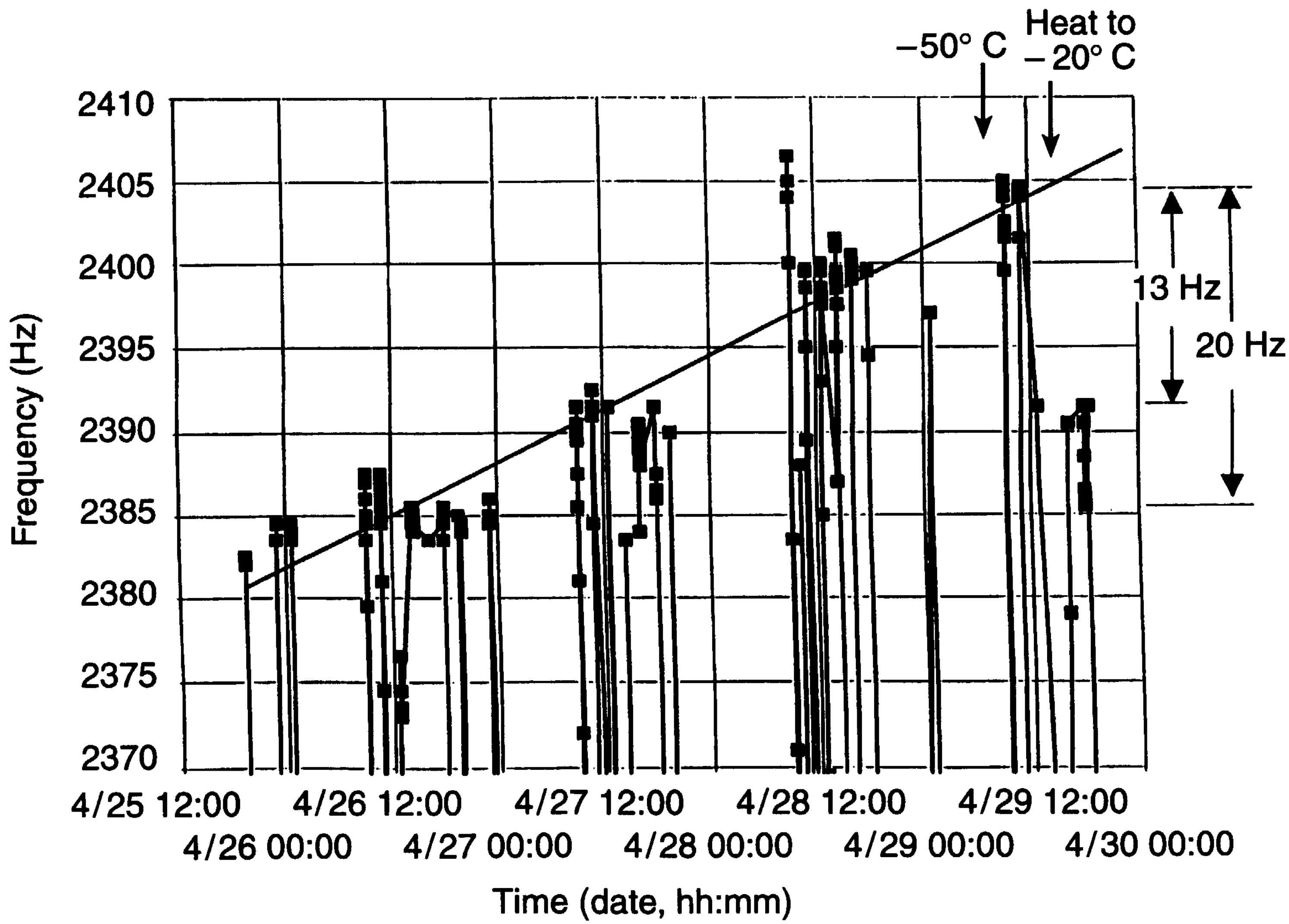
TSP 97-7362- 4

Inferred Total Organic Densities During Early Operations



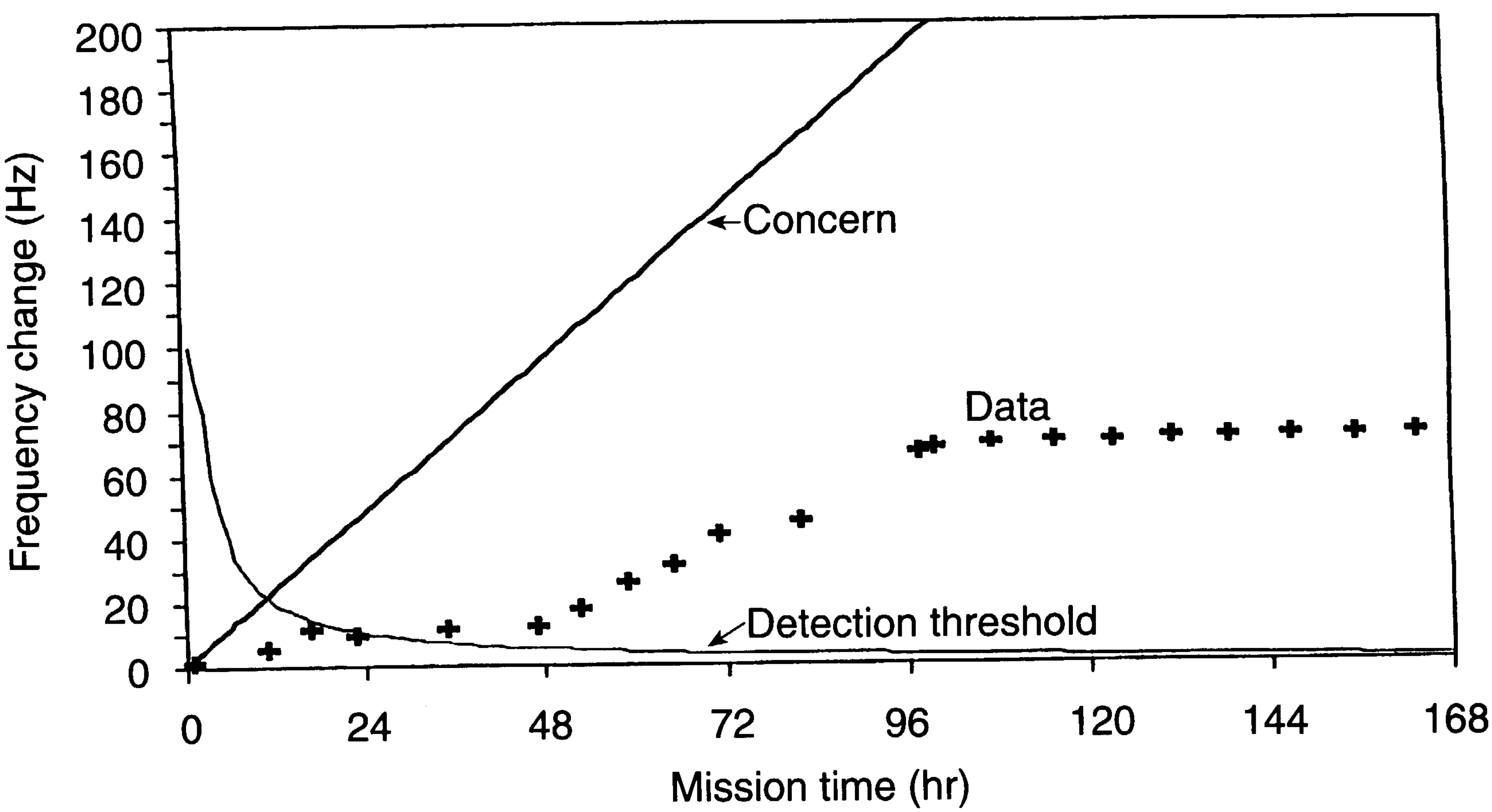
TSP 97-7362- 5

TQCM Measurement Showing Decreased Deposition When Heated to −20°C



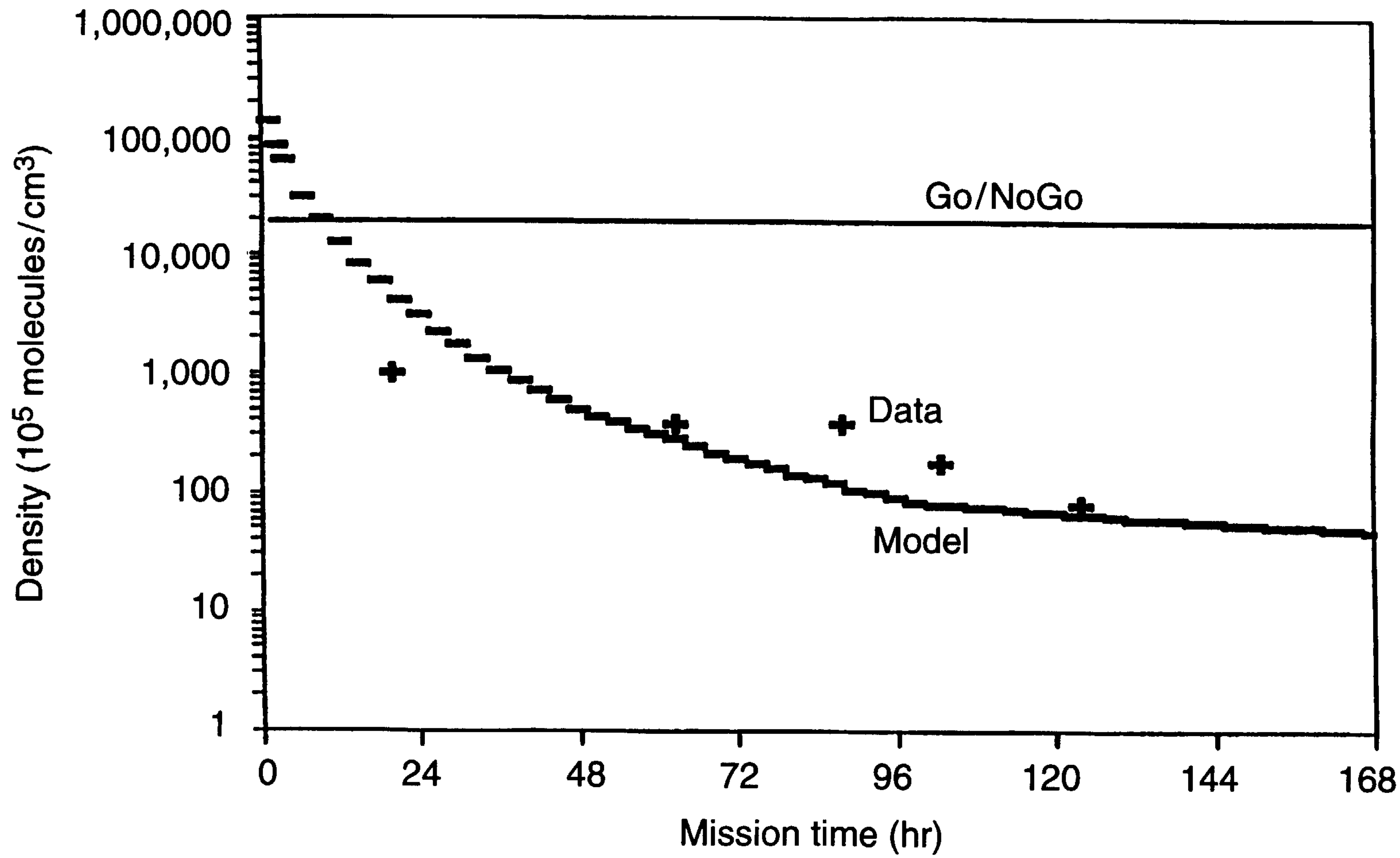
TSP 97-7362- 6

Early Operations Accretion Rate on the CQCM



TSP 97-7362- 7

Early Operations Measurements for Water Vapor by the KRE

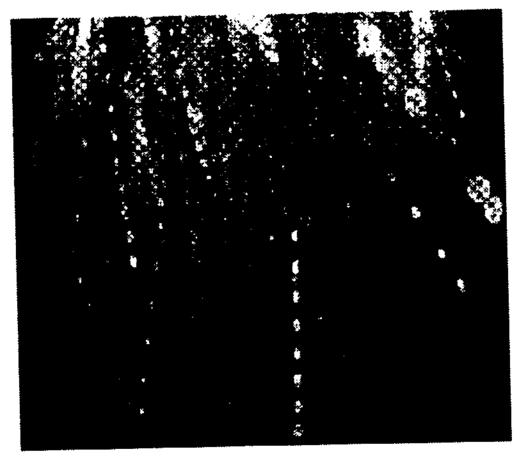


TSP 97-7362- 8

Particles Measured by the XFE During SPIRIT III Door Opening

Particle velocities were several meters per second.

Frame 63

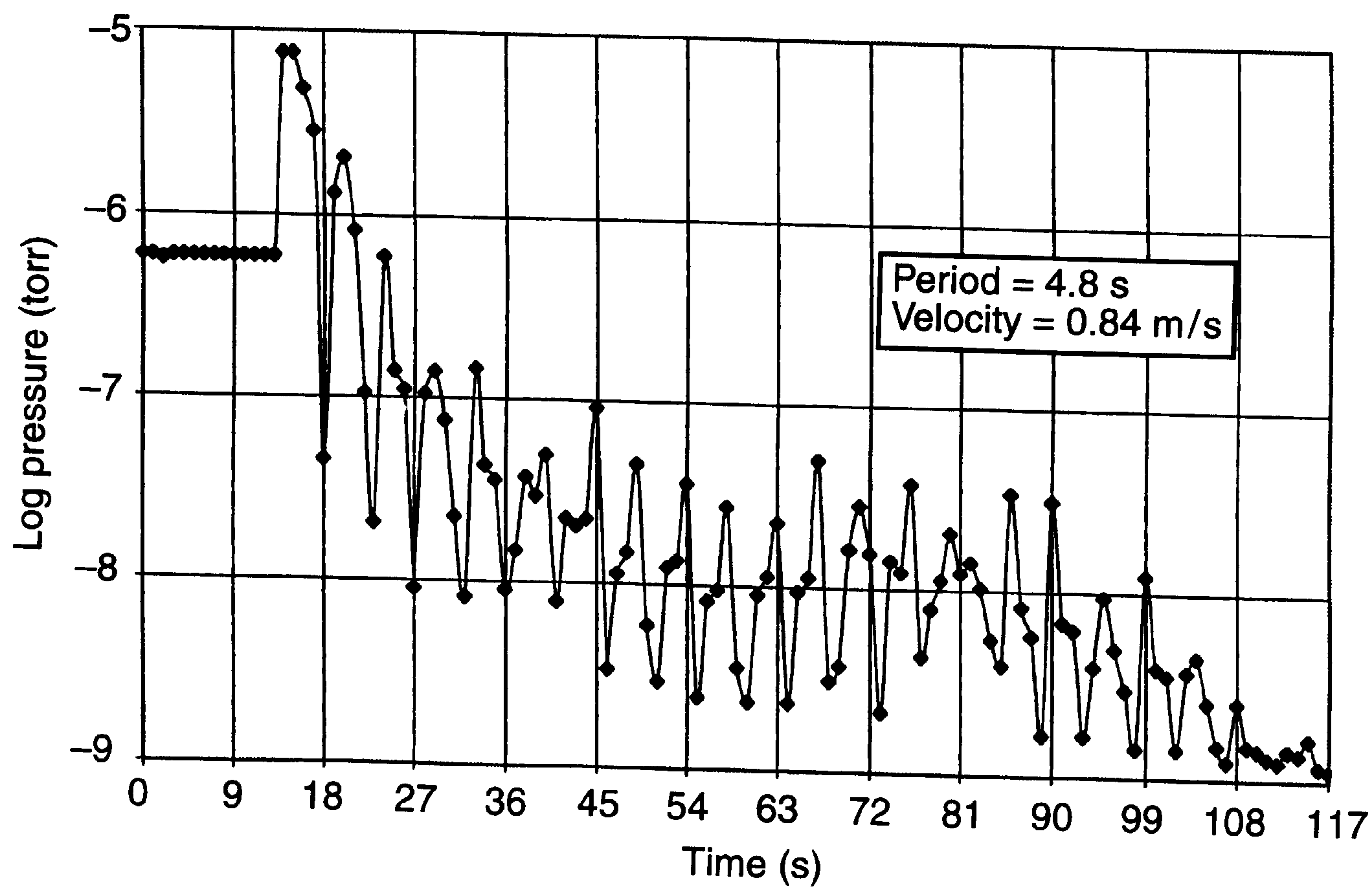


Frame 64

Frame 65

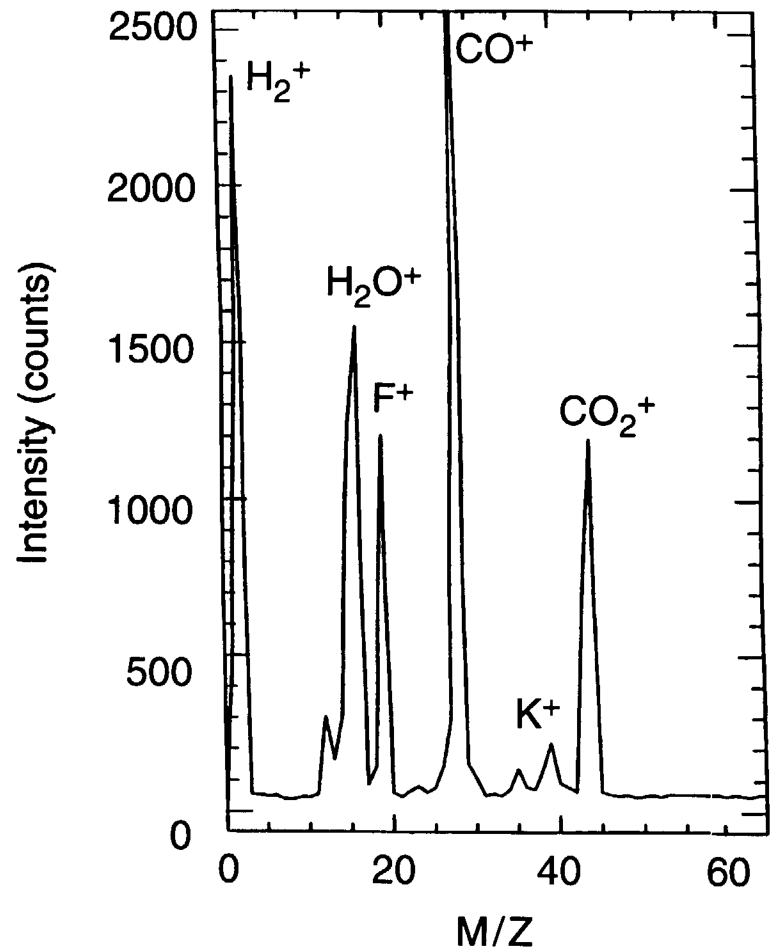
TSP 97-7362- 9

Rapid Pressure Decay and Fluctuations of Argon Gas as SPIRIT III Door Was Ejected



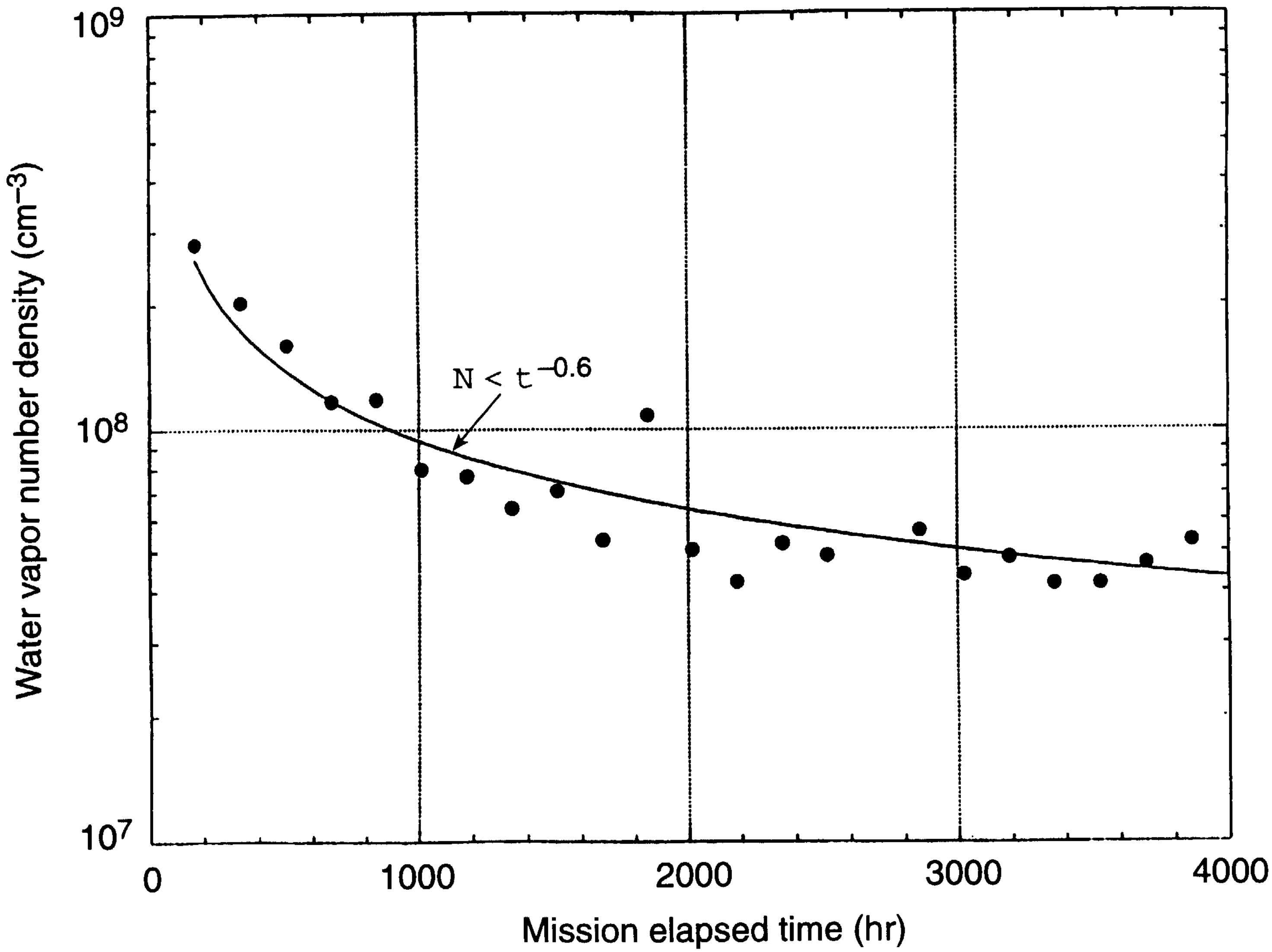
TSP 97-7362- 10

Mass Spectrum Above MSX After SPIRIT III Door Ejection



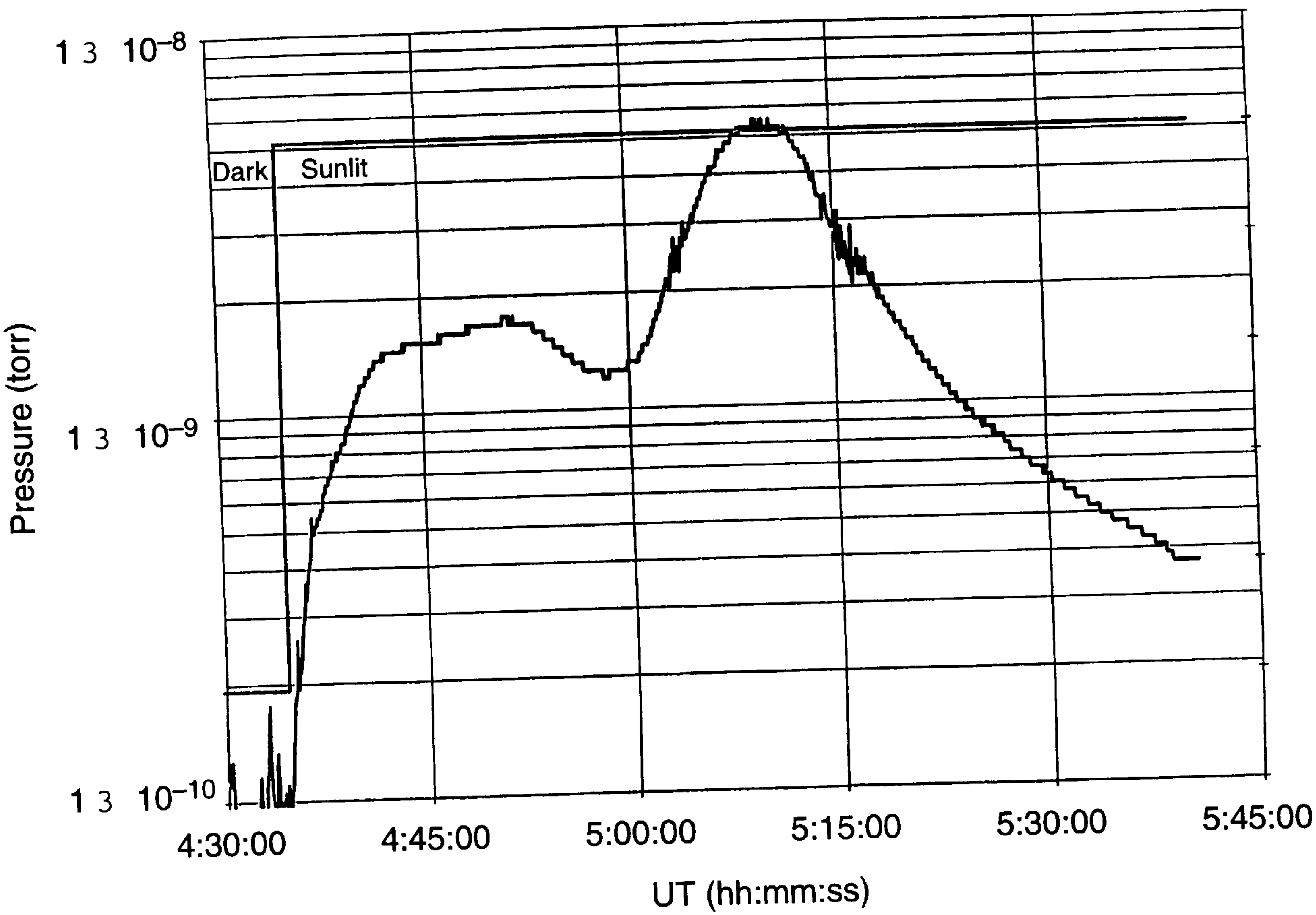
TSP 97-7362- 11

Total Pressures Measured by TPS During Cryogen Phase



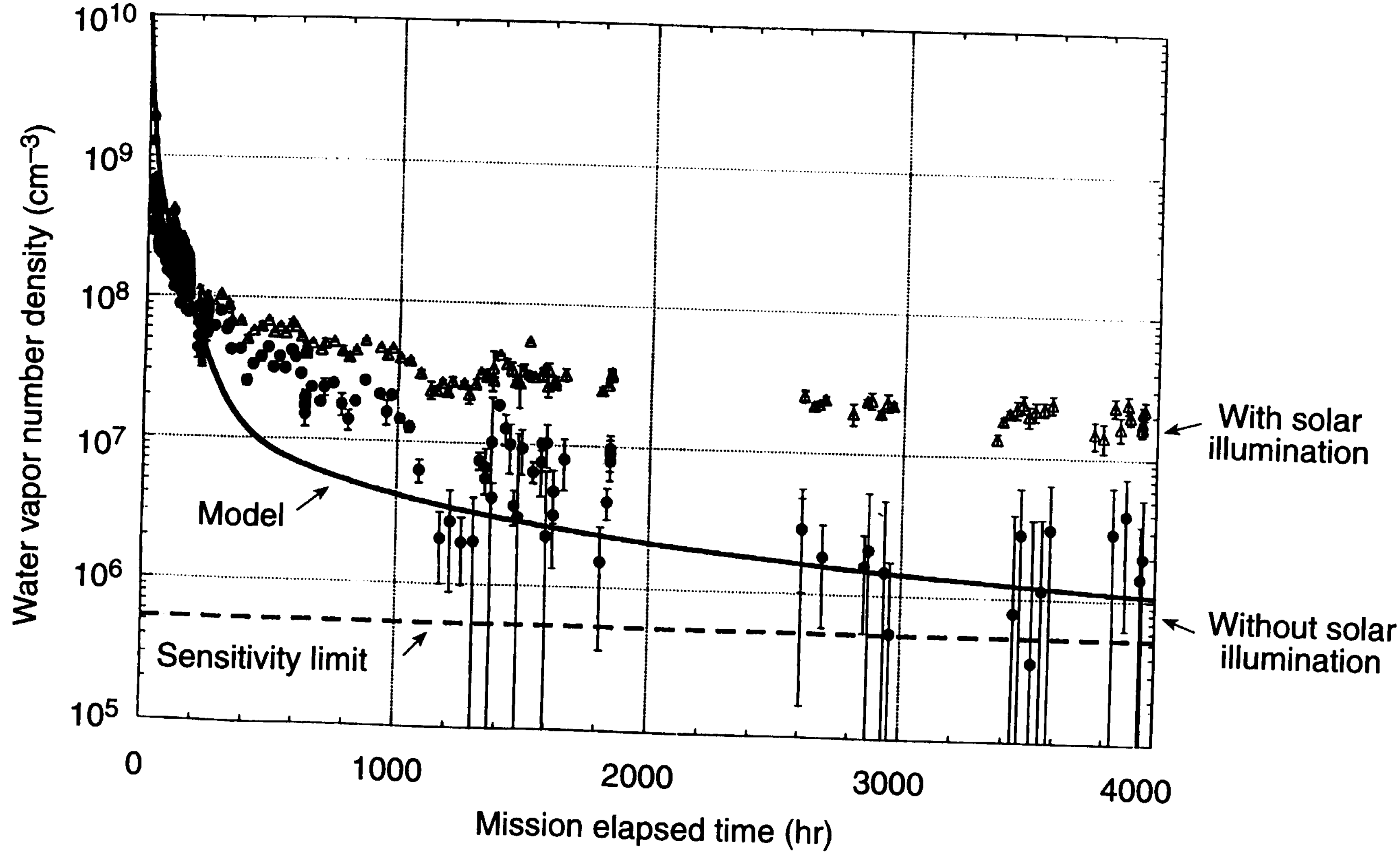
TSP 97-7362- 12

Pressures Induced by Solar Heating



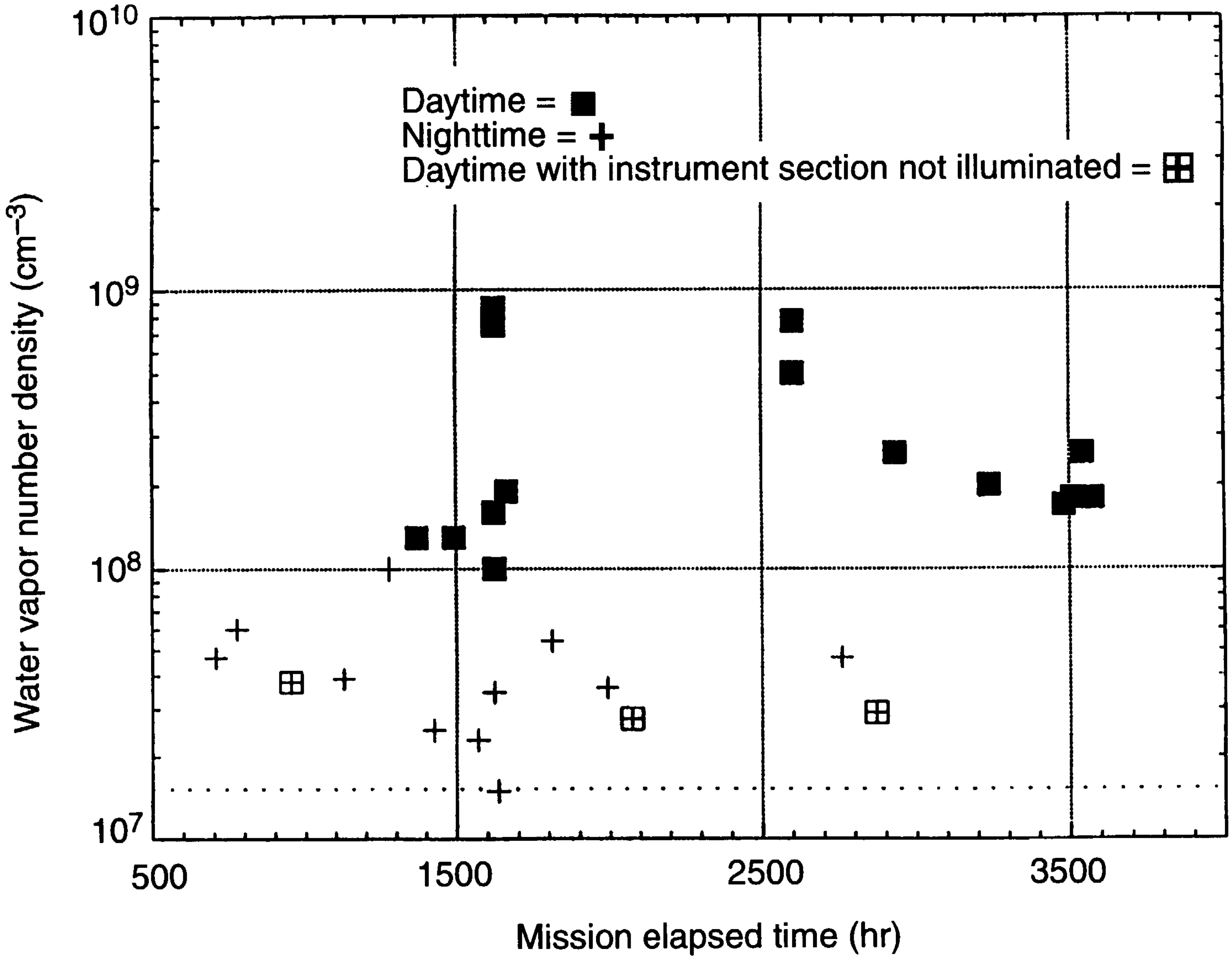
TSP 97-7362- 13

Water Vapor Densities Measured by KRE



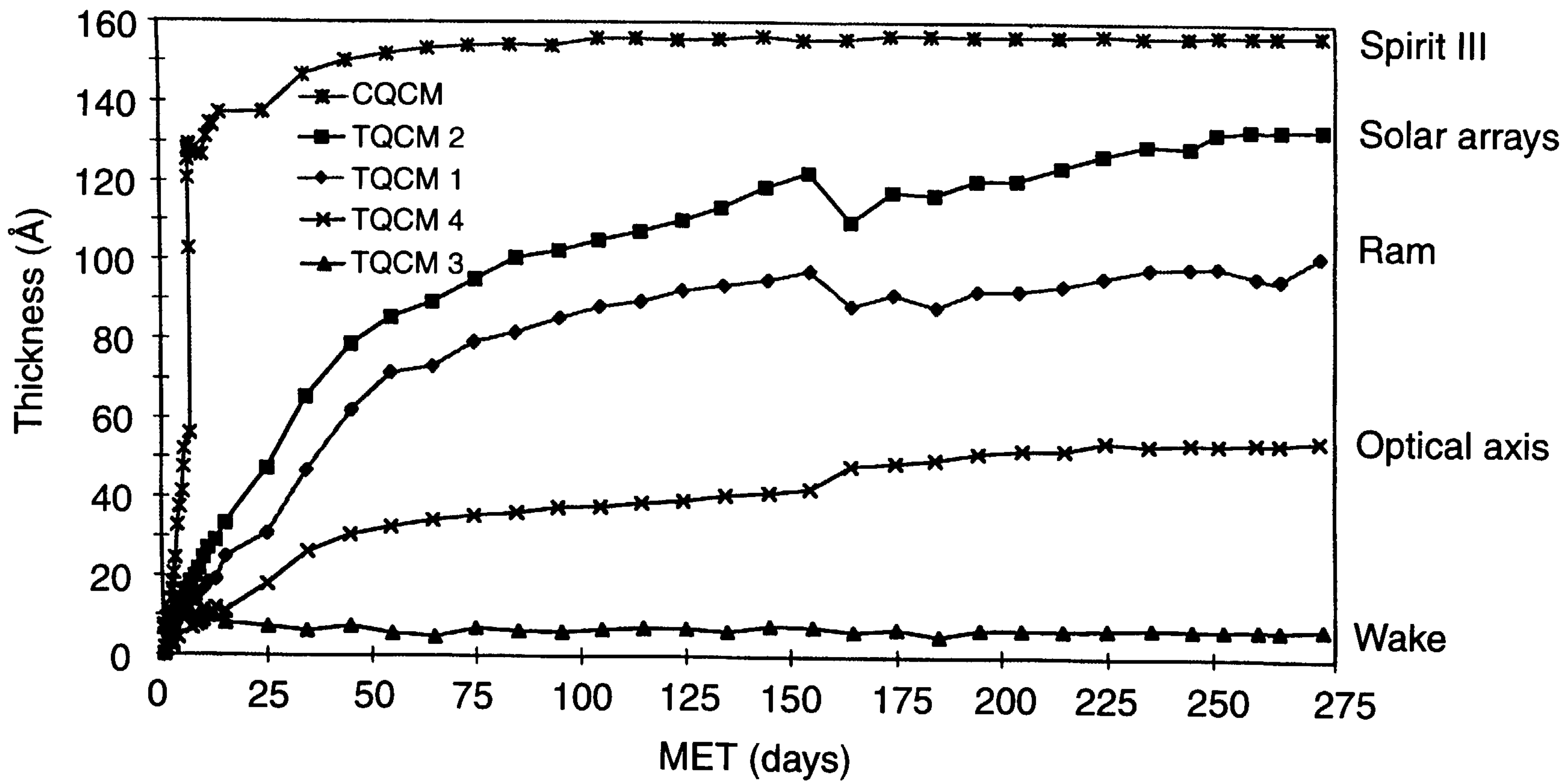
TSP 97-7362-14

Water Densities Measured by KRE Correlated with Solar Illumination



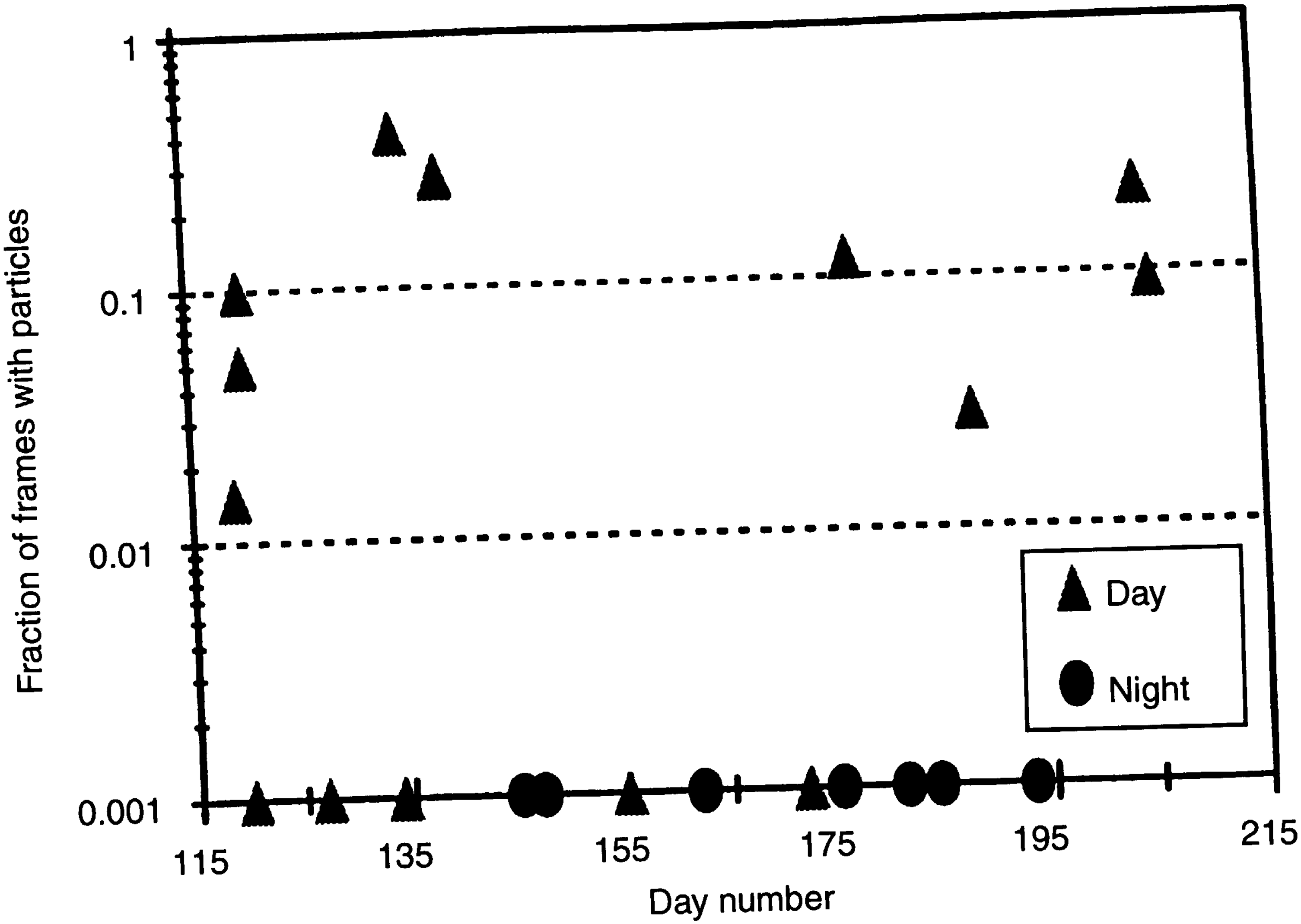
TSP 97-7362- 15

Mass Deposition During the Cryogen Phase for All QCMs



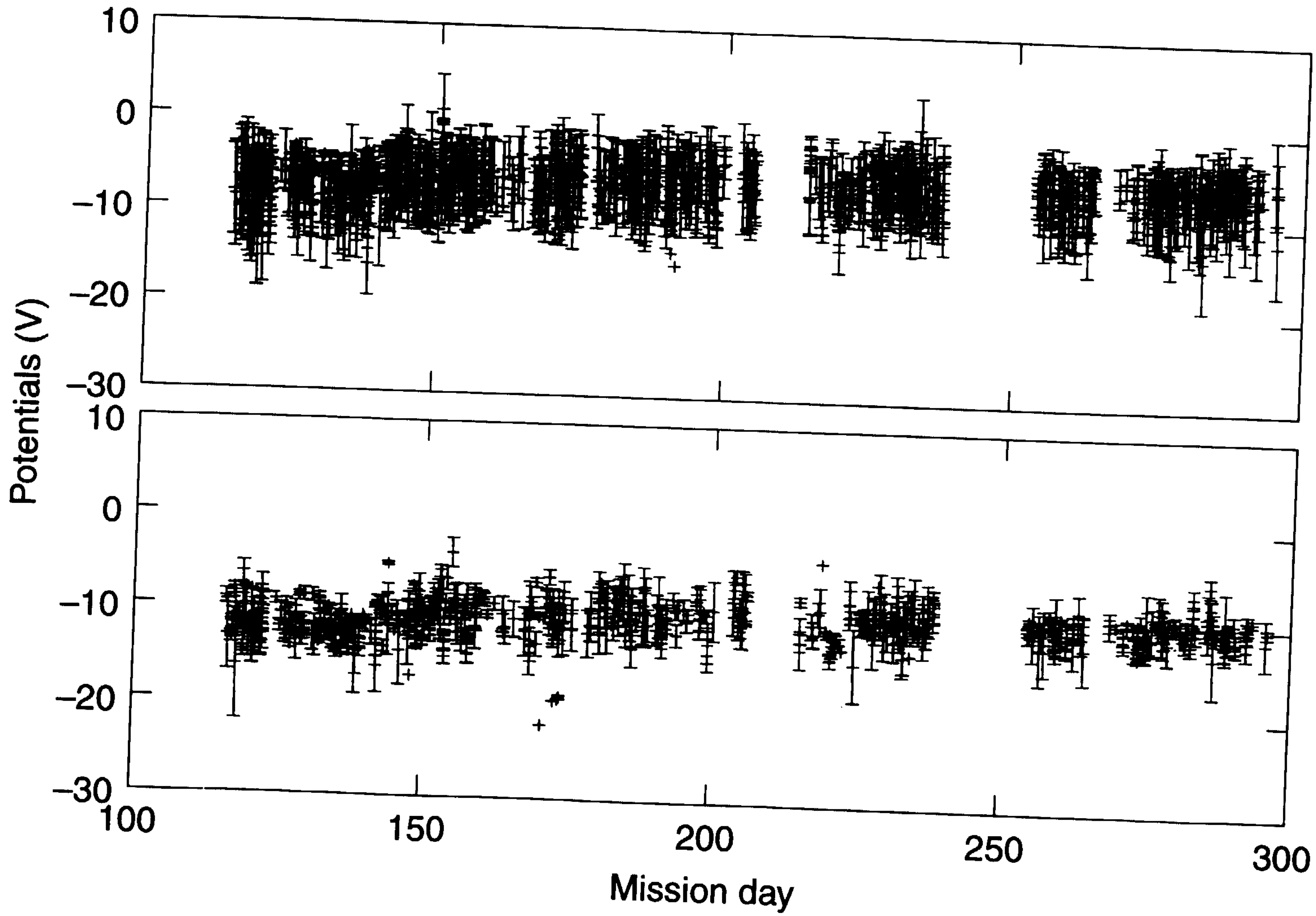
TSP 97-7362- 16

Particles Measured by XFE During Quiescent Times



TSP 97-7362- 17

Spacecraft Charging Measured by the IMS



TSP 97-7362- 18

Contamination Experiment

Summary:

- MSX Contamination Control Plan successful in launching a clean spacecraft, e.g. negligible hydrocarbon contamination and rapid decay of water vapor
- Contamination model and contamination instruments successful in performing rapid evaluation of risk to optical sensors during early operations
- MSX contamination model for quiescent spacecraft has been validated
  - Future models need to account for spacecraft dynamics
- MSX contamination instruments will continue to monitor outgassing, film deposition, and particulate generation for long-term effects.

LDEF
MATERIALS/CONTAMINATION
NAS8-40581

1997 SPACECRAFT CONTAMINATION and COATINGS WORKSHOP

GARY PIPPIN
BOEING DEFENSE & SPACE GROUP
JULY 1997

TOPICS

Long Duration Exposure Facility(LDEF)

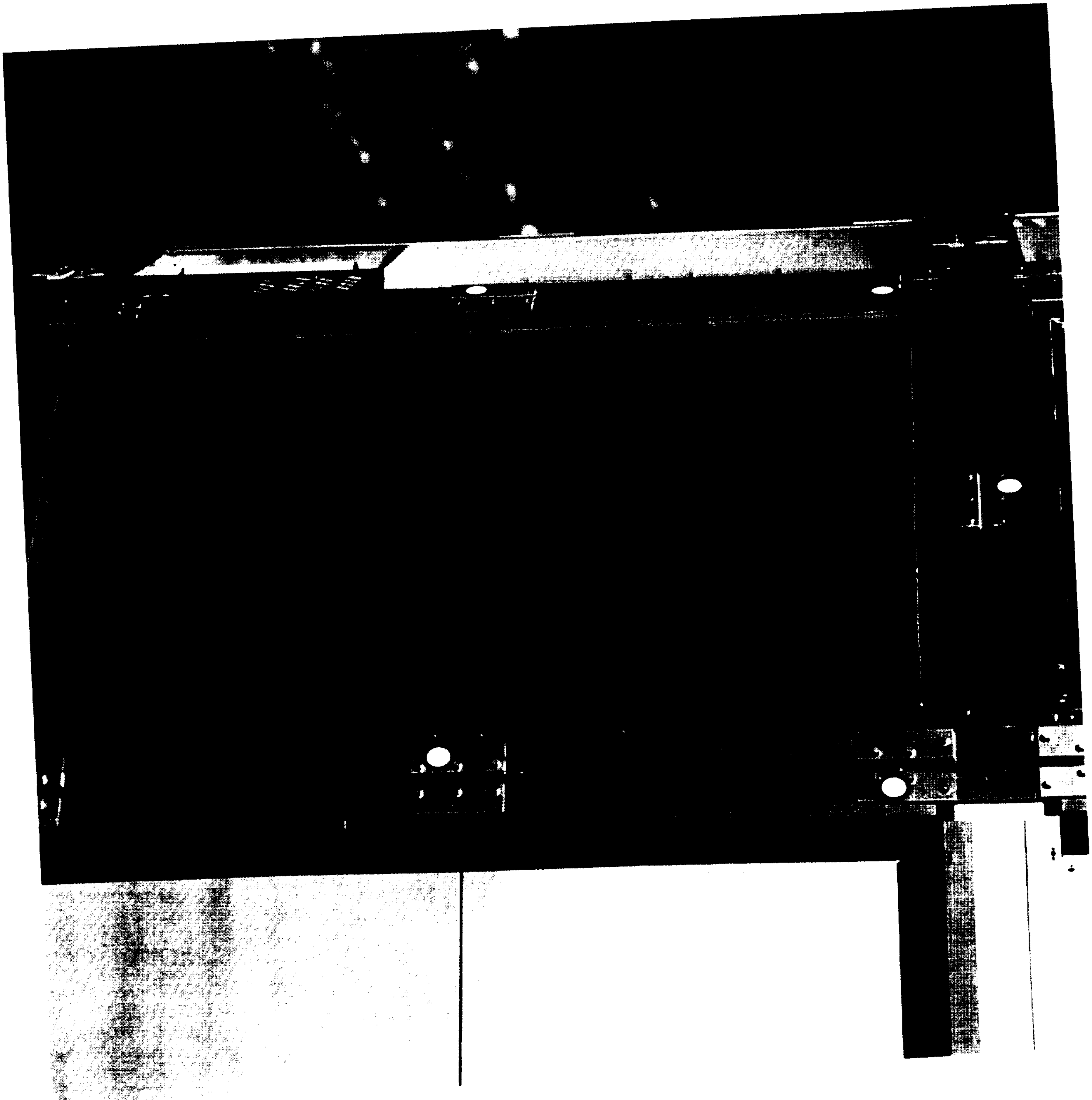
- **TRAY CLAMP BOLT HEADS**
- **UHCRE FLIGHT EXPERIMENT TRAY WALLS**

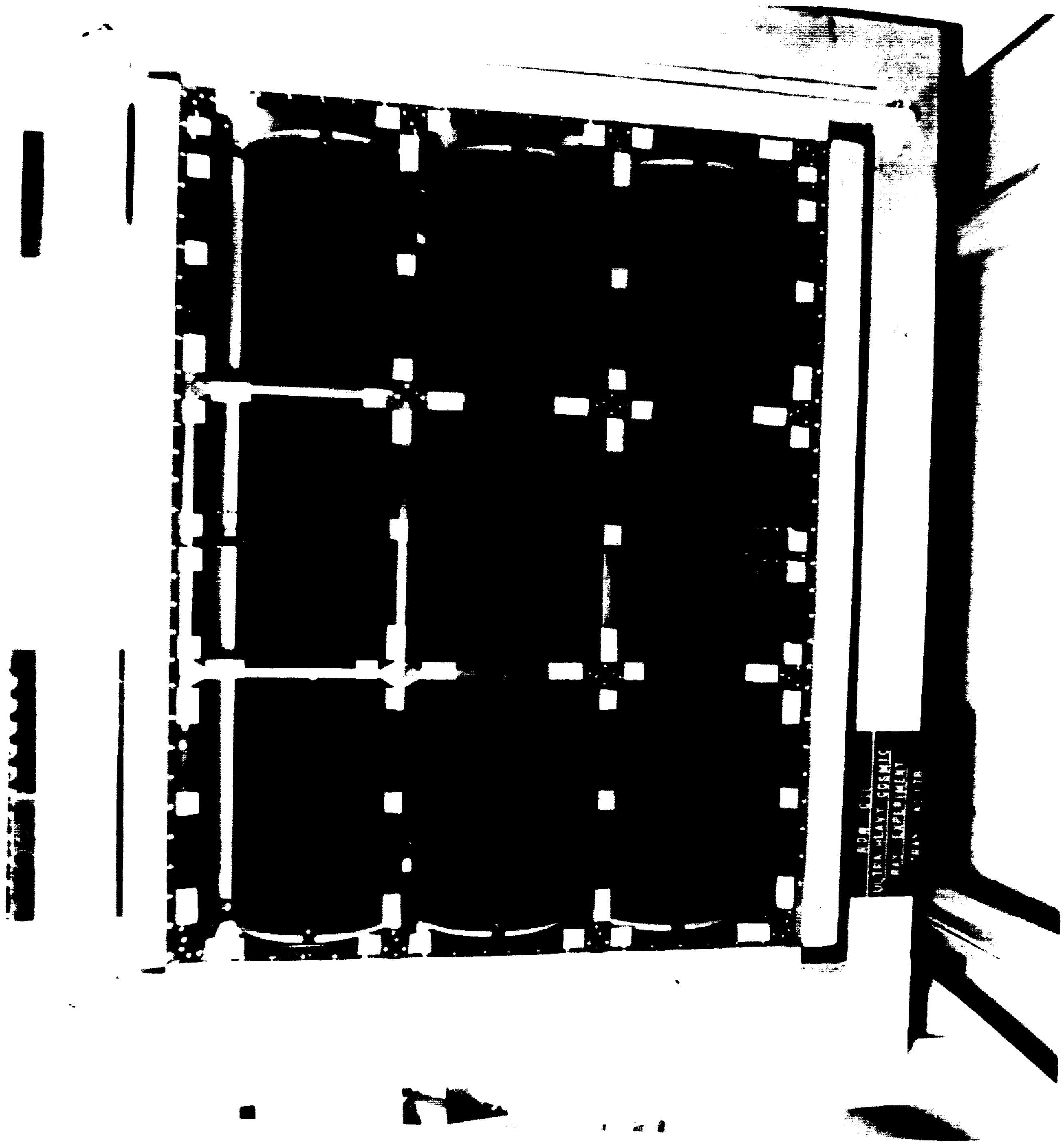
Effects of the Space Environment on Materials(ESEM) FLIGHT EXPERIMENT

Passive Optical Sample Assembly(POSA) I and II FLIGHT EXPERIMENTS

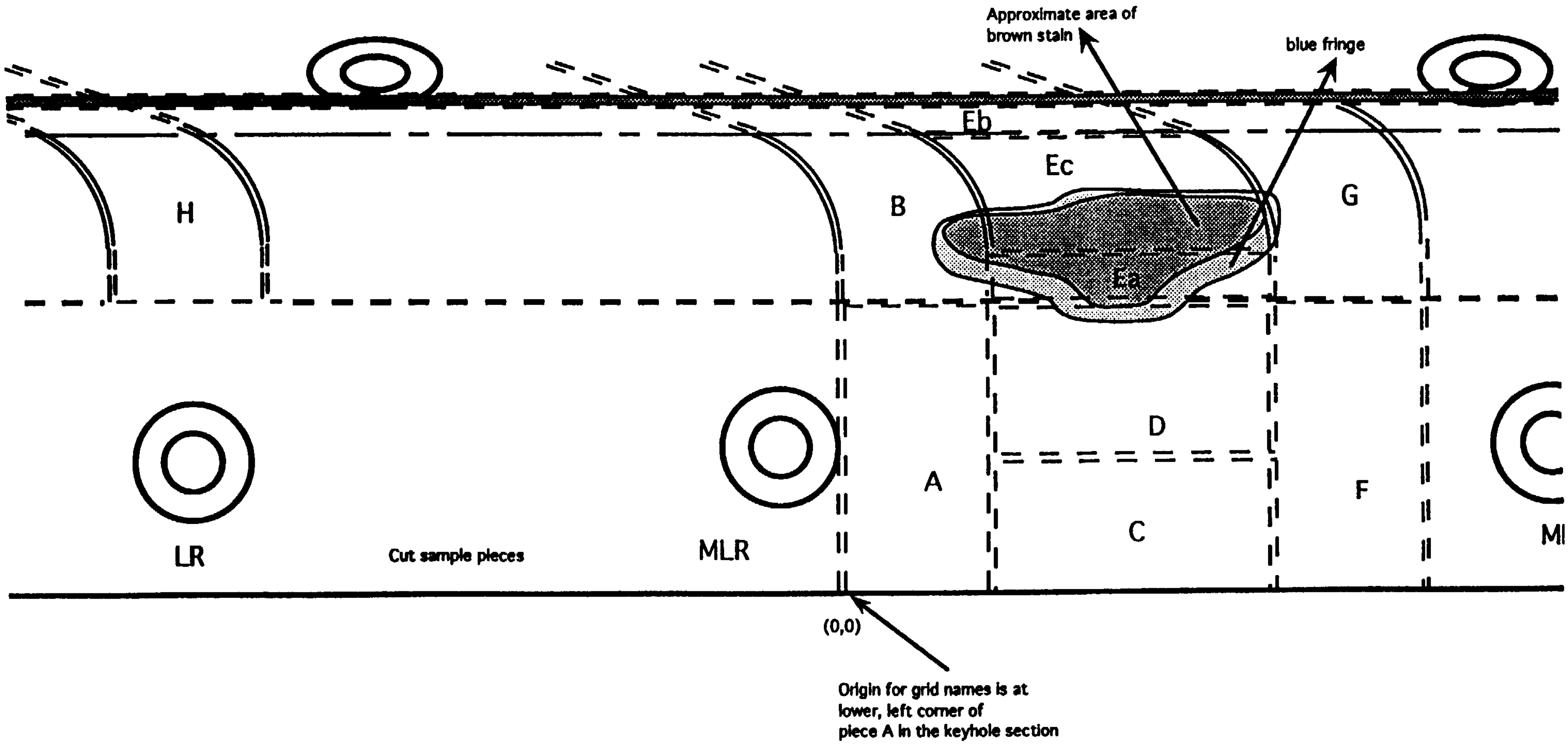
RESULTS OF SURFACE Si% MEASUREMENTS and MEASUREMENT LOCATIONS

TRAYS: E10
C6
A4

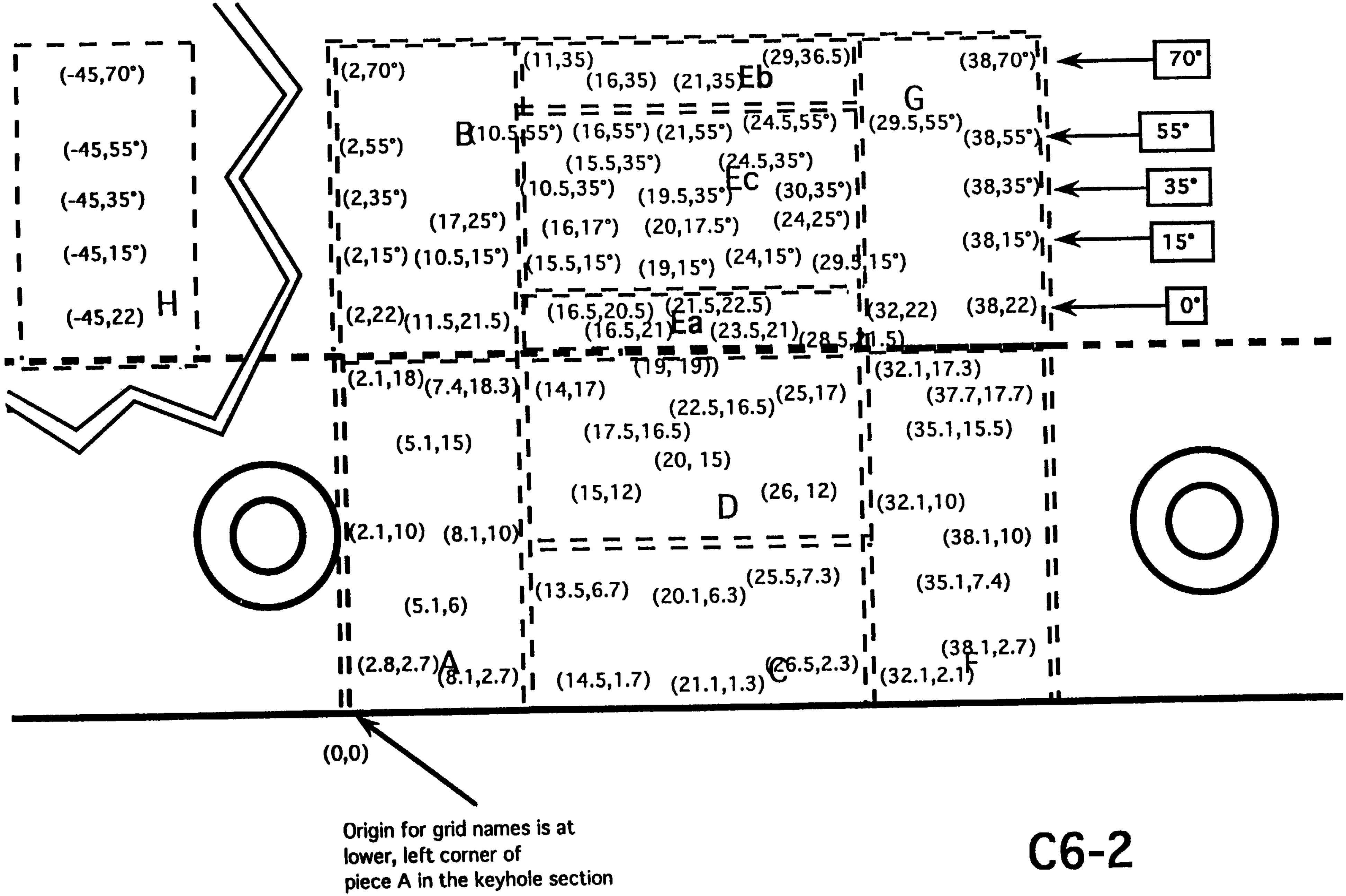



ULTRA HEAVY COSMIC
RAY EXPERIMENT

C6-2



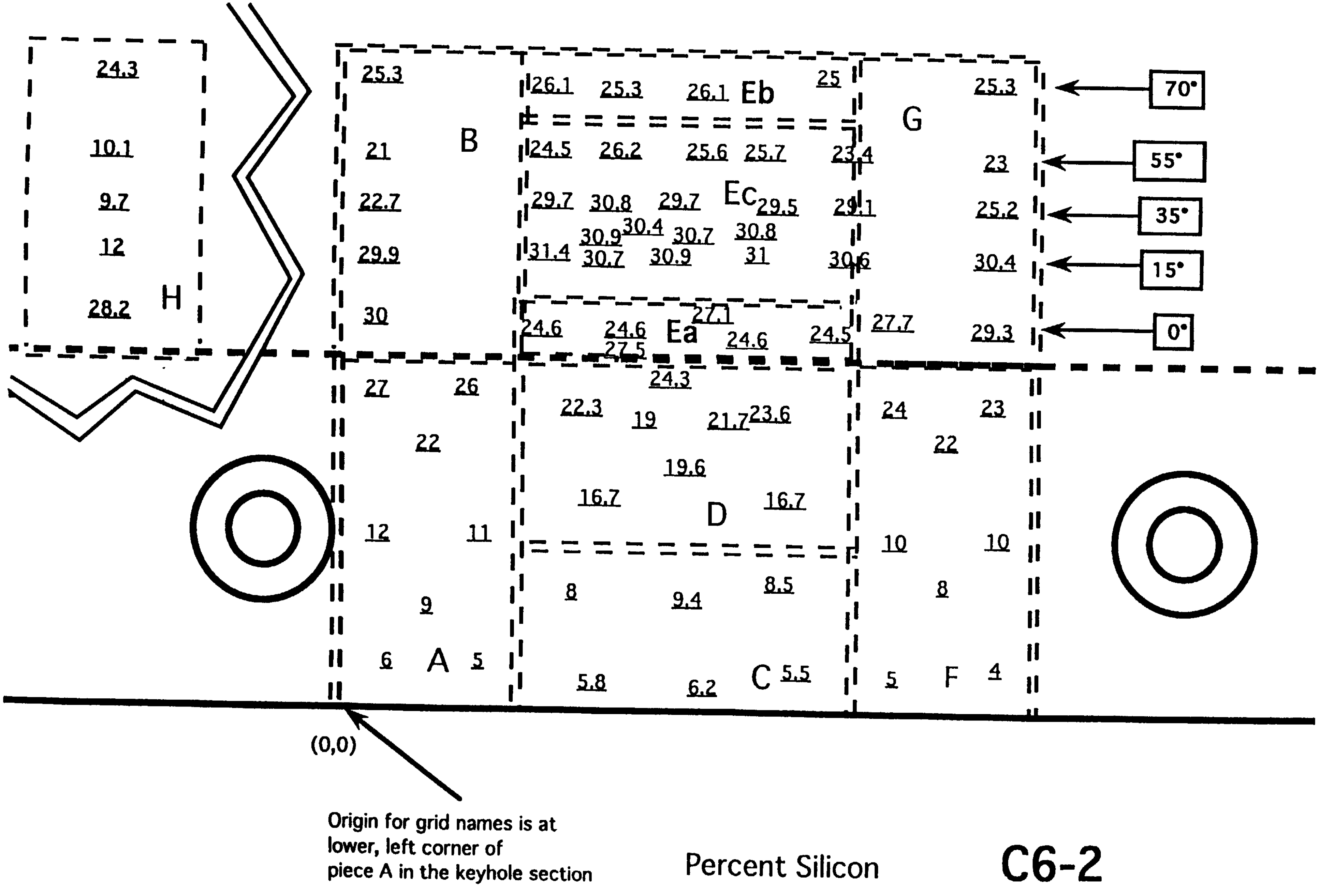
Approximate area of
brown stain
blue fringe
Eb
Ec
Ea
H
B
G
D
A
F
C
LR
Cut sample pieces
MLR
MI
(0,0)
Origin for grid names is at
lower, left corner of
piece A in the keyhole section



C6-2

Grid names of analysis positions

'Unbent' sample pieces

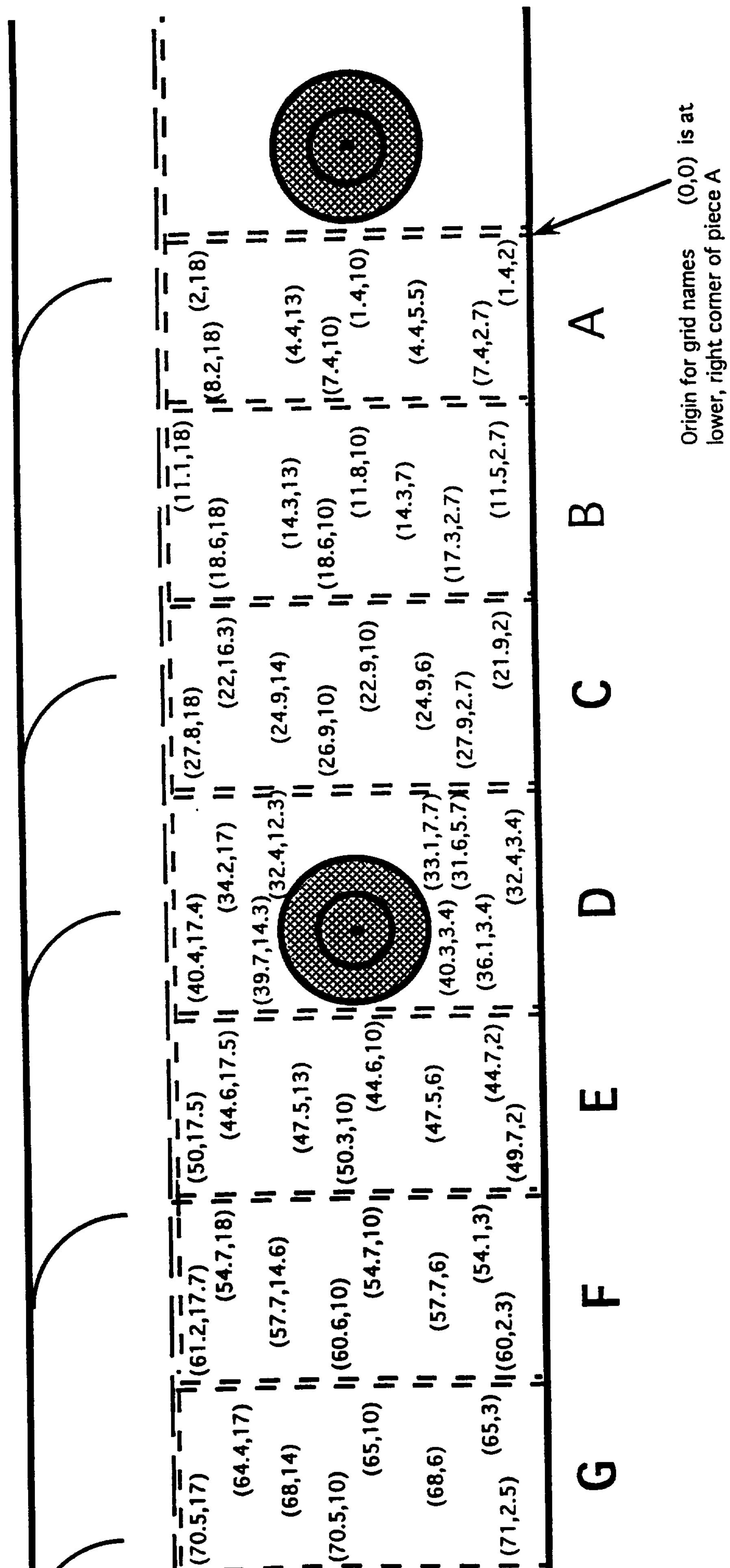


Percent Silicon

C6-2

'Unbent' sample pieces

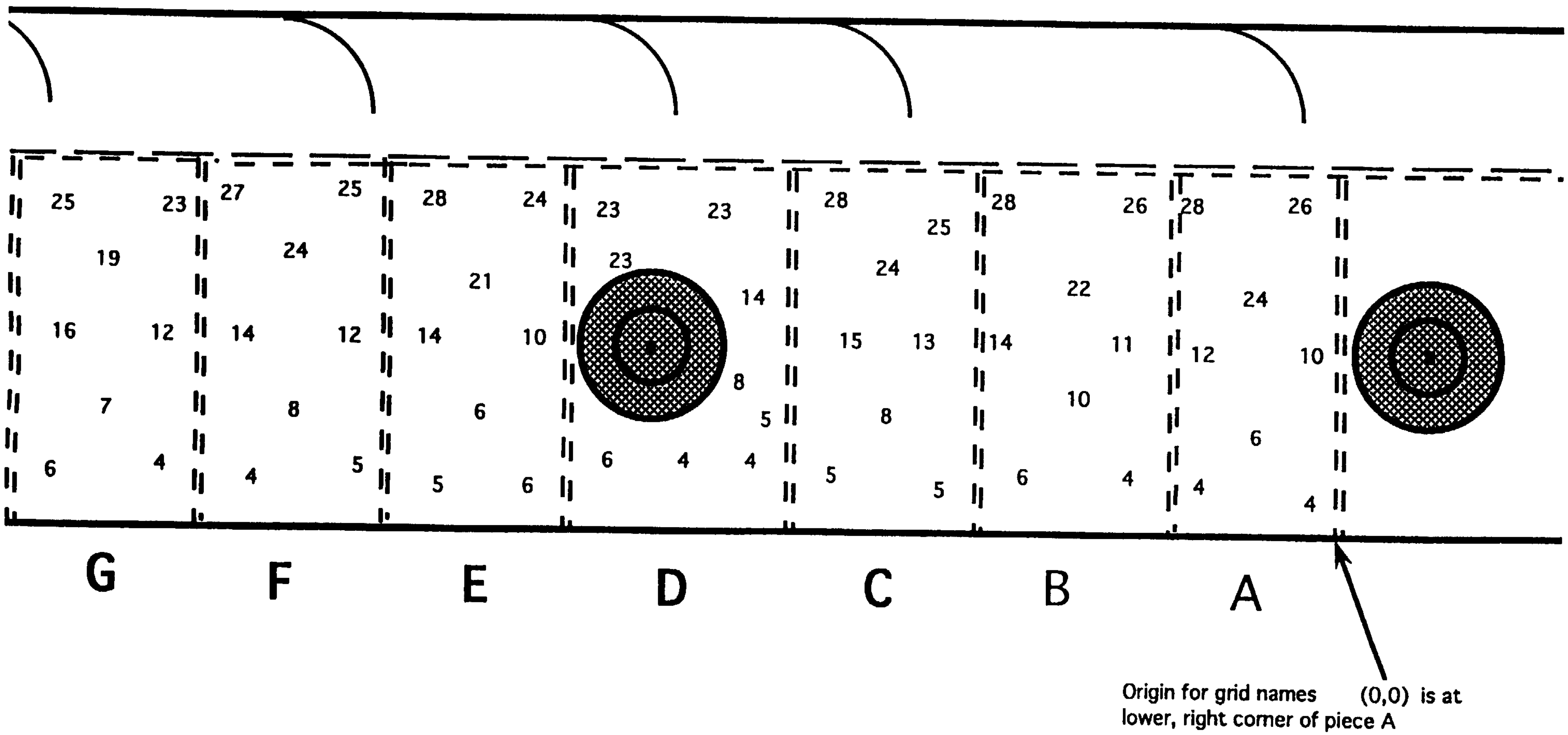
C6



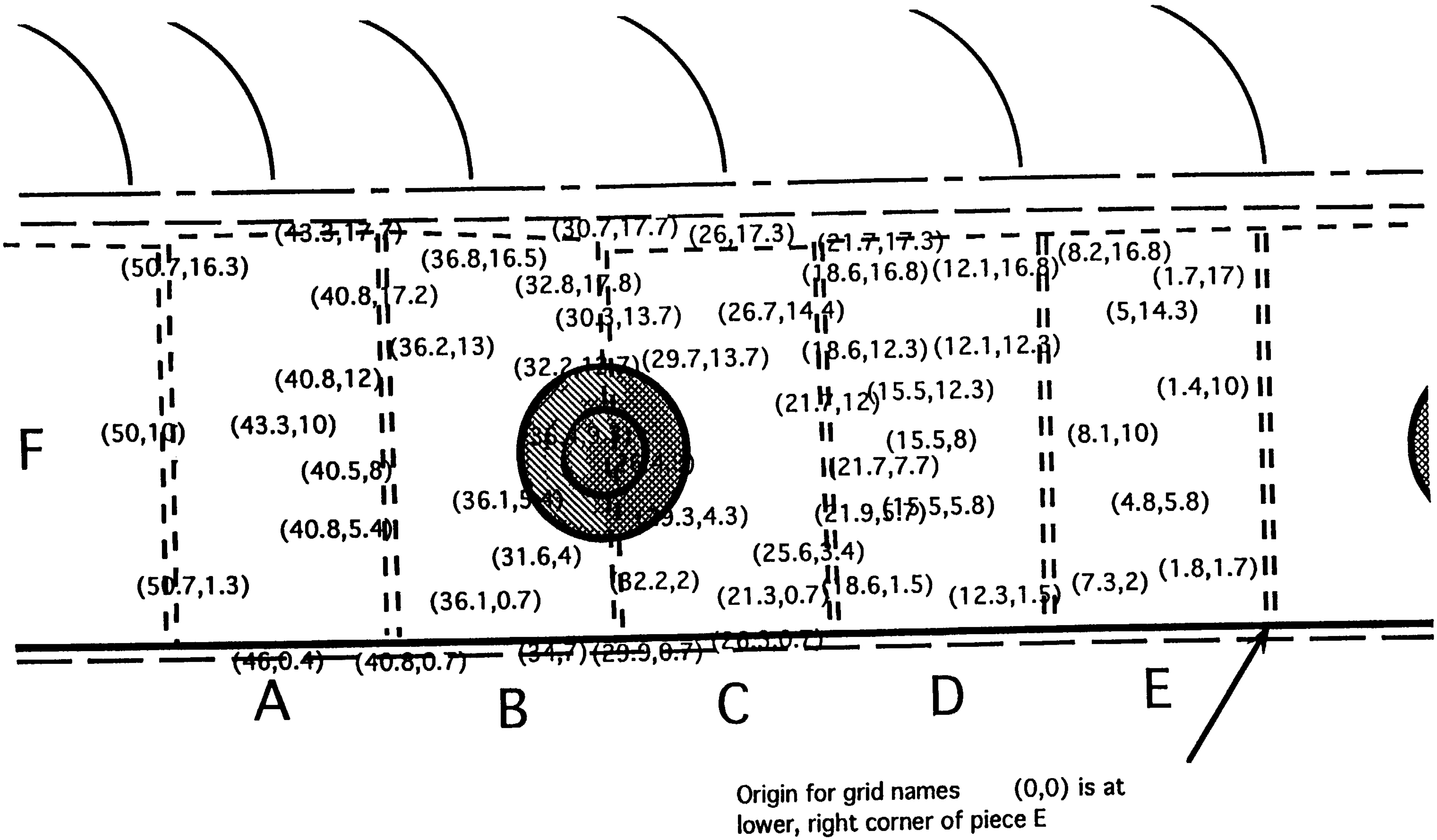
A
B
C
D
E
F
G
Origin for grid names (0,0) is at lower, right corner of piece A
(2,18)
(8.2,18)
(4.4,13)
(7.4,10)
(1.4,10)
(4.4,5.5)
(7.4,2.7)
(1.4,2)
(11.1,18)
(18.6,18)
(14.3,13)
(18.6,10)
(11.8,10)
(14.3,7)
(17.3,2.7)
(11.5,2.7)
(27.8,18)
(22,16.3)
(24.9,14)
(26.9,10)
(22.9,10)
(24.9,6)
(27.9,2.7)
(21.9,2)
(40.4,17.4)
(34.2,17)
(39.7,14.3)
(32.4,12.3)
(33.1,7.7)
(40.3,3.4)
(31.6,5.7)
(36.1,3.4)
(32.4,3.4)
(50,17.5)
(44.6,17.5)
(47.5,13)
(50.3,10)
(44.6,10)
(47.5,6)
(44.7,2)
(49.7,2)
(61.2,17.7)
(54.7,18)
(57.7,14.6)
(60.6,10)
(54.7,10)
(57.7,6)
(54.1,3)
(60,2.3)
(70.5,17)
(64.4,17)
(68,14)
(70.5,10)
(65,10)
(68,6)
(65,3)
(71,2.5)

C6

% Silicon

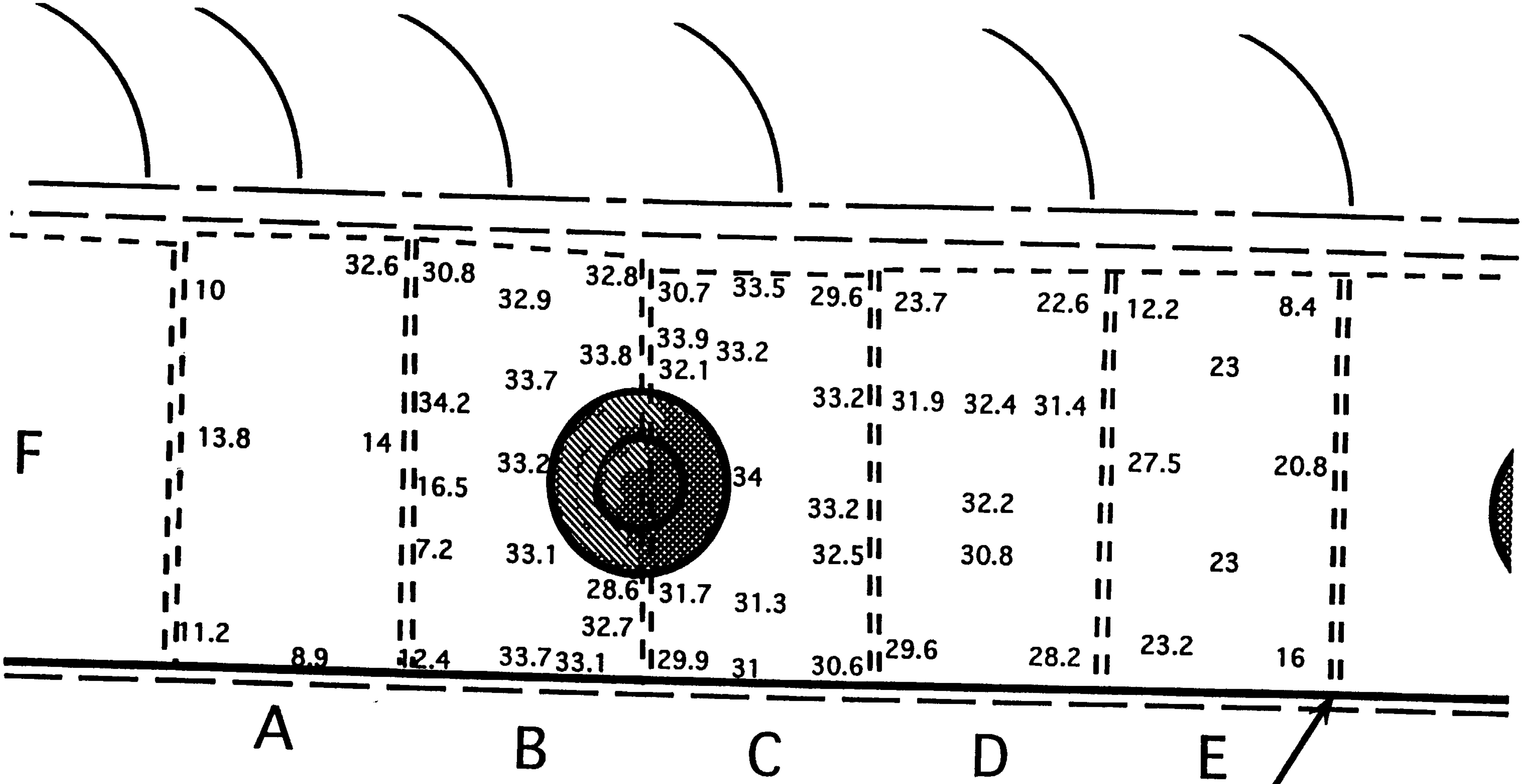


25
23
19
16
12
7
6
4
27
25
24
14
12
8
4
5
28
24
21
14
10
6
5
6
23
23
23
14
8
5
6
4
4
28
25
24
15
13
8
5
5
28
26
22
14
11
10
6
4
28
26
24
12
10
6
4
4
G
F
E
D
C
B
A
Origin for grid names (0,0) is at
lower, right corner of piece A



F
A
B
C
D
E
(50.7,16.3)
(43.3,17.7)
(40.8,17.2)
(36.8,16.5)
(30.7,17.7)
(26,17.3)
(21.7,17.3)
(32.8,17.8)
(30.3,13.7)
(29.7,13.7)
(26.7,14.4)
(18.6,16.8)
(12.1,16.8)
(8.2,16.8)
(1.7,17)
(5,14.3)
(36.2,13)
(40.8,12)
(18.6,12.3)
(12.1,12.3)
(15.5,12.3)
(21.7,12)
(1.4,10)
(50,10)
(43.3,10)
(40.5,8)
(15.5,8)
(21.7,7.7)
(8.1,10)
(40.8,5.4)
(21.9,5.7)
(15.5,5.8)
(4.8,5.8)
(31.6,4)
(25.6,3.4)
(50.7,1.3)
(36.1,0.7)
(32.2,2)
(21.3,0.7)
(18.6,1.5)
(12.3,1.5)
(7.3,2)
(1.8,1.7)
Origin for grid names (0,0) is at lower, right corner of piece E

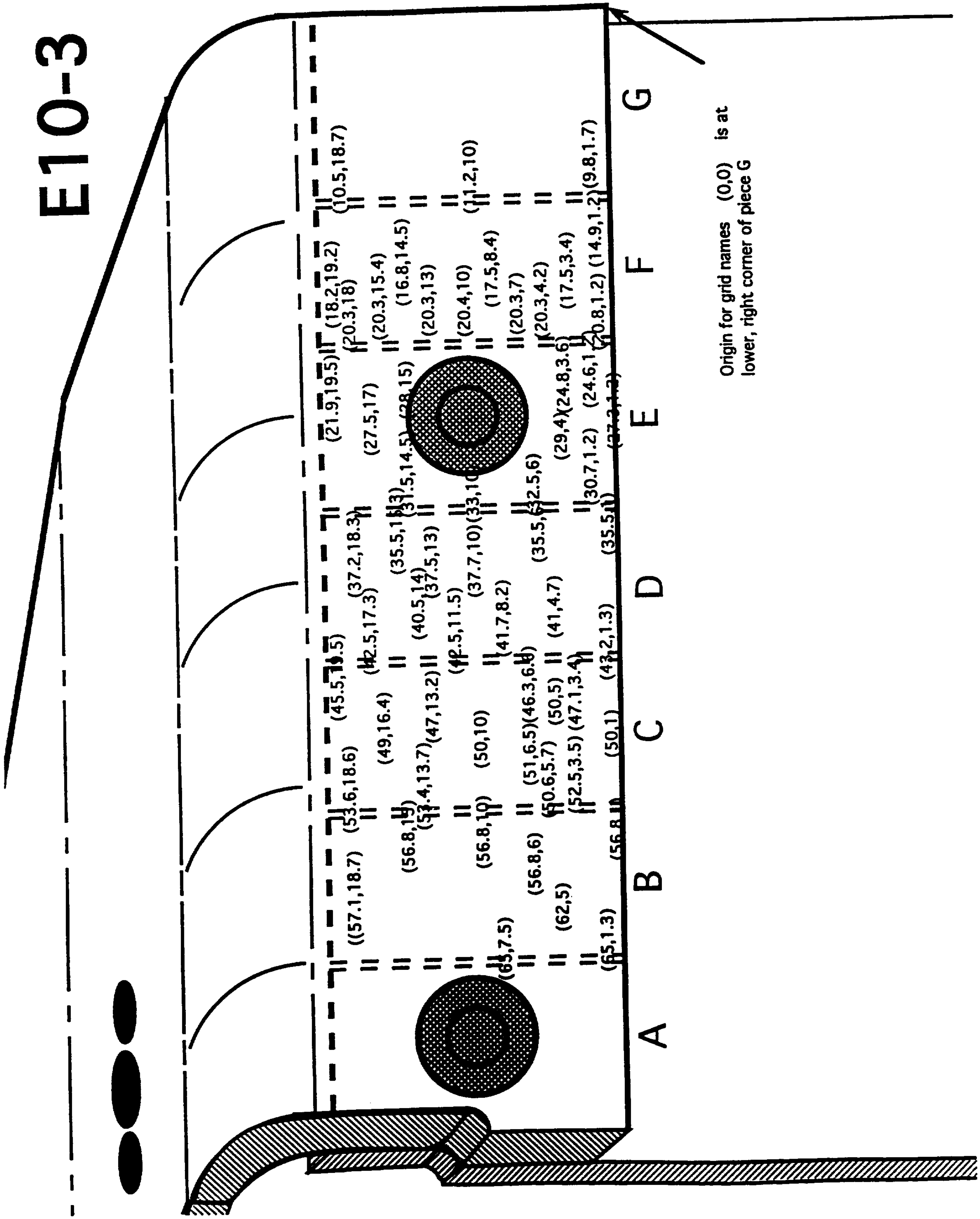
E10-8

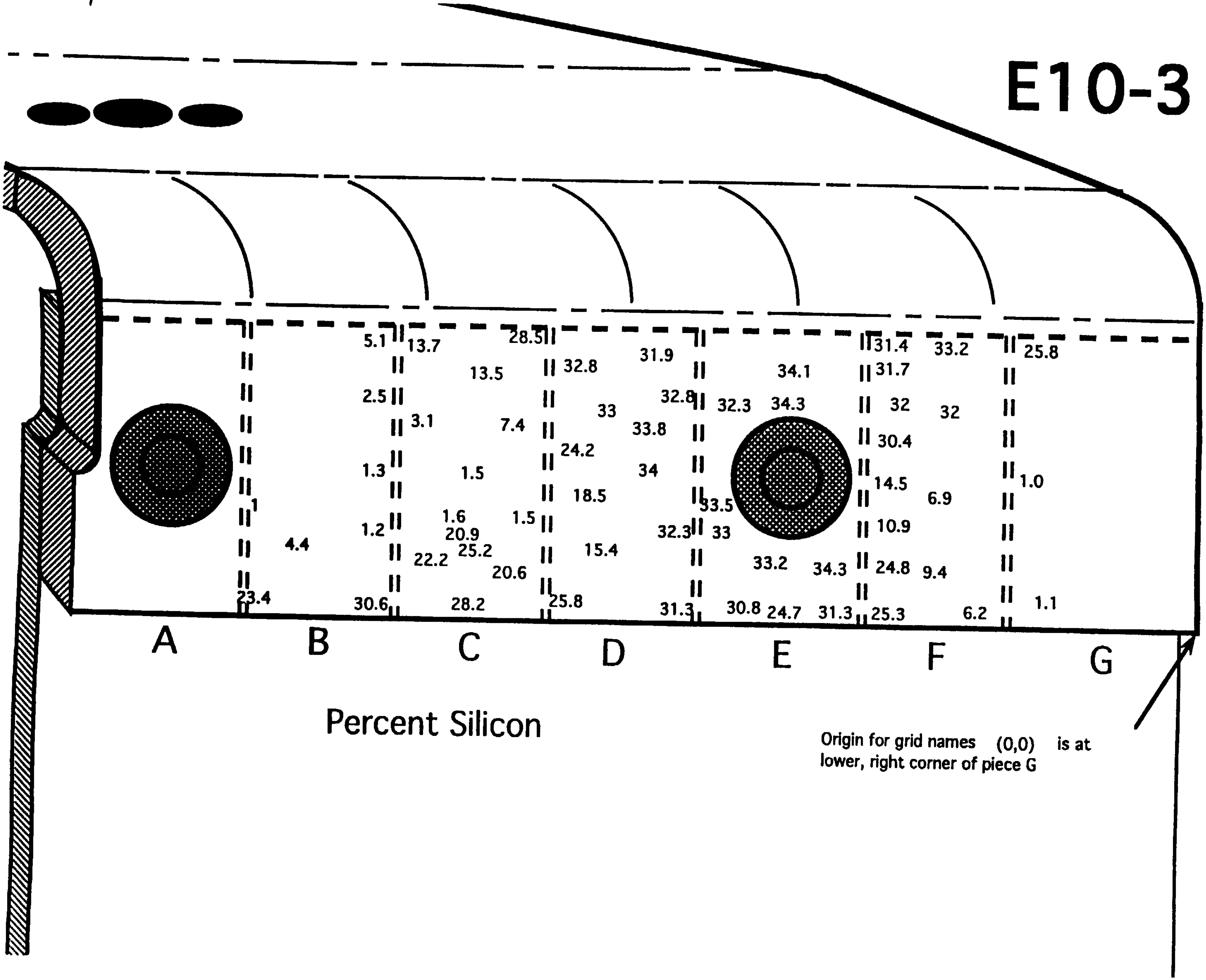


Percent Silicon

Origin for grid names (0,0) is at lower, right corner of piece E

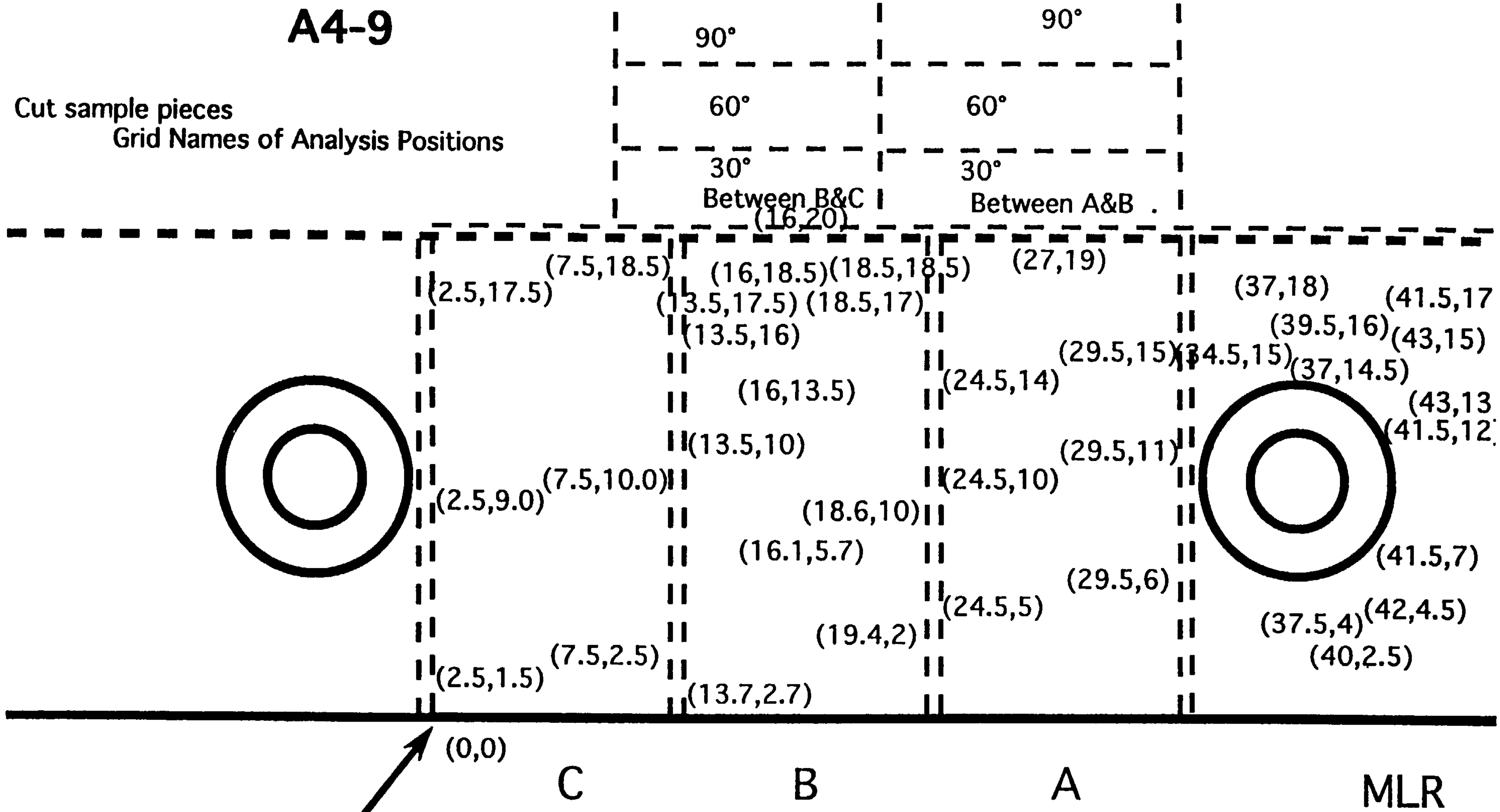
E10-8


E10-3
A
B
C
D
E
F
G
Origin for grid names (0,0) is at lower, right corner of piece G


E10-3
A
B
C
D
E
F
G
1
4.4
23.4
5.1
2.5
1.3
1.2
30.6
13.7
3.1
22.2
13.5
7.4
1.5
1.6
20.9
25.2
20.6
28.2
28.5
1.5
32.8
24.2
18.5
15.4
25.8
31.9
33
33.8
34
32.8
32.3
31.3
32.3
34.1
34.3
33.5
33
33.2
30.8
24.7
34.3
31.3
31.4
31.7
32
30.4
14.5
10.9
24.8
25.3
33.2
32
6.9
9.4
6.2
25.8
1.0
1.1
Percent Silicon
Origin for grid names (0,0) is at lower, right corner of piece G

A4-9

Cut sample pieces
Grid Names of Analysis Positions

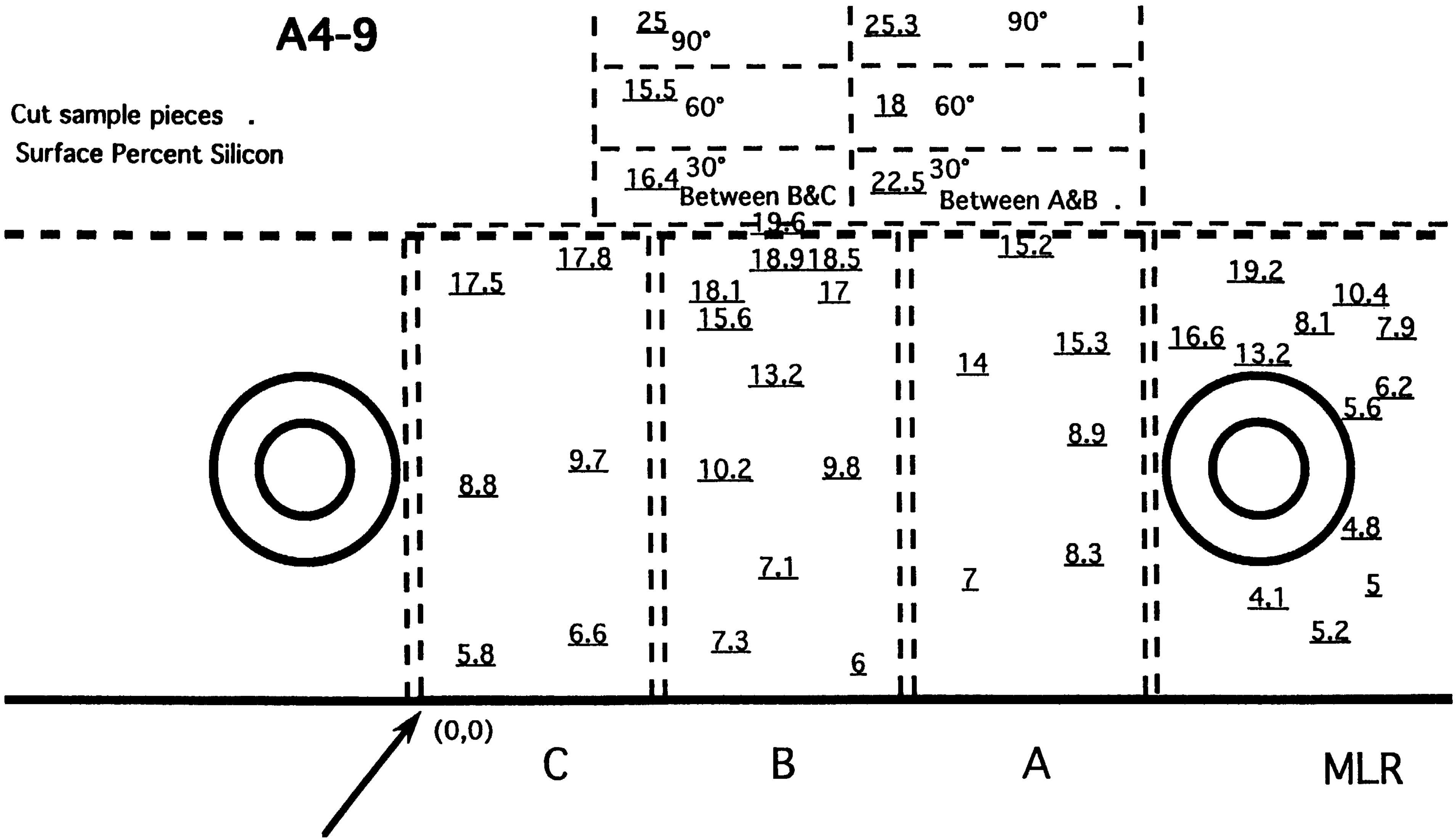


Origin for grid names is at lower, left corner of piece C in the keyhole section which is 1.0mm to the right of the right edge of the left rivet.

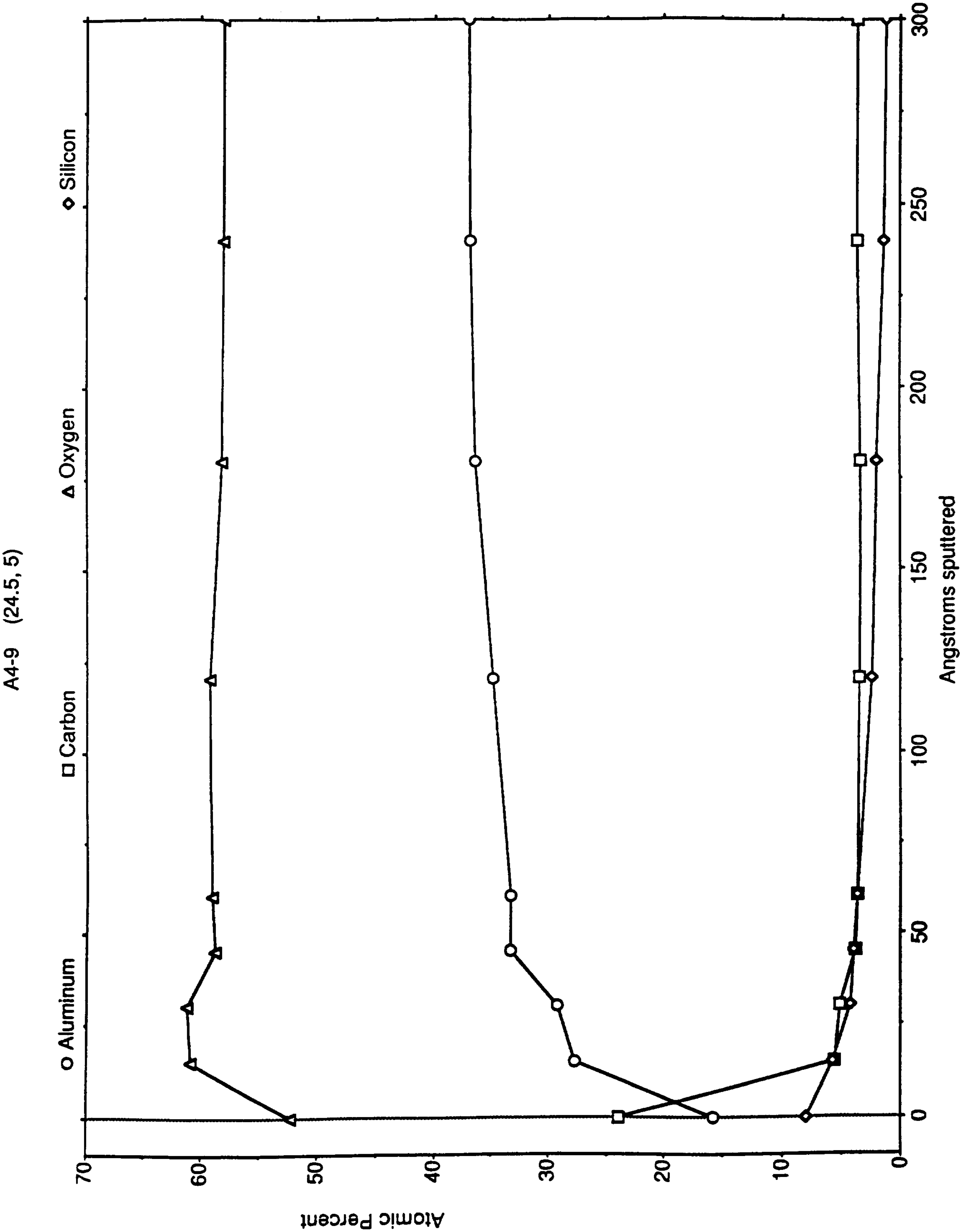
Coordinates are given in (-x-mm, -y-mm)

A4-9

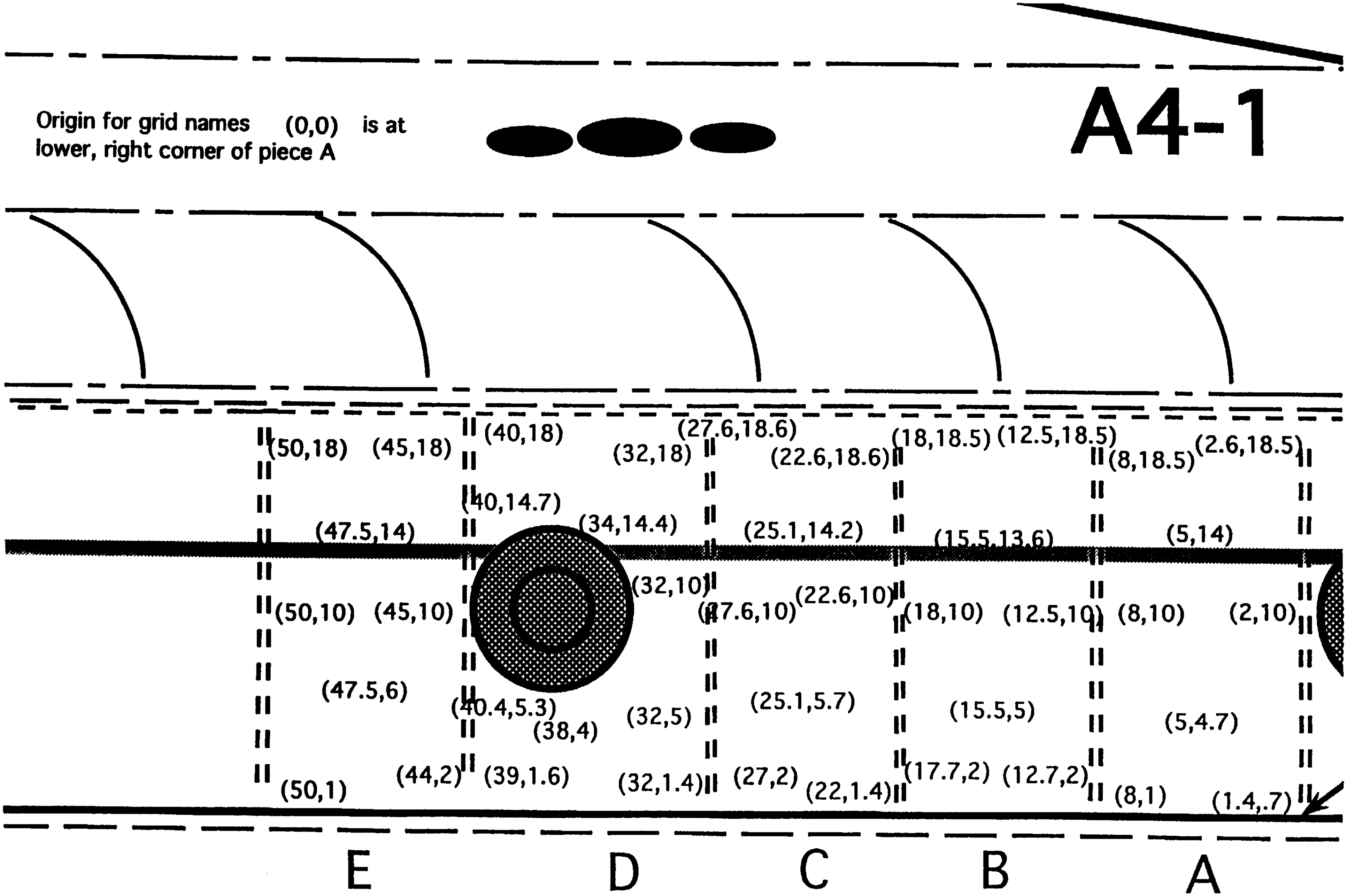
Cut sample pieces .
Surface Percent Silicon

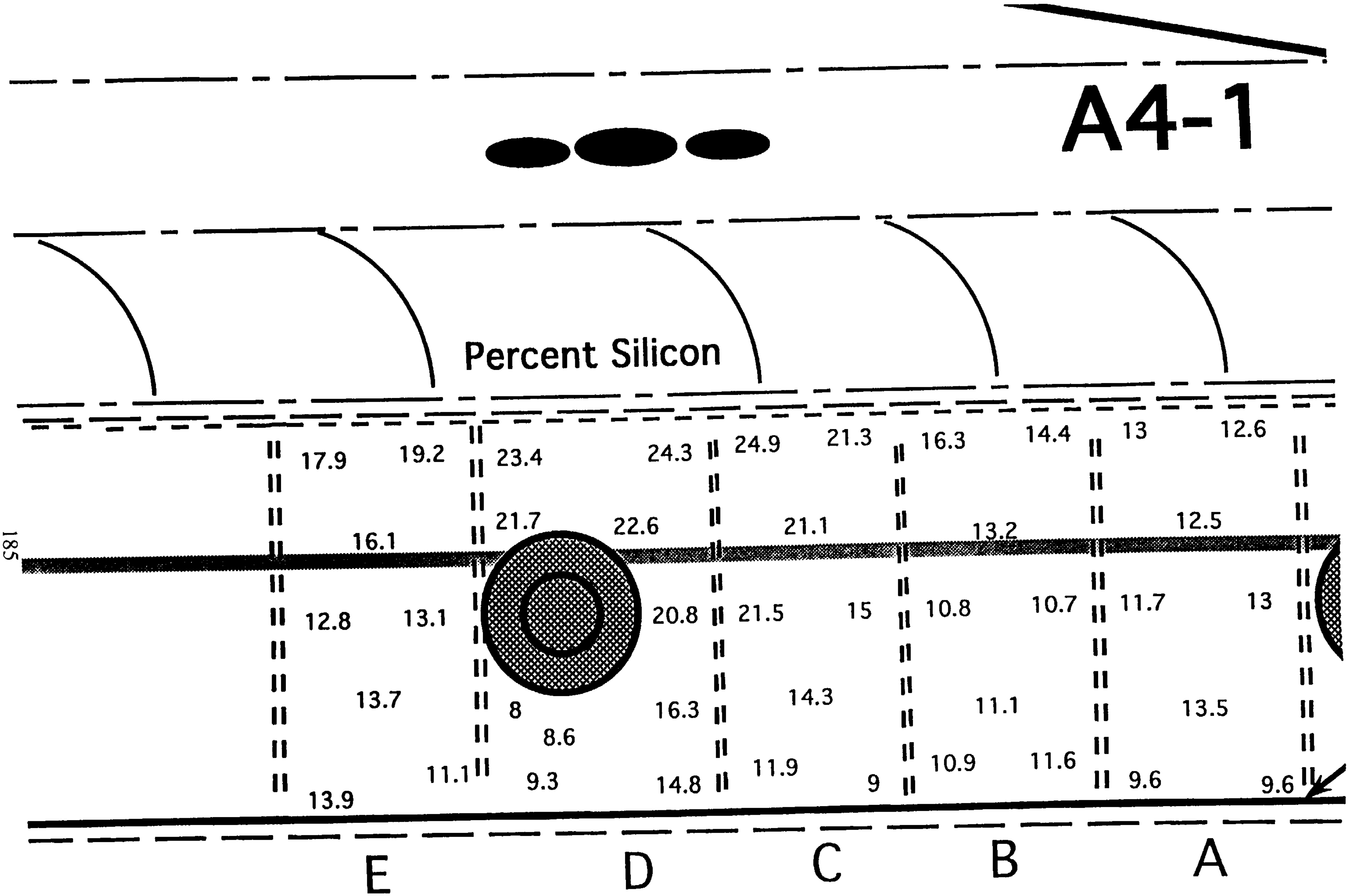


Origin for grid names is at
lower, left corner of
piece C in the keyhole section .



A4-9 (24.5, 5)
Aluminum
Carbon
Oxygen
Silicon
Atomic Percent
Angstroms sputtered
0
10
20
30
40
50
60
70
0
50
100
150
200
250
300


A4-1
Origin for grid names (0,0) is at lower, right corner of piece A
(50,18) (45,18) (40,18) (32,18) (27.6,18.6) (22.6,18.6) (18,18.5) (12.5,18.5) (8,18.5) (2.6,18.5)
(47.5,14) (40,14.7) (34,14.4) (25.1,14.2) (15.5,13.6) (5,14)
(50,10) (45,10) (32,10) (27.6,10) (22.6,10) (18,10) (12.5,10) (8,10) (2,10)
(47.5,6) (40.4,5.3) (38,4) (32,5) (25.1,5.7) (15.5,5) (5,4.7)
(50,1) (44,2) (39,1.6) (32,1.4) (27,2) (22,1.4) (17.7,2) (12.7,2) (8,1) (1.4,.7)
E
D
C
B
A


A4-1
Percent Silicon
17.9
19.2
23.4
24.3
24.9
21.3
16.3
14.4
13
12.6
16.1
21.7
22.6
21.1
13.2
12.5
12.8
13.1
20.8
21.5
15
10.8
10.7
11.7
13
13.7
8
8.6
16.3
14.3
11.1
13.5
13.9
11.1
9.3
14.8
11.9
9
10.9
11.6
9.6
9.6
E
D
C
B
A

NAS8-40581 CONTRACT STATUS

SURFACE ELEMENTAL % MAPS ESSENTIALLY COMPLETE

AUGER DEPTH PROFILES CURRENTLY BEING OBTAINED

EXPERIMENTAL RESULTS WILL BE COMPARED WITH RESULTS OF PREDICTIONS OF CONTAMINATION LEVELS FROM ISEM AND MOLFLUX COMPUTER MODELS

TRAILING EDGE LOCATIONS(A4) SHOW THIN BUT WIDESPREAD SURFACE SILICON DISTRIBUTION

DISCOLORED AREAS ON LEADING EDGE (E10) AND "SIDE" (C6) LOCATIONS

TRAY LIPS APPEAR CONTAMINATED BY TRAY COVER GASKETS USED PRE-FLIGHT

TRAY WALLS ESSENTIALLY CONTAMINATED ONLY FROM DC6-1104 ADHESIVE FROM INTERIOR OF TRAYS
RESULTS SUGGEST MINIMAL CONTRIBUTION FROM OTHER POSSIBLE SOURCES

ELEMENTAL SILICON SURFACE %'S APPEAR TO TRACK SOLAR EXPOSURE LEVELS

DISCOLORED AREAS ONLY OCCUR WHERE SURFACE RECEIVED BOTH SOLAR AND ATOMIC OXYGEN EXPOSURE

POSA I & POSA II FLIGHT EXPERIMENTS

DEPLOYED ON MIR DOCKING MODULE MARCH 1996

SCHEDULED RETRIEVAL SEPTEMBER 1997

INTERNATIONAL SPACE STATION CONTAMINATION RISK MITIGATION EXPERIMENT

~900 PASSIVE MATERIAL SPECIMENS

POSA I TECHNICAL LEAD JIM ZWIENER, NASA MSFC

POSA II TECHNICAL LEAD GARY PIPPIN, BOEING DEFENSE & SPACE GROUP

PARTICIPATING ORGANIZATIONS NASA MSFC, LaRC, JSC, and LeRC, BOEING, BOEING NORTH AMERICAN, MCDONNELL-DOUGLAS, AZ TECHNOLOGY, IITRI, SHELDAHL, PARKER-HANNIFIN

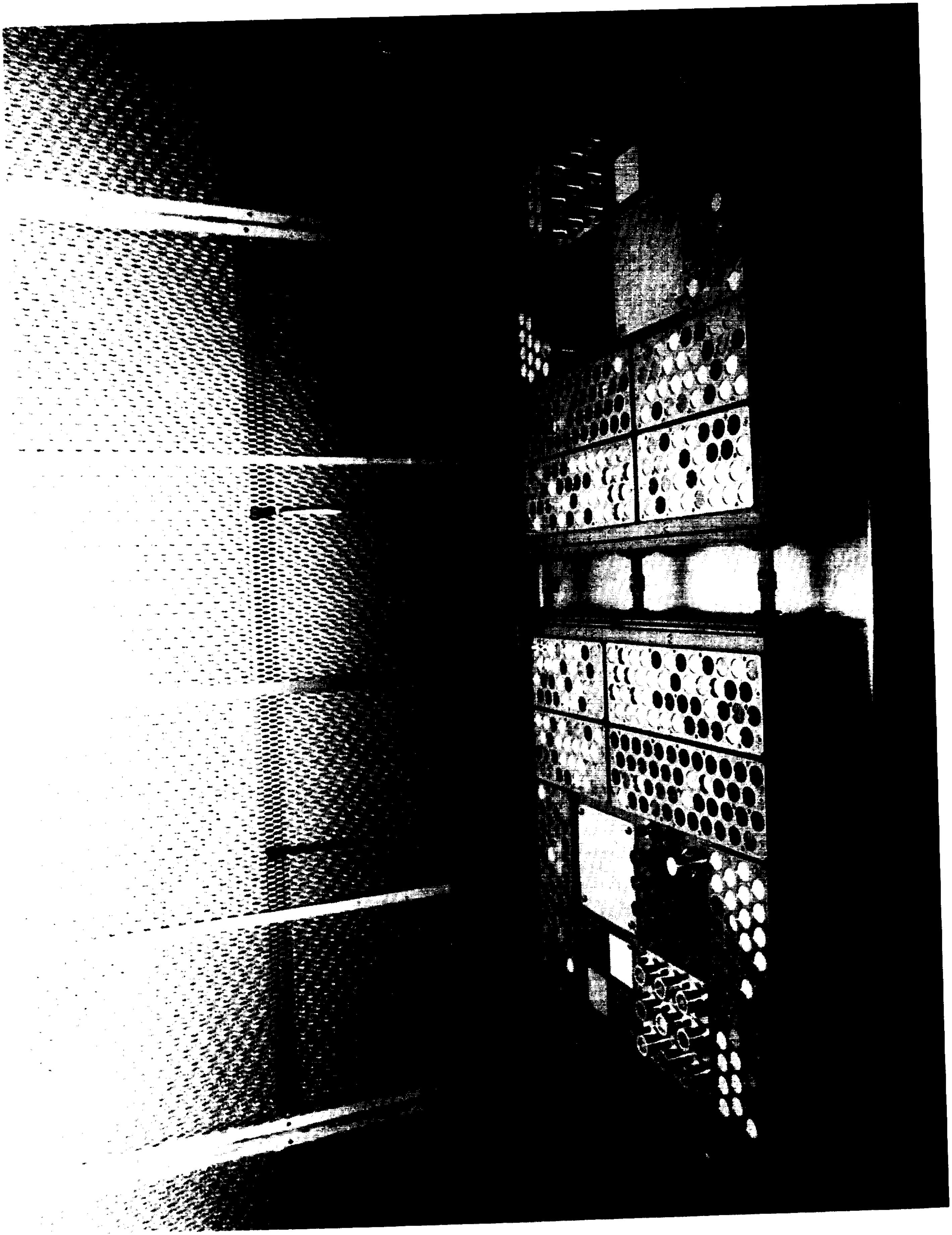
TWO METEOROID & ORBITAL DEBRIS EXPERIMENTS UNDERGOING SIMULTANEOUS EXPOSURE

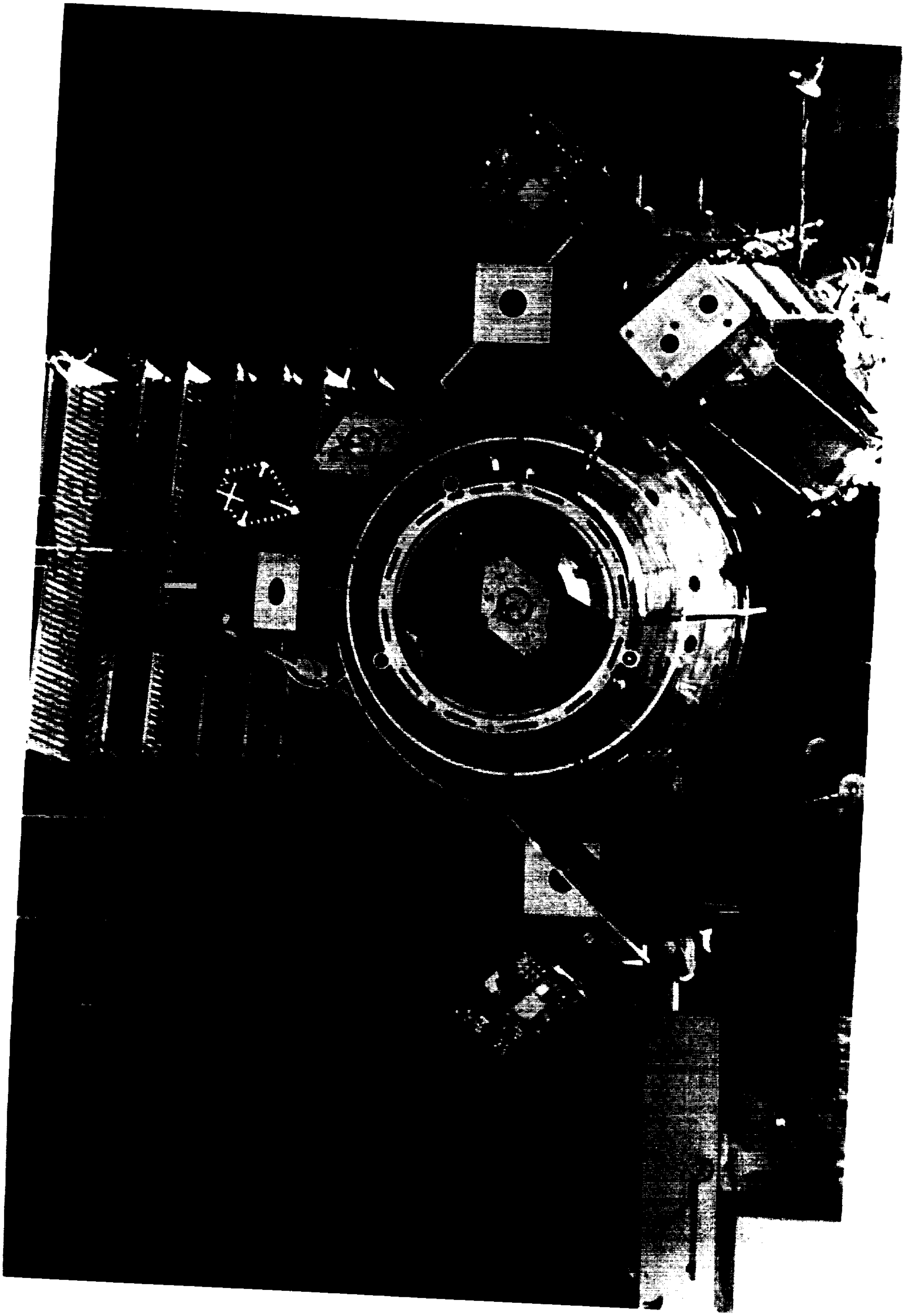
MATERIAL CATEGORIES FLOWN ON POSA II

ANODIZED AND ALODINED ALUMINUMS, WHITE PAINTS, Ag/FEP
KAPTON, OPTICAL WITNESS SAMPLES,
SILICONE RUBBER, FLUOROSILICONE RUBBER, VITON
BLACK PAINTS, CR-39,
"PRE-CONTAMINATED" SURFACES-VARIETY,
MULTI-LAYER INSULATION BLANKET,
CYANATE ESTER RESIN/GRAPHITE COMPOSITE,
BRAYCOTE 601 AND BRAYCOTE 803

POSA I CARRIED NO SILICON-CONTAINING MATERIALS

POSA I & II ARE NOT LINE OF SIGHT TO EACH OTHER

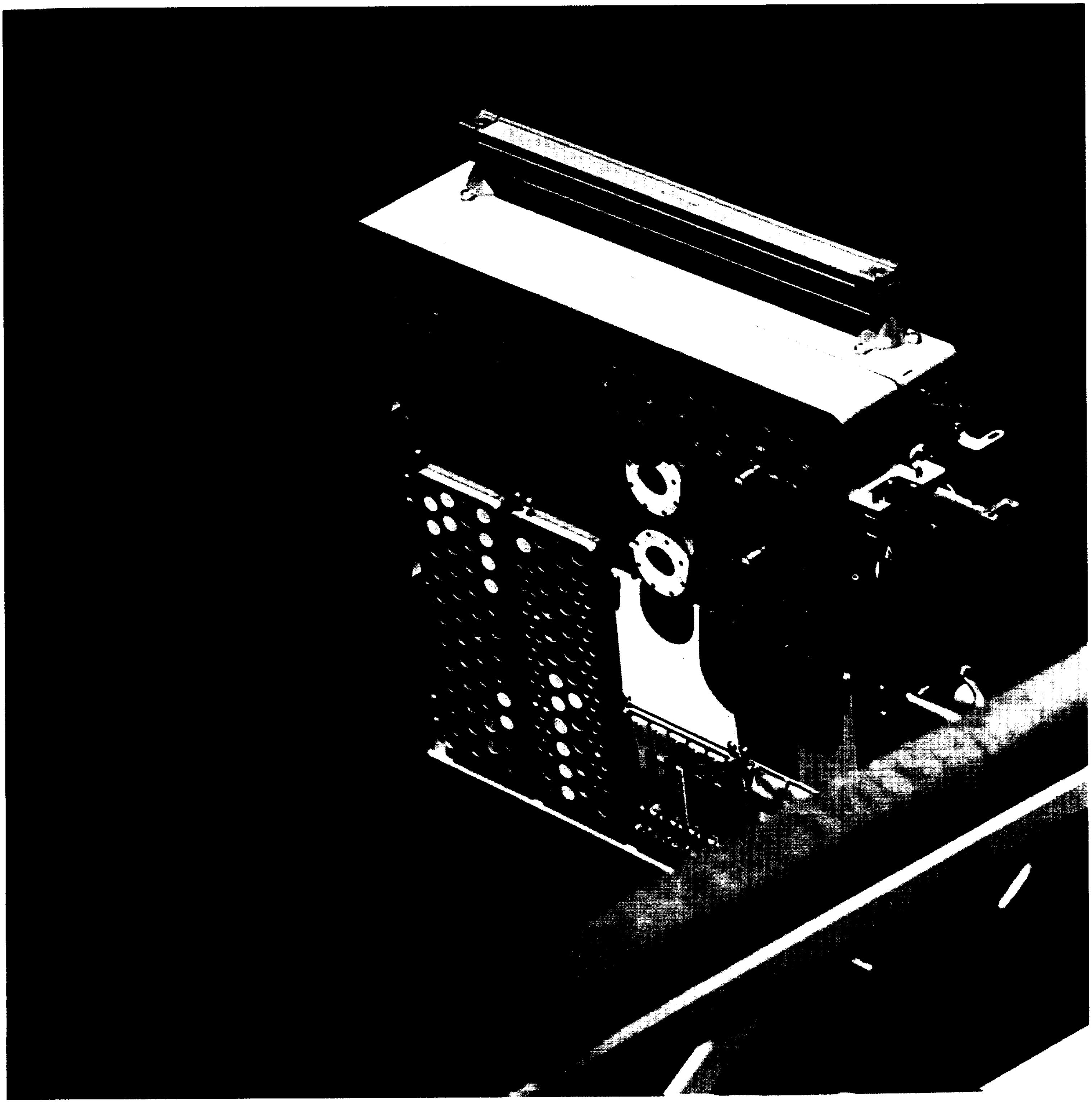


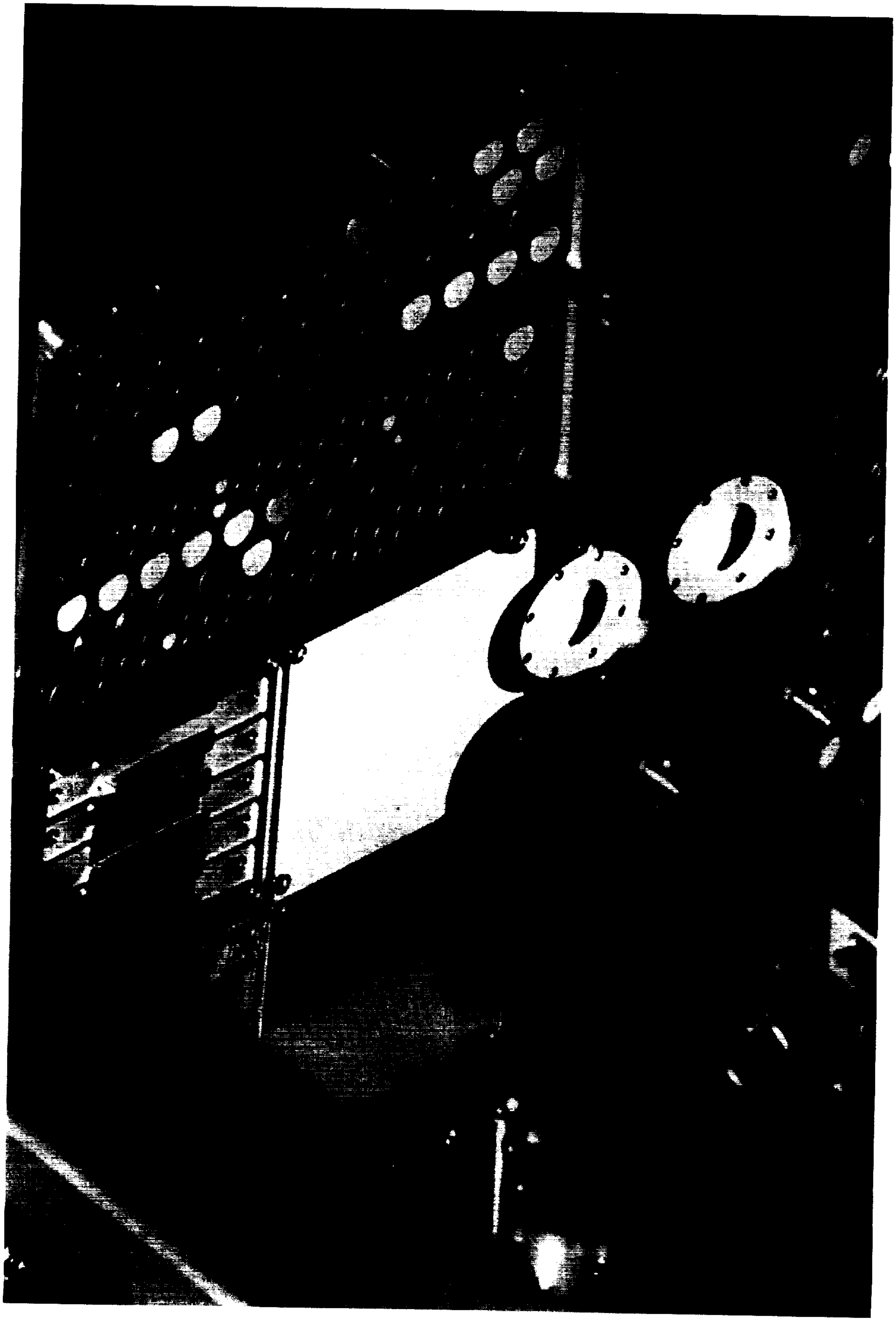


National Aeronautics and Space Administration

STS079-834-050

Lyndon B. Johnson Space Center
Houston, Texas 77058





JAPANESE FLIGHT DEMONSTRATION
STS-85
AUGUST 1997

METEOROID & DEBRIS EXPERIMENT
NASA-LaRC

MATERIALS EXPERIMENT
NASA-LaRC, COLLEGE OF WILLIAM & MARY, BOEING

Project Manager Junilla Applin NASA LaRC

Participants NASA LaRC Bill Kinard, Jim Jones, John Connell, Gale Harvey, Shiela Thibeault

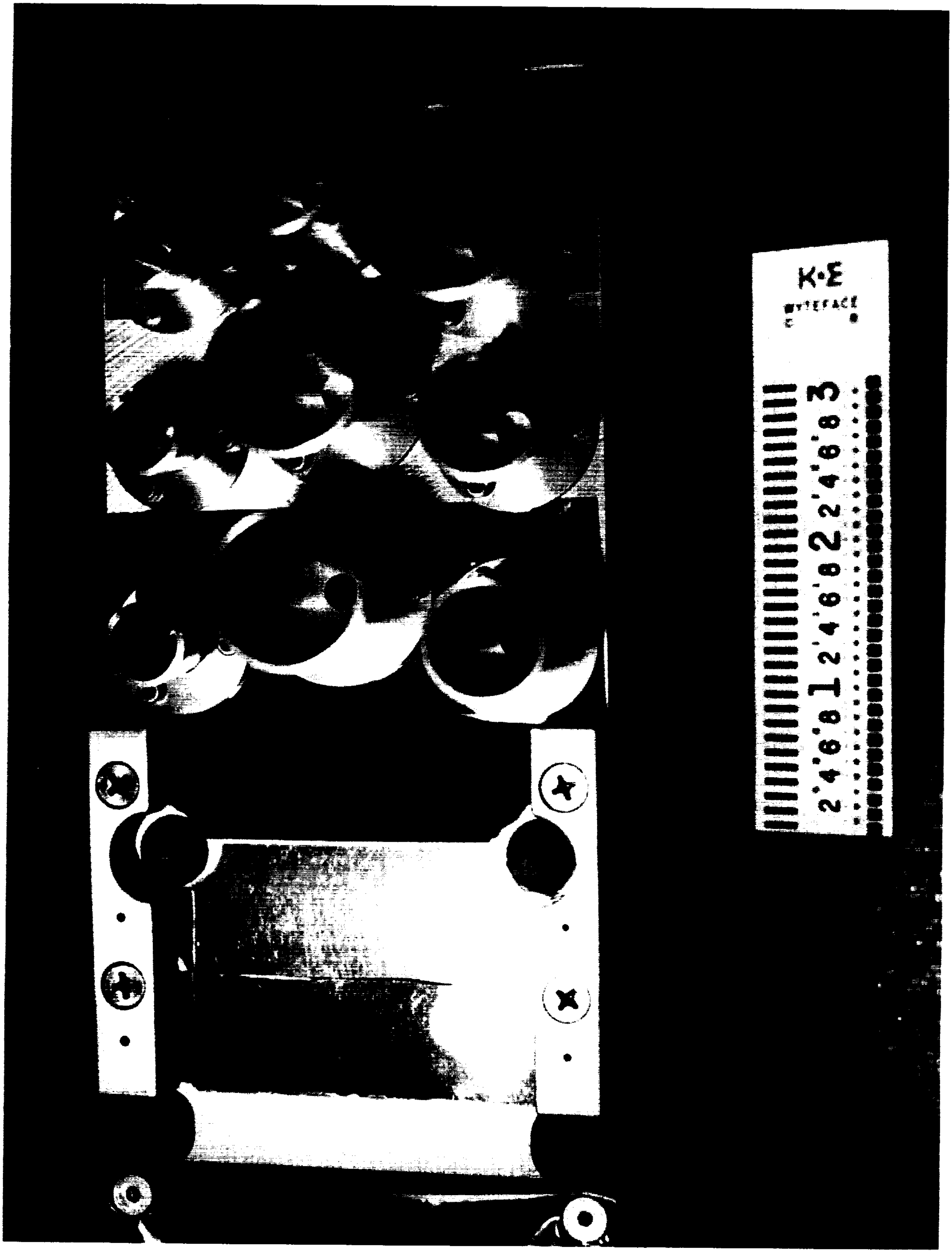
College of William & Mary Robert Orwoll, Richard Kiefer

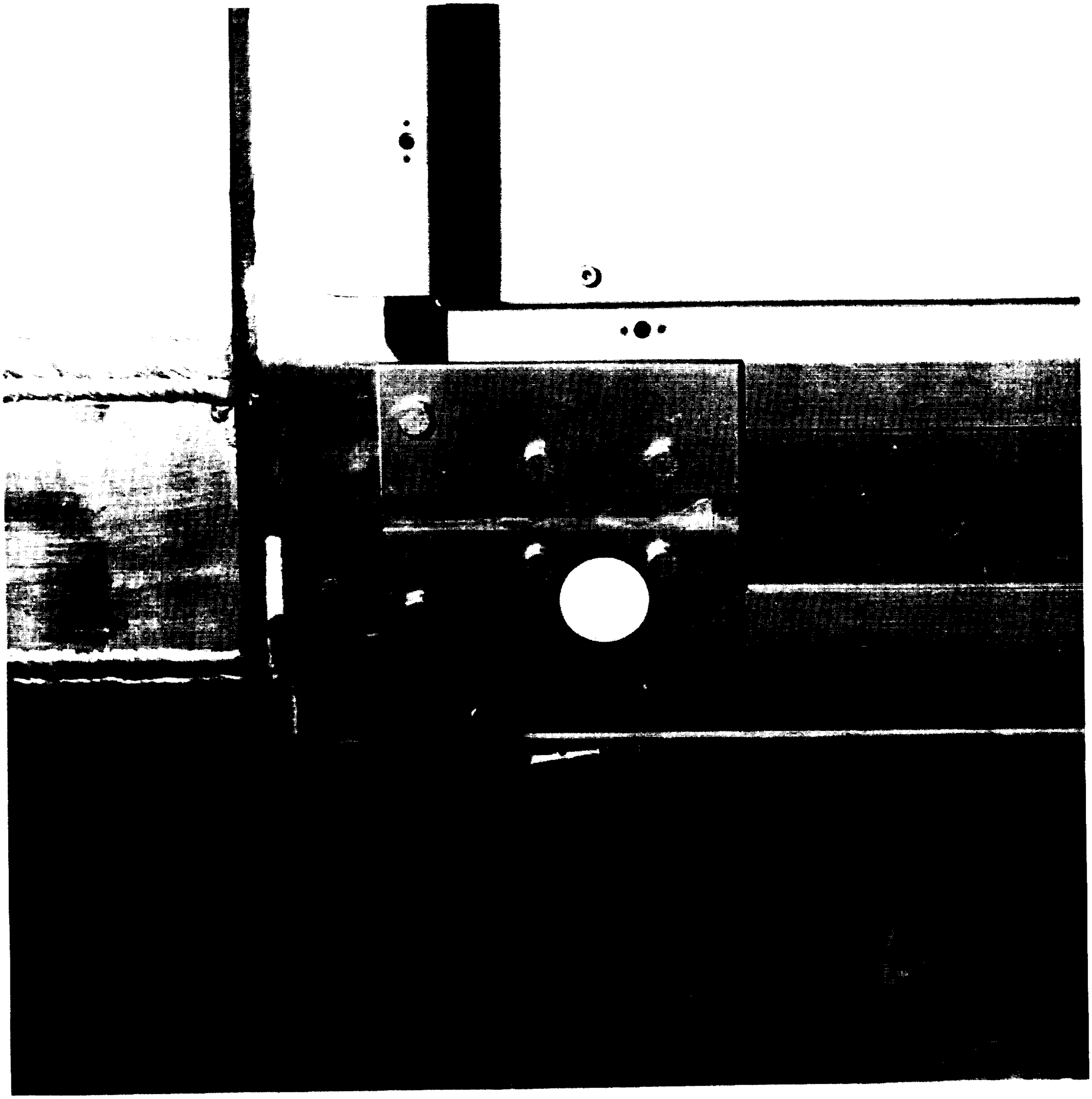
Boeing Gary Pippin, Gail Bohnhoff-Hlavacek

ESEM MATERIAL SPECIMENS

KAPTON, KAPTON Laminate, Aluminized KAPTON from STS-61
AORAMID(TOR, COR)
Polyetherimide, Polyetherimide with BTO coating(2 thicknesses)
Ag/FEP, 10 mil Ag/FEP from LDEF
ITO coated FOSR (2 samples, differing ITO thickness)
Cyanate Ester/graphite composite
Viton (V835) Braycoat 601(perfluoroether) on V835 Braycoat 803(perfluoroether) on V835
Silicone (S383) Braycoat 601 on S383 Braycoat 803 on S383
Fluorosilicone
White Paint (BMS 10-79)
Contamination witness plates
Compound parabolic Solar Concentrator - perforated Ag/FEP film
Atomic Oxygen concentrators (x4, x9, x16)


ESEM Materials Sample Holder





REFERENCE STANDARDS USED FOR Si CHARACTERIZATION

ORGANIC SILICONE

HIGH VACUUM SILICONE GREASE RUBBED ONTO GOLD WAFER

INORGANIC SILICATE

1000A THICK SiO2 LAYER ON A SILICON WAFER

Si Sp PEAKS USED FOR CHARACTERIZATION

SILICATEPEAK AT ~103.5 ev, PEAK WIDTH ~1 ev

SILICONES PEAK AT ~102.5 ev, PEAK WIDTH ~1.5 ev

CARBON 1s REFERENCE PEAKS ALSO OBTAINED FOR EACH BOLT HEAD MEASUREMENT

SINGLE BROAD PEAK IN THE ~99-105 ev RANGE IS CURVE FIT TO TWO PEAKS

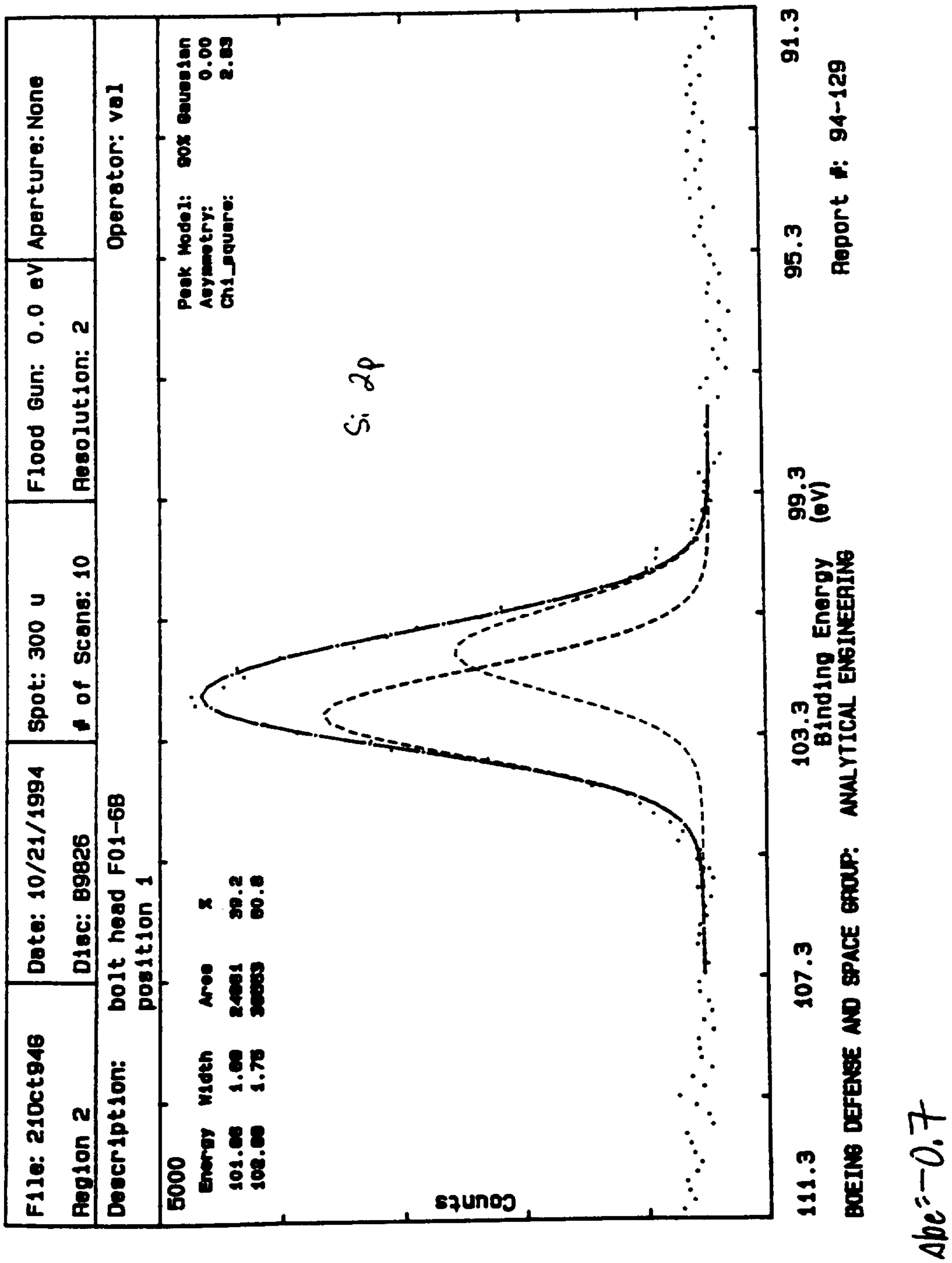


Figure G-27. Silicon 2p spectrum for bolt F1-6b, position 1.

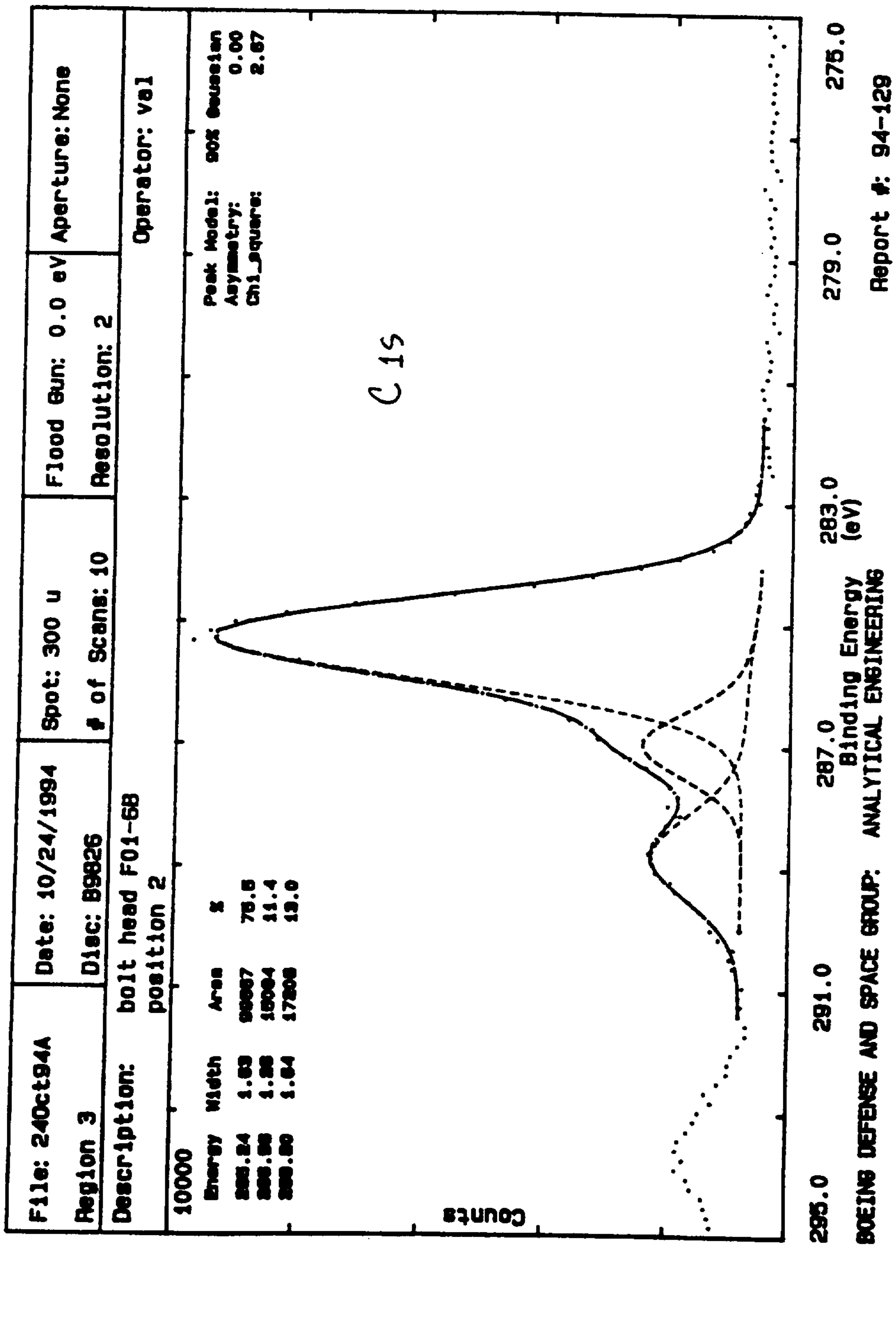


Figure G-28. Carbon 1s spectrum for bolt F1-6b, position 2.

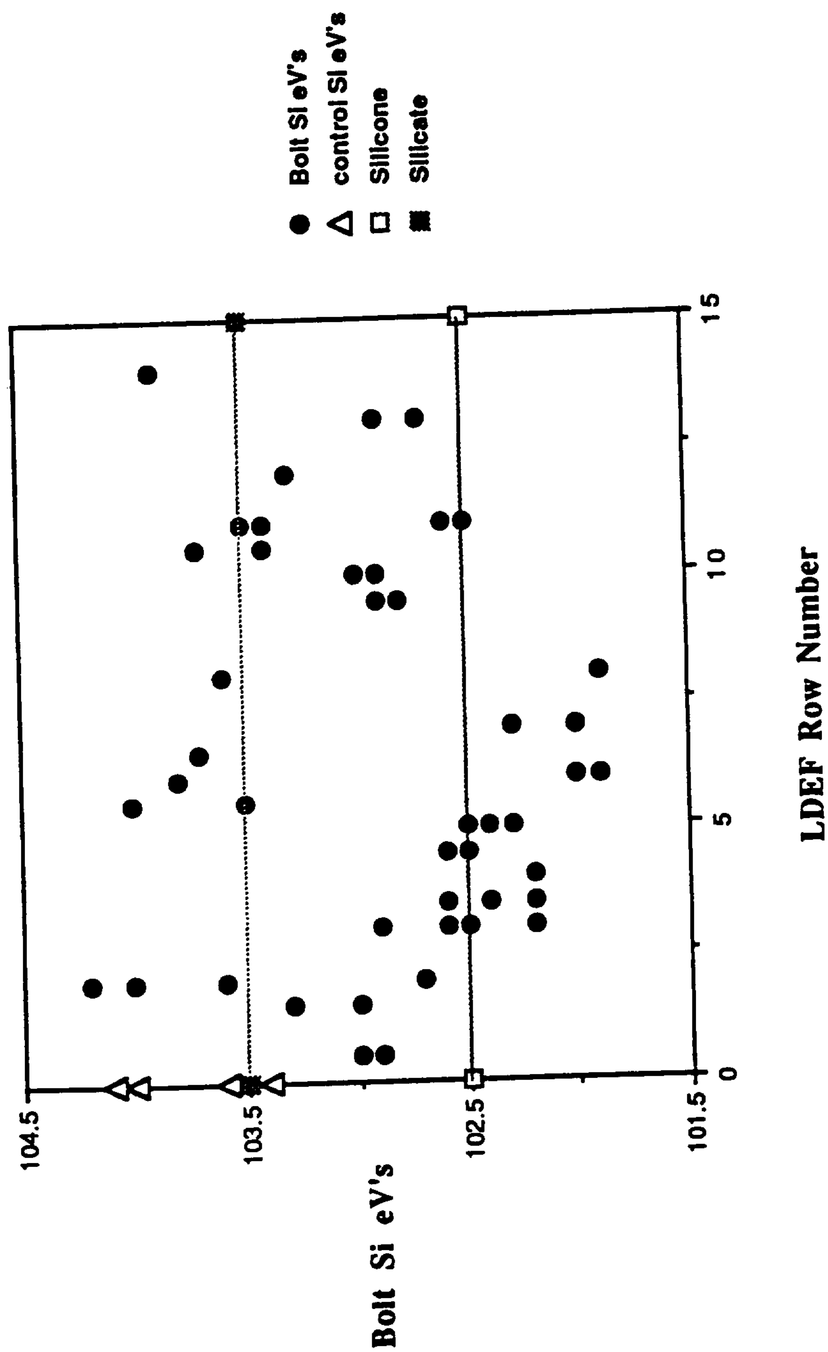
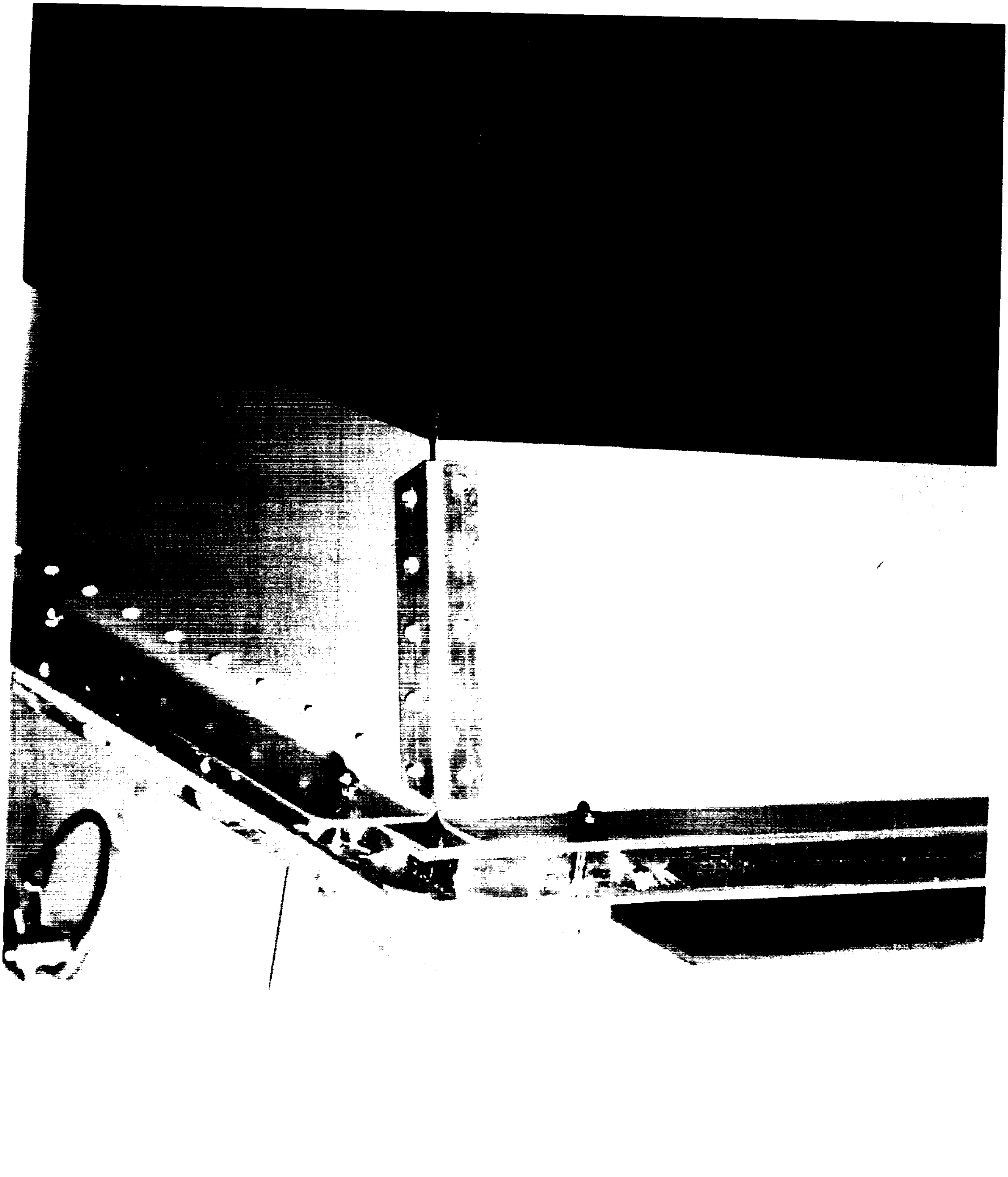


Figure 17. Results of high resolution ESCA measurements on selected stainless steel bolt heads from LDEF.



CONTAMINATION CONTROL FOR COMMERCIAL VEHICLES

QUESTION IS ALWAYS "HOW MUCH IS ENOUGH?"

IDENTIFY THE MOST CONTAMINATION-SENSITIVE STEPS

SEEK TO MINIMIZE COST OF NECESSARY OPERATIONS

FREQUENT CLEANLINESS VERIFICATION TESTING TO DEFINE PROCESS

LESSONS FROM EARLIEST HARDWARE APPLIED TO LATER UNITS

CONTAMINATION AND THERMAL CONTROL COATING ACTIVITIES FOR THE INTERNATIONAL SPACE STATION AT MDA

Presented at

1997 Spacecraft Contamination and Coatings Workshop

9-10 July 1997

by

Henry W. Babel

E-mail: babel#d#hank@ssdgwy.mdc.com

714-896-4283

DISCUSSION TOPICS

☒ **MDA ISS contamination activities**

☐ **MDA Thermal control activities**

MDA CONTAMINATION RELATED ACTIVITIES FOR THE INTERNATIONAL SPACE STATION

- Predicted End-of-Life (EOL) absorbance and emittance properties of different types of silicone and Tefzel contaminated thermal control coatings

- OPM flying on Mir has ground contaminated silicone and Tefzel samples
  - Some samples exposed to 10,000 ESH of VUV on the ground
  - In-situ opticals being measured permitting comparison to ground test results

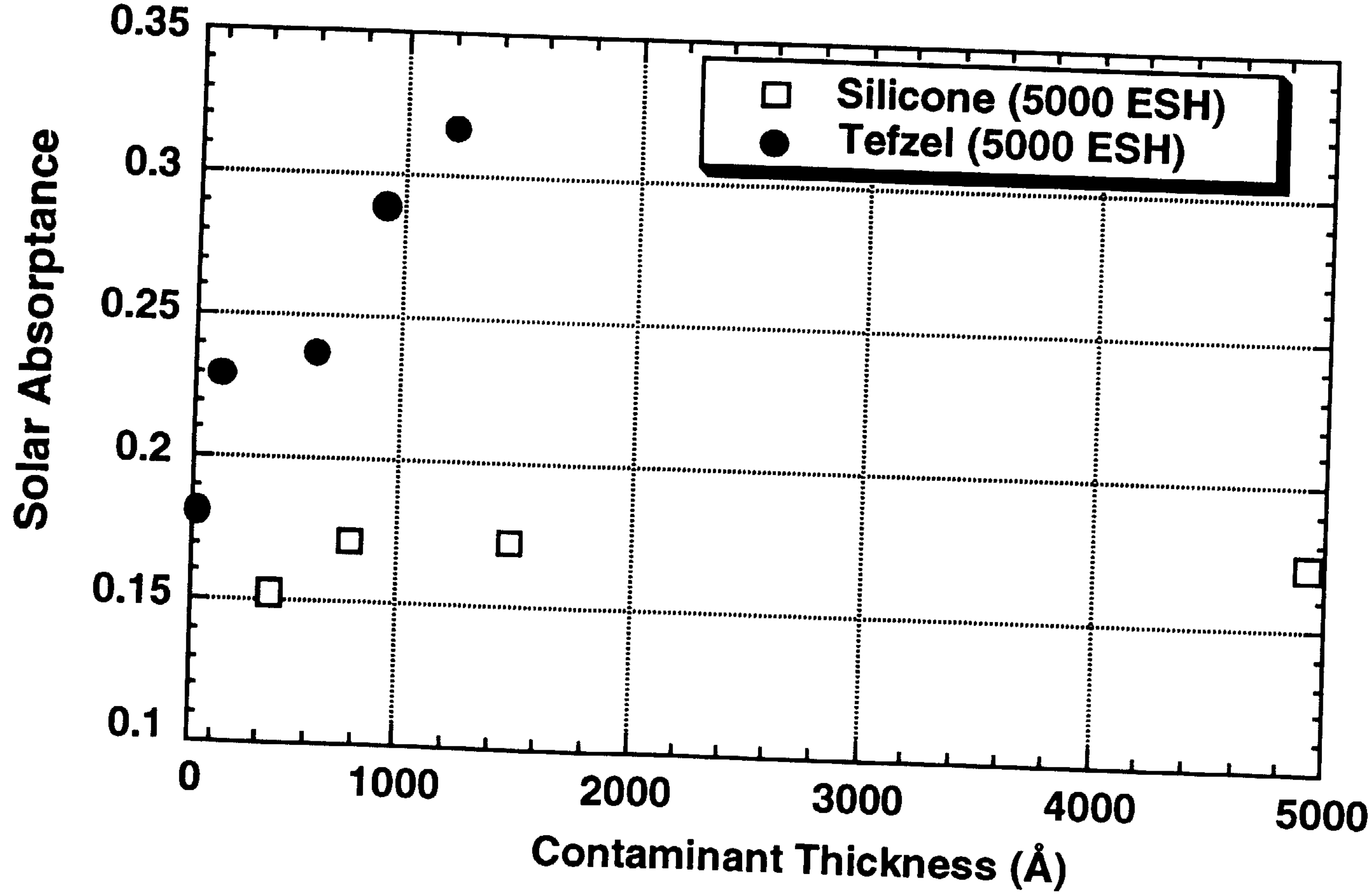
- Coated Z-93P with fluorocarbon coating for cleanliness protection
  - Commercialized by AZ Technology

- Controlled silver and cadmium plated fasteners

END-OF-LIFE PREDICTIONS

- NASA measured outgassing rate of potential contaminating material with usages > 10 lb. per ASTM 1559 as a function of source and receiver temperature
  - A variety of silicones and Tefzel contaminants were characterized
- Used MOLFLUX and NASAN (uses NASTRAN) to predict deposition rates and added refinements to analysis when worst case analysis resulted in exceeding requirements
  - Accounted for temperature of source and receiver
    - Accounted for temperature at different beta angles but not for diurnal variations
- Evaluated change in absorptance of coatings bare and with silicone and fluorocarbon contaminants using approximately 100x solar VUV exposures and independent AO exposure tests
- Predicted EOL depends on total UV and AO exposure and contaminant deposition

COMPARISON OF SILICONE AND TEFLON CONTAMINATION DEGRADATION RATES



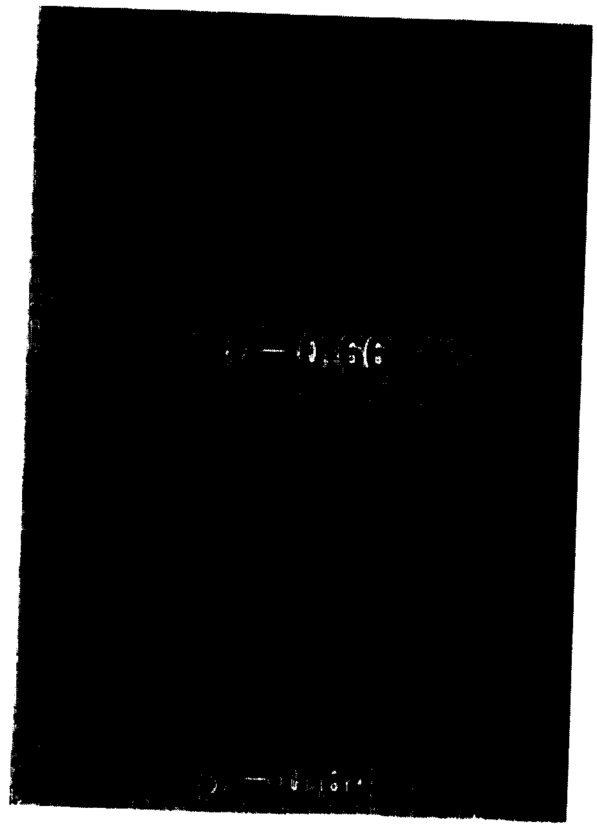
OPTICAL PROPERTIES OF VARIOUS FLUOROPOLYMER COATINGS ON Z-93

Fluoropolymer Overcoat (Plasma Sprayed)	Appearance	Absorptance (α)	Emittance (ε)
Z-93 Control (no coating)	White	0.15	0.92
FEP - Fluorinated Ethylene Propylene	Smooth, white, clean	0.15	0.91
PFA - Tetrafluoroethylene with a perfluoroalkoxy side chain	Smooth, white	0.16	0.90
PVDF - Polyvinylidene fluoride (Kynar™)	Smooth, brown	0.37	0.90
UHMWPE - Ultrahigh Molecular Weight Polyethylene	Smooth, brown	0.39	0.90

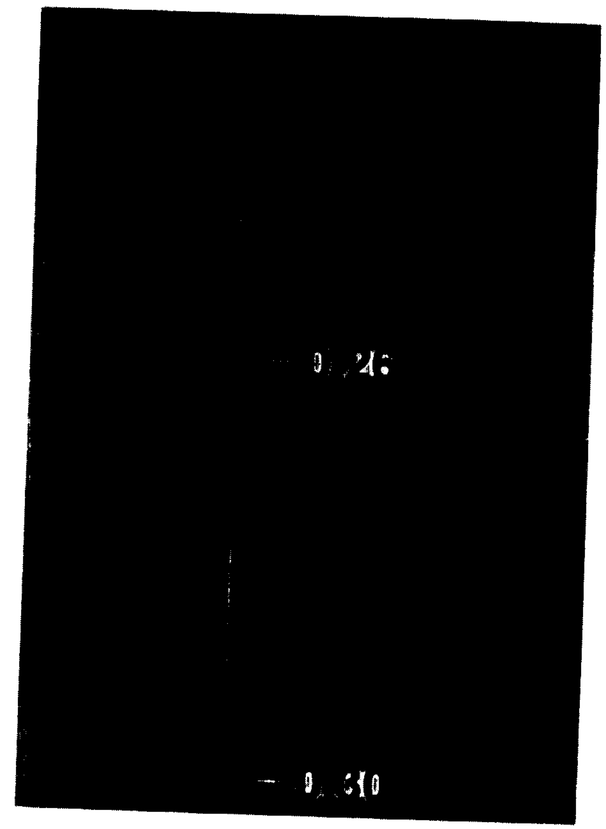
CONTAMINATION RESISTANCE OF Z-93 WITHOUT A TOP COATING

Dirt/Dust

Dirt/Dust with Oil



Contaminated

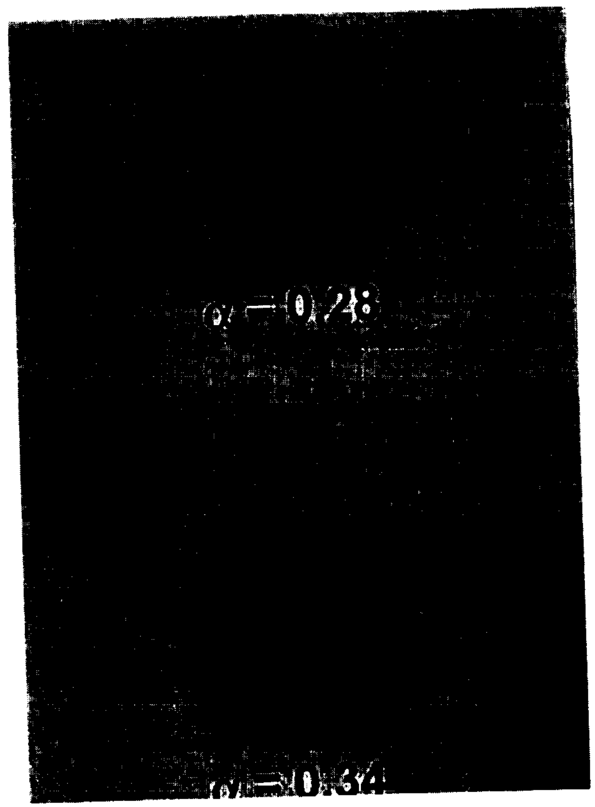


After Cleaning with Alconox

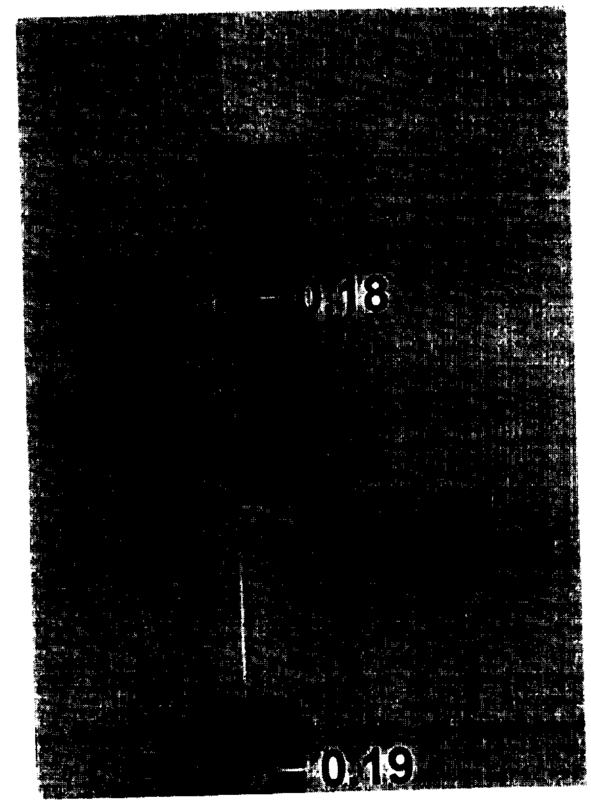
CONTAMINATION RESISTANCE OF Z-93 WITH FEP TOP COATING

Dirt/Dust

Dirt/Dust with Oil



Contaminated



After Cleaning with Alconox

INTERNATIONAL SPACE STATION

SSE Contamination Working Group H.W. Babel — 9-10 July '97

McDonnell Douglas Aerospace

Astro • Honeywell • Lockheed Martin

8

SILVER AND CADMIUM PLATED FASTENERS

- Silver plated nuts, coated on all surfaces
  - AO was known to oxidize silver, producing a loose, flaky oxide; not known to the fastener specialists working ISS
  - About 25,000 silver plated fasteners baselined
  - AO does not penetrate into a threaded joint
  - Solutions - silicone encapsulate and strip silver except on threads, replace with MoS_2 lubricated part, or use capped nuts

- Cadmium - Preload Indicating (PLI) washers and HI-LOK™ fasteners
  - Limited AO exposure oxidizes Cd producing toxic CdO
    - Oxide adhered to the substrate for the limited duration tests
    - Chromate conversion coating not continuous
  - Cadmium sublimates in vacuum - rate uncertain
  - Solutions - switched to stainless PLI washer, schedule permitting

DISCUSSION TOPICS

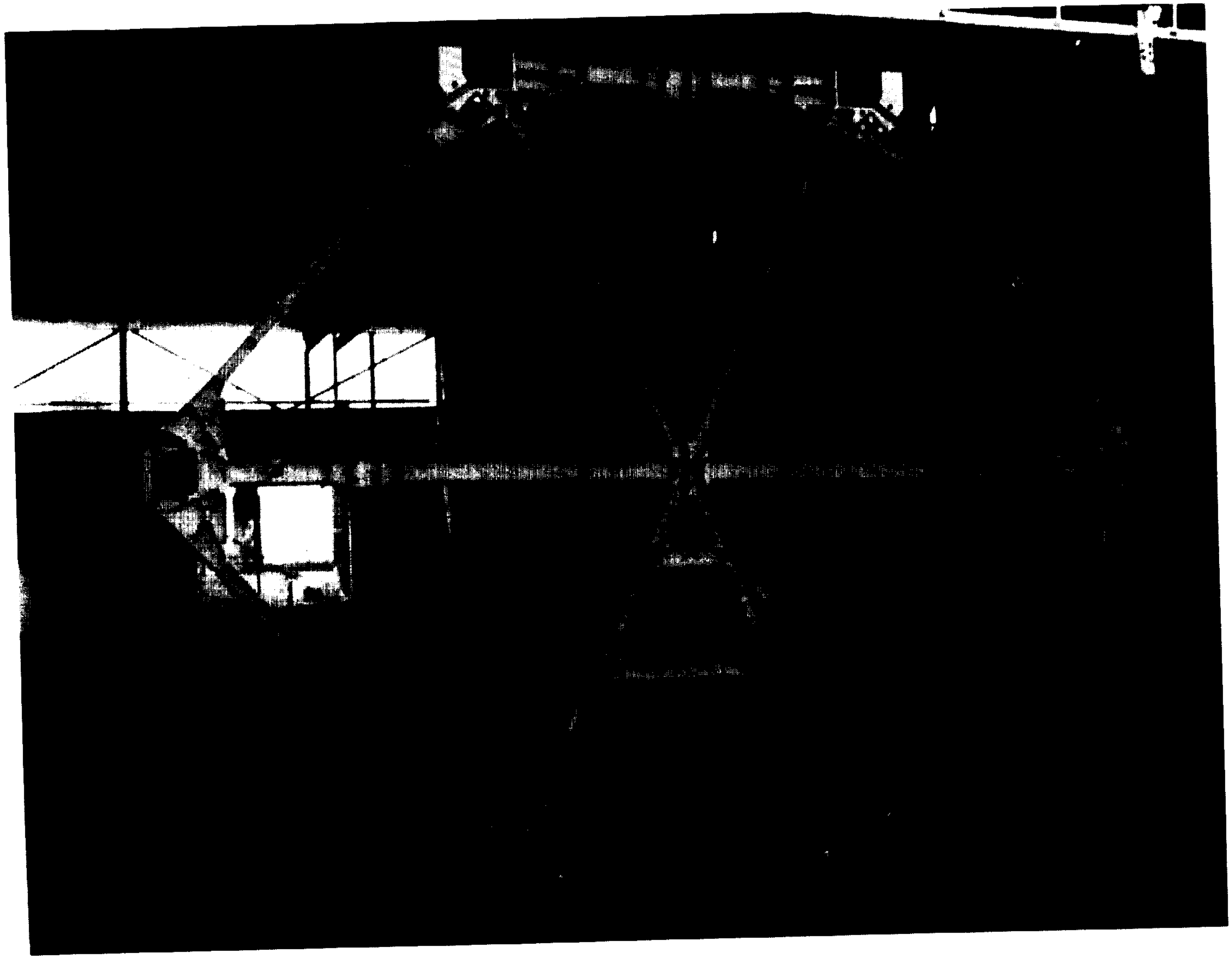
- ☐ MDA ISS contamination activities
- ☒ <u>MDA Thermal control activities</u>

MDA THERMAL CONTROL ACTIVITIES FOR THE INTERNATIONAL SPACE STATION

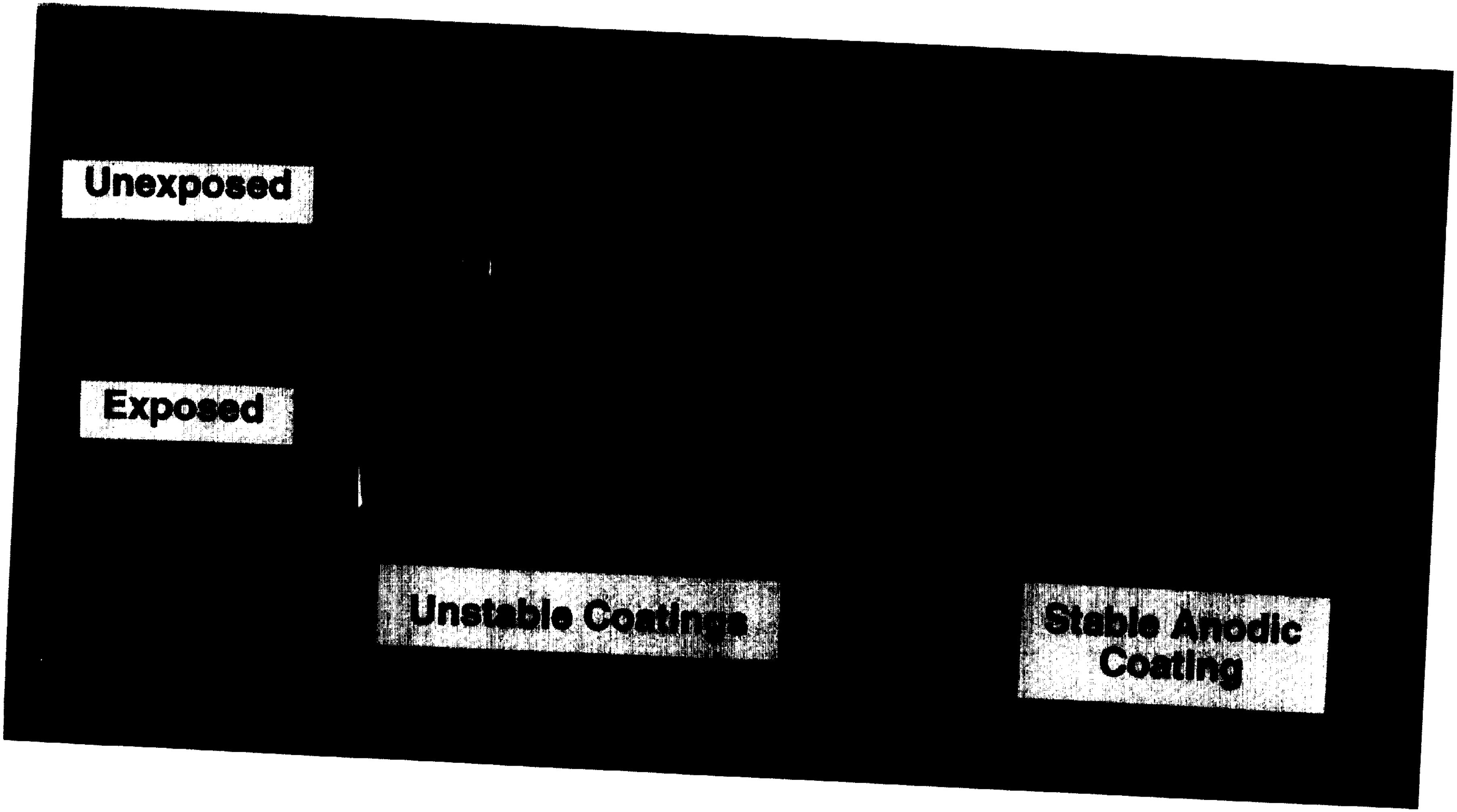
Development	On ISS
Sulfuric acid anodizing to provide controlled optical properties	Yes
Sulfuric acid anodizing to provide stable reds, blues, yellows	Yes
Stable (black) coatings where $\alpha/\varepsilon \cong$ constant with contamination	Yes
Z-93 applied to anodized aluminum	Yes
Tailored optical properties of inorganic paints	No
Characterized low emittance conversion coatings	Yes
Thermal control coating working standards established Measured optical properties from 250 nm to 28,000 nm Design properties for BOL, EOL with tolerances for contaminated thermal control coatings used on ISS	Yes
Instrument developed to measure absorptance on the vertical leg of an I-beam	Used
Instrument developed to measure emittance of small tubes	No

INTERNATIONAL SPACE STATION

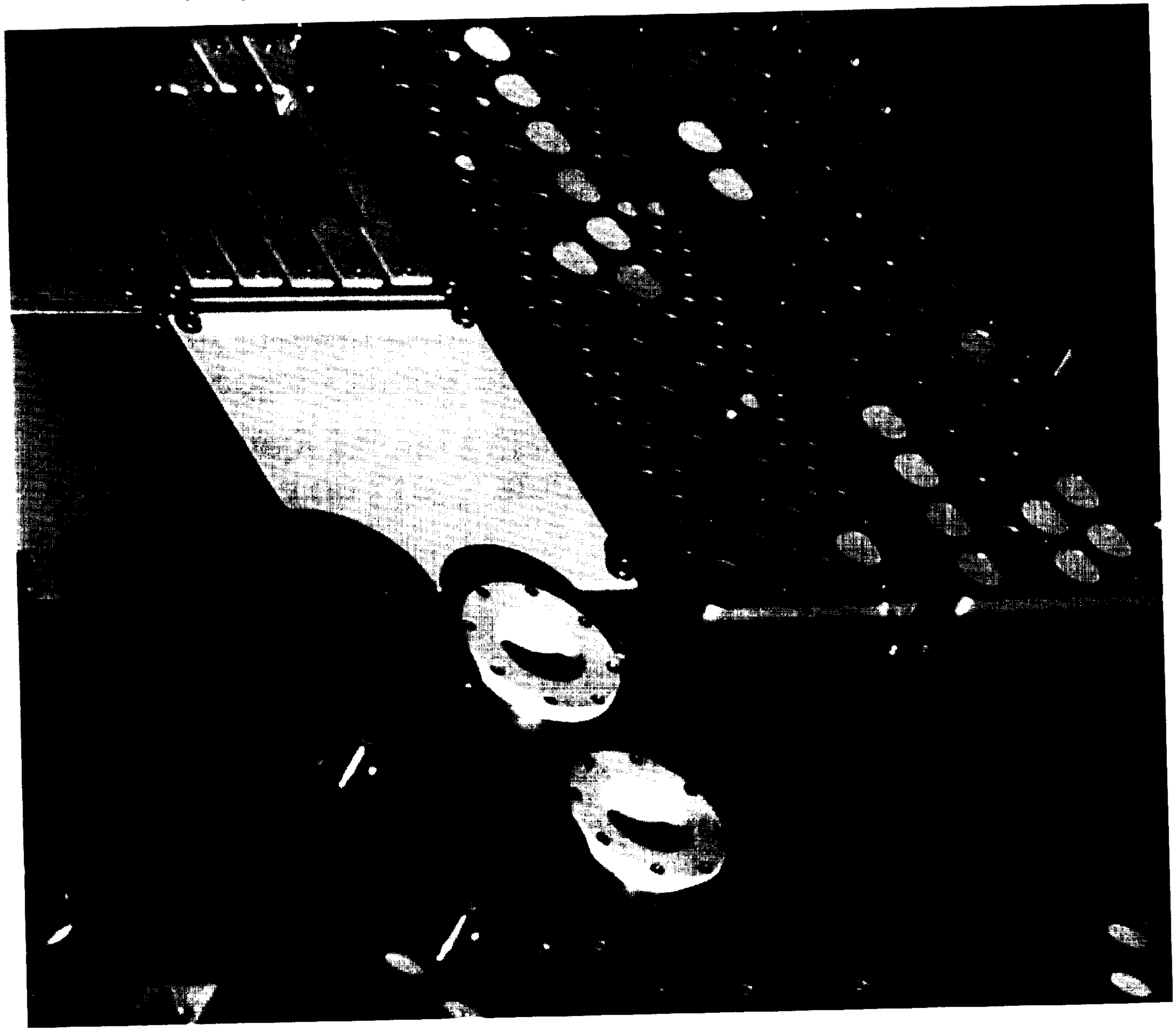
SAA PRODUCTION TRUSS BULKHEAD



COLOR FADING IN SPACE



AO AND UV STABLE COLORS



STABLE ABSORPTANCE/EMITTANCE RATIO NEAR ONE WITH CONTAMINATION

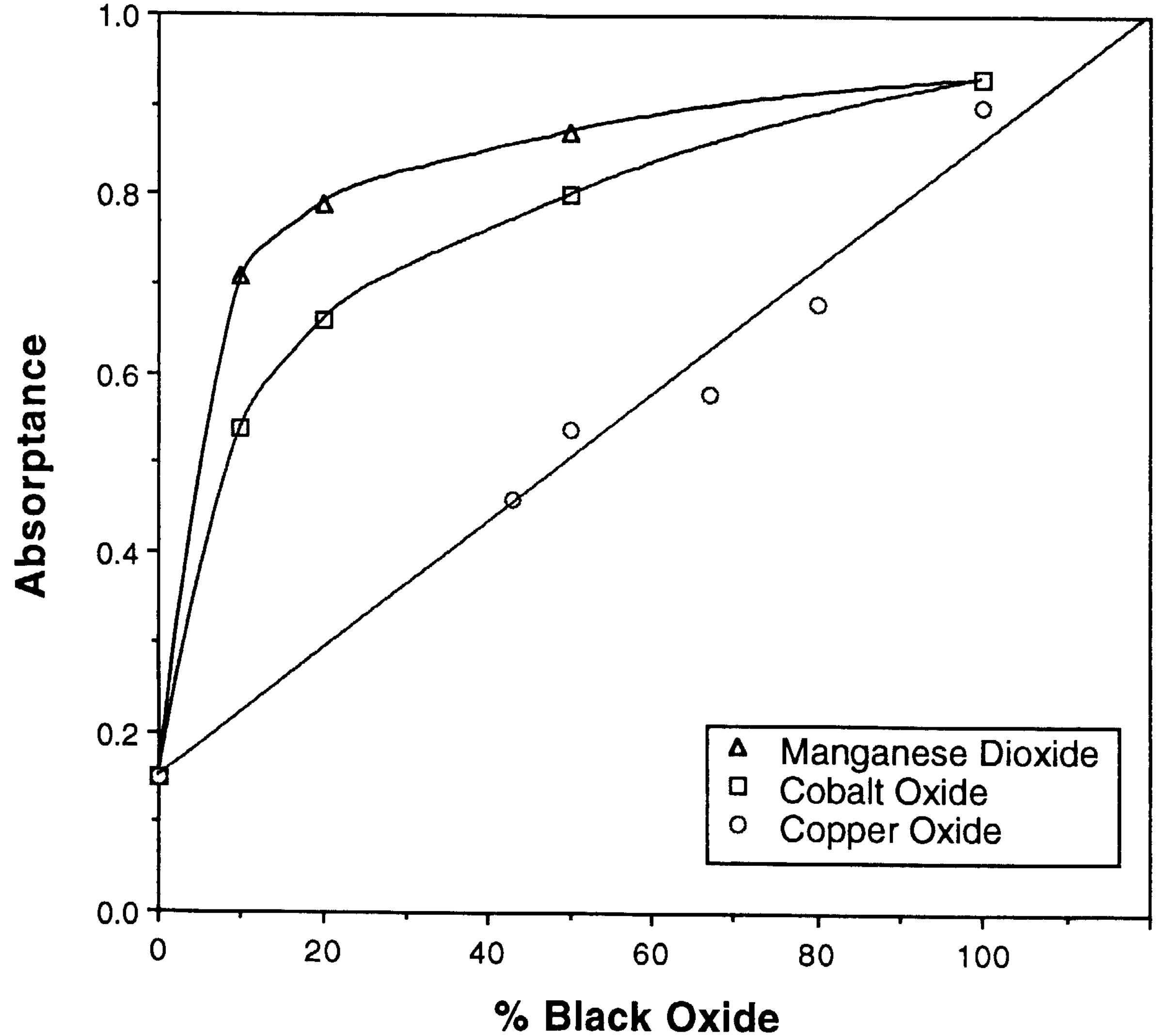
- Uncontaminated
  - Chromic acid anodize: approximately 0.30/0.30 = 1
  - Black anodize: approximately 0.85 to 0.95/0.85 = 1
    - Not all black anodize processes result in LEO stable coatings
- Contaminated
  - Chromic acid on LDEF, amount unknown. $\Delta\alpha = 0.07$ max. after approximately 11,000 ESH after measurement in air
  - Black anodize - 2800Å of silicone. $\Delta\alpha = 0.01$ max. after 1,000 ESH after measurement in air

In-situ measurement required for confirmation

IITRI TORSION TEST RESULTS ON SPECIMENS PREPARED BY LVS, MDA & IITRI

Binder	Substrate	Surface Prep	Average Angle at Failure			
			LVS	MDA	IITRI	ITTRI (H_2O)
PS-7 (Z-93)	6061-T6	Bare	82	68	60	--
	2219-T851	Bare	123	62	53	--
	2219-T851	SAA	67	78	70	--
Kasil 2130 (Z-93P)	6061-T6	Bare	87	36	43	72
	2219-T851	Bare	94	36	36	77
	2219-T851	SAA	62	54	49	90

TAILORED OPTICAL PROPERTIES

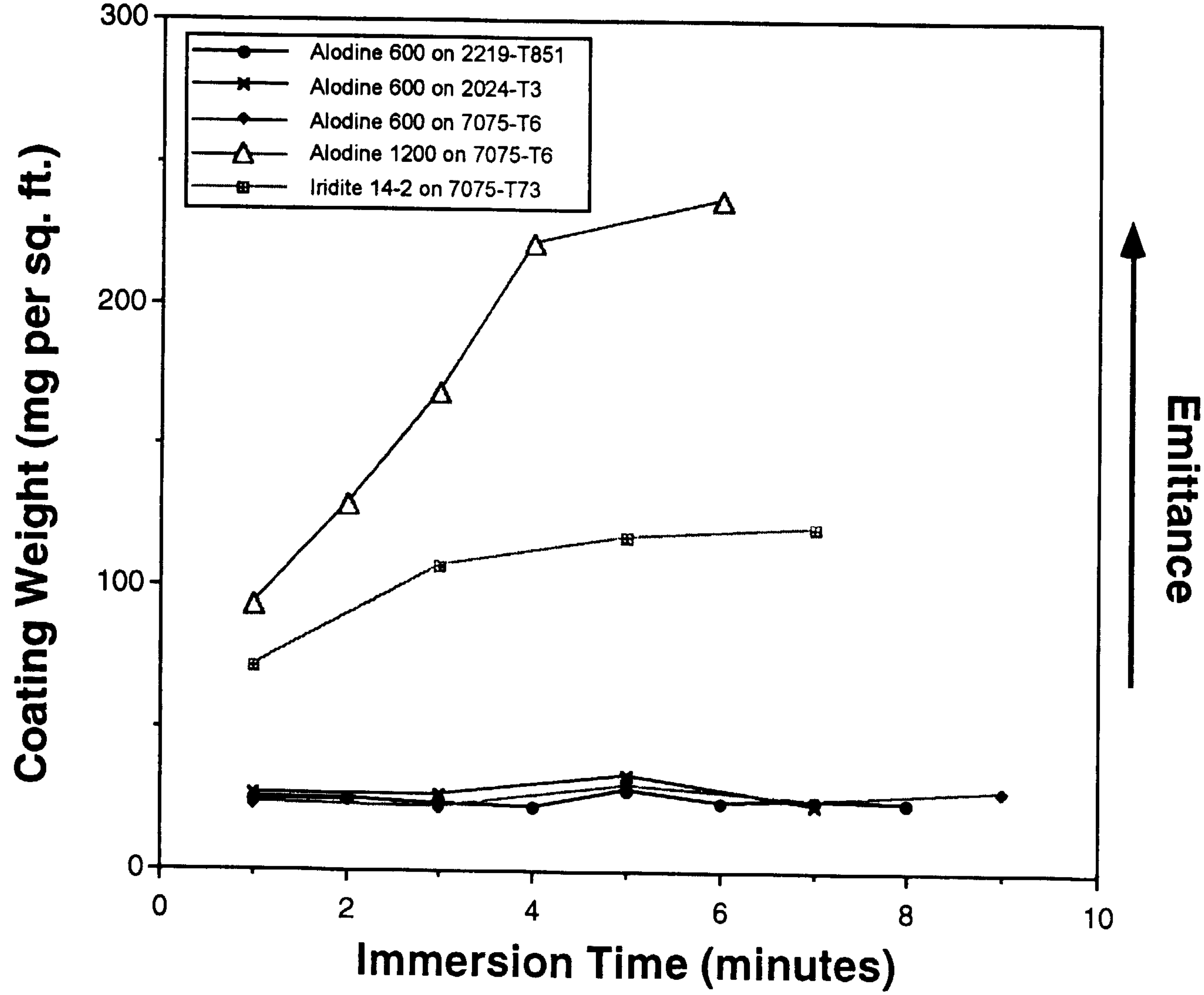


CONTROLLED LOW EMITTANCES

	Solar Absorptance			IR Emittance		
Sample (Alloy, Alodine 600 or 1200, Exposure time)	Initial	After Vacuum Baking	After AO	Initial	After Vacuum Baking	After AO
7075-T6 Clad, 600, 3 min.	0.50	0.56	0.54	0.03	0.03	0.02
7075-T6 Clad, 1200, 3 min.	0.45	0.57	0.55	0.08	0.06	0.05
7075-T6 Clad, 14-2*, 3 min.	0.44	0.54	0.54	0.04	0.03	0.02
2219-T851, 1200, 3 min.	0.51	0.60	0.61	0.08	0.08	0.05

*Iridite

COATING WEIGHT OF CONVERSION COATINGS



INTERNATIONAL SPACE STATION

SSE Contamination Working Group H.W. Babel — 9-10 July '97

McDonnell Douglas Aerospace
Astro • Honeywell • Lockheed Martin

DESIGN PROPERTIES FOR BEGINNING-OF-LIFE AND END-OF-LIFE

- ❑ Thermal designs critical - therefore required accurate measurements of hemispherical emittance and absorptance
  - NIST no longer providing standards
  - Created working standards
  - Measured reflectances from 250 nm to 28,000 nm using Surface Optics
    - Z-93 has a significant change between 2,500 & 3,000 nm

- ❑ Requested AZ Technology to provide an instrument which measures absorptance beyond 2,500 nm. Instrument provided measure to 2,800 nm

- ❑ Established nominal design properties and typical manufacturing variations of optical properties of contaminated samples using Surface Optics measurements as a comparison standard

TOPICS THAT WARRANT FURTHER INVESTIGATION

- ❑ Characterize contamination deposition rates of materials
  - Measure source and receiver temperature dependent material deposition outgassing rates
  - Determine UV-enhanced deposition and diurnal temperature effects

- ❑ Correlation between in-situ measurements in space with the results of ground simulation tests
  - Understanding degradation from near and far UV wavelengths

- ❑ Measure contamination deposition rates in space and correlate with contamination prediction models

- ❑ Develop ways to restore optical properties in space without having to replace the hardware

Summary of MDA Supporting Documentation for the Topics Discussed

Outgassing Rate Data

1. Fussell, J. V and Warnes, N., Contamination Deposited on PG-1 Critical Surfaces from Node-1 Sources, MDC Report 97H0520, April 1997 (Available from Boeing at Houston)

2. Hasegawa, M. M., Fussell, J. V. and Babel, H. W., Contamination Deposited on PG-1 Critical Surfaces from PMA-1 Sources, MDC Report 97H0340, March 1997 (Available from Boeing at Houston)

3. Fussell, J. V., Hasegawa, M. M., and Babel, H. W., Contamination Analysis of the Vacuum Baked Ku-Band Antenna Group, MDC Report 96H0424, June 1996 (Available from Boeing at Houston)

4. Fussell, J. V. and Babel, H. W., Contamination analysis of the Silicone Cable Pigtails, MDC Report 95H0469, April 1996 (Available from Boeing at Houston)

5. Hakes, C., Garrett, J., Ehlers, H. and Albyn, K., Measurements of Condensable Outgassing Rates of External Materials on the International Space Station, AIAA Paper AIAA-96-0628, 34th Aerospace Sciences Meeting, Reno, NV, Jan 15-18, 1996

OPM

6. Hasegawa, M. M., MDA Memorandum describing sample preparation

7. Edwards, D. L., MDA/OPM Pre-Contaminated Z-93P Contamination Migration Investigation, NASA MSFC Report, 26 August 1996

8. Edwards, D. L., Long Term Ultraviolet and Vacuum Ultraviolet Exposure of McDonnell Douglas Aerospace Pre-Contaminated Z-93P, 19 February 1997

Fluorocarbon Coating of Z-93

9. Daneman, S.A., and Babel, H.W. "Advanced (Improved) Thermal Control Coatings for Use in low Earth Orbit Applications," presented at the 24th International Conference on Environmental Systems & 5th European Symposium on Space and Environmental Control Systems, Friedrichshafen, Germany, 20-23 June 1994.

Controlled Silver and Cadmium Plated Fasteners

No published documentation

Sulfuric Acid Anodizing to Provide Controlled Optical Properties

10. Jones, C.A., David, K.E., LeVesque, II R.J., and Babel, H.W., "Modification of Commercial Sulfuric Acid Anodize Process for Control of Thermal Properties," presented at the 45th International Astronautical Congress of the IAF, Jerusalem, Israel, 9-14 October 1994

11. David, K.E. and Babel, H.W., "Optical Property Degradation of Anodic Coatings in the Space Station Low Earth Orbit," presented at the AIAA Materials Specialist Conference, Dallas, Texas, 16-17 April 1992.

12. Le, H.G., Simpson, K.E., Smith, C.A. and O'Brien, D.L., "Modified Sulfuric Acid Anodic Coatings for Spacecraft Thermal Control," presented at the 5th International Conference on

Surface Modification Technologies, University of Birmingham, United Kingdom, 2-4 September 1991

Stable Reds, Blues and Yellows in Space

13. LeVesque, R. J. II, Jones, C. A., and Babel, H. W., Clear, Colored and Black Anodic Coatings for Passive Thermal Control of the International Space Station, SAE Technical Paper 951653, 25th International Conference on Environmental Systems, Sand Diego, 10-13 July 1995

Stable Black Coatings in Space

14. LeVesque, R.J., Ho, M.M., Vickers, B.D., Babel, H.W. and Pard, A.(1), "Black Anodize as a Thermal Control Coating for Space Station Freedom," presented at the AIAA Materials Specialist Conference, Dallas, Texas, 16-17 April 1992

Z-93 Applied to Anodized aluminum

15. Daneman, S.A., Babel, H.W., and Thomlinson, M.M. "Advancements in Long-Life Thermal Control Coatings for Low Earth Orbit Applications," presented to 23rd Conference on Environmental Systems, Colorado Springs, Colorado, 12-15 July 1993.

16. Babel, H. W. and Le, G. H., High Emittance Low Absorptance Coatings, U. S. Patent Number 5,296,285, May 26, 1992

Tailored Optical Properties

See reference 15

Characterized Low Emittance Conversion Coatings

17. LeVesque, R. J., DeJesus, R. R., Jones, C. A., and Babel, H. W., Low Emittance Chromated Chemical Conversion Coatings for Spacecraft Thermal Control in Low Earth Orbit, presented at the Space Technology & Application International Forum for The Institute for Space and Nuclear Power Studies, 7-11 Jan 1996, Albuquerque, NM

Thermal Control Working Standards and Design Properties for BOL and EOL with Contamination

18. Smith, C. A., Dever, J. A., and Jaworske, D. A., Measurement of Solar Absorptance and Infrard Emittance of Spacecraft Materials, Proceedings of the 7th International Symposium on Materials in a Space Environment, 16-20 June 1997, Toulouse, France.

19. Smith, C.A., Jones, C.A. and Babel, H. W. Measurement Effects on Optical Property Design Values, Report MDC 92H0783A, February 1993

20. David, K., Normal and Hemispherical Emittance Measurements Made at Surface Optics Corporation, Report MDC 95H0397, August 1995

21. Babel, H. W., Jones, C. and David, K., Design Properties for State-of-the-Art Thermal Control Materials for Manned Space Vehicles in LEO, Acta Astronautica, Vol. 39, No. 5, pp 396-379, 1996

Instrumentation

22. Unpublished information from AZ-Technology on their instrument TEMP2000 for emittance measurements on round-tube, 8-16-94.

Additional MDA Publications and Work Related to Thermal Control Coatings

23. Le, H. G. and O'Brien, D. L., Process for Producing a High Emittance Coating and Resulting Article, U.S. Patent No. 5, 217,600, May 1, 1992

24. David, K. E., Jones, C. A., and Babel, H. W., "Update on the Degrading Effects of Silicone on Exposed Spacecraft Surfaces," presented at the 1995 International ASME/JSME/JSES Solar Energy Conference, Kaanapali, Maui, Hawaii, 19-24 March 1995.

25. Smith, C. A., Jones, C. A., and Babel, H. W., "Development of a Facility and Testing Procedures for Vacuum Ultraviolet Exposure of Spacecraft Materials," October 1994

26. Babel, H. W., Hasegawa, M, Jones, C. and Fussell, MDA, The Effects of Contamination from Silicones and a Modified-Tefzel™ Insulation on Critical Surfaces of the International Space Station, 47th IAF Conference, Beijing, China, 7-11 October 1996

27. Jones, C.A., David, K.E., LeVesque II, R.J., Babel, H.W., "Environmental Effects on Passive Thermal Control Materials of the Space Station Freedom," presented at the 44th Congress of the International Astronautical Federation, Graz, Austria, 16-22 October 1993.

28. Babel, H. W., Jones, C. A., Daneman, S. A., David, K. E., Smith, C. A., "Understanding and Controlling the Degrading Effects of Silicone on Exposed Spacecraft Surfaces," presented at the 6th International Symposium on Materials in a Space Environment, Noordwijk, The Netherlands, 19-23 September 1994.

29. Dever, J. A. unpublished data VUV Exposure of Tefzel-Contaminated Z-93-P, NASA LERC test Results on tests conducted between 10/29/96 and 11/20/96

30. Babel, H. , Hasegawa, M., Jones, C., and Fussell, J., The Effects of Contamination from Silicones and a Modified-Tefzel™ Insulation on Critical Surfaces of the International Space Station, 47th IAF Congress, Beijing, China, October 7-11, l996 Paper IAF 96-1.5.08

31. Smith, C.A., Lan, E.H., Cross, J.B.(3), "A Technique to Evaluate Coatings for Atomic Oxygen Resistance," presented at the 33rd SAMPE International Symposium, Anaheim, California, March 1988.

32. Cross, J.B.(3), Lan, E.H., Smith, C.A. and Arrowood, R.M.(5), "Evaluation of Atomic Oxygen Interaction with Thin Film Aluminum Oxide," presented at the 3rd International Conference on Surface Modification Technologies, Neuchatel, Switzerland, August 1989.

33. Babel, H. W., "LDEF's Contribution to the Selection of Thermal Control Coatings for the Space Station," presented at the Third LDEF Post-Retrieval Symposium, Williamsburg, Virginia, 8-12 November 1993.

Current Modeling Tools and Applications

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Contamination Engineering, Code 724.4
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1997 Spacecraft Contamination and Coatings Workshop, Annapolis MD, 9 July 1997

Overview

- What is Contamination Modeling?
- Contamination Modeling Areas
- Analytical Tools:
  - Available
  - Description
    - Function
    - Employment
    - Pro/Cons
    - Acquisition
- Applications
- The Future
  - Where are we going?
  - Areas of Improvement

"What is Contamination Modeling?"

- Definitions:
  - *Model:* Any mathematical construct that can be used to describe, and suitably forecast, a particular system's behavior.
  - *Contamination Model:* Any mathematical tool that quantitatively describes and adequately forecasts the transfer and behavior of contaminants in a vacuum environment.
  - *Contaminant:* Any foreign material that causes a degradation in a system intolerant of its presence.
    - Molecular
    - Particulate
- Why do it?
  - It is essential to understand the contaminant environment, as well as be able to forecast its impact, if adequate (and reasonable) contamination control is to be realized.
    - This information provides the basis for many Contamination Engineering decisions (e.g. OGR, material selections, etc..)

Shaun R. Thomson
GSFC/NASA

Contamination Modeling Goals & Areas

- What is the overall Goal of Contamination Analysis?
  - Verify adherence to mission design specifications and requirements.
  - If current configurations fail to adhere to requirements:
    - Identify the potential problem area(s)
    - Propose specific design changes to achieve requirements
    - Recommend operational changes to reach requirements.

- Typical Contamination Modeling Areas*:
  - Molecular Transport Modeling
  - Particle Transport Modeling
  - Atomic Oxygen Erosion
  - Rarefied Pressure Analyses (local pressure)

* Typical to GSFC

Molecular Transport - Explanation

- **Molecular Transport**
- Particle Transport
- Atomic Oxygen
- Pressure Analyses

- Most common analyses area.
- Tracking the transport of molecular contamination.
- Molecular Contamination:
  - Volatile organics within the bulk of polymer materials of construction can diffuse out under vacuum conditions.
    - Curing agents & Unreacted components, Processing materials, Handling agents.
  - Surface contaminants deposited during Integration.
- Role of molecular contamination:
  - Loss of Reflectivity
  - Increase in Absorptivity
  - Transmission loss
- Two Transport Mechanisms:
  - Direct Flux (LOS and Reflection)
  - Return Flux (Atmospheric Collisions)
- Transport affected by
  - Temperature
  - Emission properties (materials and thruster/vents)
  - Geometry (and operational modes)
  - Local environment (e.g. Atmosphere, UV, etc.)

Molecular Transport - Modeling Tools

- **Molecular Transport**
- Particle Transport
- Atomic Oxygen
- Pressure Analyses

- Commonly used Transport packages:

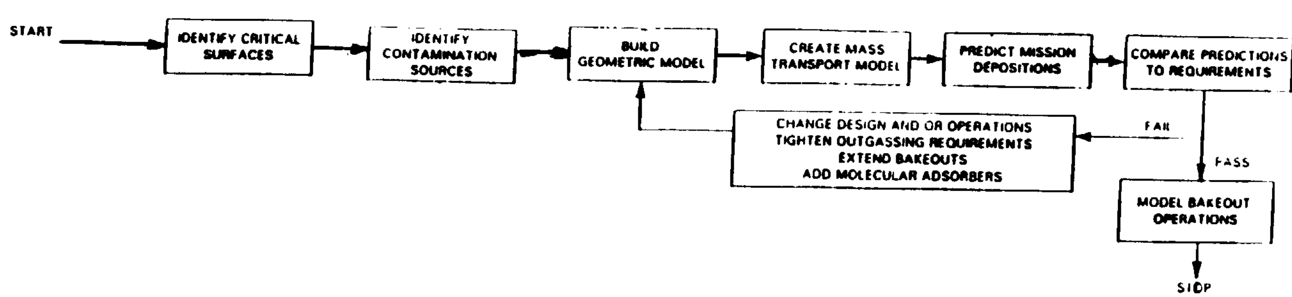
Package	Platform	Function	Pro/Con
SPACE II	FORTRAN	Direct/Return	*Pro: Fast, Friendly, Plumes, Reflections, database* *Con: 300 nodes, Steady-state only, no reemission*
Molflux	FORTRAN	Direct/Return	*Pro: Fast, Friendly, Plumes, Reflections, database* *Con: 300 nodes, Steady-state only, no reemission*
CAP	FORTRAN	Direct	*Pro: Transient, Reemission, Plumes, Assess. Code* *Con: Direct Flux only, Kinetic Constants, Long Runs*
ISEM	UNIX	Direct/Return	*Pro: Reemission, Multi Collisions, Shadowing, Multi Ambient, Plumes, No node limit (mem. governed)* *Con: Steady-state, Long Runs, Large memory req, no user interface (input subroutine)*
EWB	PC	Direct	*Pro: Very User friendly, database, plumes* *Con: Not completely verified*
DSMC	PC/UNIX	Direct/Return	*Pro: More accurate, transient, reemission* *Con: Very long runs, hardware req, Input data*

- Since most packages were commissioned under NASA contract they are available as public domain (e.g. COSMIC)
- Many Organizations have proprietary codes based, in part or at least in applied theory, on these packages.

Molecular Transport - General Procedure

- **Molecular Transport**
- Particle Transport
- Atomic Oxygen
- Pressure Analyses

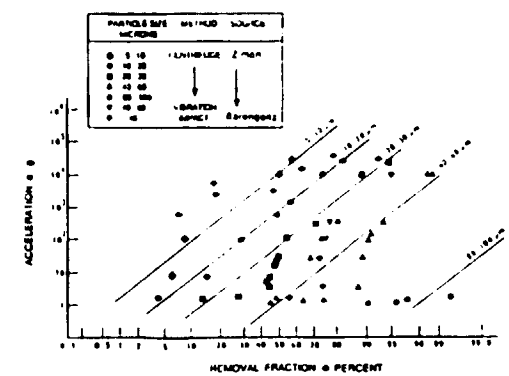
- Generate Geometry Model
  - 3-D representation of spacecraft/instrument.
    - Build, Borrow Thermal, or convert from CAD
    - Generate for each unique geometric condition.
  - Determine Transport Factors.
    - Diffuse viewfactors (identical to thermal viewfactors)
- Acquire Transport Model Input Data.
  - Surface Temperature Data.
  - Flight Parameters (e.g. Altitude, orbit, orientation).
  - Material Parameters (e.g. OGR, kinetic constants, etc.)
- Generate Cases for each unique condition.
- Run Cases through appropriate Modeling code.
- Compile and Analyze Results.



Particle Transport Modeling

- Molecular Transport
- **Particle Transport**
- Atomic Oxygen
- Pressure Analyses

- Tracking the transport of Particulate Contamination.
- Particulate Contamination:
  - Particles reside on hardware despite the best environments.
    - Cleanroom Air.
    - Personnel.
    - Operations.
  - Particles can redistribute following launch:
    - Launch and Ascent vibrations.
    - On-orbit operations.



- Role of Particulate Contamination:
  - Obscuration
  - Scattering
  - Obstruction
- Particle Transport Mechanism
  - Many technical papers have been written that study particle dislocation (particle size and load required to dislodge)
- Currently, Modeling consists of “hand” calculations, based:
  - Particle dislocation probability.
  - Worst case redistribution patterns.
  - No automated tool similar to Molecular Transport Modeling.

Atomic Oxygen Erosion

- Molecular Transport
- Particle Transport
- **Atomic Oxygen**
- Pressure Analyses

- Becoming a more and more requested Analysis
- Examining role of Atomic Oxygen on erosion of S/C materials.
- Atomic Oxygen:
  - Major component of the Earth's residual Atmosphere.
  - Highly reactive.
- Role of AO:
  - High velocity (energy) AO can strip (erode) exposed material.
    - Remove coatings, tapes, films.
  - LDEF demonstrated the phenomenon.
- Current Calculational Procedure:
  - Calculate AO density at numerous orbital and temporal points.
    - MSIS-86 (Atmospheric Model)
  - Integrate AO density over expected orbit. Fluence = atoms/area
  - Correct for angle of surfaces to velocity vector and Shadowing.
- No Ideal Automated tool exists to perform AO calculations.
  - Completely self-contained.
  - Self-adjusting for orbit/seasonal/orbital variations.
  - Spacecraft orientation, geometry, and shadowing.
  - Determine erosion amount from internal tables of reactivity.
  - **EWB is very Close!** (User Input & Shadowing still)

Rarefied Pressure Analyses

- Molecular Transport
- Particle Transport
- Atomic Oxygen
- **Pressure Analyses**

- Responsibility for these analyses have recently fallen on GSFC Contamination Engineers.
- Determining the local pressure on pressure-sensitive detectors.
- Local Pressure:
  - Emission of products from materials of construction can produce a local pressure that is higher than that of the ambient.
  - Many detectors are extremely intolerant of pressure.
  - Since emission of mass decreases with time, Models are sometimes required to determine when pressure is within tolerable range.
- No dedicated tool exists to model this environment.
- Natural extension of the Molecular Transport mechanism.
  - Make use of existing Molecular Transport modeling tools.
    - Consider all released species as "contaminants"
    - Determine impingement flux
    - Use derivation of molecular kinetics equations to determine forces (pressure) on critical surfaces.

Applications

- Evolution of Modeling Activities at GSFC:
  - GSFC Begins Developing Modeling Capability (1987)
  - Basic Model Verification/Experimentation
    - Theoretical Rarefied Gas Models
    - Laboratory-based facilities/experiments (e.g. LAVA, TV/TB)
    - Previous Flight Experiments (SCATHA, NOAA-7, OGO-6)
  - Upgrade/Improve Software to reflect Verification/Experimentation
  - Develop techniques to integrate with existing projects
    - Verification of existing (non-model generated) Outgassing requirements
    - Limited to on-orbit phases.
  - Development of Contaminant Source Requirements
    - Applying models directly to determine requirements
  - Impact Design.
    - Functioning as a (pre) Phase-A subsystem.
    - Minimizing Contamination during design process.

Applications - Requirements Development

- **Req. Dev.**
- Design Impact

- Cleanliness requirements are necessary to ensure nominal operation of spacecraft systems over the mission lifetime.
  - Cleanliness requirements: Reflectance/transmission loses, absorptance change, erosion limits, etc.
- Use of on-orbit contamination models allows the "back calculation" of contamination <u>source</u> requirements.
  - Contaminant source requirements: Outgassing rate, AO fluence, particle level, etc.
- Results from on-orbit models then can be used as input to verify that contamination source requirements have been met.
  - Example: A model of thermal-bakeout operations can derive TQCM requirements necessary to verify a source outgassing rate.

Applications - Design Impact

- Req. Dev.
- **Design Impact**

- Modeling presents an opportunity to reduce contamination impact by design. *Prevention vs. Correction*
- Projects are allowing Contamination Engineers to become part of the design team at very early stages.
- Models can be created and exercised throughout the design process (as do thermal and structural subsystems)
  - Maintaining models of all evolving configurations.
  - Continually examining different avenues for contamination reduction.
- Contamination Engineering becomes integrated in final design.
  - Rather than locked into mitigative solutions during I&T.
- Economic & Schedule Benefits
  - Example: Can reduce bakeout requirements, which save time and money.

Applications - Design Impact (Examples)

- Req. Dev.
- **Design Impact**

- At GSFC, Contamination modeling tools commonly influence:
  - Spacecraft venting paths & locations
    - Main spacecraft
    - Electronics packages
  - Thruster placement
    - From a set of provided appropriate designs
  - Instrument and hardware placement
  - Operational modes
    - Stowage positions
    - Turn-on times
  - Material selection
    - AO resistance
    - Reduced OGRs)
  - New Hardware
    - Ascent vent design
    - Molecular adsorbers

The Future

- What's Ahead?
  - Faster Machines for processing
    - Enable greater resolution of geometry models.
    - Ability to track more material species.
    - Perform more complex transient studies.
    - DSMC (for contamination) moves from science to engineering tool.
  - Tools that greatly enhance the pre- and post- processing steps
    - More visually based geometry building.
    - Superior analysis of model results (also visual based)
- What do we still need to do?
  - More/Continued material measurements to compile large database of contaminant properties.
    - One of the most limiting factors in modeling at present.
  - More flight experiments for refinement of modeling theory.
    - For more investigation of phenomena mechanisms (AO, UV, et.)
    - Continued investigation/verification of transport mechanisms (RF)
  - Development of workhorse particle redistribution analysis tools.

Contamination Edition of the Environment Work Bench

Barbara Gardner
Gary Jongeward
Maxwell Technologies, Inc.
Federal Division
San Diego, CA

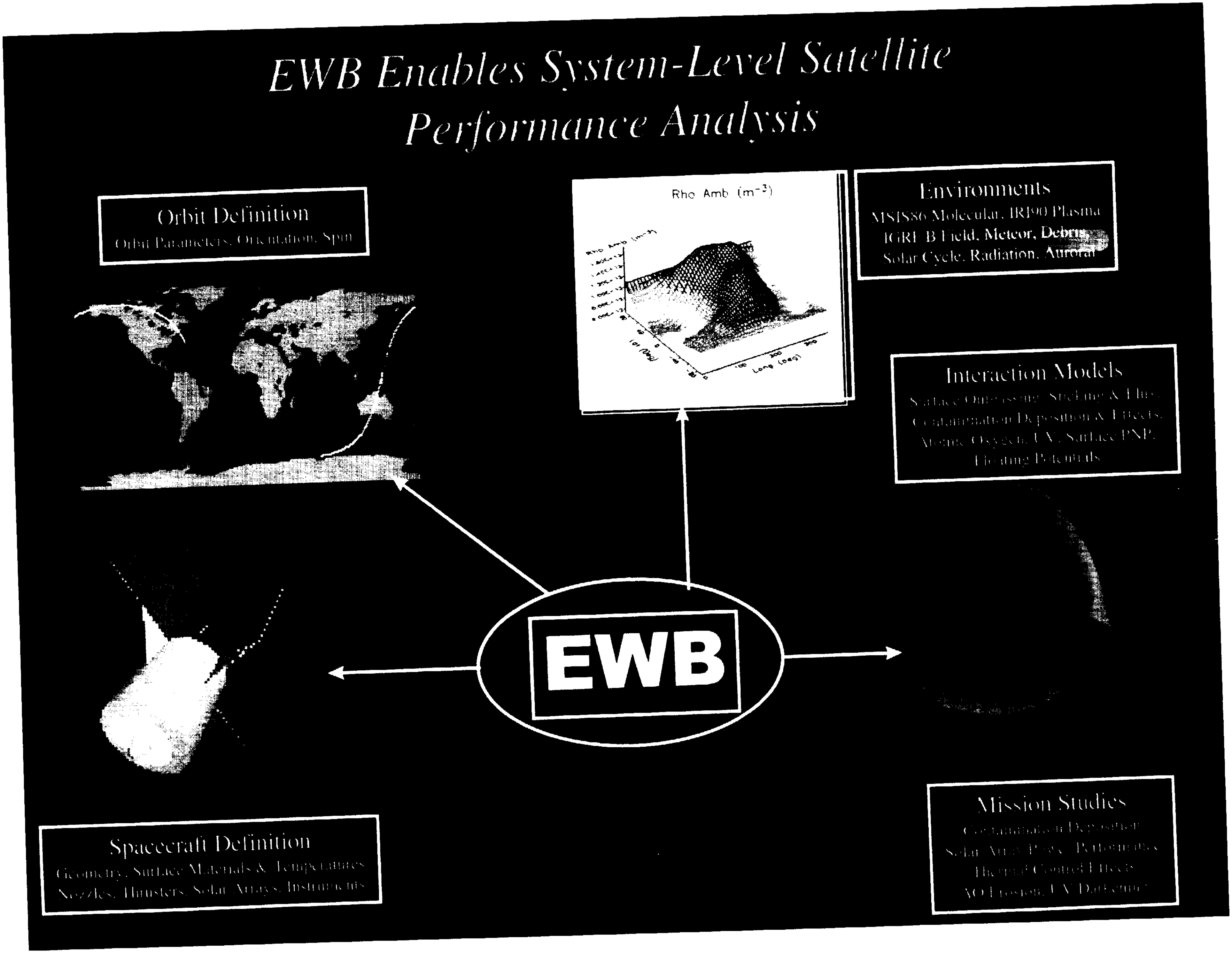
Presented at
1997 Spacecraft Contamination and Coatings Workshop
July 9-10
Annapolis, MD

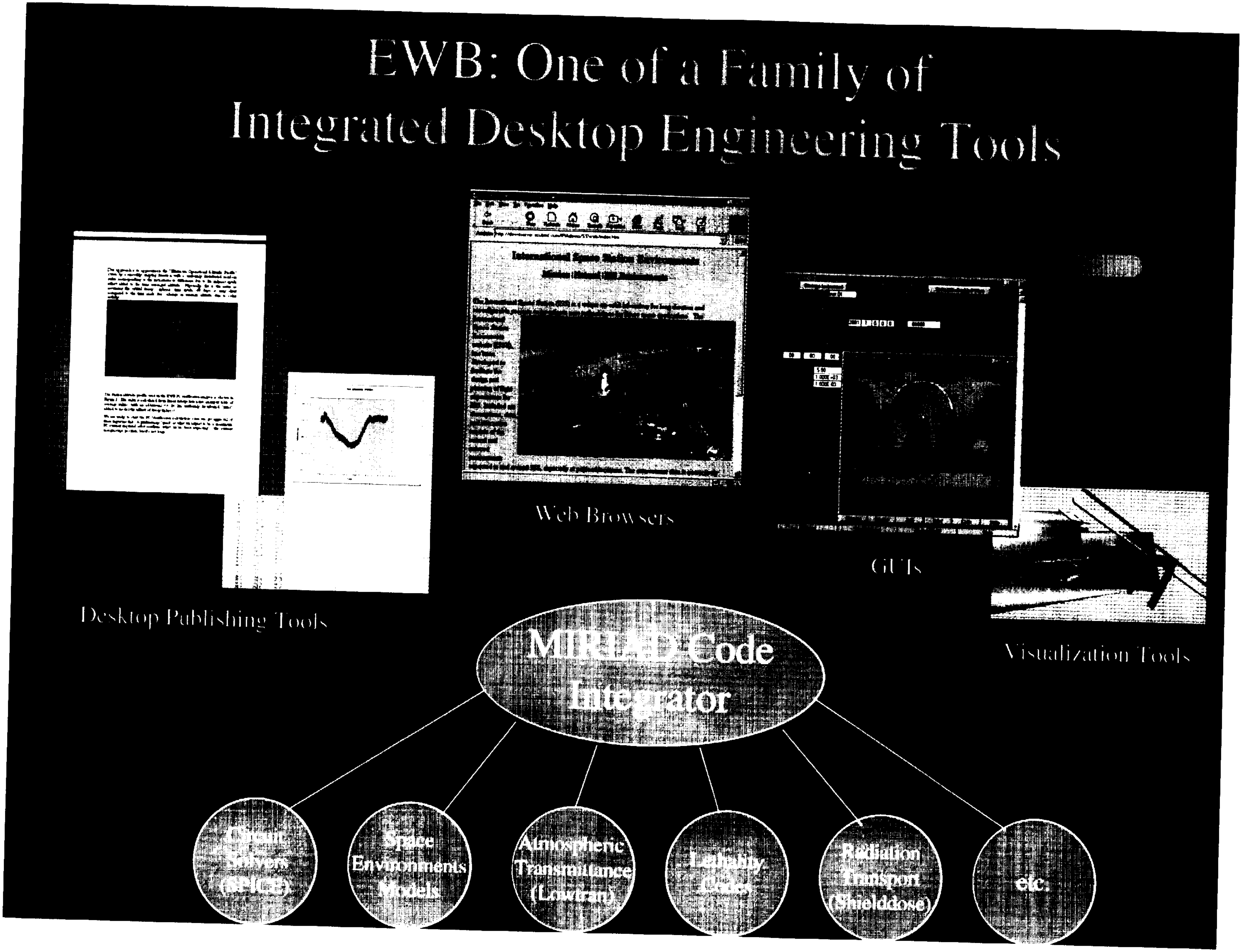
Introduction

- What is Environment Work Bench?
- Contamination Edition of EWB
- What you'll be seeing - an overview

What is EWB?

- Developed under contract to NASA/Lewis
- Desktop engineering tool
- Assessment of spacecraft/environments interactions effects
- Built using the MIRIAD (Module Integrator and Rule-based Intelligent Analytic Database) architecture
- Client-server Windows-based architecture (UNIX version also available


EWB Enables System-Level Satellite
Performance Analysis
Orbit Definition
Orbit Parameters, Orientation, Spin
Rho Amb (m⁻³)
Lat (deg)
Long (deg)
Environments
MSIS86 Molecular, IRI90 Plasma
IGRF B Field, Meteor, Debris
Solar Cycle, Radiation, Auroral
Interaction Models
Surface Outgassing, Sticking & Flux
Contamination Deposition & Effects,
Atomic Oxygen, UV, Surface PNP,
Floating Potentials
EWB
Spacecraft Definition
Geometry, Surface Materials & Temperatures
Nozzles, Thrusters, Solar Arrays, Instruments
Mission Studies
Contamination Deposition
Solar Array Power Performance
Thermal Control Effects
AO Erosion, UV Darkening


EWB: One of a Family of
Integrated Desktop Engineering Tools
Desktop Publishing Tools
Web Browsers
GUIs
Visualization Tools
MIRIAD Code Integrator
Circuit Solvers (SPICE)
Space Environments Models
Atmospheric Transmittance (Lowtran)
Lethality Codes
Radiation Transport (Shielddose)
etc.

Interfaces/Plotters

- First Impressions
- Olectra
- OpenGL
- Visual Basic 4 and 5
- C++
- Excel

Contamination Edition of EWB - CWB

- Produced under contract to TRW for the SEE program through NASA/Langley
- Use LDEF data
- Update models
- Integrate new models "Rules-of-thumb"
- Materials compliance matrix
- Calculation wizard

What we'll show you today

- New and enhanced models
- The CWB Wizard
- The EWB Interface
- Producing "Live" Documents
- What's in the future?

CWB - New and Enhanced Models

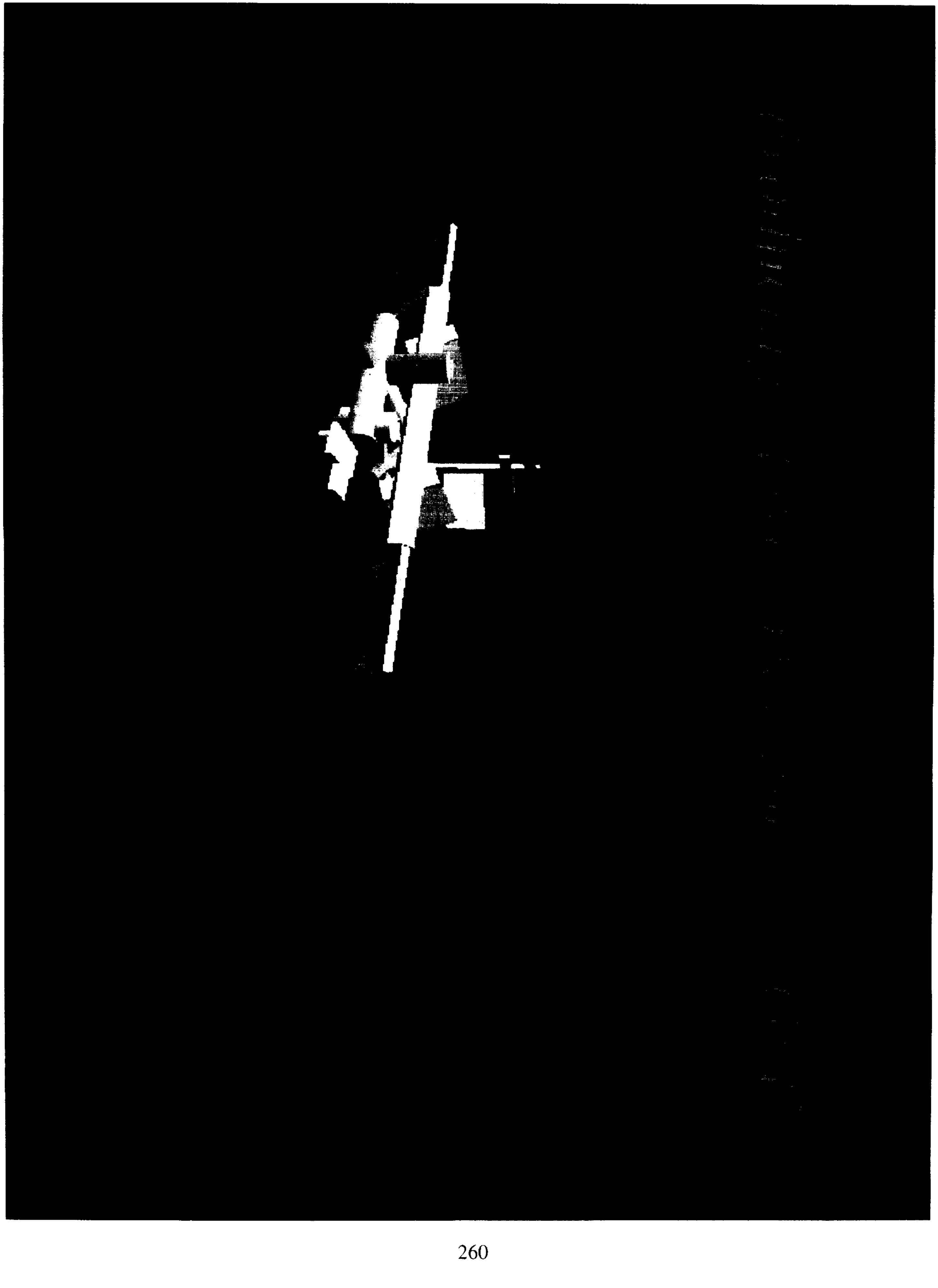
- Expanded materials database and properties
- UV radiation absorptivity effects
- Enhanced AO erosion effects
- Enhanced outgassing - time and temperature dependence
- Flux to surfaces - outgassing, thrusters, ram
- Enhanced surface sticking - temperature dependence
- Spacecraft surface contamination deposition
- Contamination effects on thermal control surfaces and solar array power performance
- Ram scattered flux into an instrument aperture
- Materials compliance matrix

Enhanced Outgassing - Time and Temperature Dependence

- Easy to use
- Takes user through steps of contamination calculation
- Focuses user from broad EWB capabilities to specifics

Standard EWB Interface

- Menu driven GUI
- >50 forms
- 100's of environments and effects models
- Custom plotting package (line and contour)
- Monte Carlo engine



The Future

- SEE program coordination
- Need to update & maintain environment & effects models
- Interplanetary & planetary environments & effects
- More wizards
- Use ODBC to access legacy databases
- Increase use of browser interface

MSFC CONTAMINATION CONTROL OVERVIEW

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINSTRATION
MATERIALS AND PROCESSES LABORATORY
ENGINEERING PHYSICS DIVISION
PHYSICAL SCIENCES BRANCH

DeWitt Burns

Physical Sciences and Environmental Effects Branch

- Ground based contamination control for manufacturing, assembly, test, transportation, and launch processing
  - RSRM, SRB, ET
  - HST, AXAF, SXI
- Material testing for flight environments exposure
  - Electron and proton radiation
  - Ultraviolet irradiation
  - Atomic oxygen exposure
  - Outgassing effects
  - Micrometeroid
- New technology for contamination monitoring and cleanliness verification

Contamination Control Responsibilities

- Contamination control requirements and plan definition
- Materials testing
  - ASTM E595 (standard outgassing test)
  - MSFC-SPEC-1443 (optical compatibility)
  - MSFC-SPEC-2223 (clean room compatibility)
- Hardware bakeout / certification - MSFC-SPEC-1238 (hardware thermal vacuum bakeout and cleanliness certification)
- Hardware / facility monitoring
- Surface Contamination Analysis Technology (SCAT) Team - instrumentation development

Surface Contamination Analysis Technology (SCAT) Team

- Surface Optics Corporation's SOC-400 portable FTIR
- University of Alabama Huntsville (UAH) development of fiber optic NIR with integrating sphere
- SAIC's Ultraviolet fluorescence (UVF) system
- Optically stimulated electron emission (OSEE)
  - **Industrial hardened model - Photo Acoustic Technology**
  - **Hand held sensor development - LaRC / MSFC / Thiokol Corporation**
- Ellipsometry
  - **John Woolam Company variable angle spectroscopic ellipsometer (VASE)**
  - **Portable ellipsometer**

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Materials and Processes Laboratory
Engineering Physics Division
Physical Sciences Branch
DeWitt Burns

Coatings Development Responsibilities

- Atomic oxygen resistant materials
  - MLI threads and films
  - Thermal control material to replace silvered Teflon
- Electrically conductive thermal control coatings - black and white
- Z93 thermal control coating development
  - Application to flexible films and composites
  - Teflon overcoat for cleaning during ground processing
- High visibility ceramic coatings for EVA crew aid

Atomic oxygen resistant materials

- TOR (Triton Oxygen Resistant) Polymer
- Developed by chemist at LaRC and is licensed by Triton Systems Inc.
- Polyaralene ether material family
- 10 times more atomic oxygen resistant than Kapton and is suitable for use as Kapton replacement materials on orbit
- TOR polymer molded into many different spacecraft applications such as solar array materials, MLI materials, thread, and wire insulation

Atomic oxygen resistant materials

- COR (Colorless Oxygen Resistant) Polymer
- Developed by chemist at Triton Systems Inc. under direction by MSFC as an atomic oxygen resistant replacement for silver / Teflon thermal control material
- Similar material to TOR with the pigmentation removed that can be metalized with either aluminum or silver
- Silver / COR has both better atomic oxygen resistance and higher infrared emittance than silver / Teflon

Flight experiments and instrument responsibility

- LDEF
- EOIM
- Optical Properties Monitor (OPM) - currently on MIR
- Passive Optical Sample Array (POSA) - currently on MIR
- Space Portable Spectroreflectometer (SPSR) - planned EVA on MIR
- Environmental Monitoring Package (EMP) - ISS

Contamination Control for Interplanetary Spacecraft

Dr. Jack Barengoltz
Jet Propulsion Laboratory

at 1997 Spacecraft Contamination and Coatings Workshop

Overview

- Comparison of CC for interplanetary missions with Earth orbiting missions
- Specific examples of CC for interplanetary missions
- Future CC issues for interplanetary missions

Unique aspects

- Guidance sensors need to work for extended durations
  - multiple maneuvers (e.g. tcm's)
  - often long after launch (e.g. orbital insertion at another planet)
- CC close to the sun (<1 au)
- Planetary Protection
- Other CC historical matters

Commonality

- Particles
- Molecular contamination
- Spacecraft instruments usually most sensitive

Particles in FOV of guidance sensors

- Particles released from surfaces and by separations/deployments
  - surface release mostly μmeteoroid impact
  - thermal (diurnal) cycling not present for 3-axis s/c or small far from sun for spinner
  - separations issue common to Earth & interplanetary missions
- Particles may stay near s/c
  - no orbital (non-inertial) "forces"
  - electrostatic fields and charges may be static

Particles in FOV of guidance sensors

- Effects
  - incorrect attitude for a maneuver (common to Earth orbiters & interplanetary s/c, e.g. TDRSS)
  - overuse of attitude control gas
    - Mariner 10 (Venus and Mercury)
  - false star sighting long-term history
    - Voyager (Jupiter, Saturn, Uranus & Neptune)
- Corrective measures
  - cleaning
  - software and flight operations changes

CC close to the sun

- Thermal control more sensitive to changes in solar absorptance α from molecular contamination
- UV photolysis (darkening) of deposition more prevalent
- Increased outgassing
  - possibly balanced by lower collection rates
  - but not for cold instruments

CC close to the sun

- Effects
  - ➤ spacecraft overheating
    - – Magellan (Venus)
  - ➤ decrease in solar array output
    - – Magellan
- Corrective measures
  - ➤ better CC, especially bake-outs
  - ➤ better mission design

Planetary Protection

- Protection of other solar system bodies from terrestrial contamination (to avoid precluding search for life)
- Has been the principal driver behind CC for interplanetary spacecraft (esp. for particles)
- Now stringent requirements only for Mars and Europa

- will show an MPF ground ops in clean room color pic here

Planetary Protection

- novel form of contamination - microorganisms
- control mostly by traditional (particle) contamination control methods
  - clean rooms
  - garment requirements
- "cleaning" can be common (alcohol wipe) or different (sterilization)
- verification of cleanliness unique (bio-assay)

Other CC historical matters

- Galileo
  - engine plume contamination analysis for cyclically varying geometry with spun/despun bus
  - data commutator lubricant contamination
- Mars Observer
  - **possible** contamination issue, preventing check valve in propulsion system from sealing properly

Future CC issues for interplanetary missions

- Planetary Protection also requires protection of Earth from potential extraterrestrial hazards
  - Mars sample return is being planned (again)
  - contamination of returned sample by biogenic materials (amino acids, carbohydrates, etc.) or dead "bug bodies" will confound science and possibly keep the sample in quarantine
  - cleaning without organic solvents for sample handling hardware (flight and GSE) is required

Future CC issues for interplanetary missions

- Very small spacecraft
  - molecular contamination sensitivity unknown, should be studied (but very small budgets)
  - more sensitive to particles
  - probably difficult to clean

Space Environmental and Contamination Effects on Optical Surfaces -- Cryogenic and Warm

Spacecraft Contamination & Coatings Workshop

July 9-10 , 1997

Bobby E. Wood, Sverdrup Technology
1077 Avenue C, MS 6400
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Outline

- Introduction
- Cryogenic Optical Properties
  - Refractive & Absorptive Indices of Condensed gases
    - Pure gases
    - Satellite Material Outgassing Products
  - BRDF
- Warm surface condensation
  - Solar Measurement wavelength range
  - Vacuum UV
- MSX Flight QCM Results
- Summary

Optical Properties of Cryogenic Contaminants

Cryofilm Optical Properties Database

- Refractive/Absorptive Indices Obtained for:

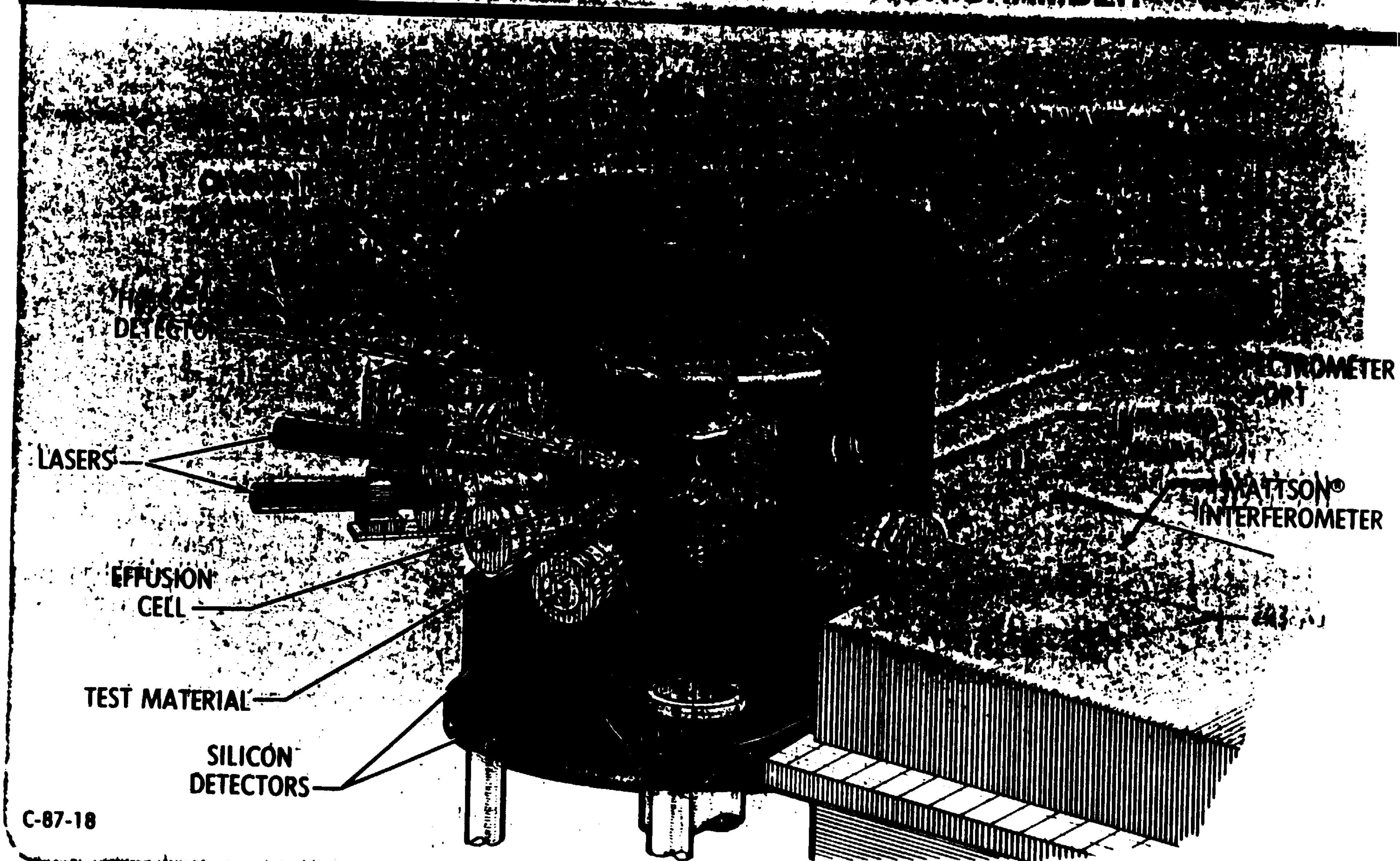
~ 35 Materials' Outgassing Products

Pure Gases such as H_2O, CO_2, N_2, O_2, NH_3, CH_4, HCl, NO, MMH, N_2O_4, and N_2H_4

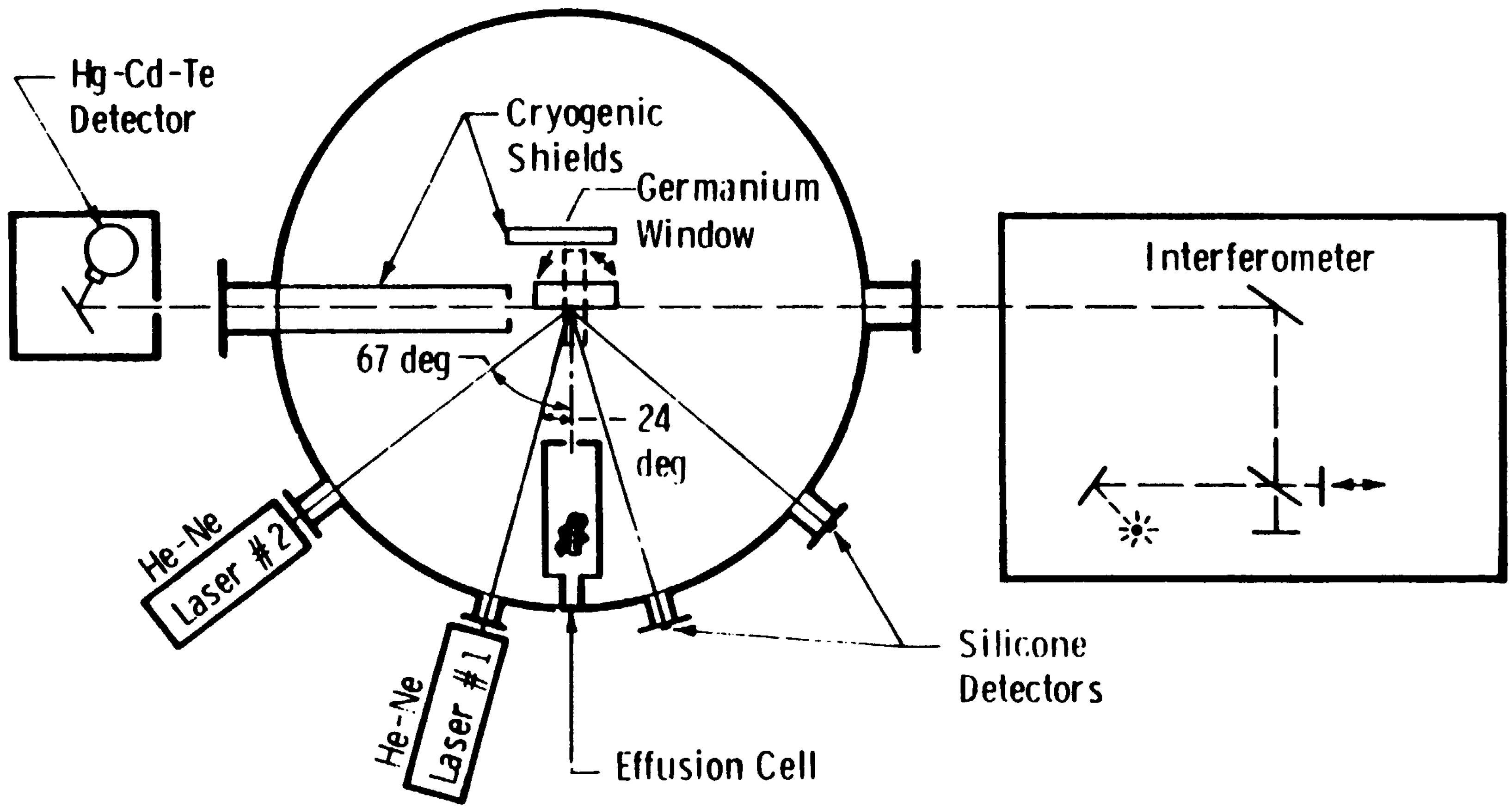
Mixtures of H_2O, CO_2, N_2, and NH_3 Gases

CONTAMINATION TESTING

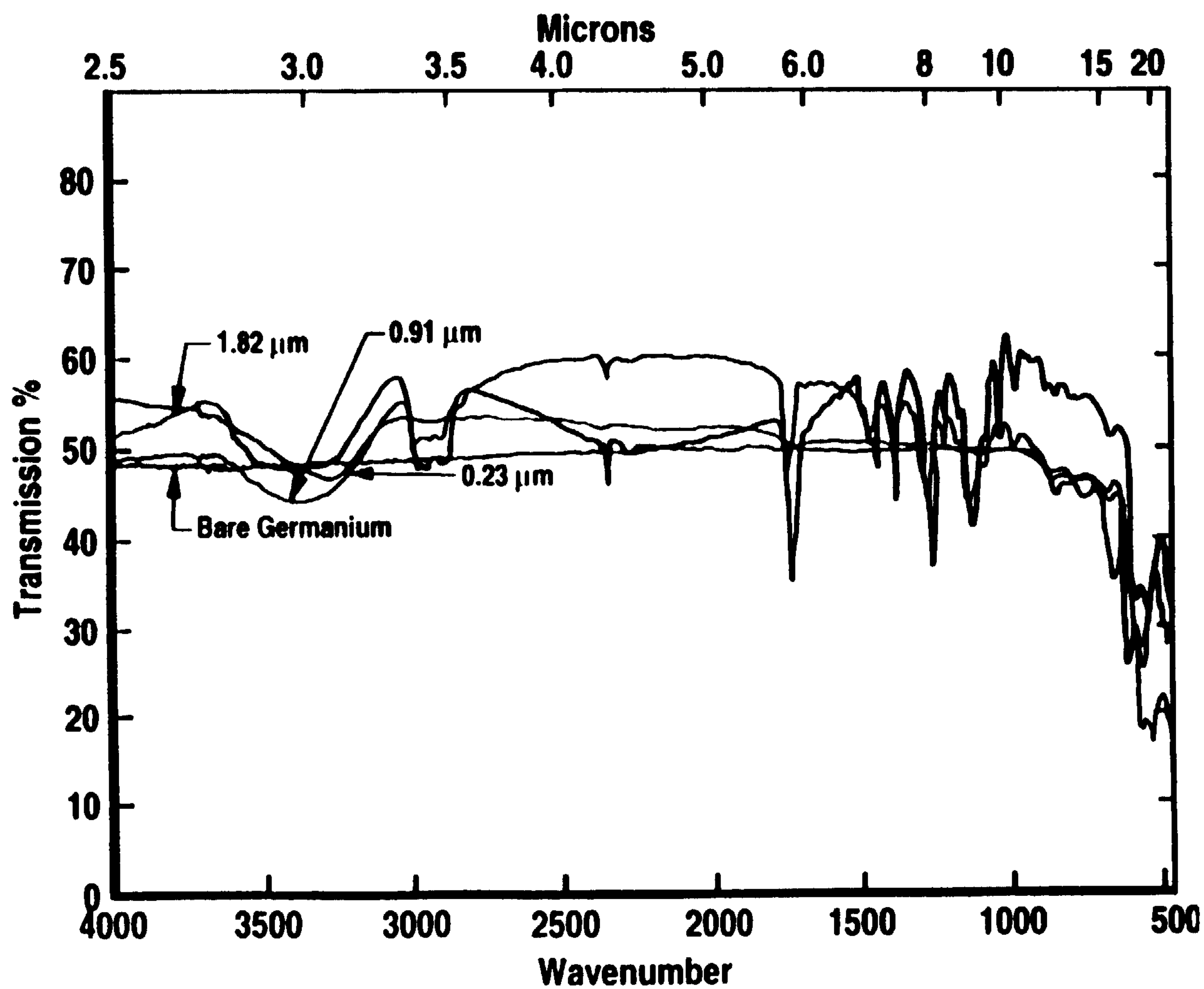
SCHEMATIC OF 2' x 3'
CRYOGENIC OPTICS DEGRADATION CHAMBER



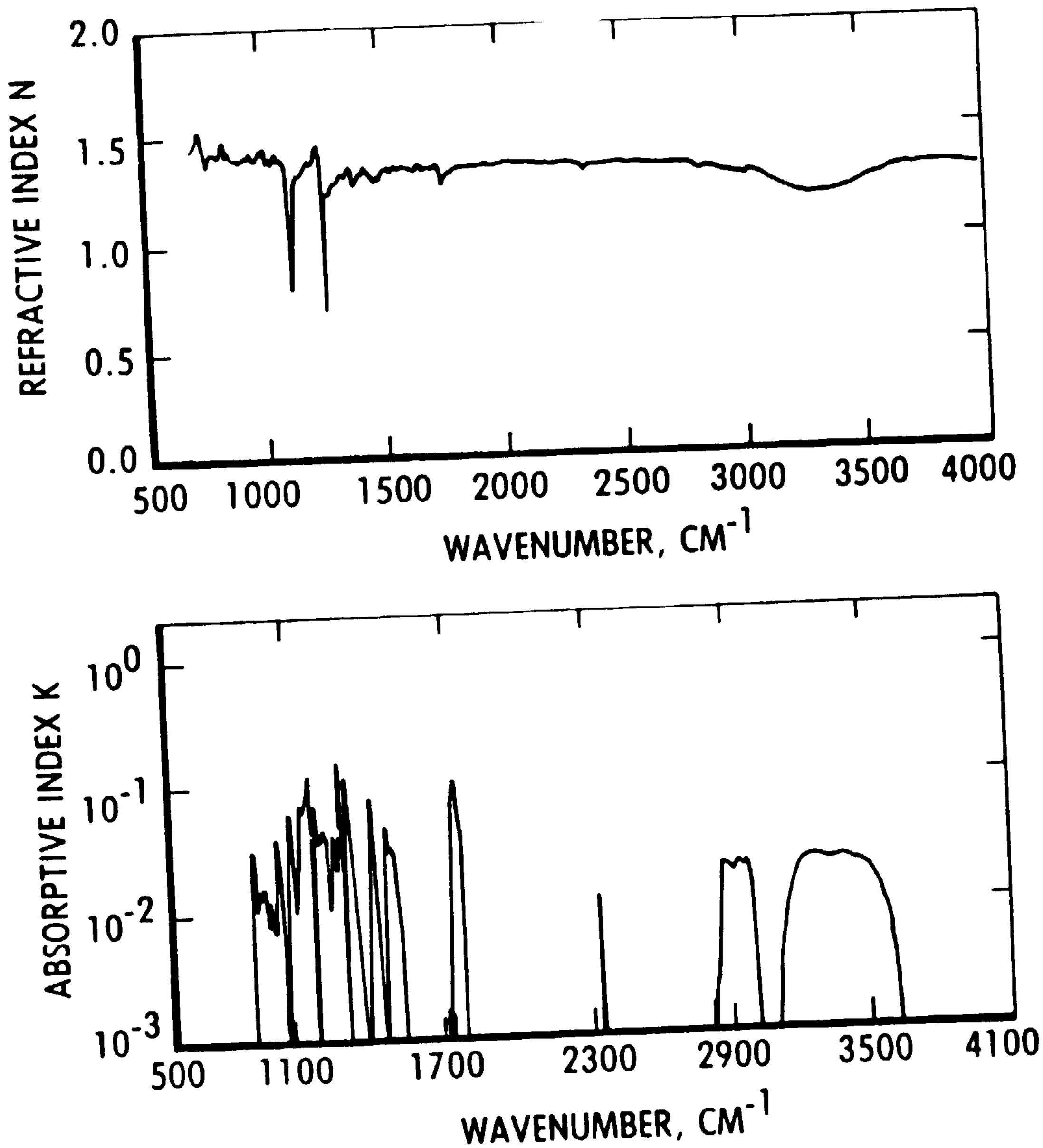
SCHEMATIC OF 2 FT X 3 FT CHAMBER COMPONENTS



Effects of Chemglaze Z306 paint contaminants on 77 K germanium window transmittance



REFRACTIVE AND ABSORPTIVE INDICES FOR CHEMGLAZE Z306 OUTGASSING PRODUCTS

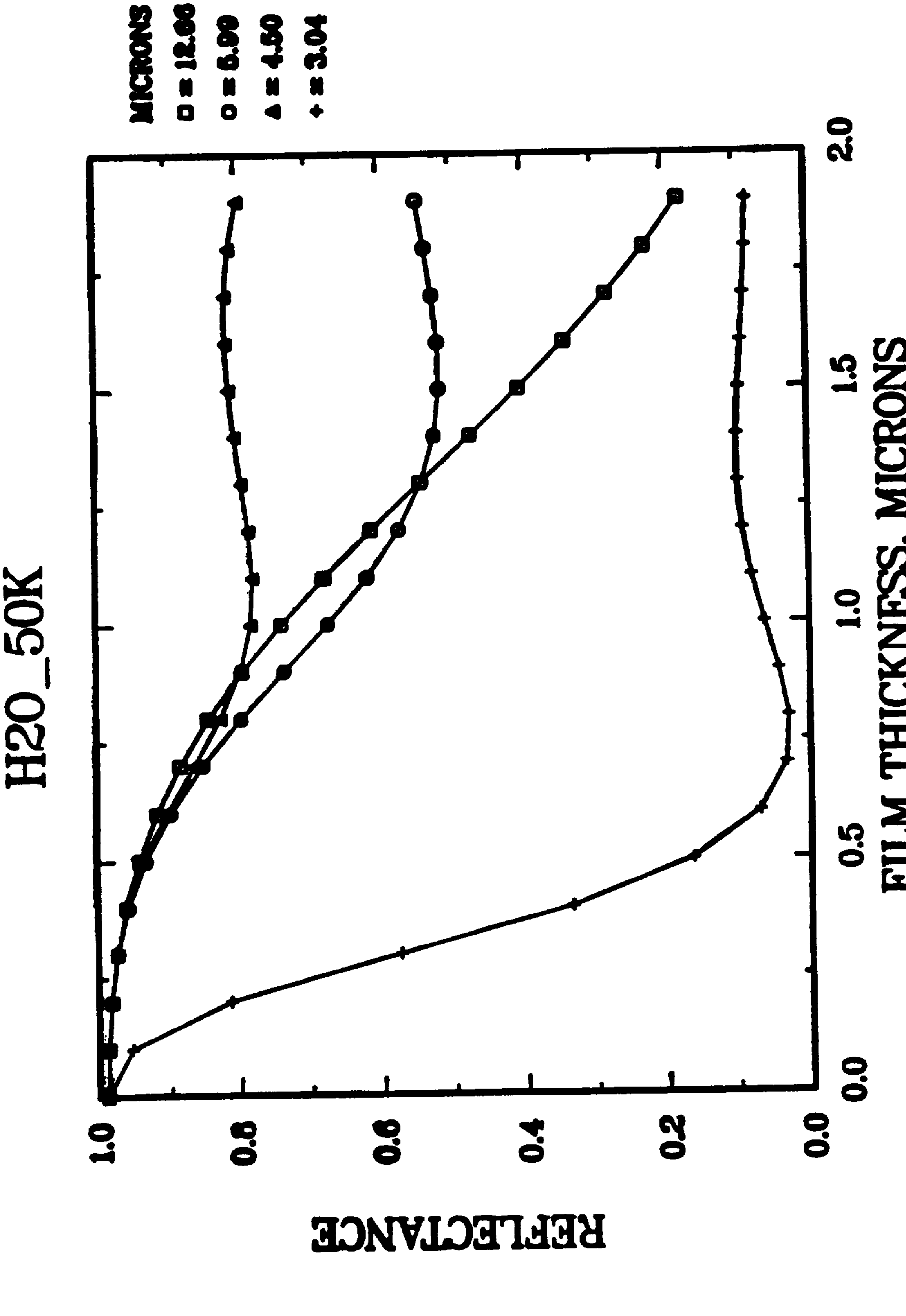


CALCRT Model

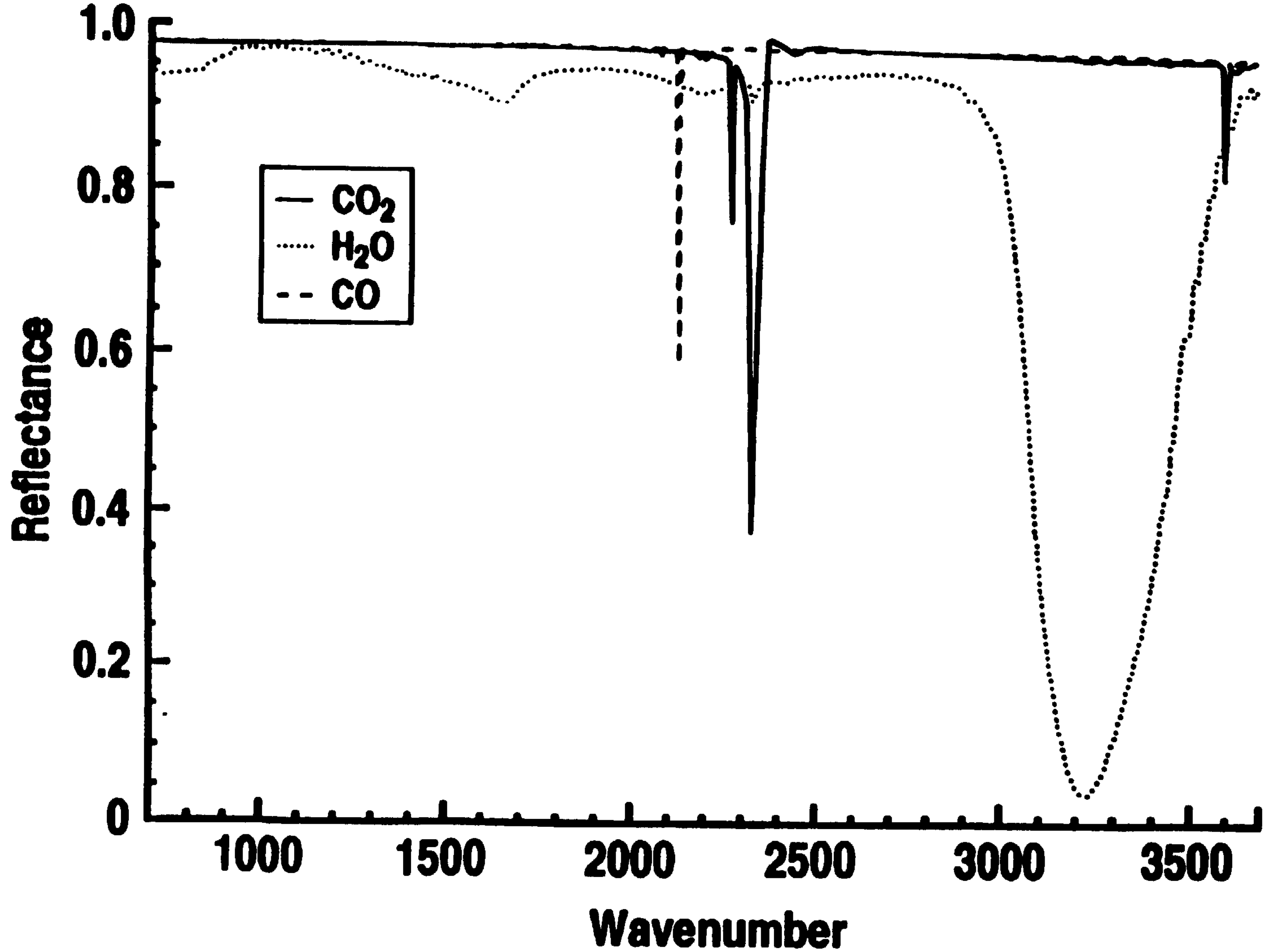
CALCulation of Reflectance and Transmittance

Calculates Transmittance or Reflectance of Optical Elements for these Parameters:

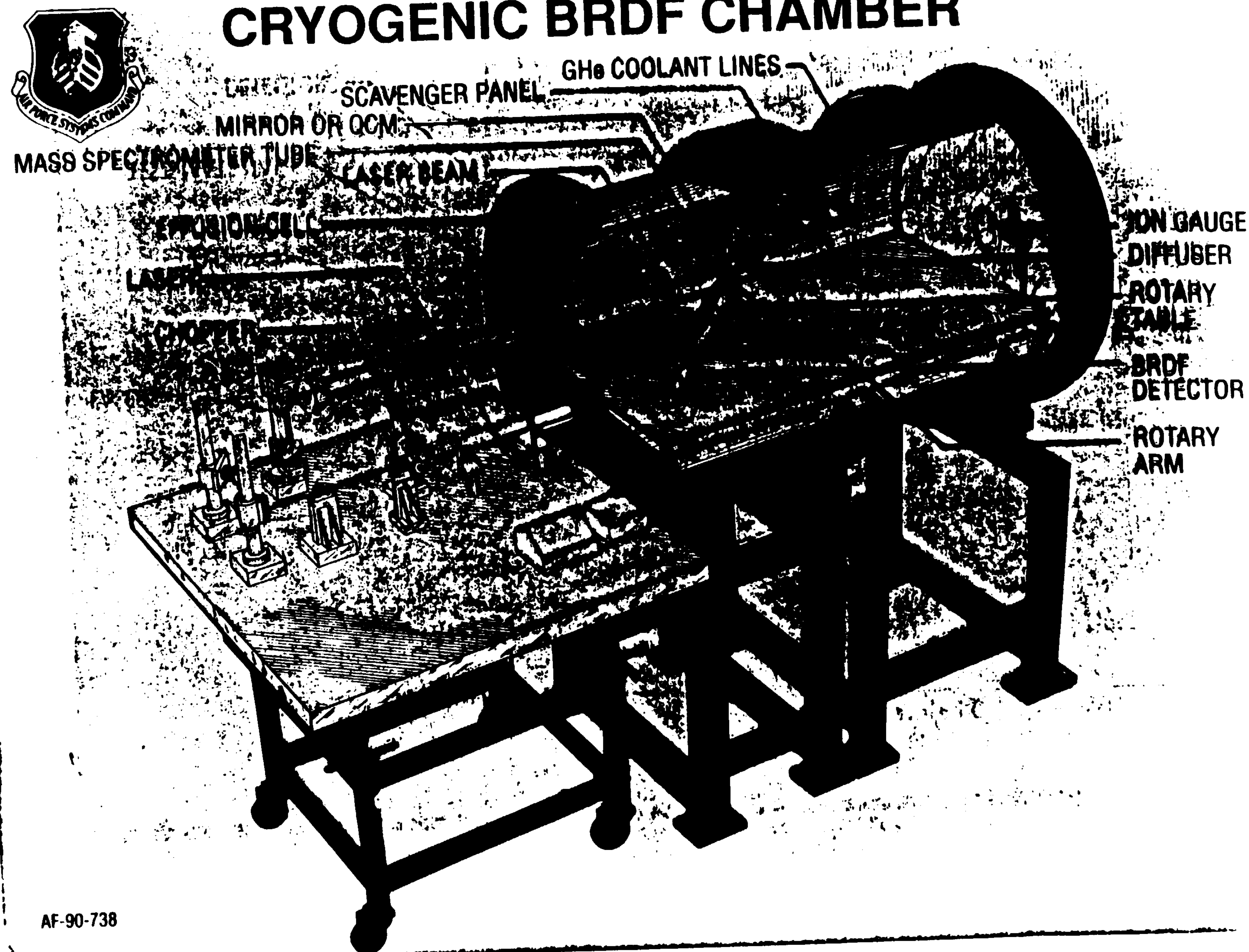
- Wavelength or Wavenumber
- Contaminant Film Thickness
- Radiation Incidence Angle
- Substrate Refractive Index

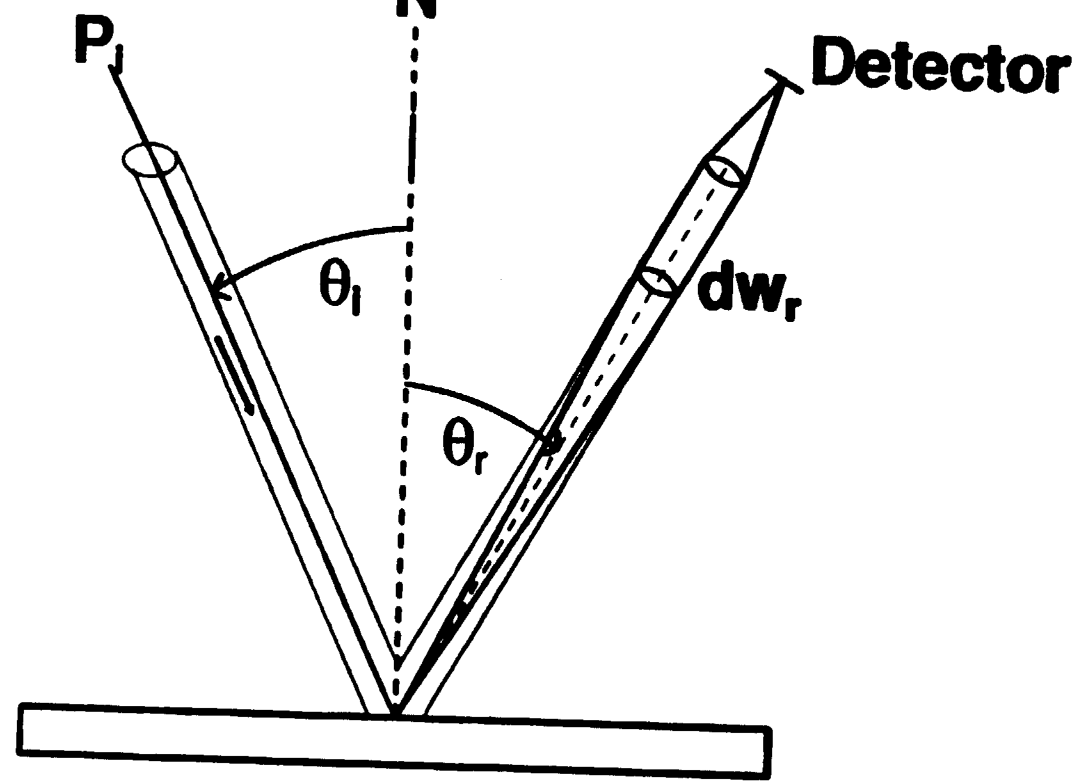

H20_50K
REFLECTANCE
FILM THICKNESS, MICRONS
MICRONS
Δ = 4.50
+ = 3.04
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0

Effects of 0.5-micron-thick CO_2, H_2O, and CO cryofilms on mirror having a 98-percent reflectance



CRYOGENIC BRDF CHAMBER

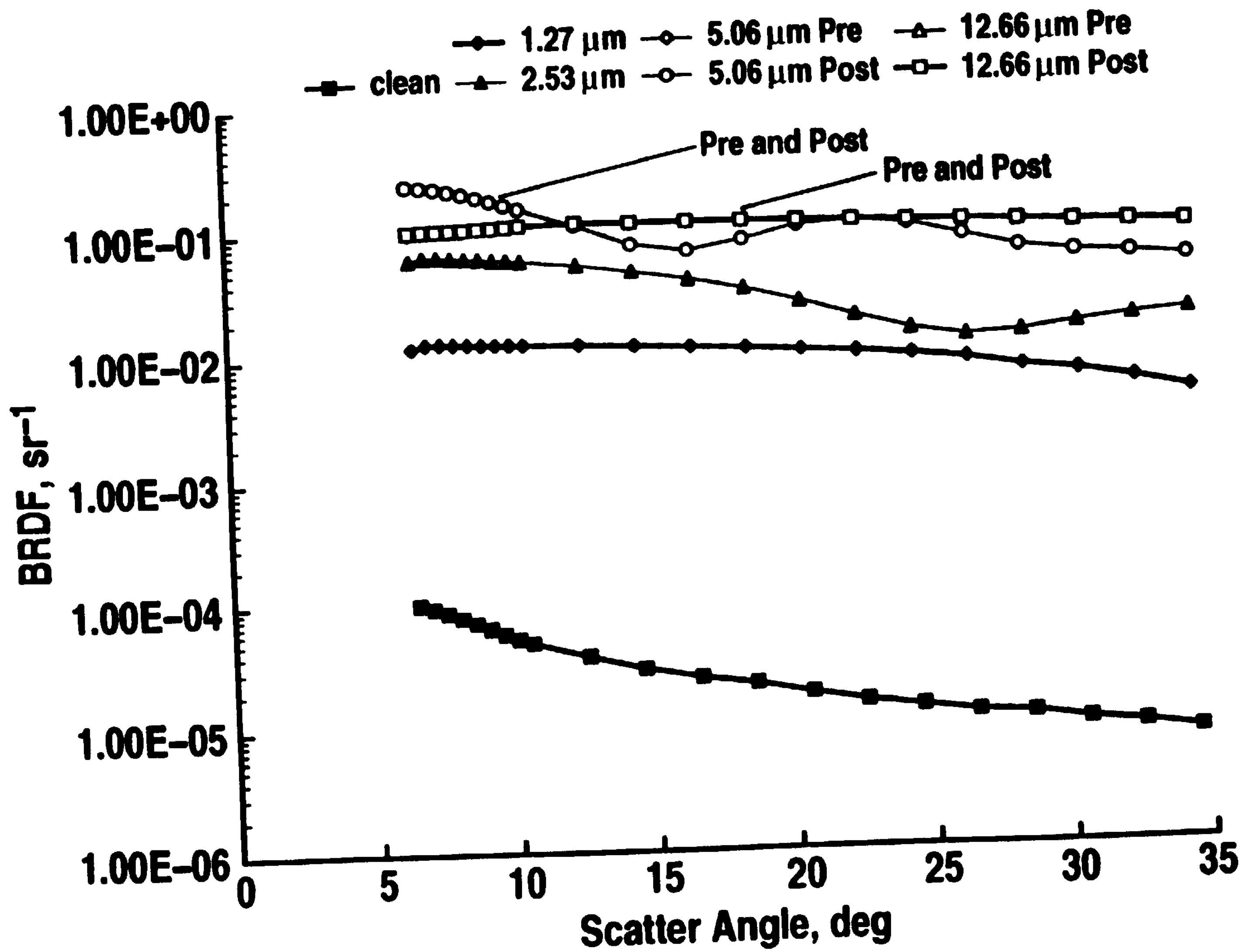




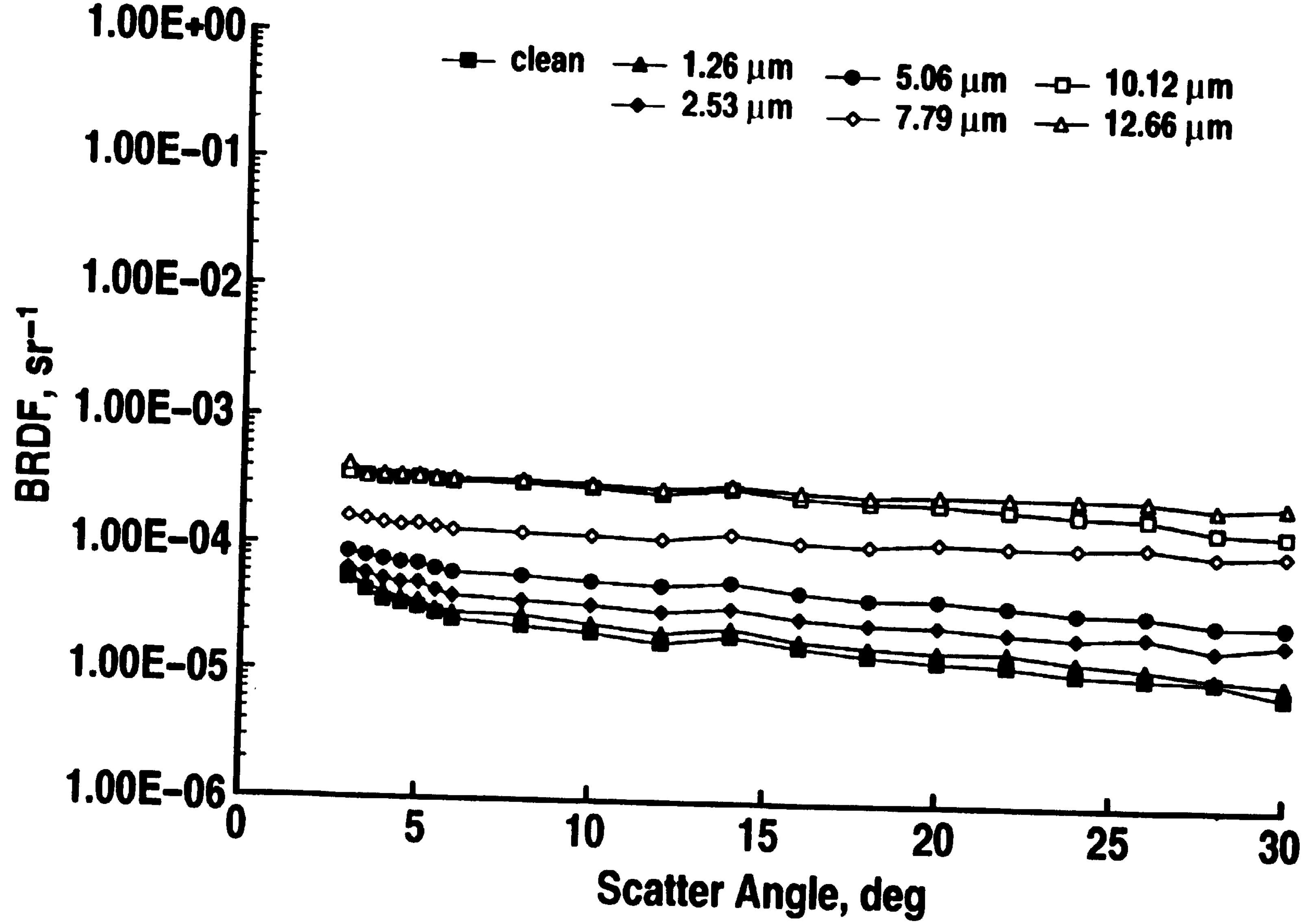
$$BRDF = \frac{P_s(\theta_I, \theta_r)}{P_I(\theta_I)\, dw_r \cos\theta_r}$$

BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION

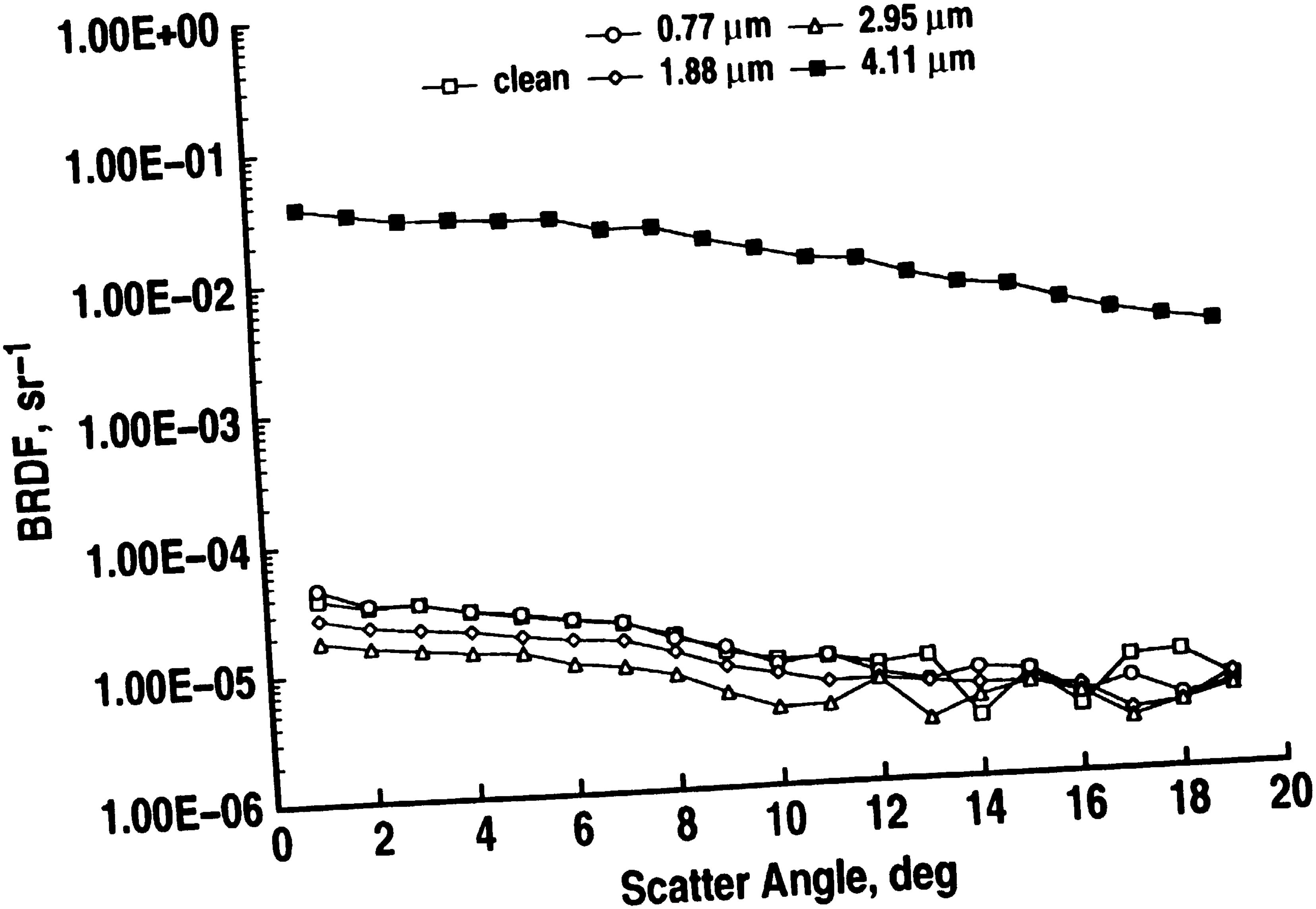
Contaminated mirror BRDF at 0.63 μm versus scatter angle for oxygen films condensed at 15K



Contaminated mirror BRDF at 10.6 μm versus scatter angle for oxygen films condensed at 15K



Contaminated mirror BRDF at 10.6 μm versus scatter angle for H_2O films condensed at 16K



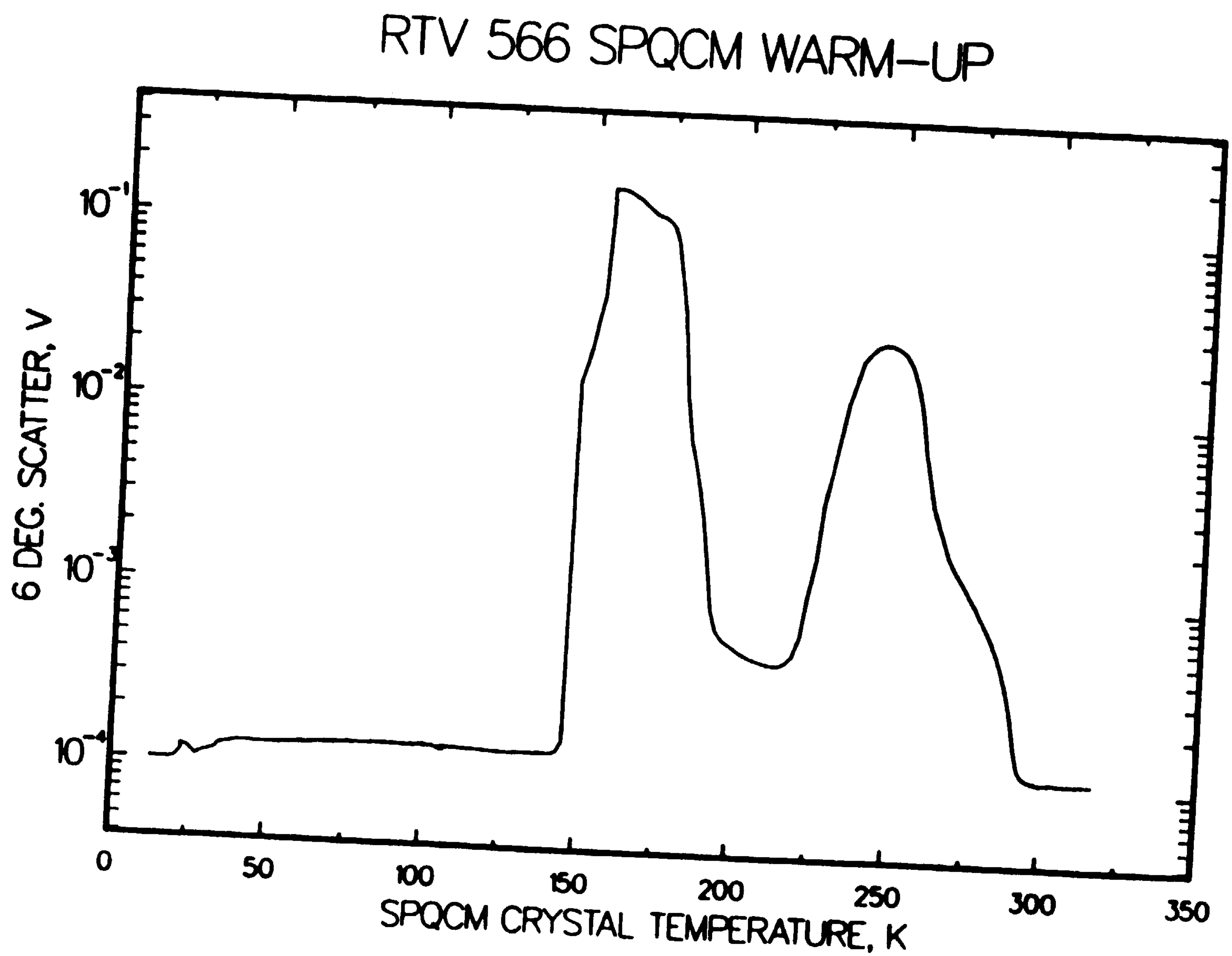


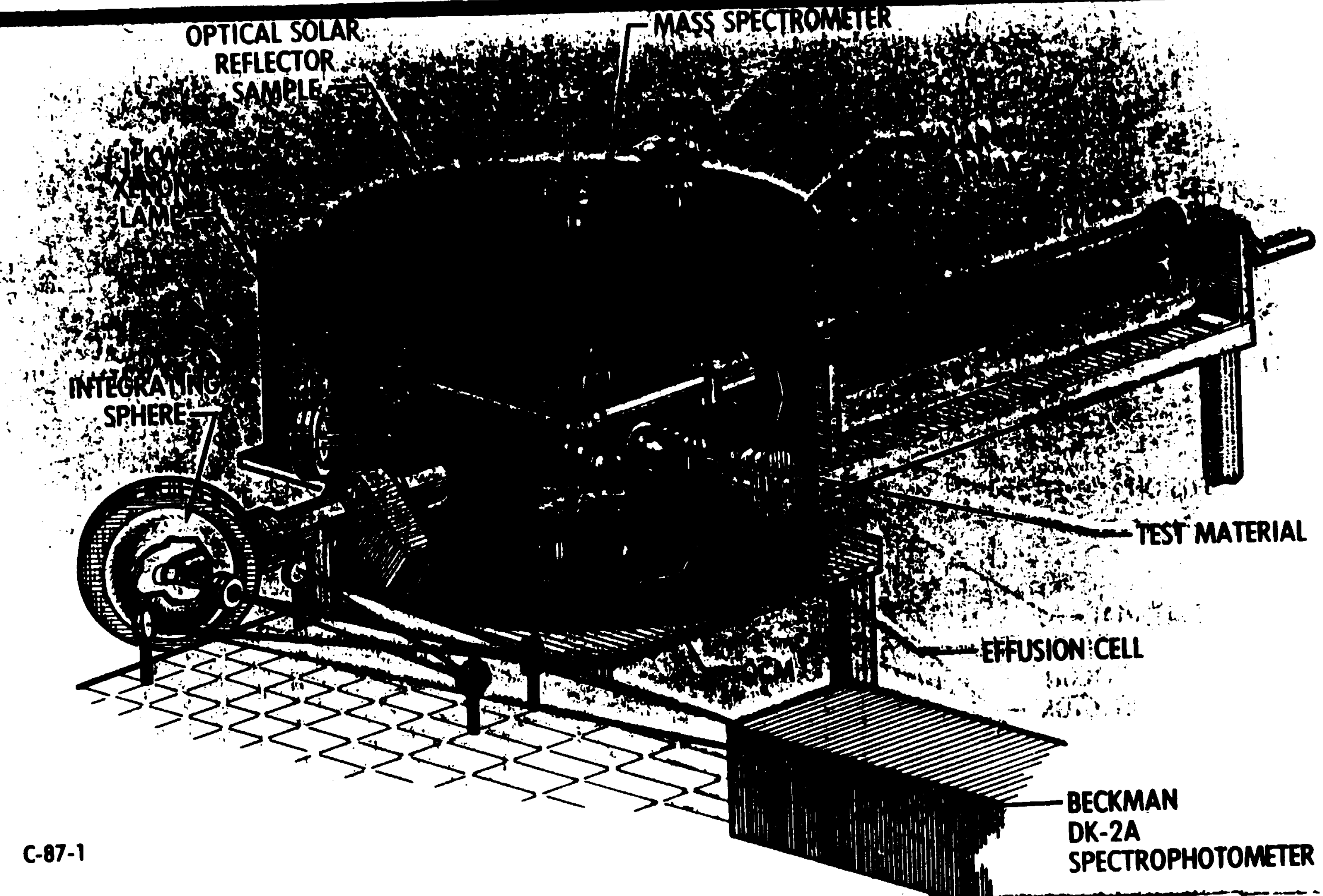
FIG. 2 CONCLUDED

Effects of Cryofilms on Mirror BRDF

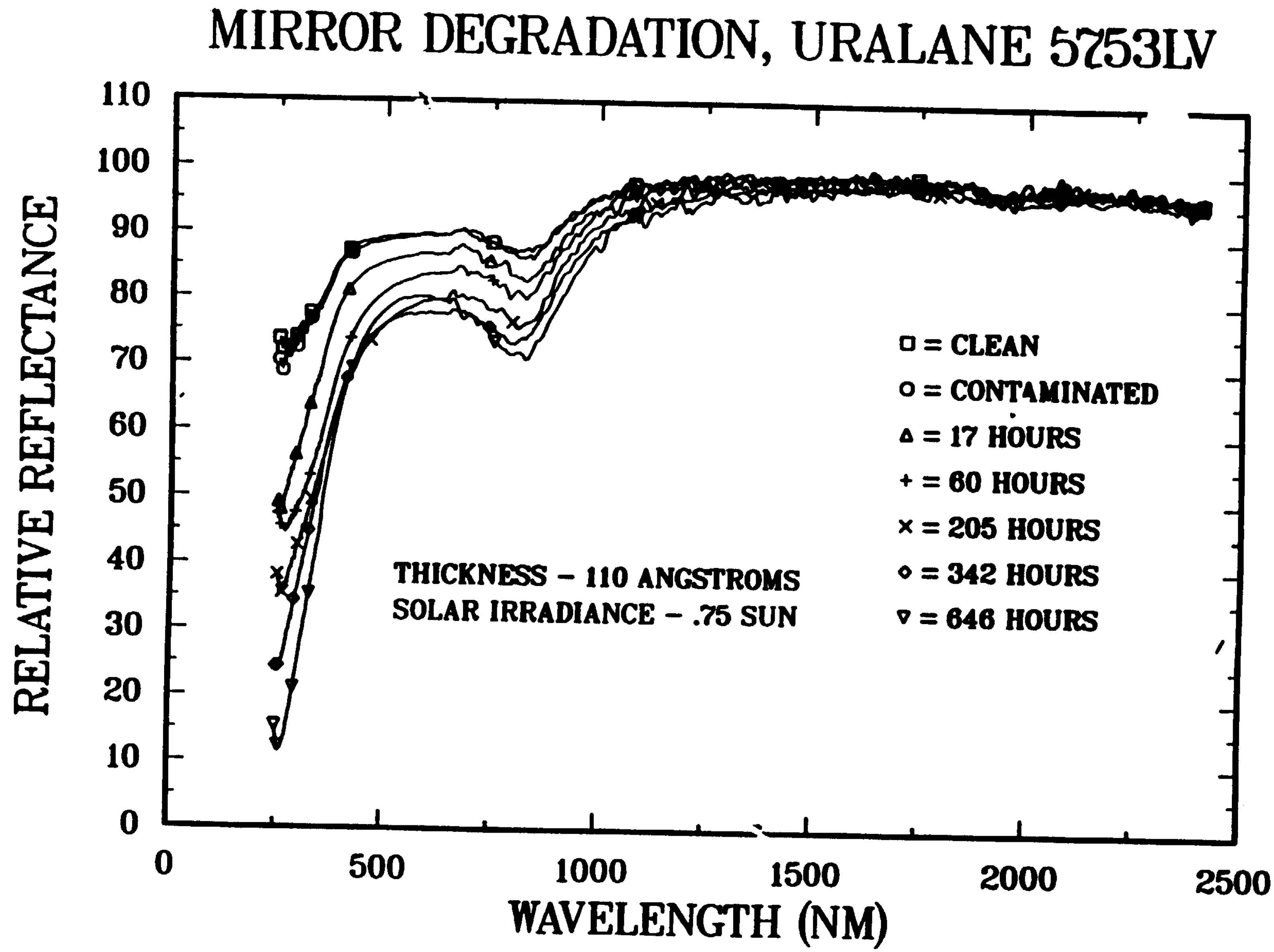
- During cryofilm deposition the film can fracture/shatter causing orders of magnitude increase in BRDF
- A warmup of the cryofilm can cause phase changes in the film (function of temperature and specie) which can cause an increase in BRDF
- Deposition of contaminant films in the 10^{-4} torr or higher pressure results in formation of crystalline films instead of an amorphous film. BRDF of crystalline films is higher than for amorphous films.
- An inçrease in scatter at short wavelengths (visible) doesn't necessarily indicate an increase at longer wavelengths (e.g. 10.6 μm)

Solar and Vacuum UV Absorptance Measurements

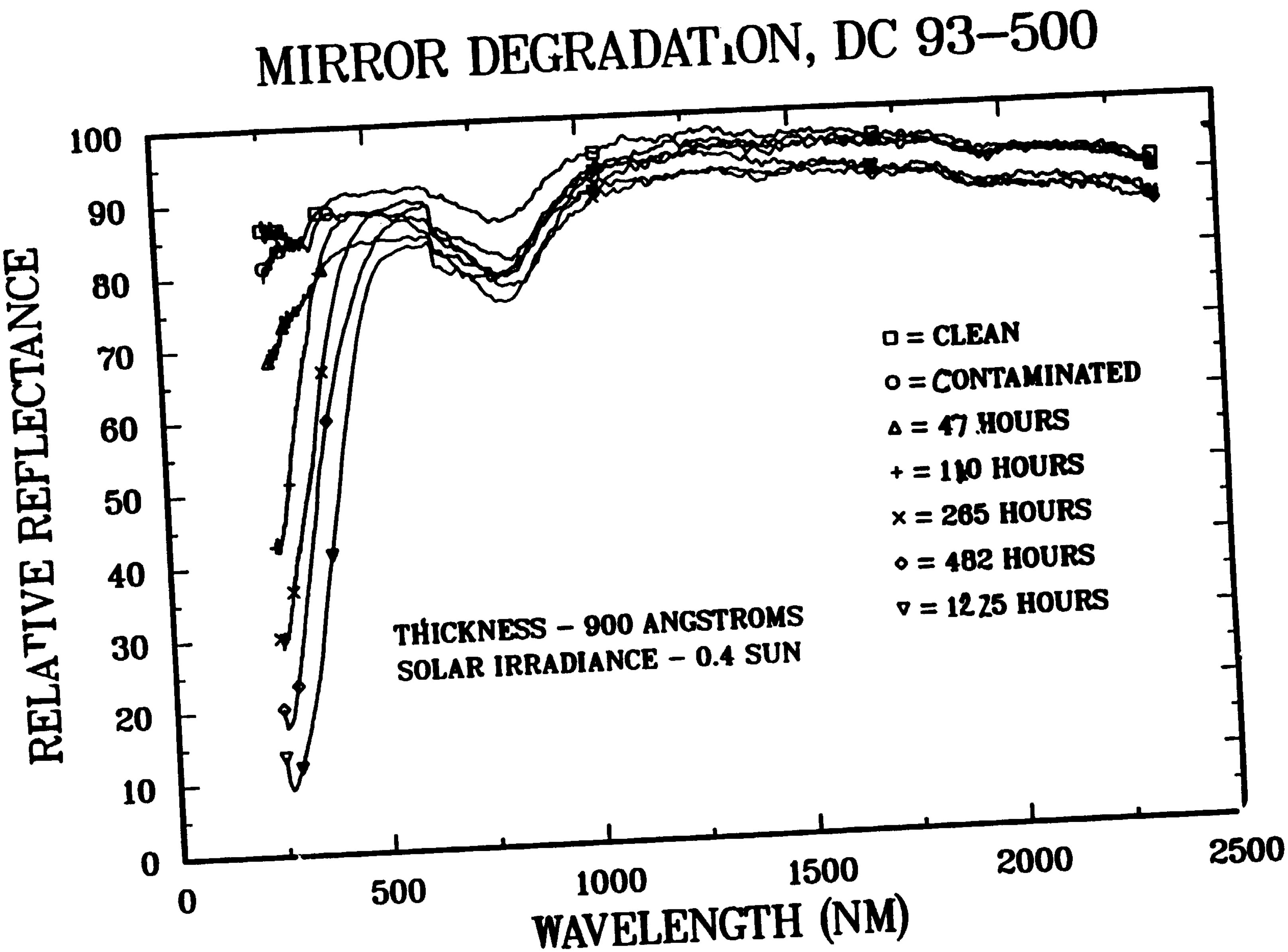
SOLAR ABSORPTANCE MEASUREMENTS FACILITY

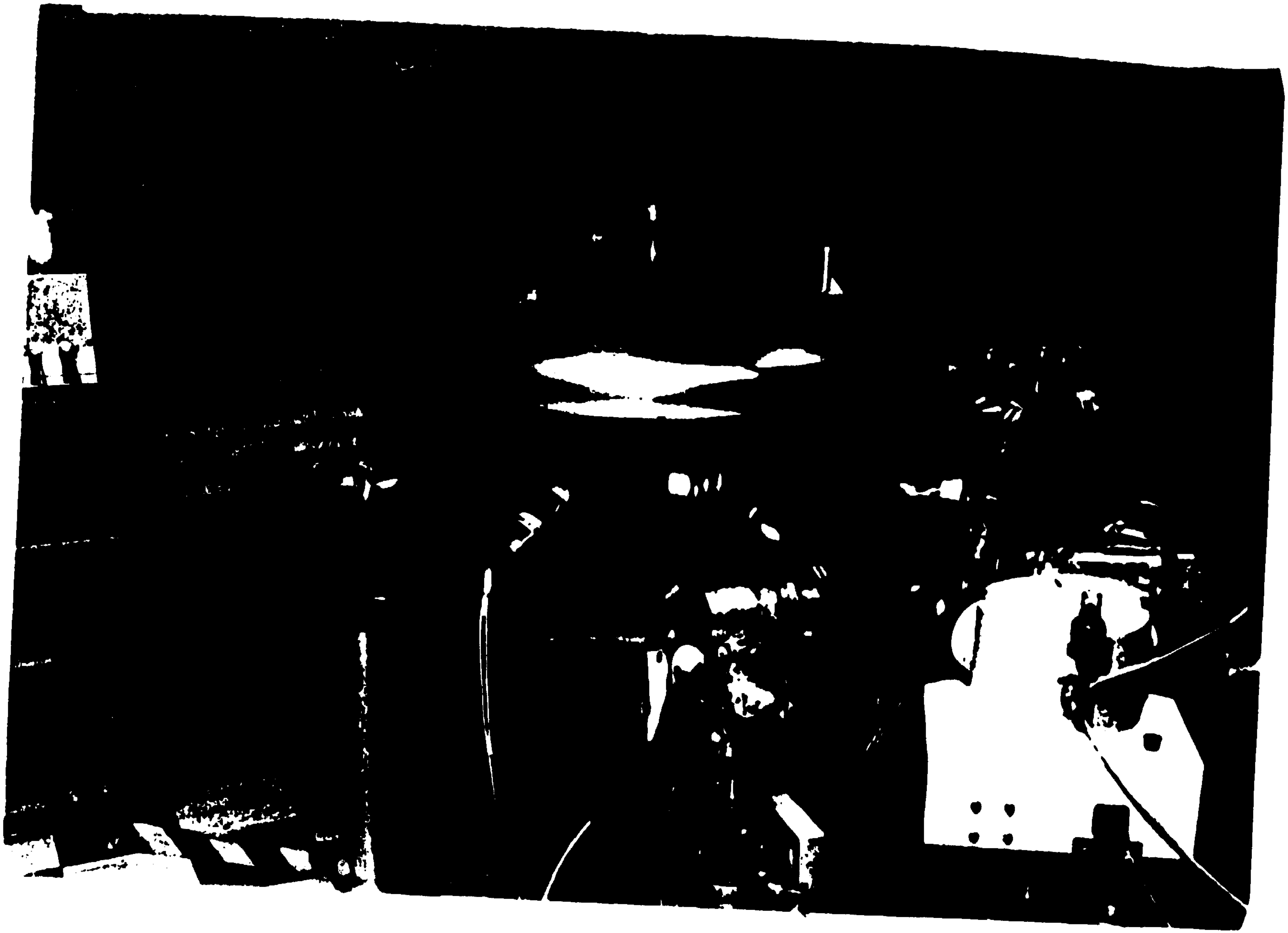


C-87-1



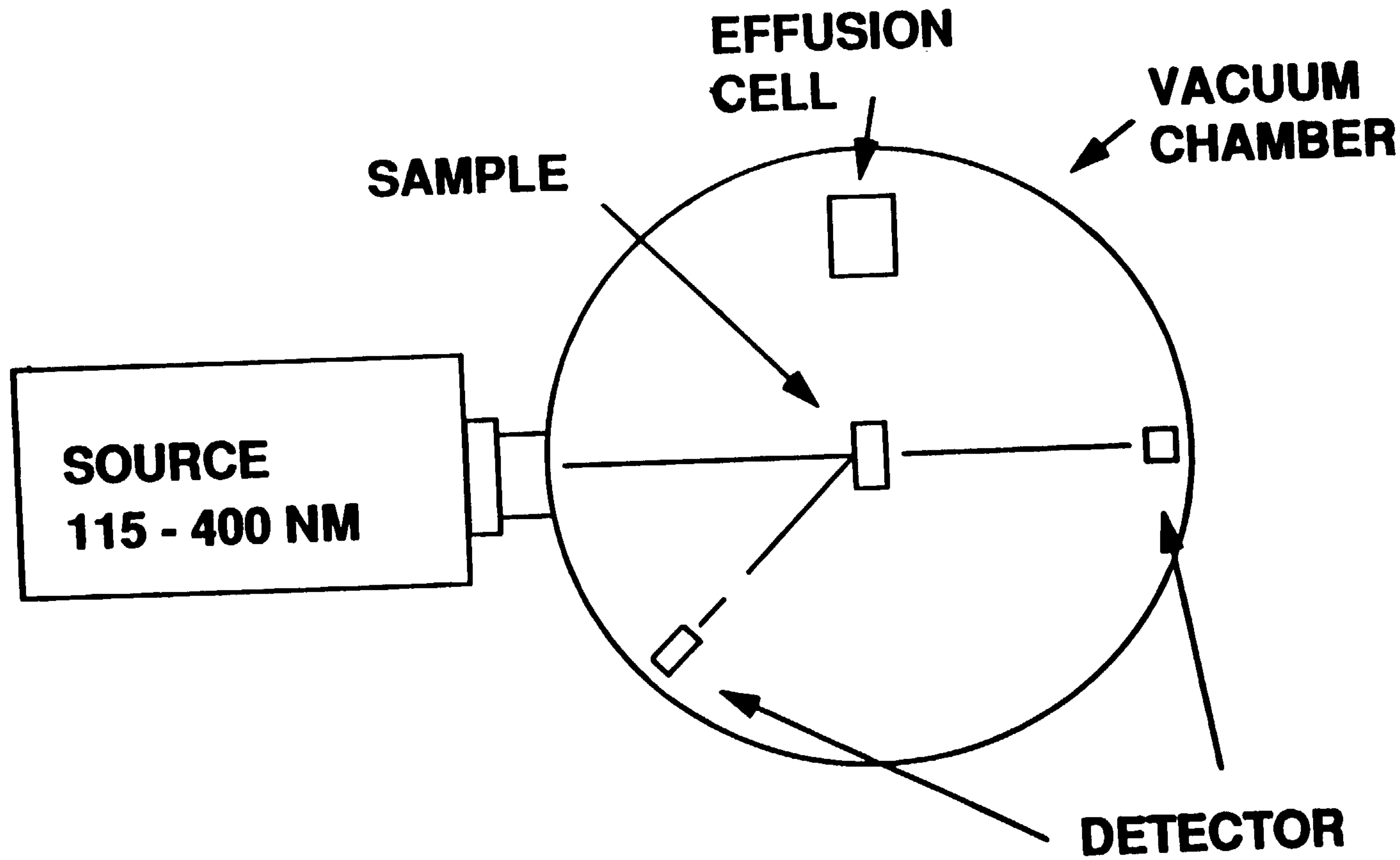
MIRROR DEGRADATION, URALANE 5753LV
RELATIVE REFLECTANCE
WAVELENGTH (NM)
0
10
20
30
40
50
60
70
80
90
100
110
0
500
1000
1500
2000
2500
THICKNESS – 110 ANGSTROMS
SOLAR IRRADIANCE – .75 SUN
□ = CLEAN
○ = CONTAMINATED
△ = 17 HOURS
+ = 60 HOURS
× = 205 HOURS
◇ = 342 HOURS
▽ = 646 HOURS

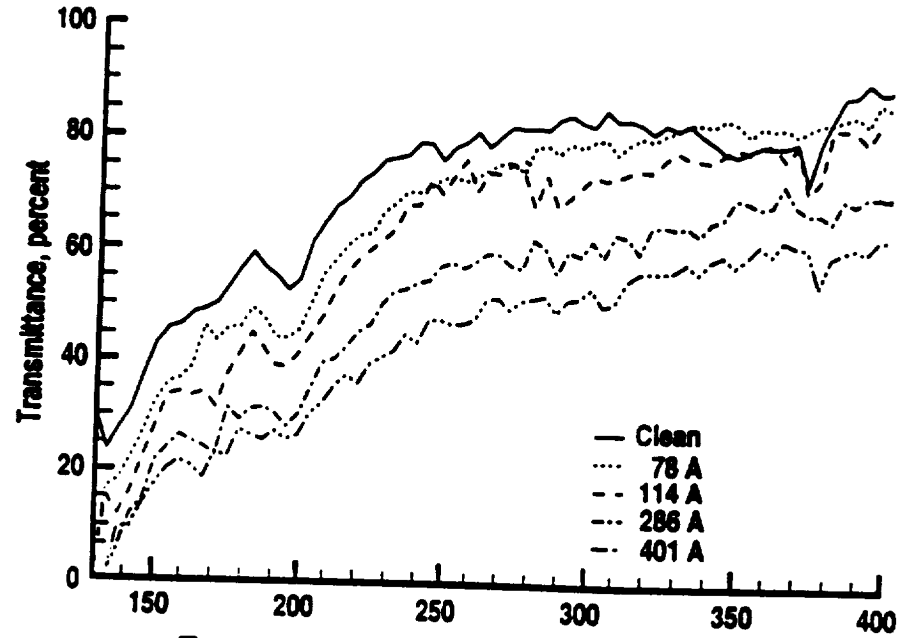

MIRROR DEGRADATION, DC 93–500
RELATIVE REFLECTANCE
0
10
20
30
40
50
60
70
80
90
100
WAVELENGTH (NM)
0
500
1000
1500
2000
2500
THICKNESS – 900 ANGSTROMS
SOLAR IRRADIANCE – 0.4 SUN
□ = CLEAN
○ = CONTAMINATED
△ = 47 HOURS
+ = 110 HOURS
× = 265 HOURS
◇ = 482 HOURS
▽ = 1225 HOURS



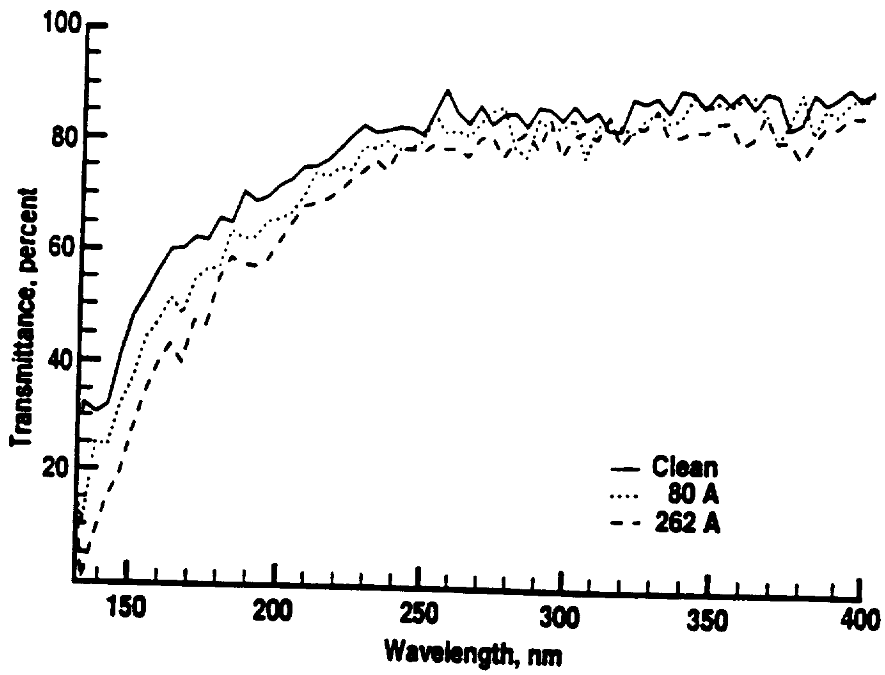
94-231114 JOB 0222 (10/31/94) SILVER BULLET

VUV/UV SPECTRAL SYSTEM

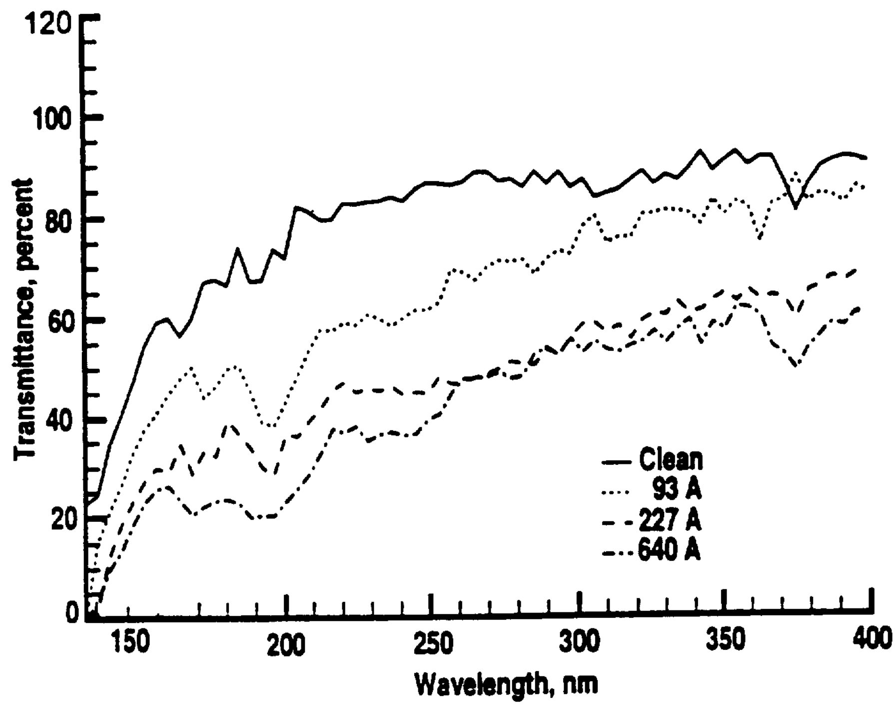




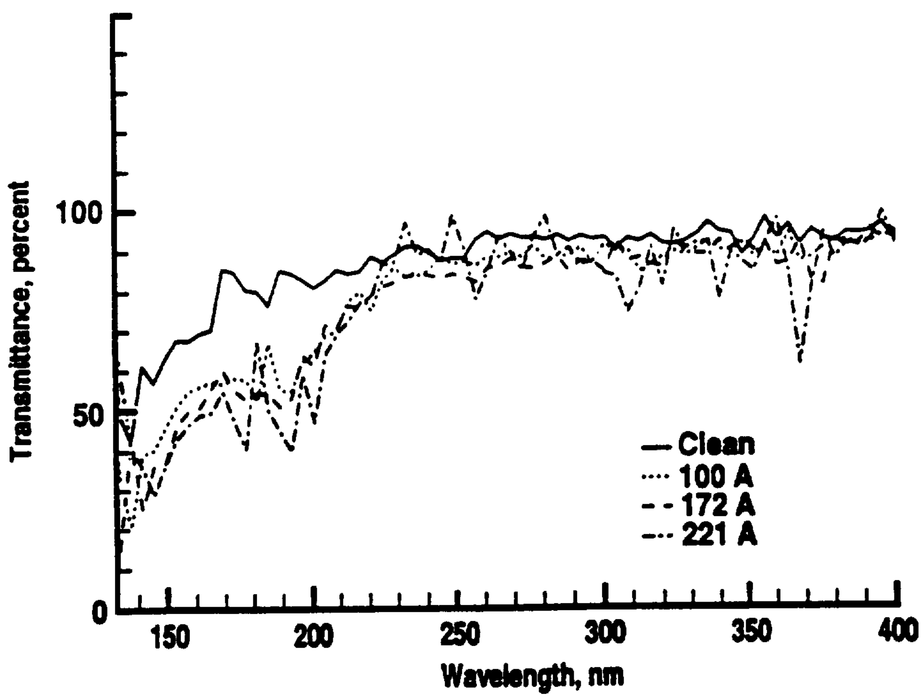
Transmittance as function of Solithane film thickness.



Transmittance as function of RTV-142 film thickness.



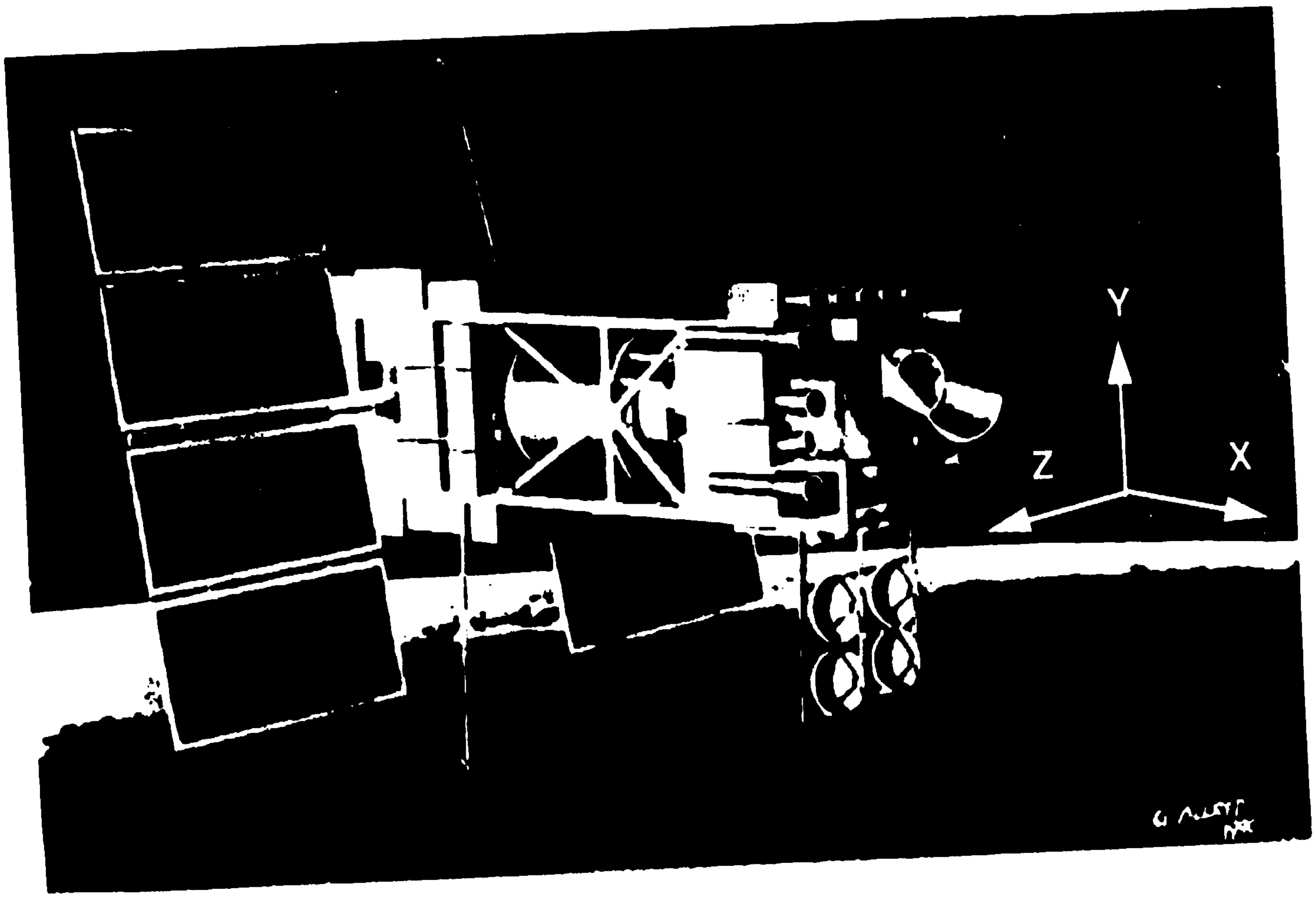
Transmittance as function of Uralane® film thickness.



Transmittance as function of RTV-566 film thickness.

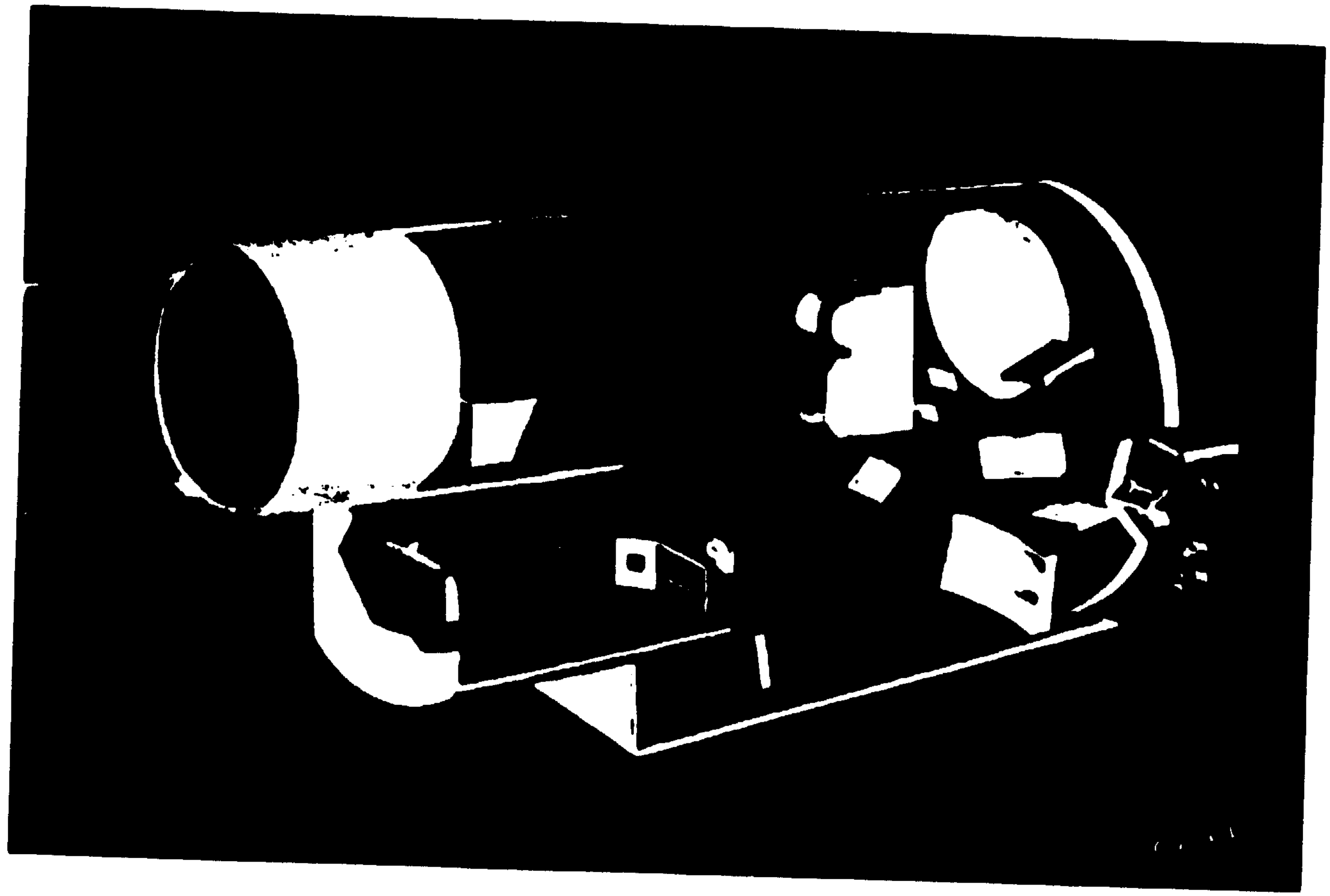
Midcourse Space Experiment (MSX) Satellite QCM Results

Artist's Drawing of Midcourse Space Experiment Showing Reference Axes



S-96-593

Artist's Drawing of Spirit III Telescope Sensor System



S-96-594

Gaseous Contaminant Sources

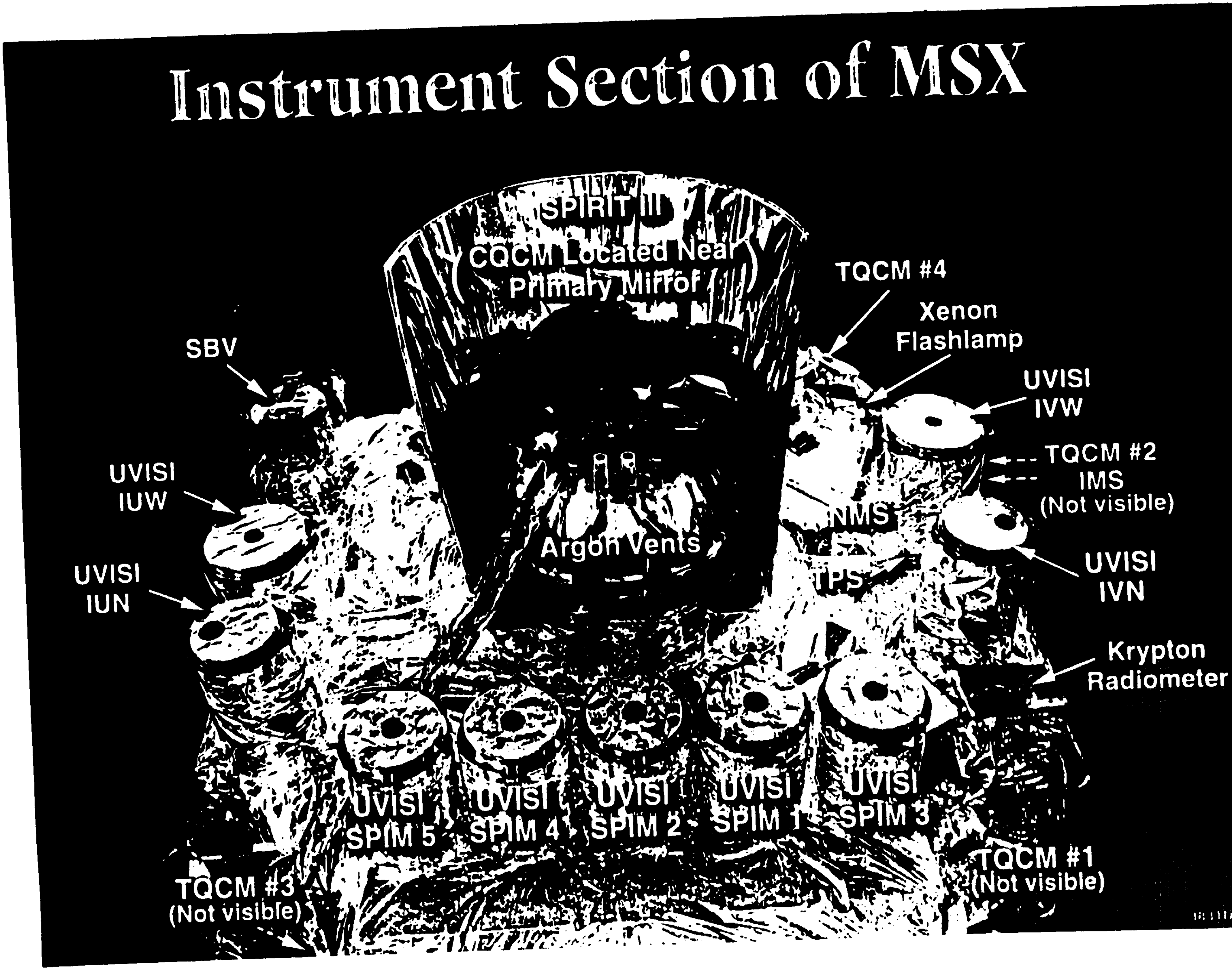
- H_2O, CO_2, organics -- Material outgassing
  - e.g. Chemglaze Z306 black paint on Spirit 3 baffle

- N_2 and O_2 -- Atmosphere of space
- CO and CO_2 -- Pyrotechnic combustion products

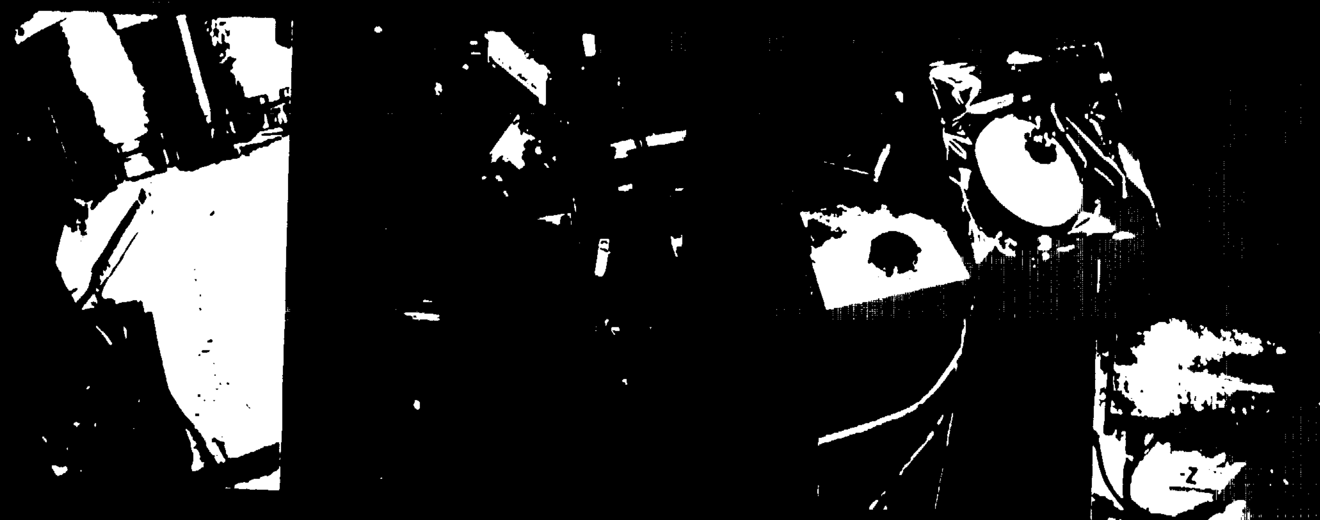
- Argon -- Spirit 3 Argon cooled cover

Objectives for QCM Instruments

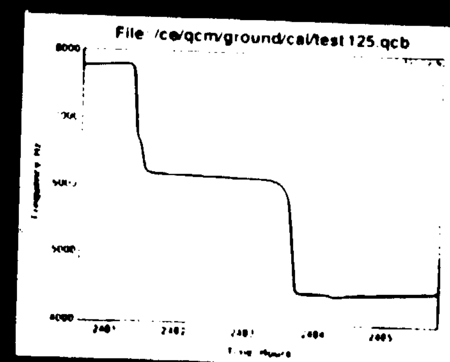
- Using a CQCM measure contaminant deposition rate on the primary mirror within Spirit 3 cryogenic Telescope
- Determine condensed contaminant level caused by Spirit 3 Cover release
- Determine species of gases condensed during pre-cryo, cryo, and post-cryo phases
- Using TQCMs determine deposition rate of silicones and organic contaminants on surfaces near UVISII and SBV
- Use external contaminant deposition rates measured by TQCMs to update MSX Contamination Model

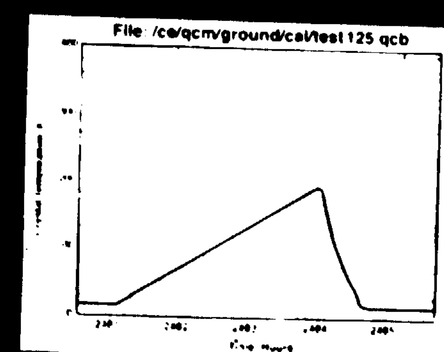

Instrument Section of MSX
SPIRIT III
(CQCM Located Near Primary Mirror)
TQCM #4
Xenon Flashlamp
UVISI IVW
TQCM #2
IMS
(Not visible)
SBV
UVISI IUW
UVISI IUN
NMS
Argon Vents
TPS
UVISI IVN
Krypton Radiometer
UVISI SPIM 5
UVISI SPIM 4
UVISI SPIM 2
UVISI SPIM 1
UVISI SPIM 3
TQCM #3
(Not visible)
TQCM #1
(Not visible)

Quartz Crystal Microbalance



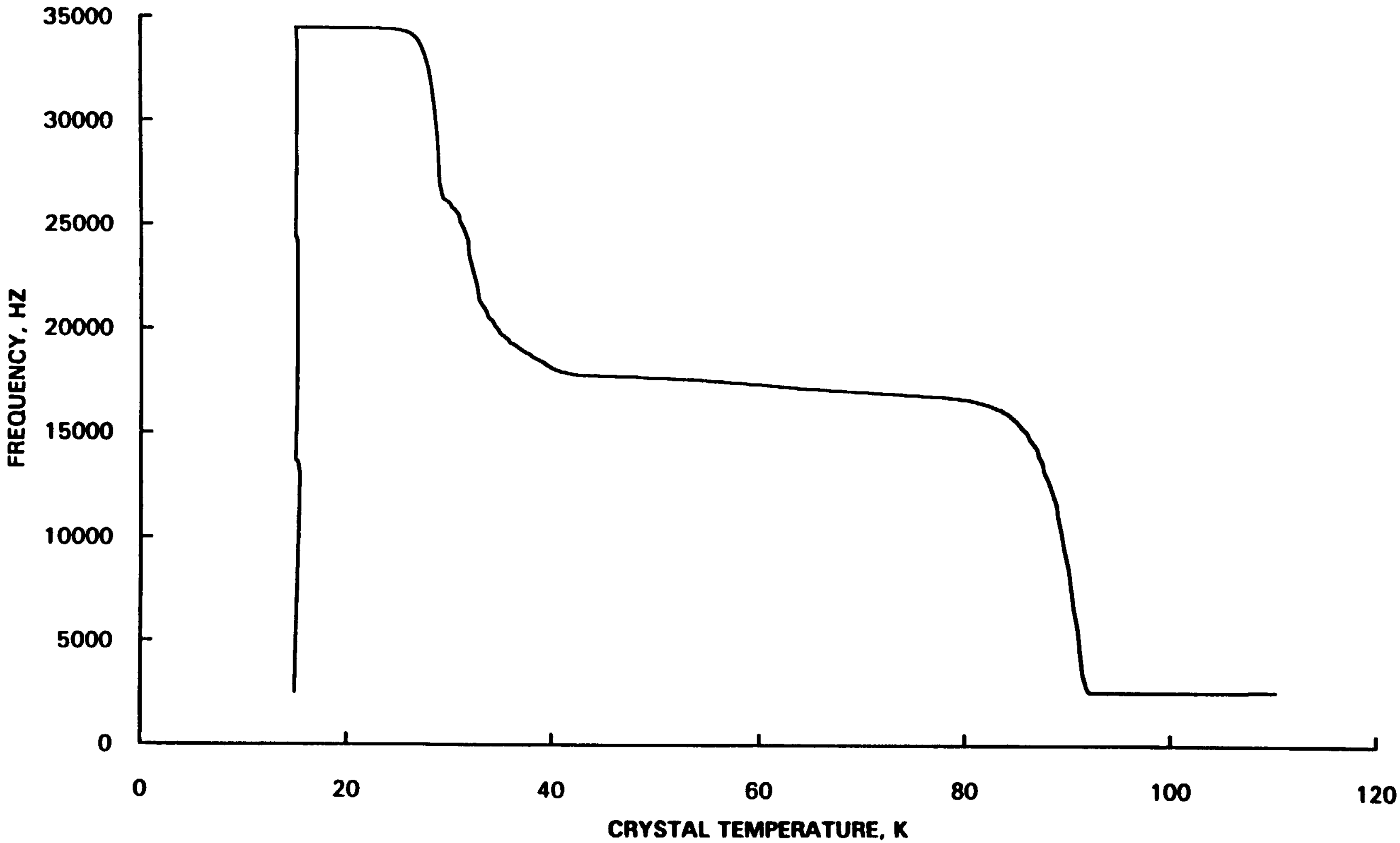
- Purpose: Measure condensed or deposited contamination
- Description: Exposed crystals change frequency when contamination deposits. 4 TQCM's will be placed to measure incoming contamination that is depositing on space craft surfaces. One CQCM is placed next to the SPIRIT III mirror to directly measure contamination thickness. All QCM's can be cleaned by heating the crystals and species type is yielded from a analysis of the frequency vs temperature during heating.
- Sensitivity: TQCM ~< 2ng/cm2/Hz CQCM < 4.2ng/cm2/Hz
- Power:12W continuous/74W Peak Weight: 15 Lbs Volume:2.1x8x12.5
- Telemetry:16 kbit housekeeping includes *f* and T for each QCM sampled once per minute; Min & Max *f*&T for a given interval; heater power; diagnostics.

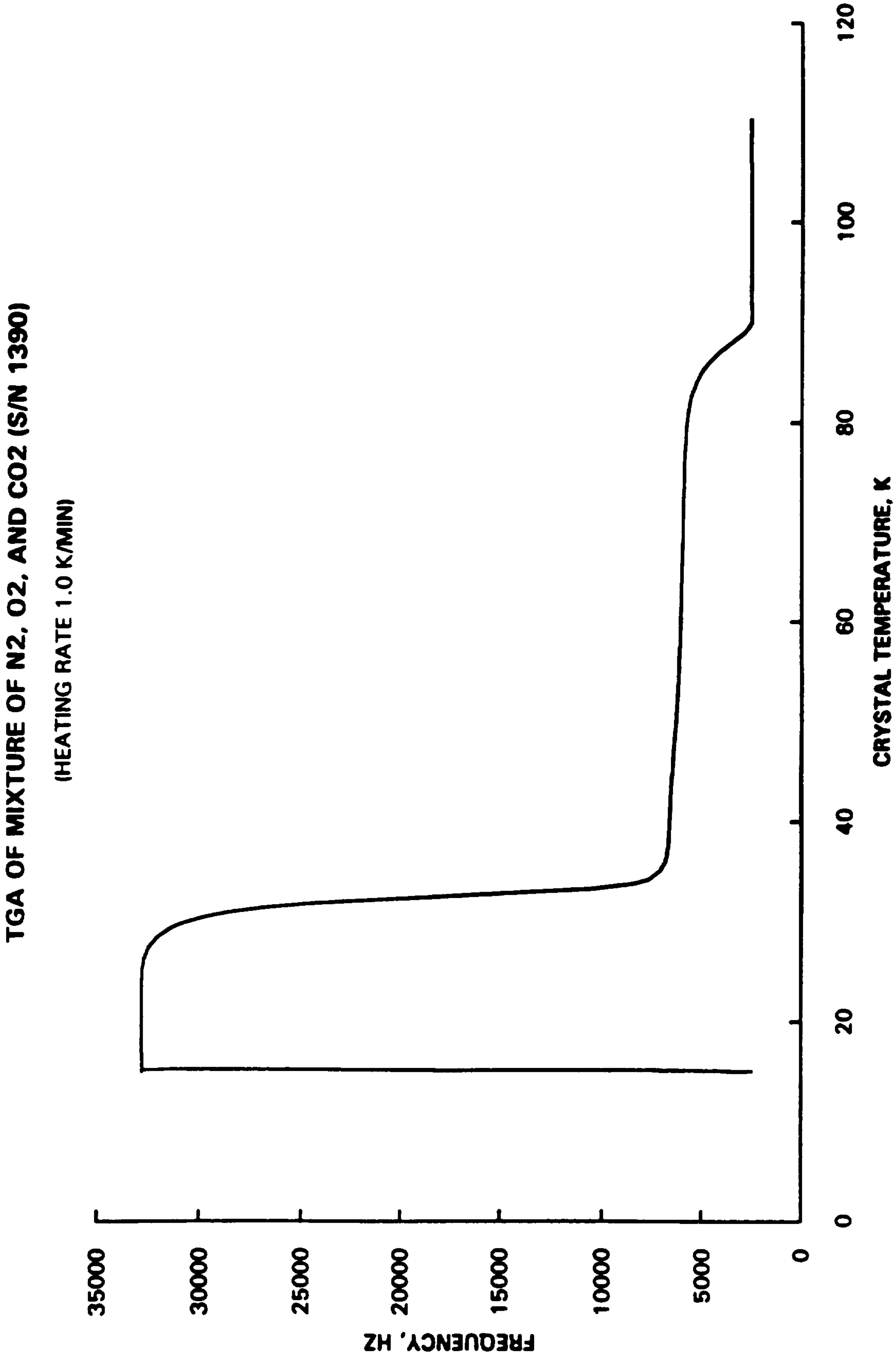




TGA OF LAYERS OF CO2, THEN O2, THEN N2 (S/N 1390)

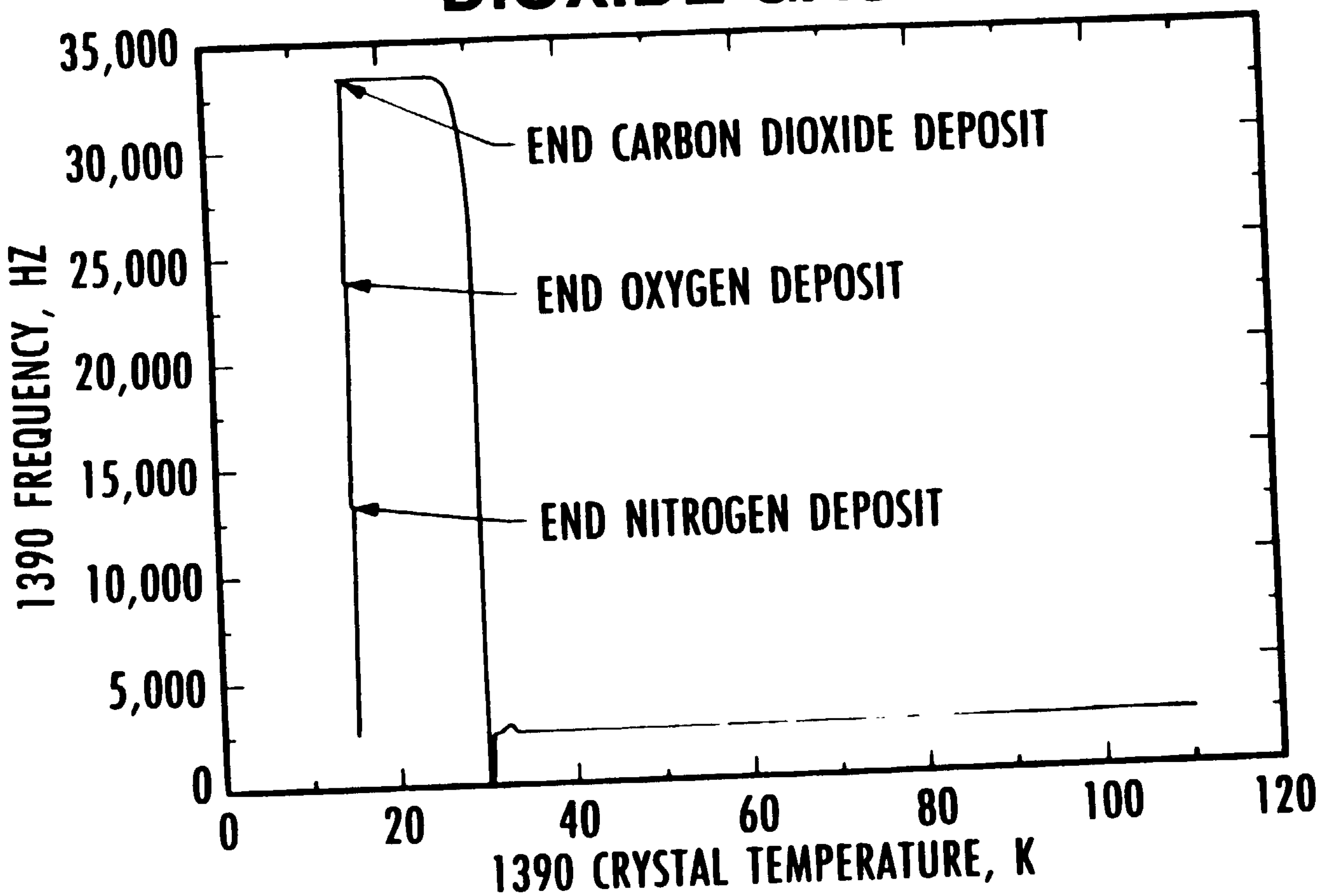
(HEATING RATE 1.0 K/MIN)



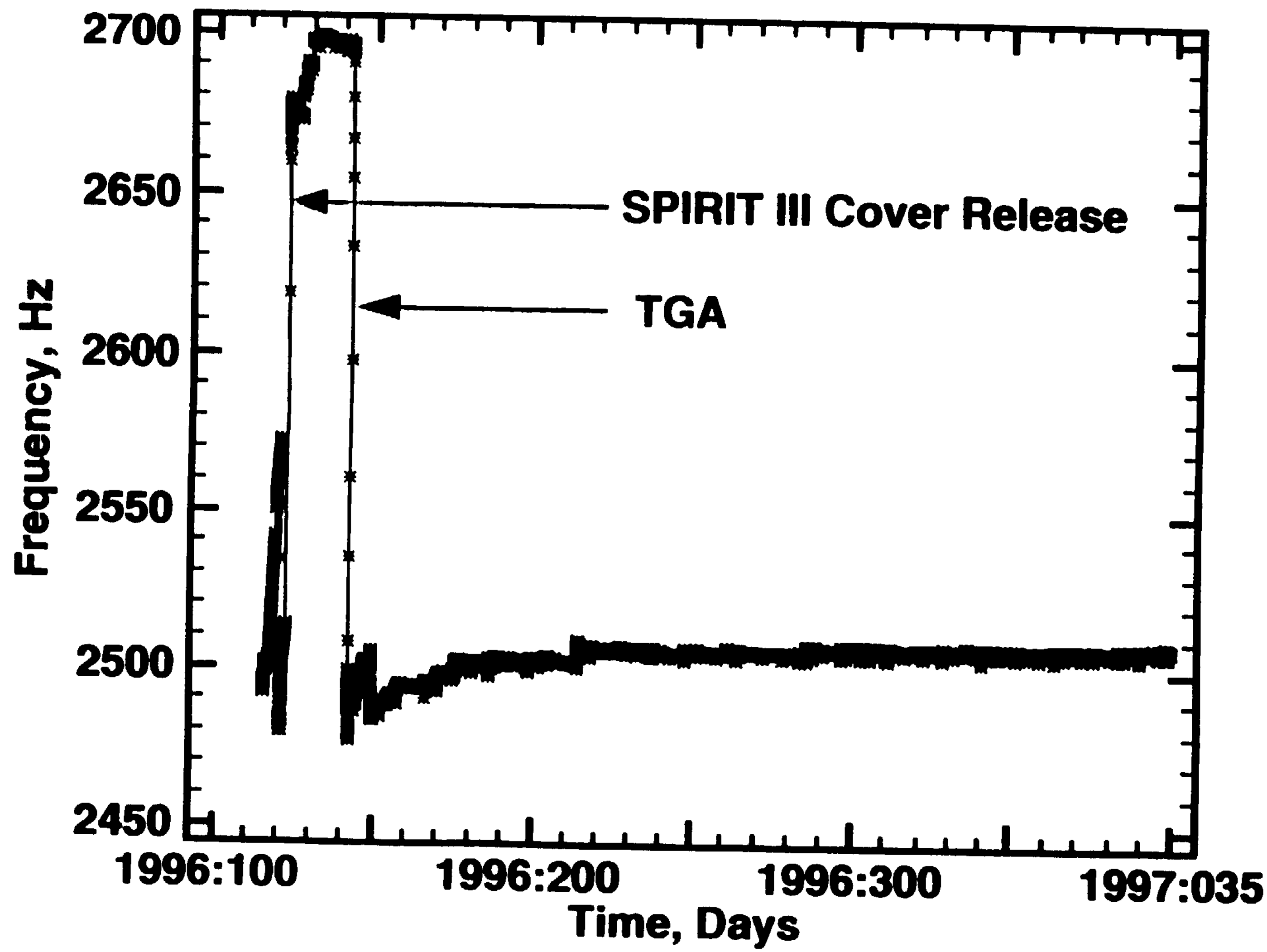


TGA OF MIXTURE OF N2, O2, AND CO2 (S/N 1390)
(HEATING RATE 1.0 K/MIN)
FREQUENCY, HZ
35000
30000
25000
20000
15000
10000
5000
0
CRYSTAL TEMPERATURE, K
0
20
40
60
80
100
120

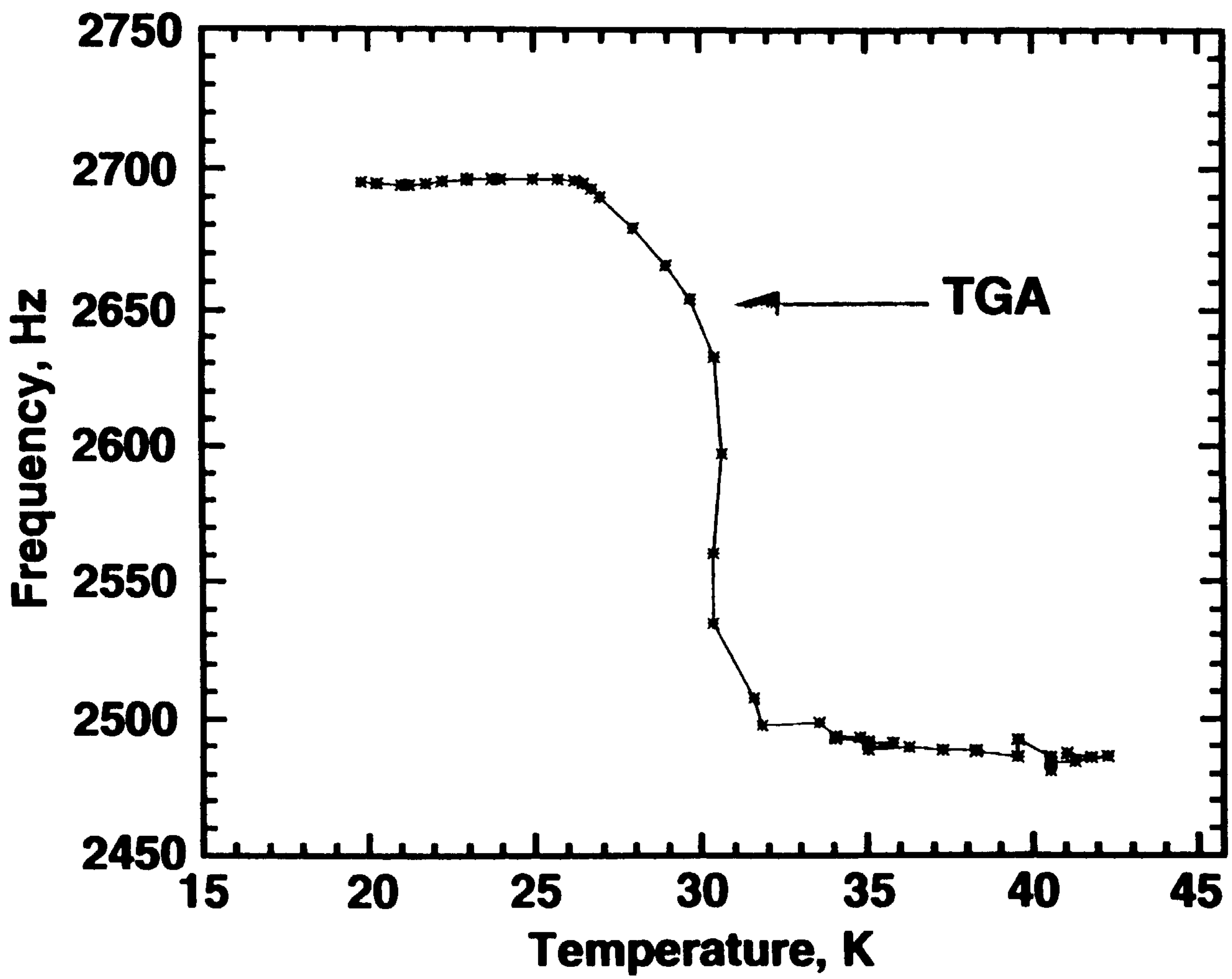
THERMOGRAVIMETRIC ANALYSIS OF CONDENSED LAYERS OF NITROGEN, OXYGEN, AND CARBON DIOXIDE GASES



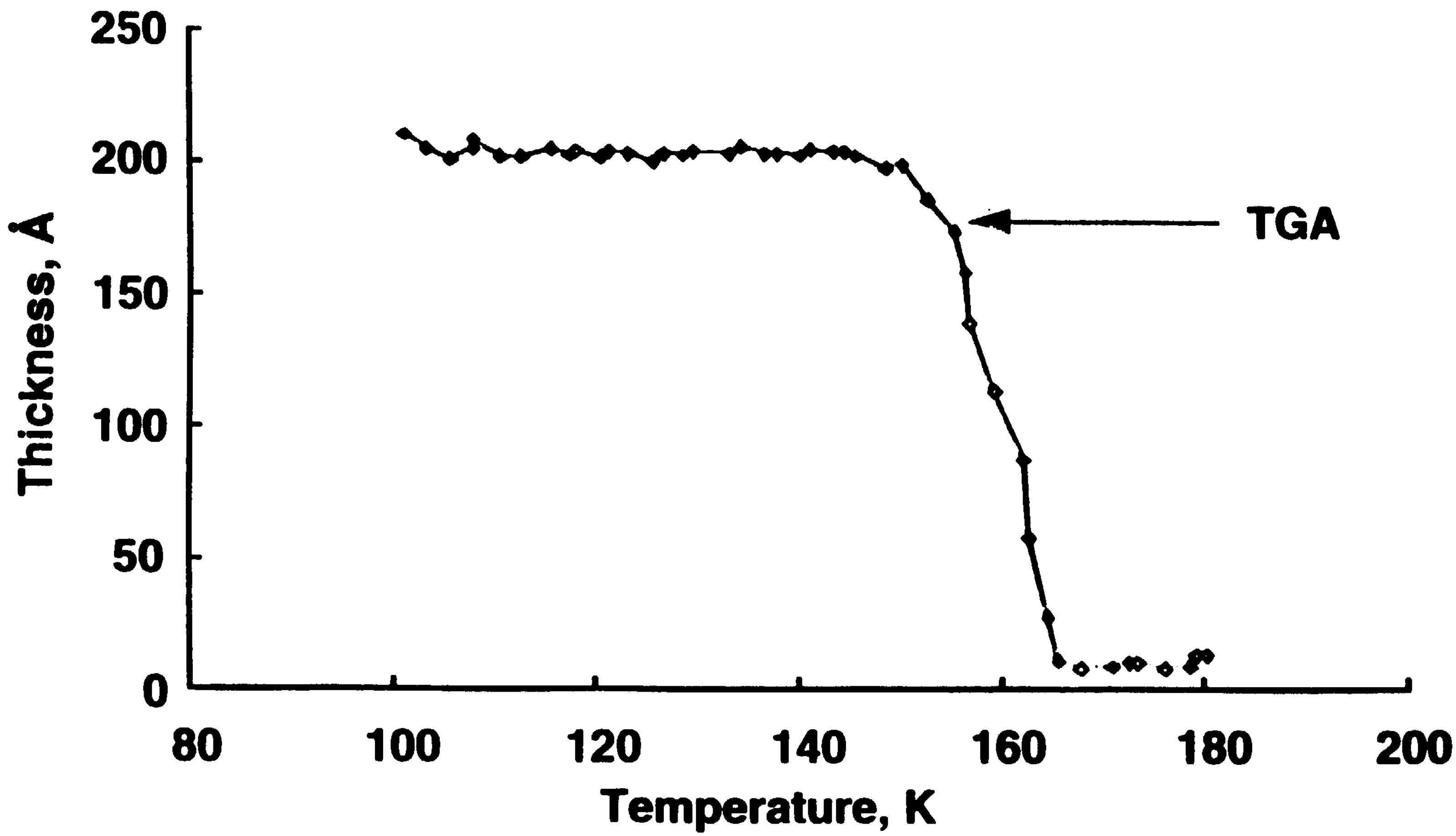
CQCM Frequency versus Time in Days



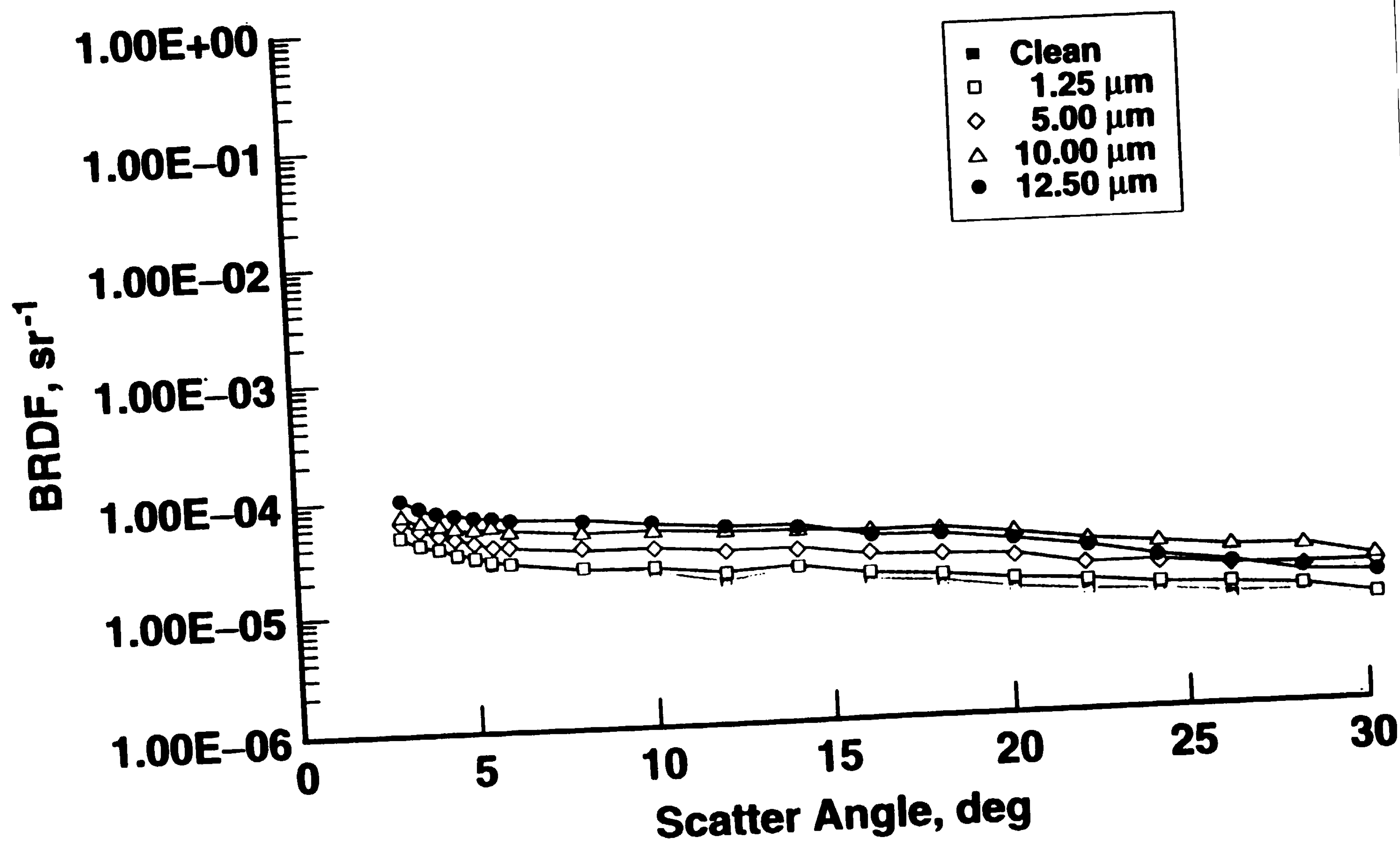
Thermogravimetric Analysis (ΔF vs. Temp) Plot of CQCM with Accreted Mass



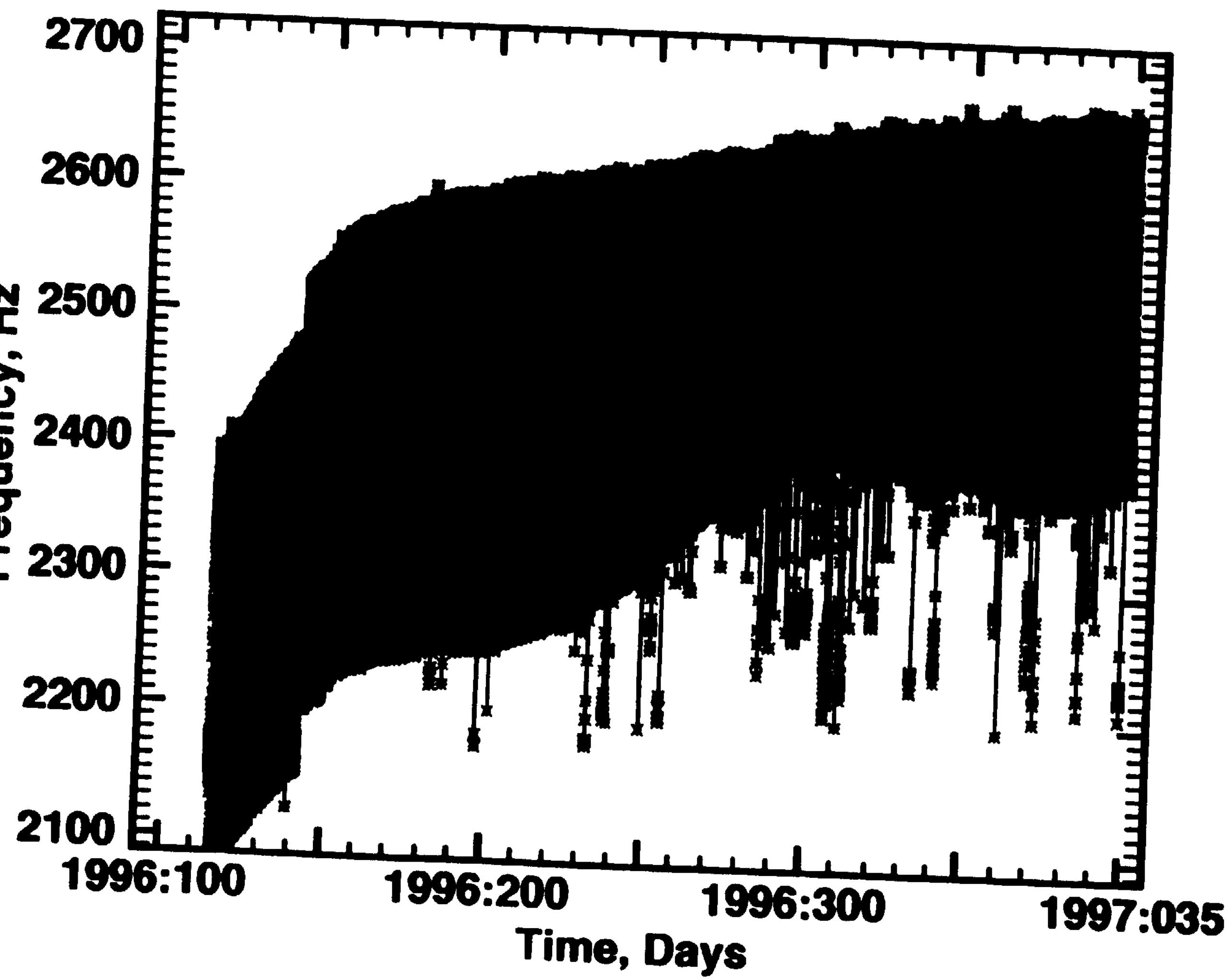
CQCM TGA Performed after SPIRIT 3 Baffle Heating during SECOT



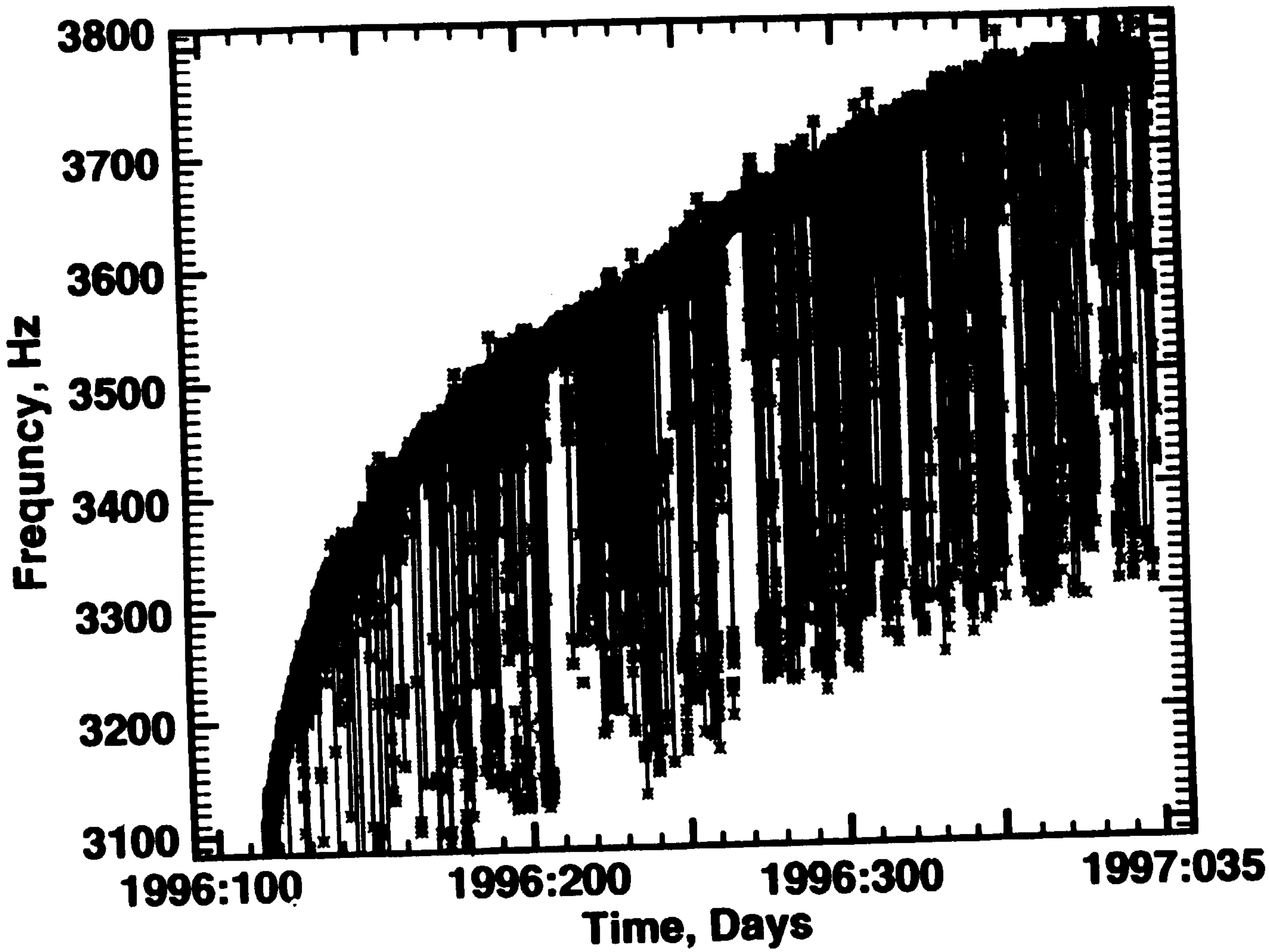
Mirror Scatter Due to Argon Films Condense at 16K and for 10.6μm Wavelength



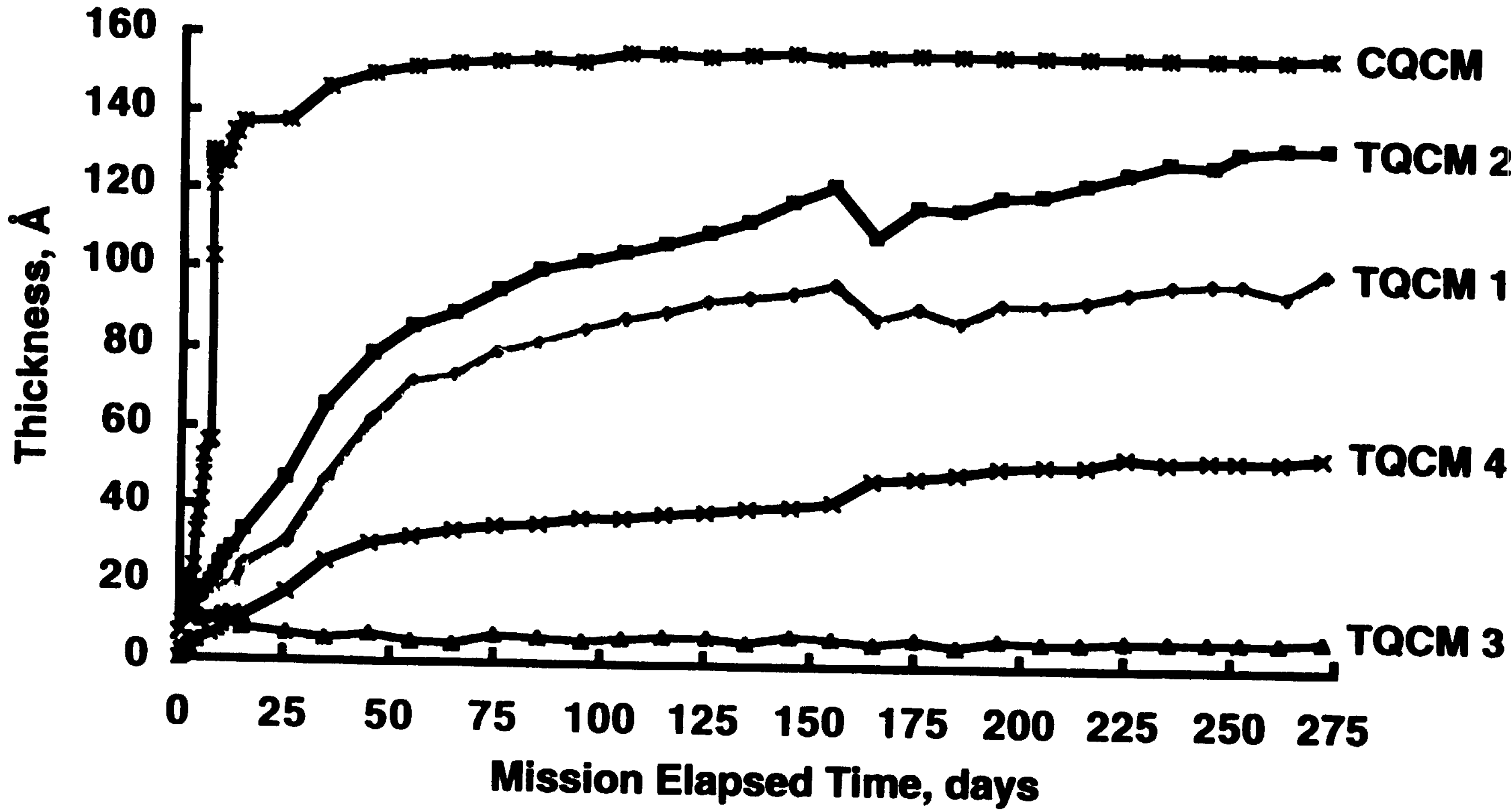
Frequency versus Time Plots for TQCM #4 Showing Increases Due to Accreted Mass



Frequency versus Time Plots for TQCM #2 Showing Increases Due to Accreted Mass



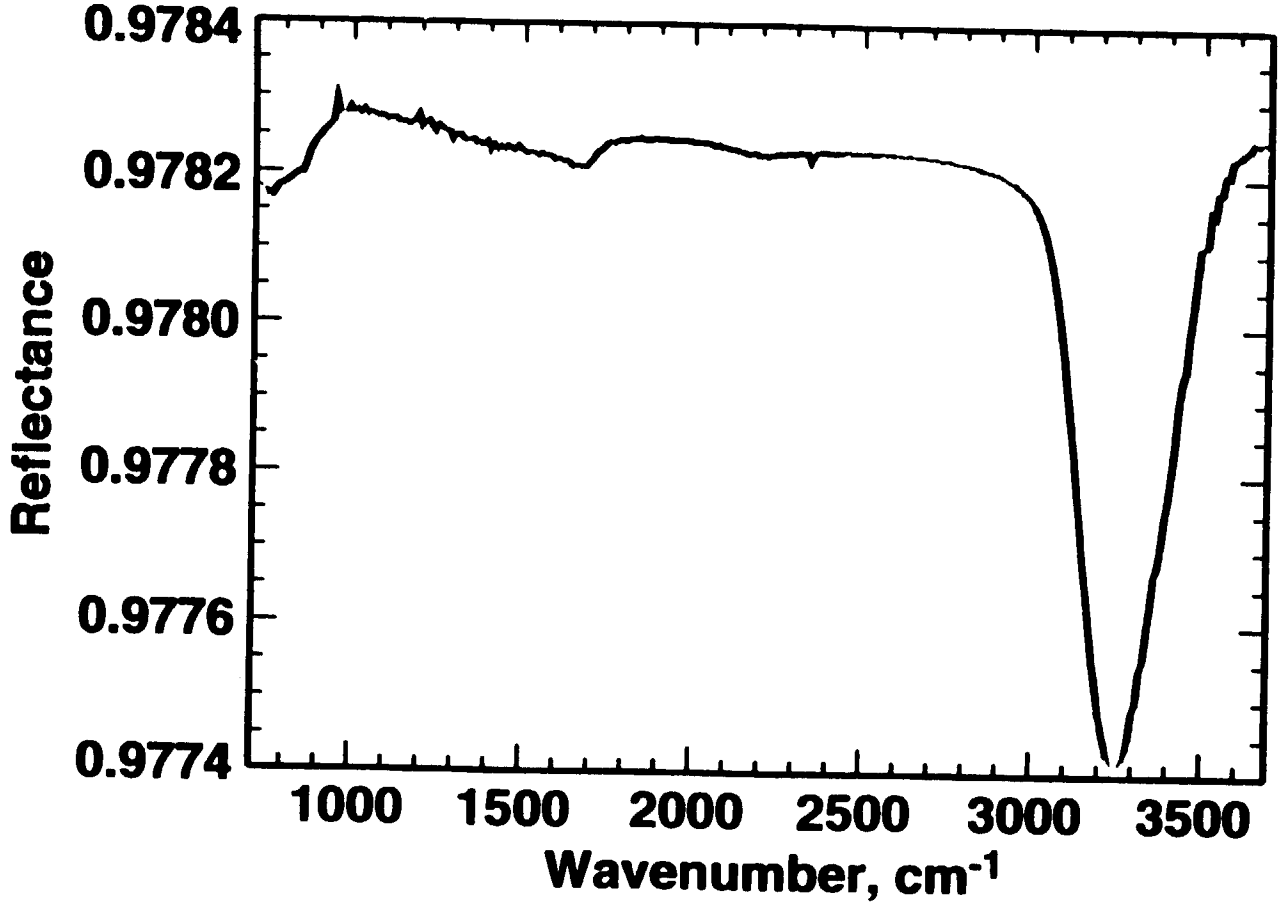
Accreted Contaminant Film Thickness versus Mission Elapsed Time for CQCM and All Four TQCMs



Film Thickness Deposition on Each of the QCMs as of 2/4/97

QCM	Thickness, Å	Location
TQCM #1	102	+Y, +Z
TQCM #2	134	+Z
TQCM #3	7	+Y, –Z
TQCM #4	55	+X, +Z
CQCM	155	SPIRIT 3 Telescope

Calculated Effect of 150 Å Film of H_2O on 20 K Mirror Reflectance



Status of MSX Quartz Crystal Microbalances (6/1/97)

- CQCM located in Spirit 3 and 4 TQCMs located externally are all functioning as designed
- CQCM data has been invaluable in determining the health of the Spirit 3 primary mirror
- Laboratory BRDF data indicates the 155 angstroms thick contaminant film should had negigible effect on scatter of primary mirror
- TQCM data indicate that even after a year in space measurable accretion is continuing on 3 of the 4 TQCMs
- TQCMs having view factors of solar panels are experiencing the largest depositon rates

Summary

- The CQCM was extremely valuable in determining the amount and species of contaminants condensed inside Spirit 3 telescope
- The TQCMs have provided real-time data of organic and silicone material outgassing deposition on satellite external surfaces
- During Spirit 3 End of Cryo Testing (SECOT) CQCM data provided a means for determining H_2O content within the telescope
- QCM radiator temperatures have provided data for determining thermal effects of solarized contaminants

Acknowledgments

The author wishes to acknowledge the support of BMDO and the other members of the MSX Contamination Experiment Team:

JHU/APL -- O.M. Uy, J.C. Lesho, M.T. Boies, D.M. Silver, R.C. Benson, R.E. Erlandson and R.P. Cain

PSI, Inc. ---B.D. Green and G.A. Galica

Aerospace Corporation -- D.F. Hall

USU/SDL -- J.S. Dyer

Applications of ASTM E 1559 for Material Characterization

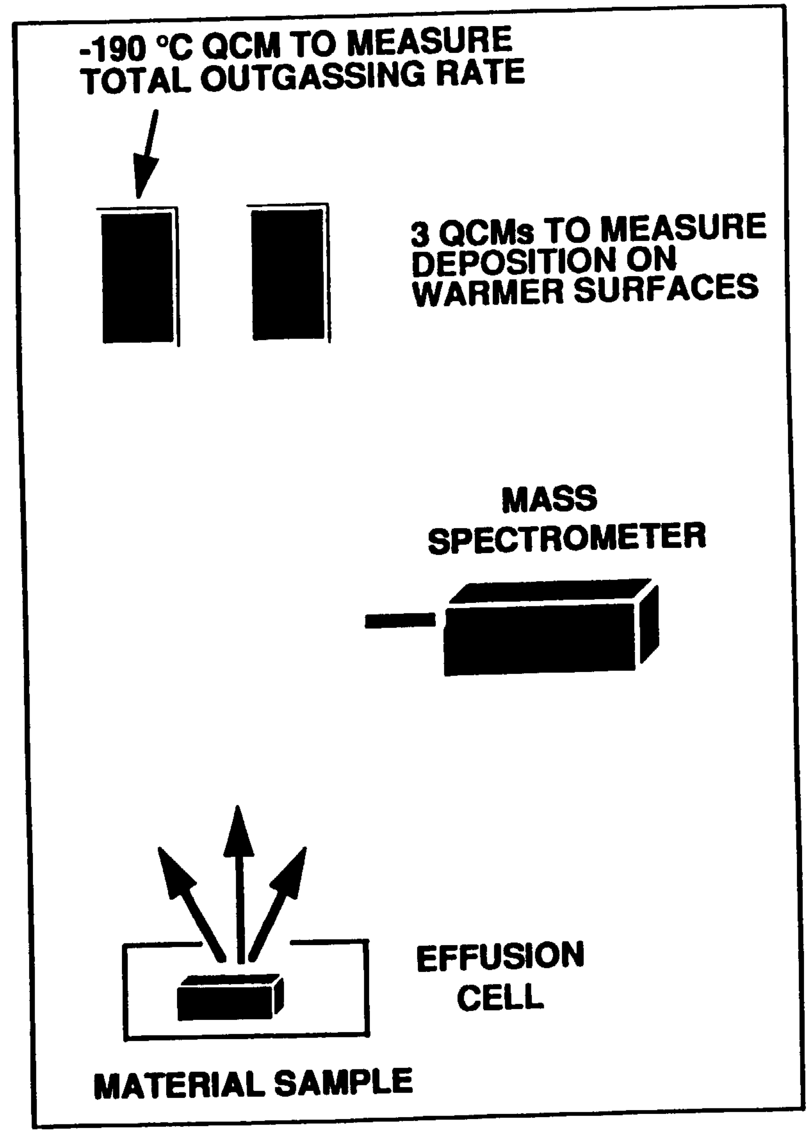
Jeff Garrett
Lockheed Martin Missiles & Space
Sunnyvale, CA

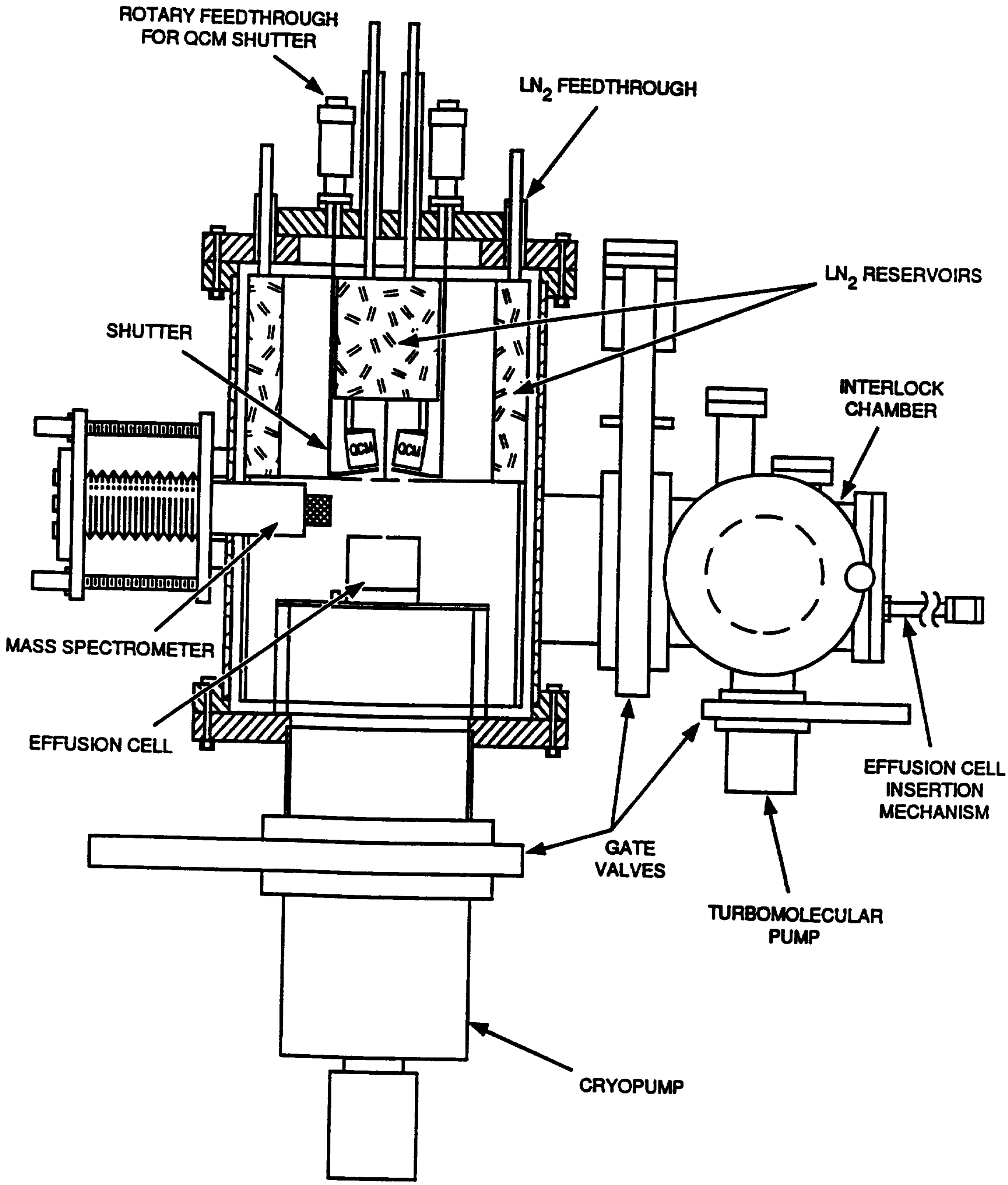
July 10, 1997

ASTM E 1559
OUTGASSING/DEPOSITION KINETICS TEST

MATERIALS OUTGASSING

- TML AND VCM OF 0.0001% ARE MEASURED
- OUTGASSING RATES FROM 10^{-14} g/cm^2/s TO 10^{-5} g/cm^2/s CAN BE MEASURED
- SAMPLE TEMPERATURE RANGE IS FROM 25° TO 150 °C
- COLLECTOR QCMs CAN BE TEMPERATURE CONTROLLED FROM -190 °C TO 125 °C
- MASS SPECTROMETER TYPICALLY SCANS SPECTRA IN THE 2 TO 800 AMU RANGE
- QCMs ARE HEATED TO ANALYZE THE COLLECTED DEPOSIT
- TEST ALSO MEASURES THE VAPOR PRESSURES OF OILS AND GREASES




ROTARY FEEDTHROUGH
FOR QCM SHUTTER
LN_2 FEEDTHROUGH
LN_2 RESERVOIRS
SHUTTER
QCM
QCM
INTERLOCK
CHAMBER
MASS SPECTROMETER
EFFUSION CELL
EFFUSION CELL
INSERTION
MECHANISM
GATE
VALVES
TURBOMOLECULAR
PUMP
CRYOPUMP

DATA REDUCTION

ISOTHERMAL OUTGASSING TEST

(Raw data: frequencies of QCMs as a function of time for a constant sample temperature)

- **ex situ Total Mass Loss** (%, g/cm^2):
  - mass loss from sample determined by pre- and post-test weighings of sample
- **Total Mass Loss** (%, g/cm^2):
  - mass loss from sample determined by deposit on 80 K QCM
- **Volatile Condensable Material** (%, g/cm^2):
  - mass loss from sample determined by deposit on 160 K, 220 K and 298 K QCMs

* **Outgassing Rate** (g/cm^2 s):
  - rate of mass loss from sample determined by deposition rate on 80 K QCM

* Optional

QCM THERMOGRAVIMETRIC ANALYSIS (QTGA)

(Raw data: frequencies of QCMs as a function of temperature - sample not present)

- **Mass Loss from QCM** (g/cm^2):
  - determined as deposit on QCM reevaporates during heat up of QCM

* **Evaporation Rate from QCM** (g/cm^2 s):
  - rate of mass loss from deposit on QCM during heat up of QCM

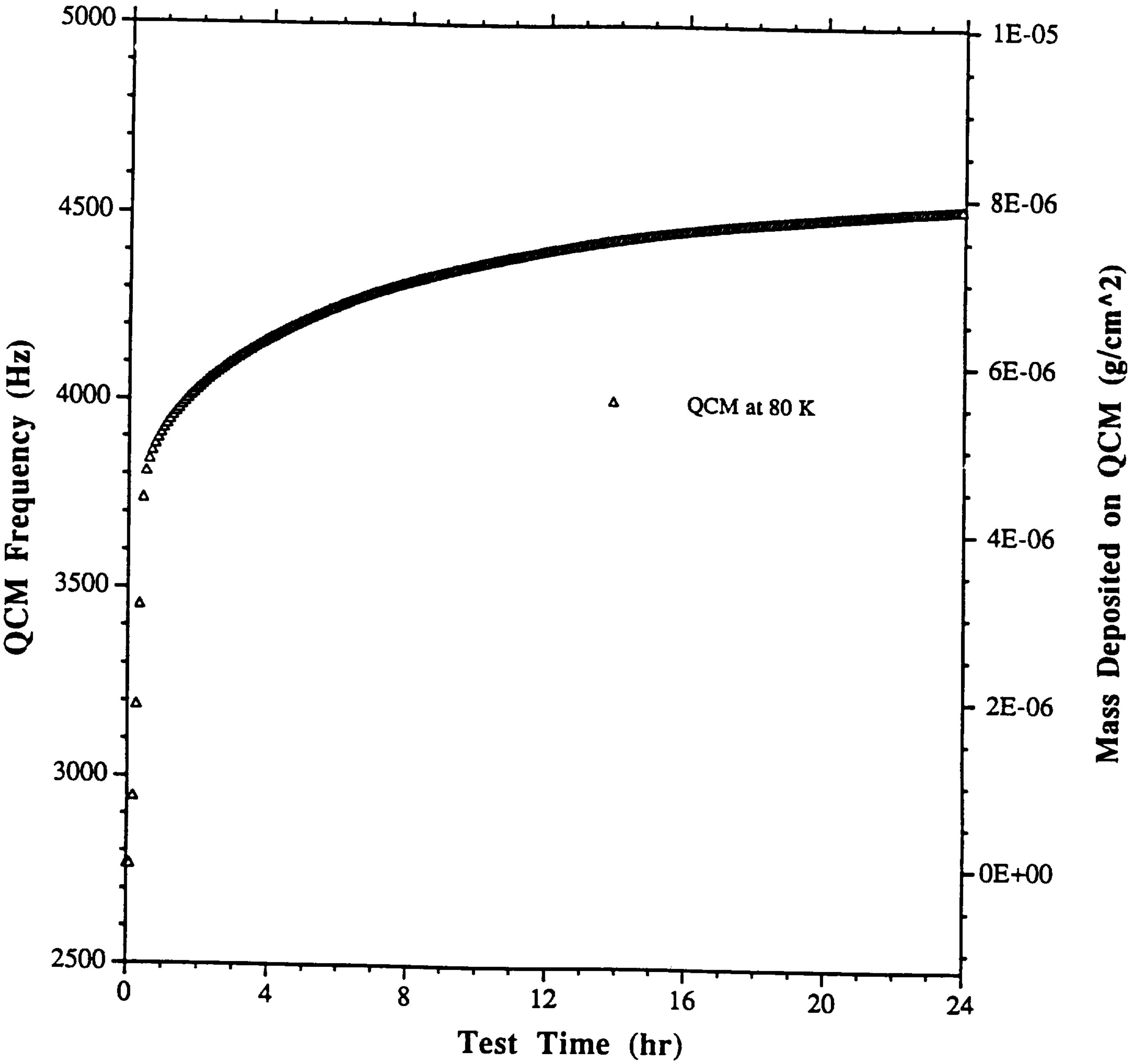
* **Relative Percentage of Species**

* **Mass Spectrometer Identification of Species**

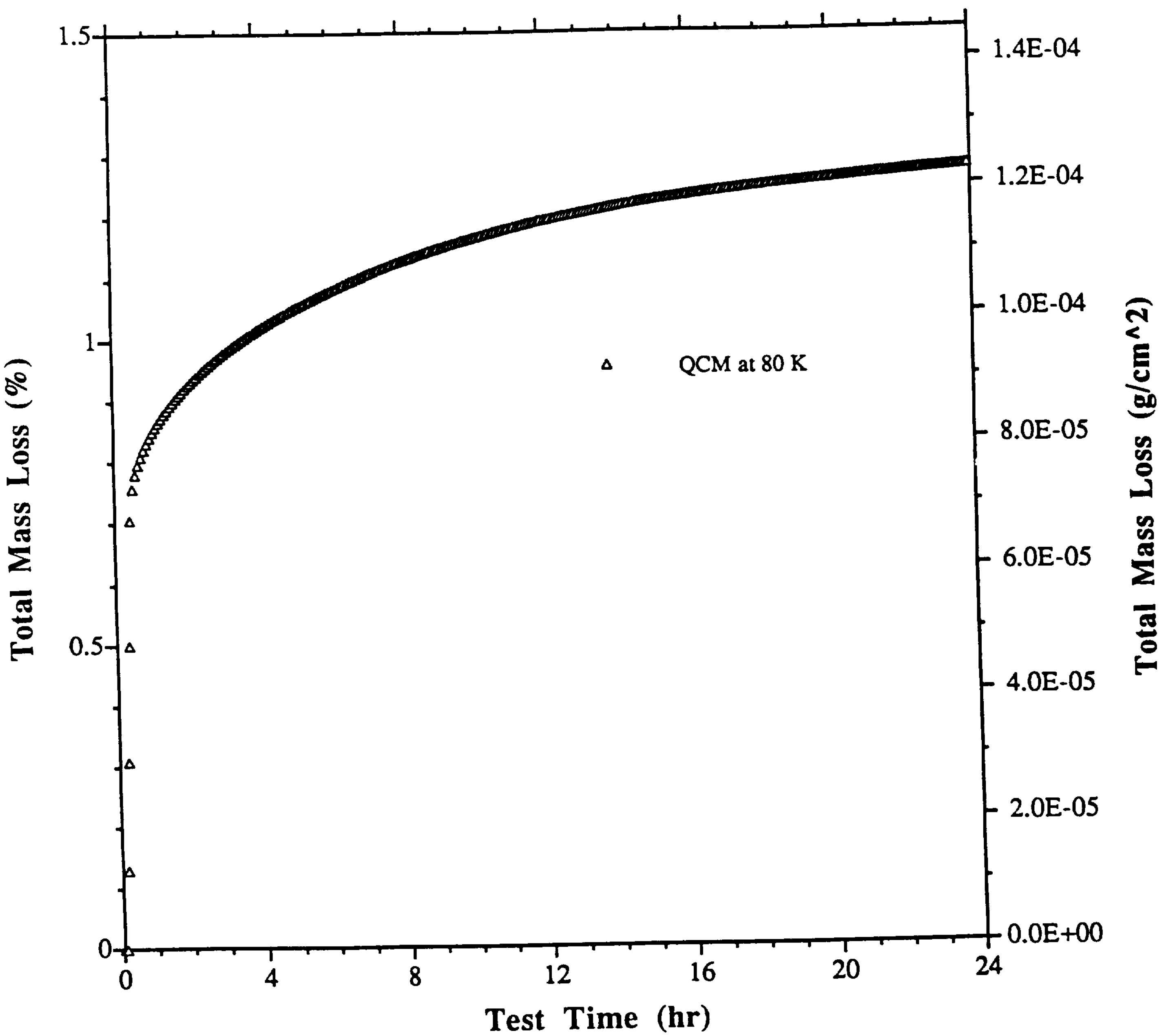
* Optional

Example #1

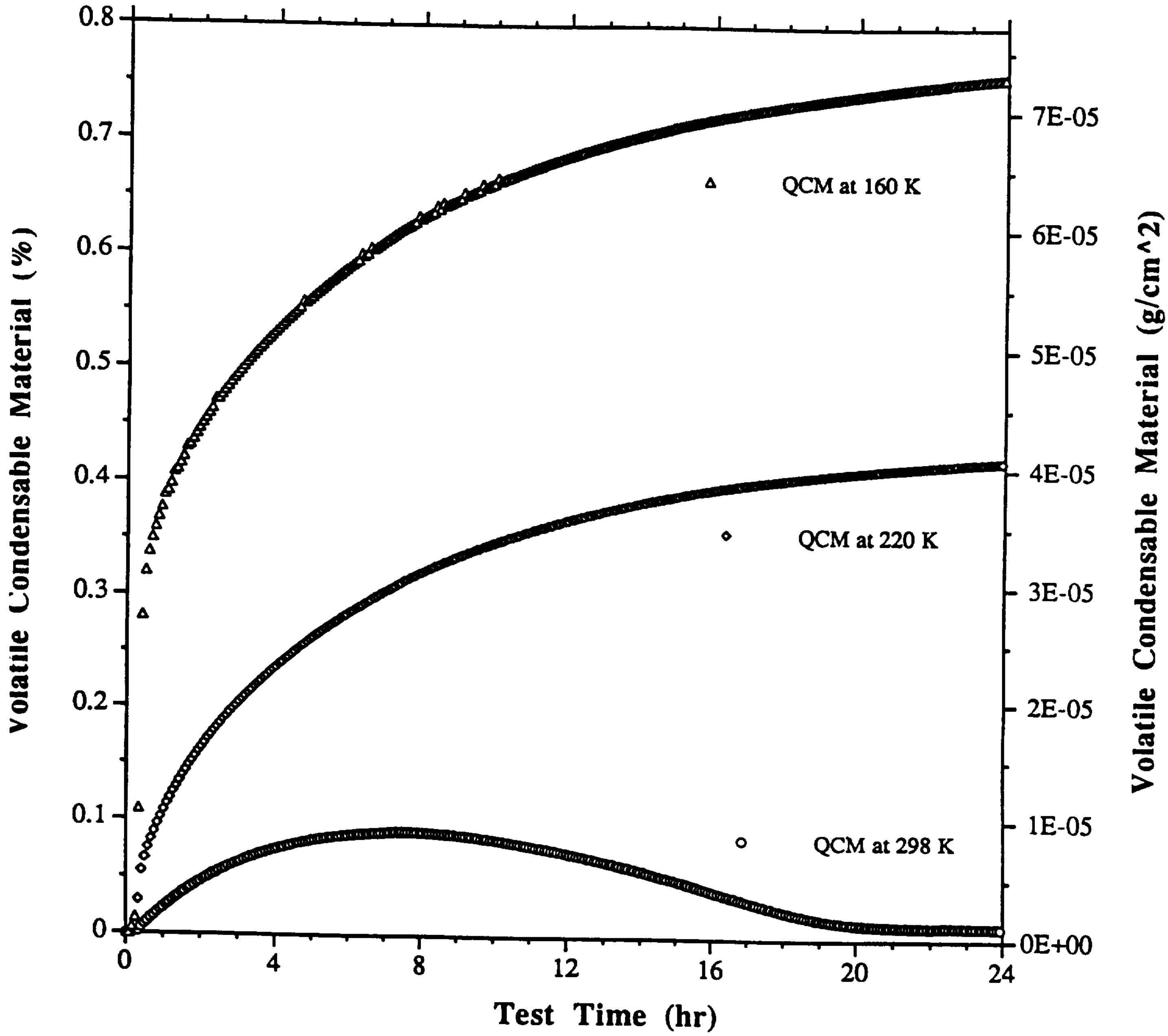
Chemglaze Z306 with Deft primer



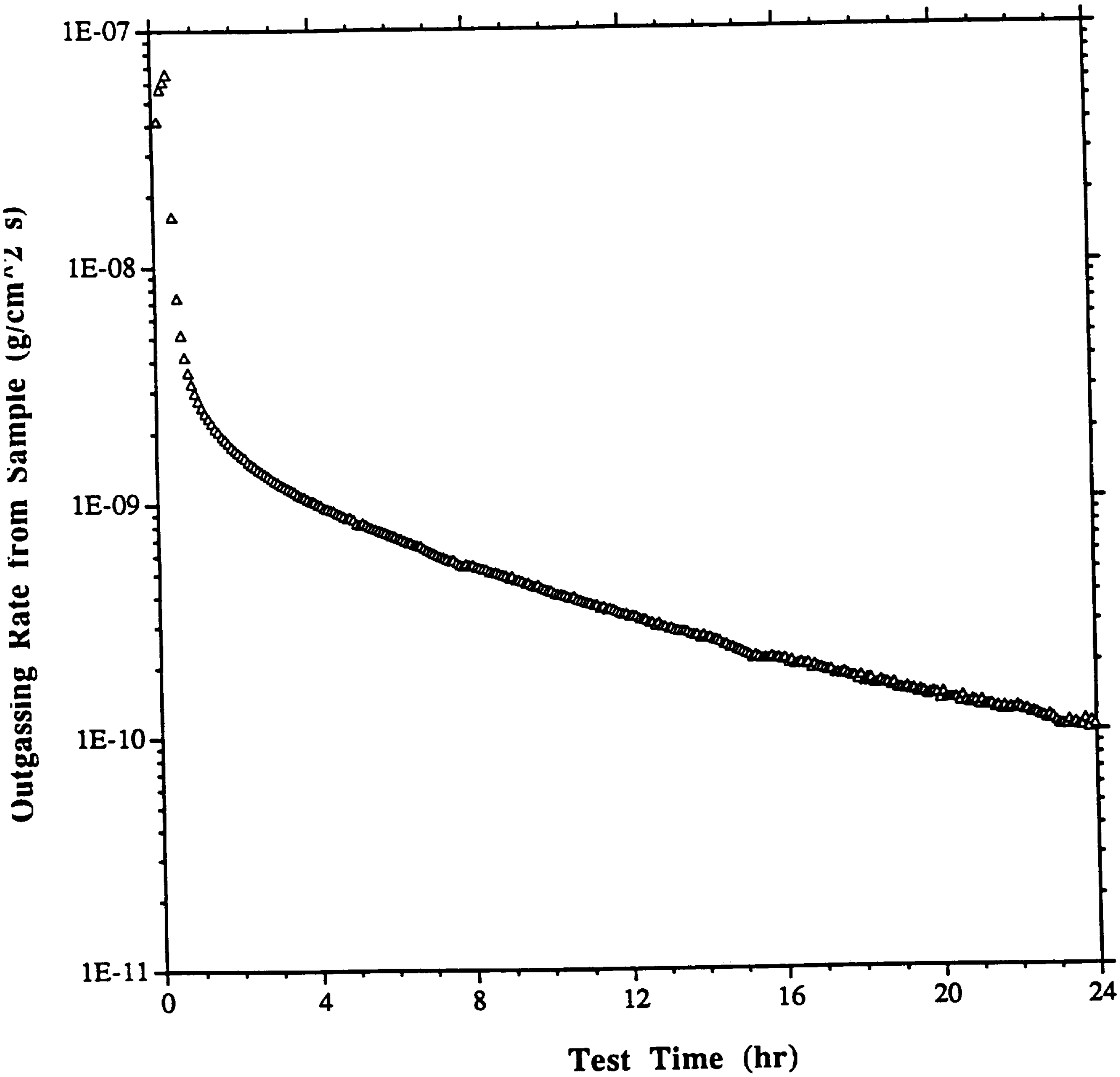
QCM Frequency and Mass Deposited on QCM during the Isothermal Outgassing Test on Chemglaze Z306/Deft Primer at 125°C.



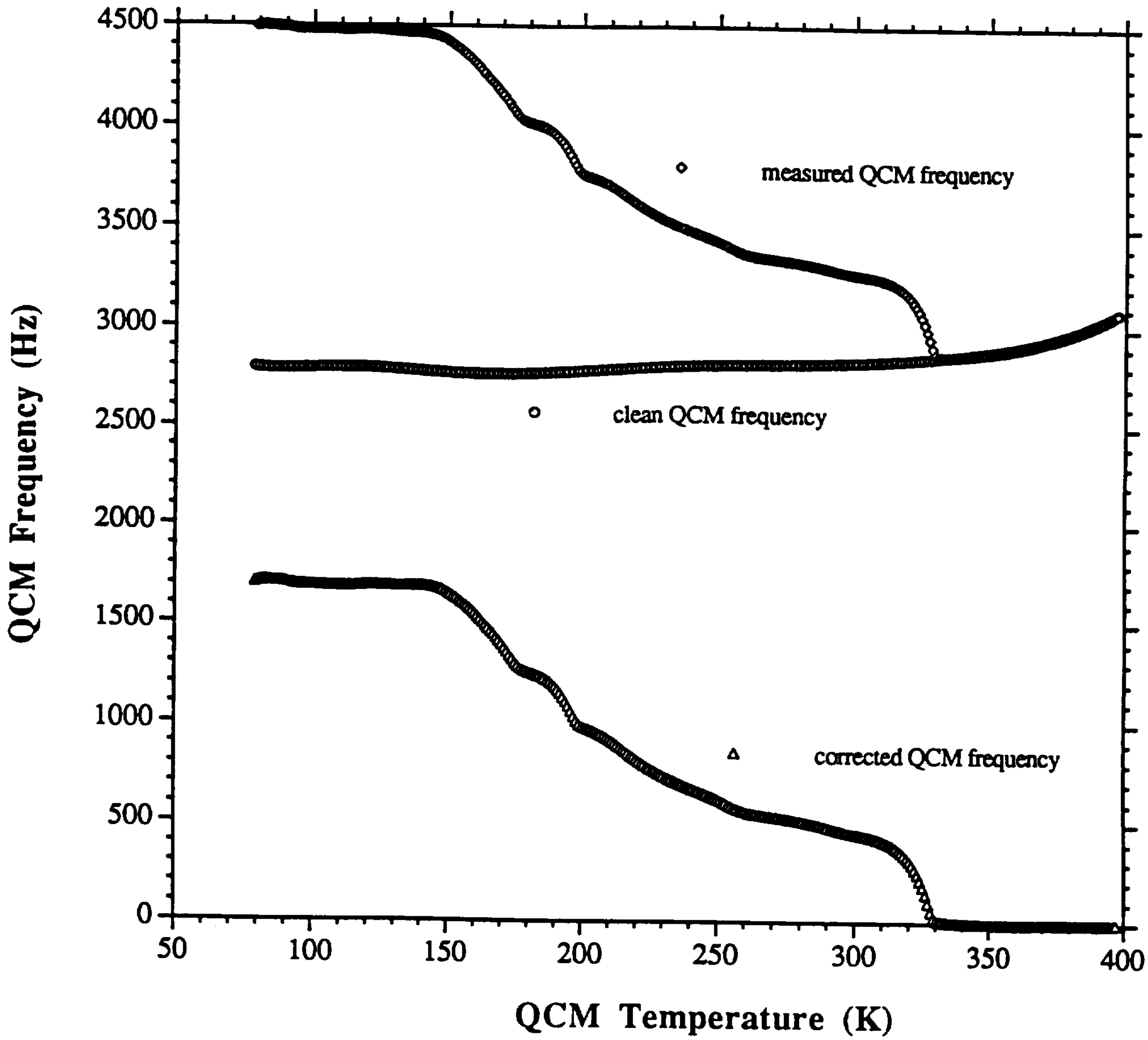
Total Mass Loss from the Sample during the Isothermal Outgassing Test of Chemglaze Z306/Deft Primer at 125°C.



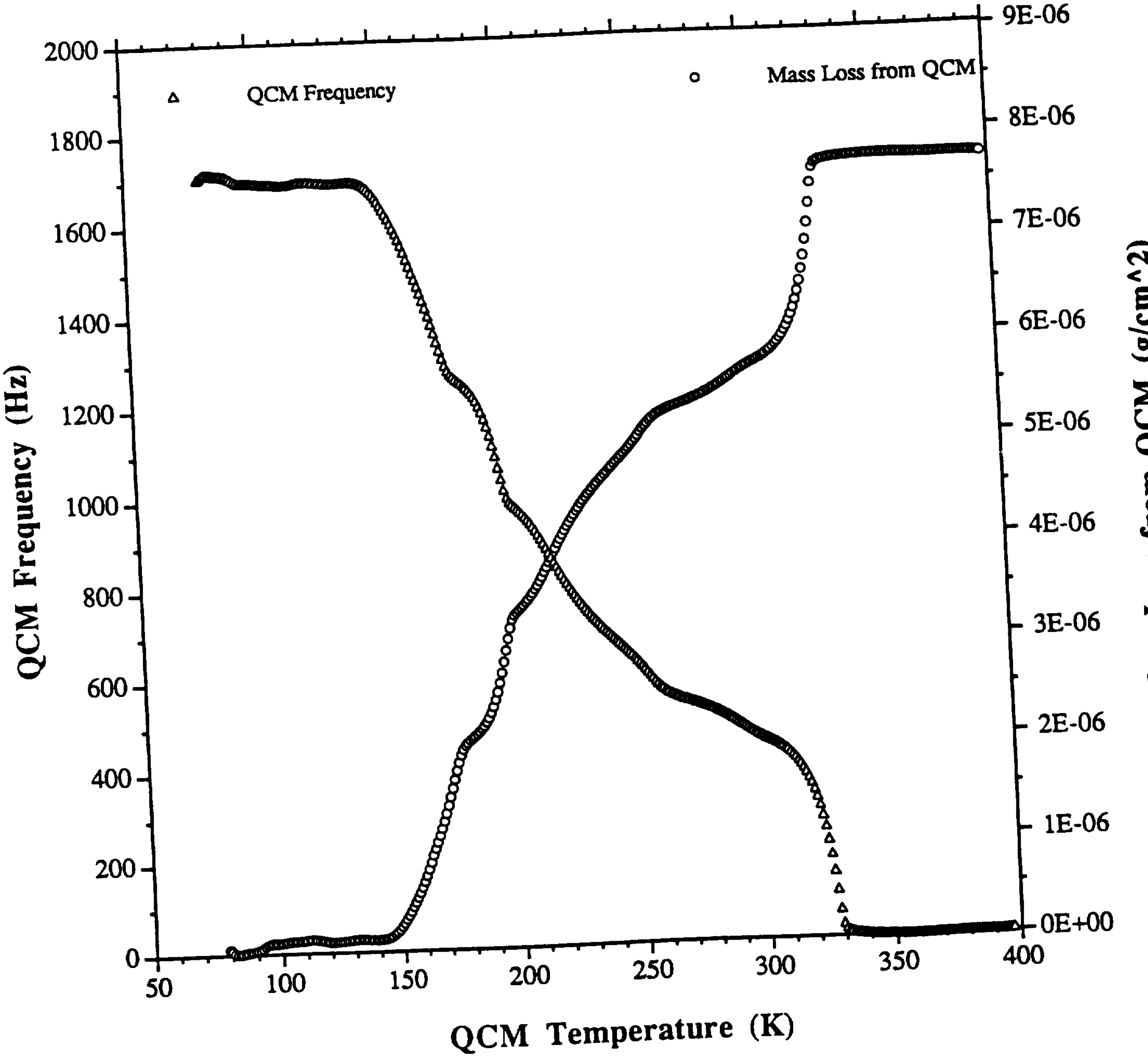
Volatile Condensable Material for QCMs at 160 K, 220 K, and 298 K during the Isothermal Outgassing Test on Chemglaze Z306/Deft Primer at 125°C.



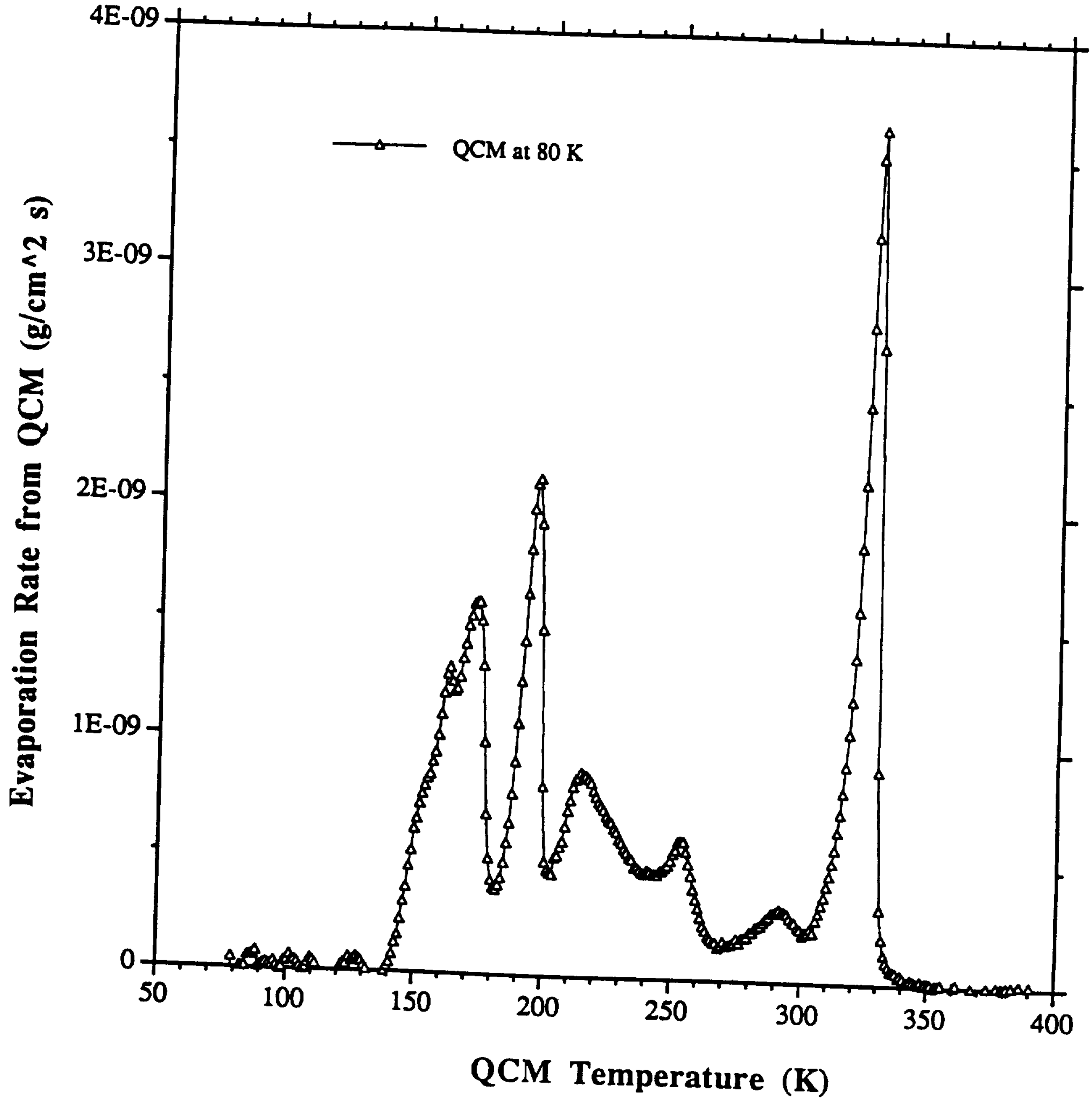
Outgassing Rate from the Sample during the Isothermal Outgassing Test on Chemglaze Z306/Deft Primer at 125°C.



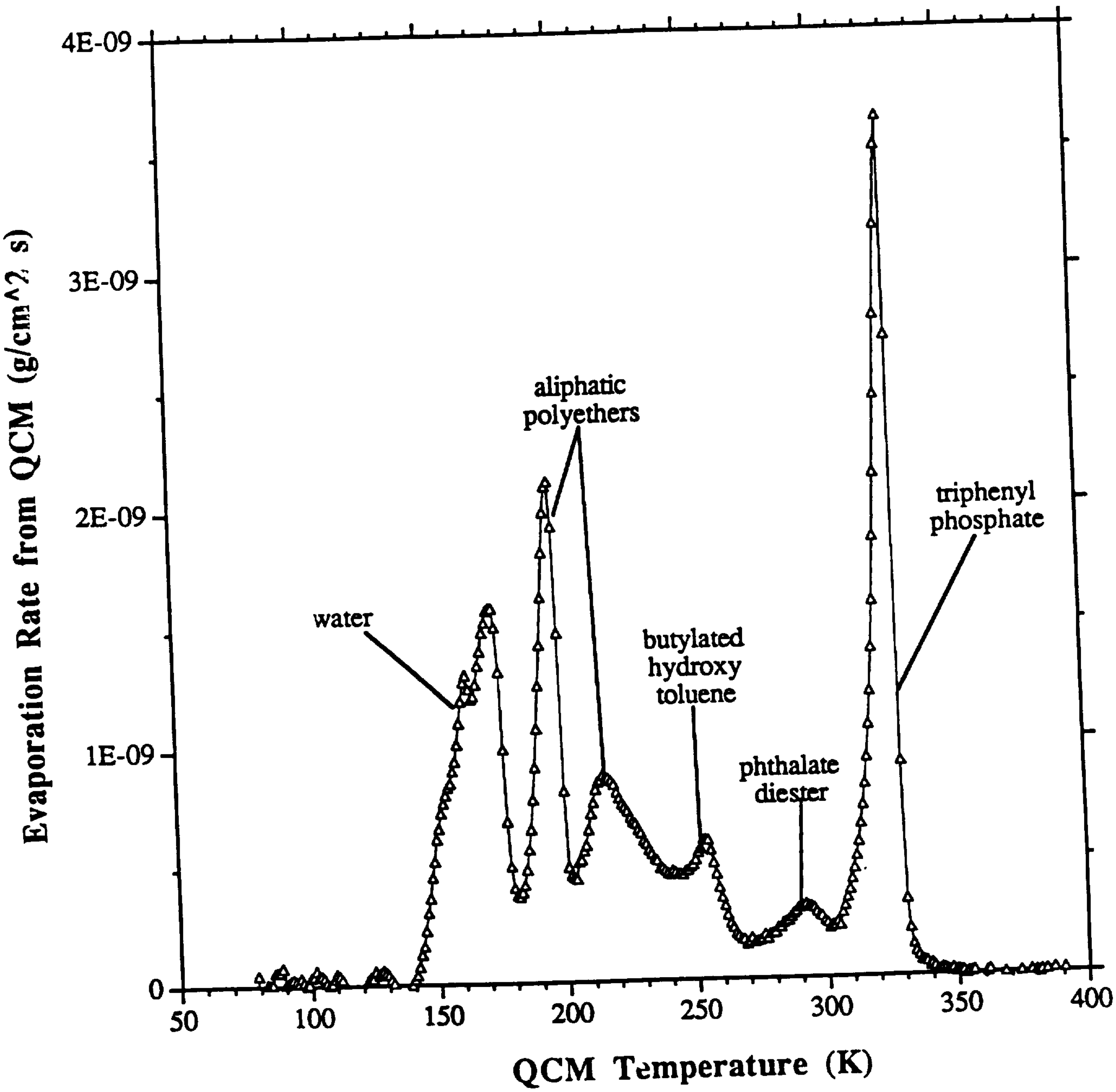
Measured and Corrected Frequencies for the 80 K QCM during the QTGA of the Collected Deposit from Chemglaze Z306/Deft Primer at 125°C.



Mass Loss from the 80 K QCM during the QTGA of the Collected Deposit from Chemglaze Z306/Deft Primer at 125°C.



Evaporation Rate from the 80 K QCM during the QTGA of the Collected Deposit from the Chemglaze Z306/Deft Primer at 125°C.

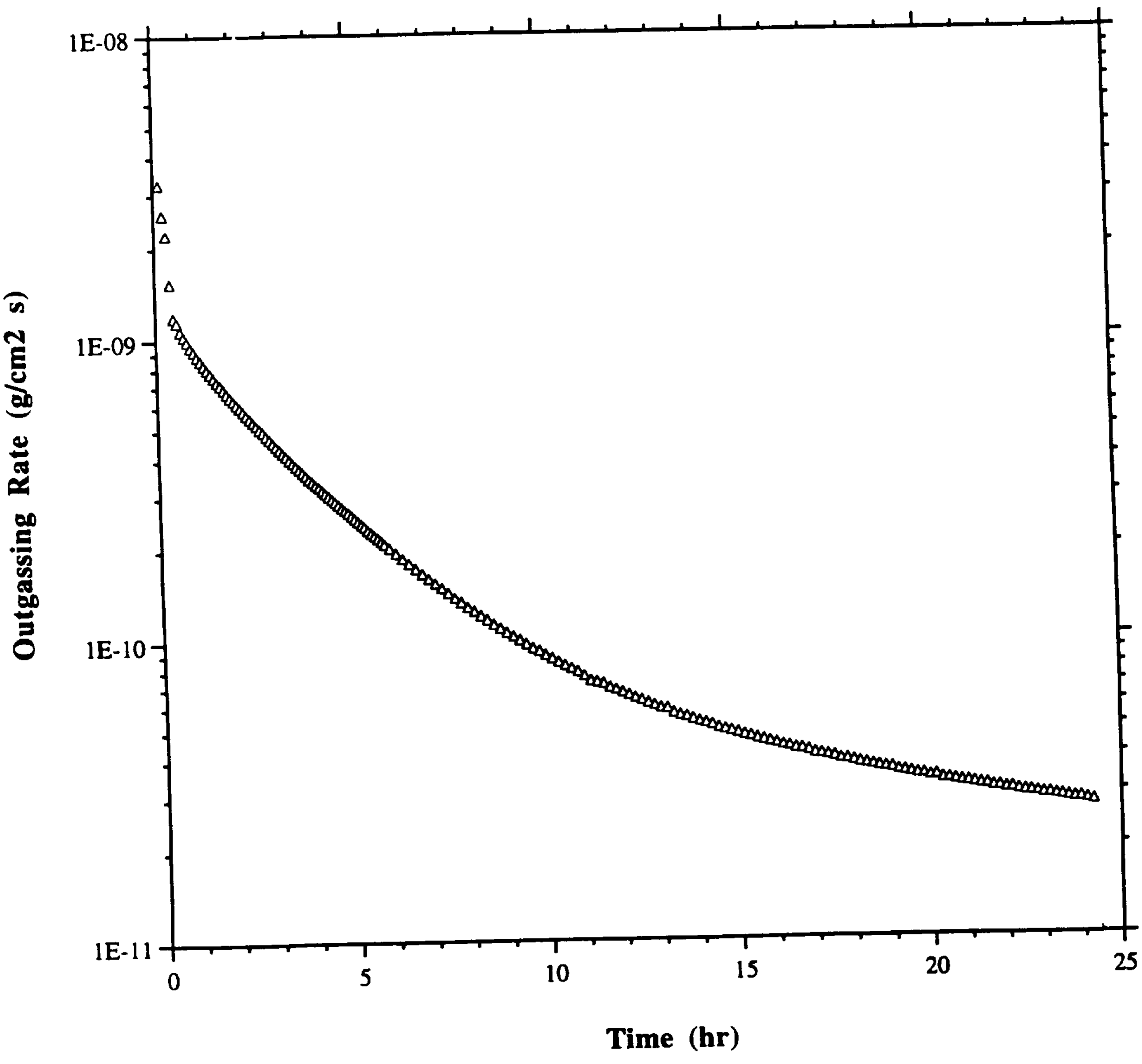


Evaporation Rate from the 80 K QCM during the QTGA of the Collected Deposit from the Chemglaze Z306/Deft Primer at 125°C.

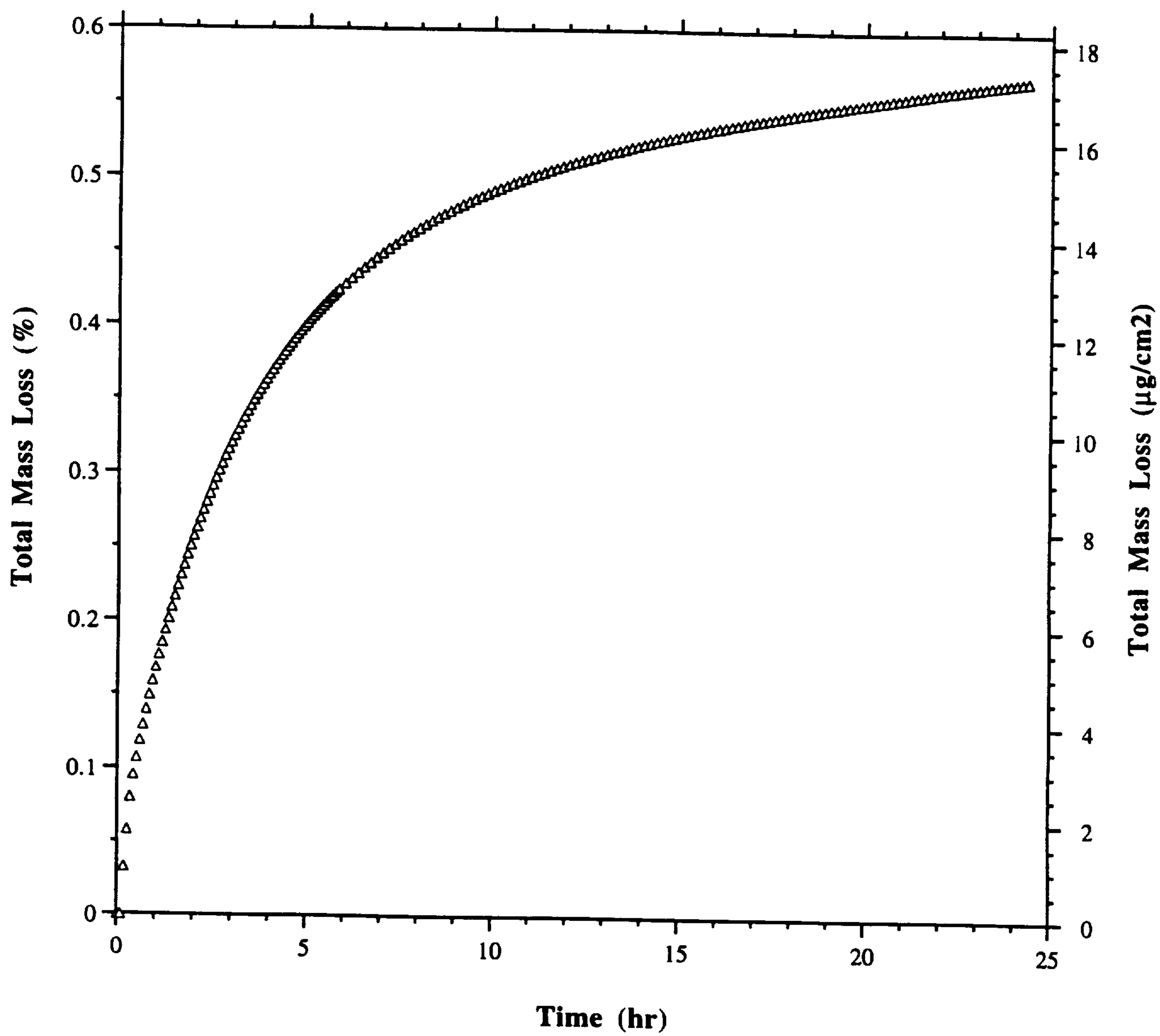
Example #2

Contaminated Kapton

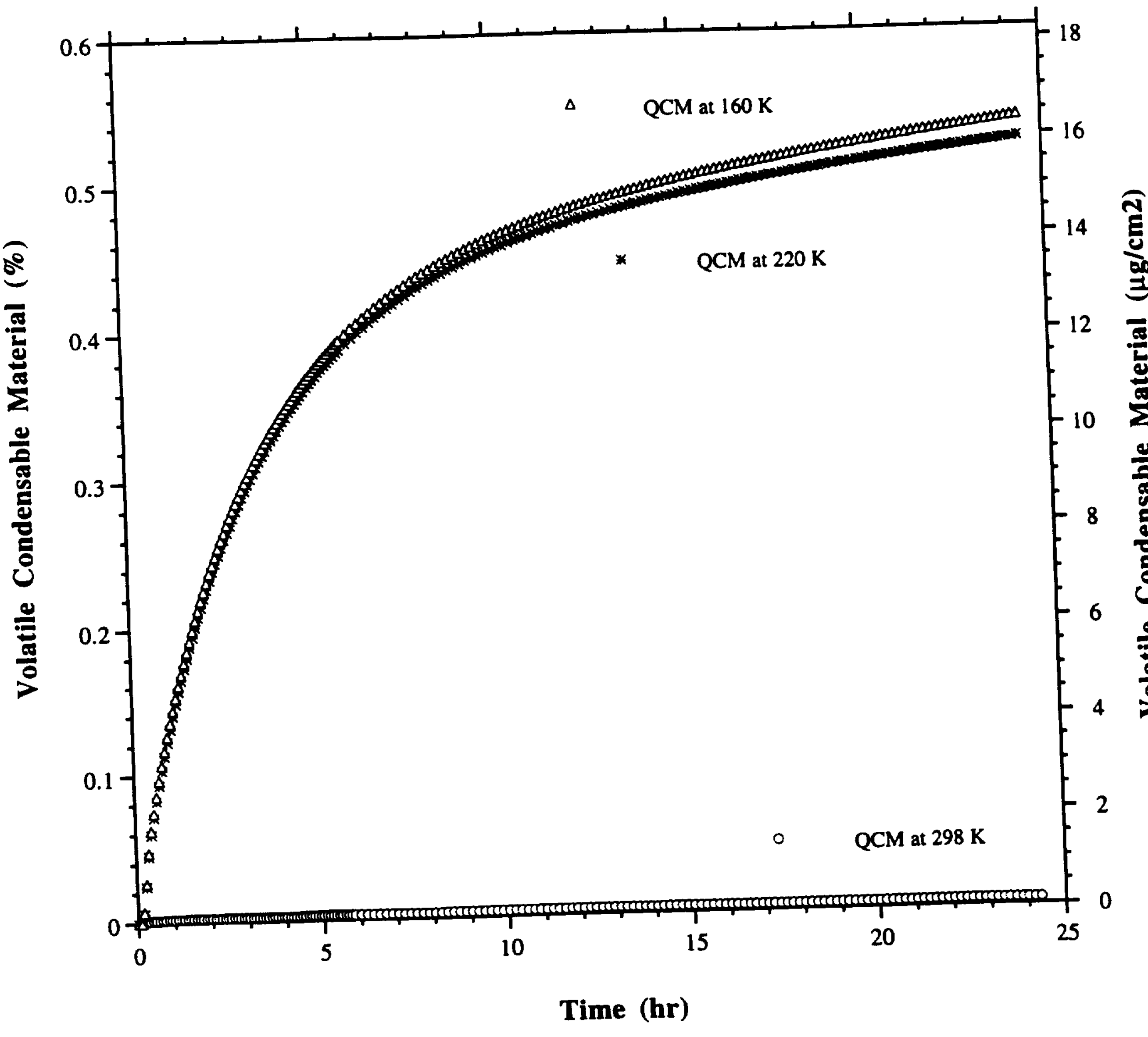
96JUN03: Kapton (contaminated) at 150°F.



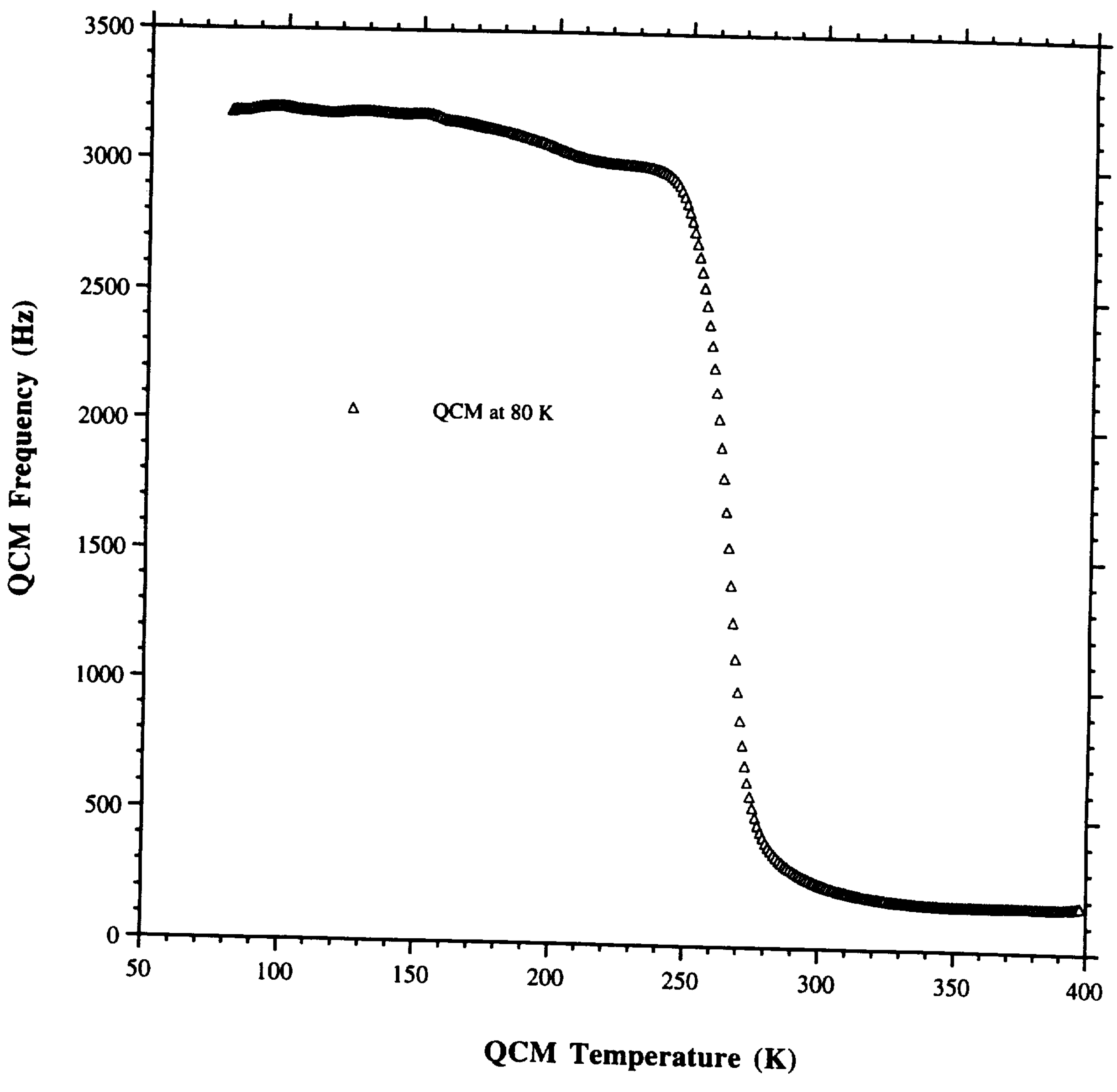
96JUN03: Kapton (contaminated) at 150°F.



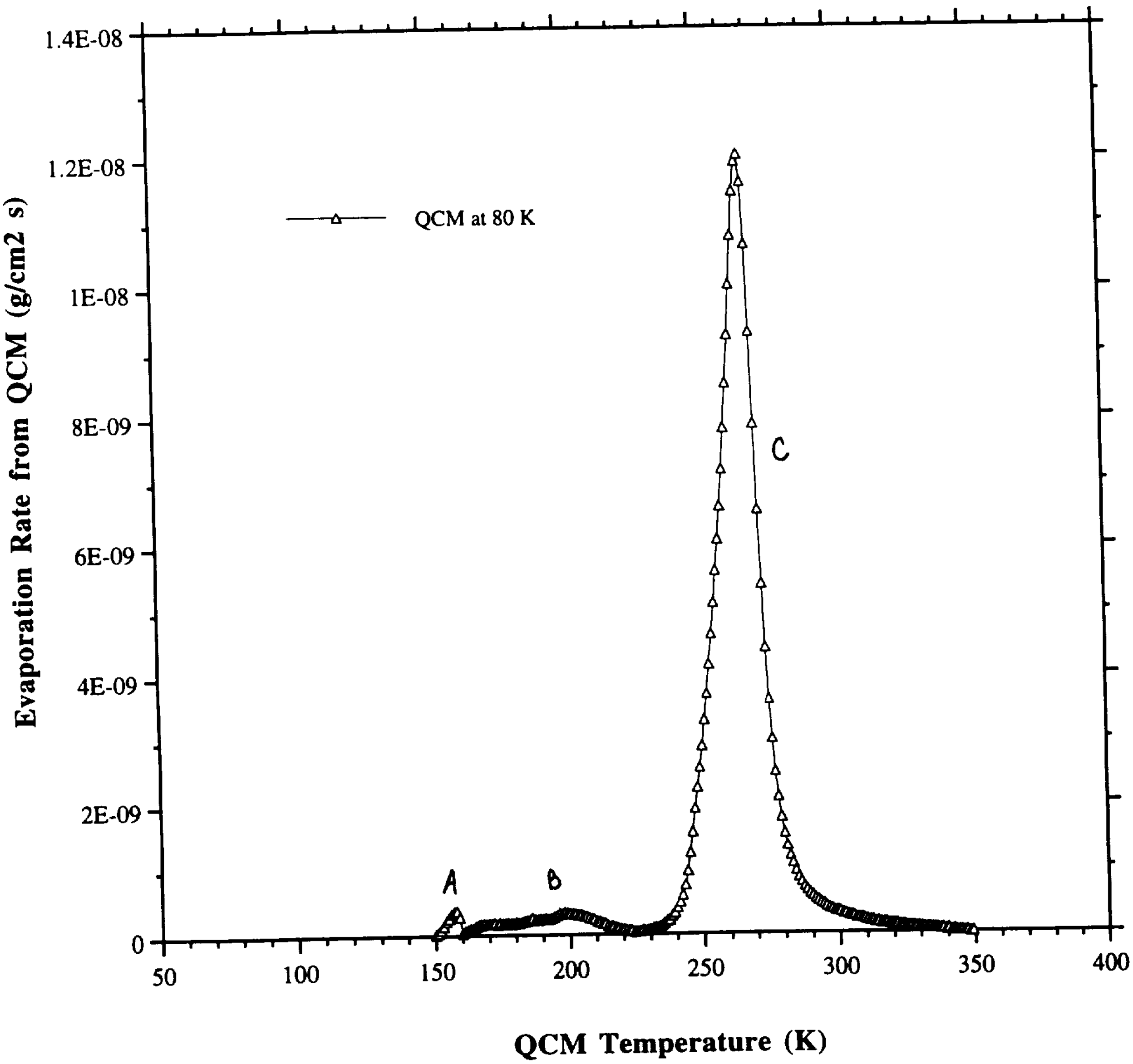
96JUN03: Kapton (contaminated) at 150°F.

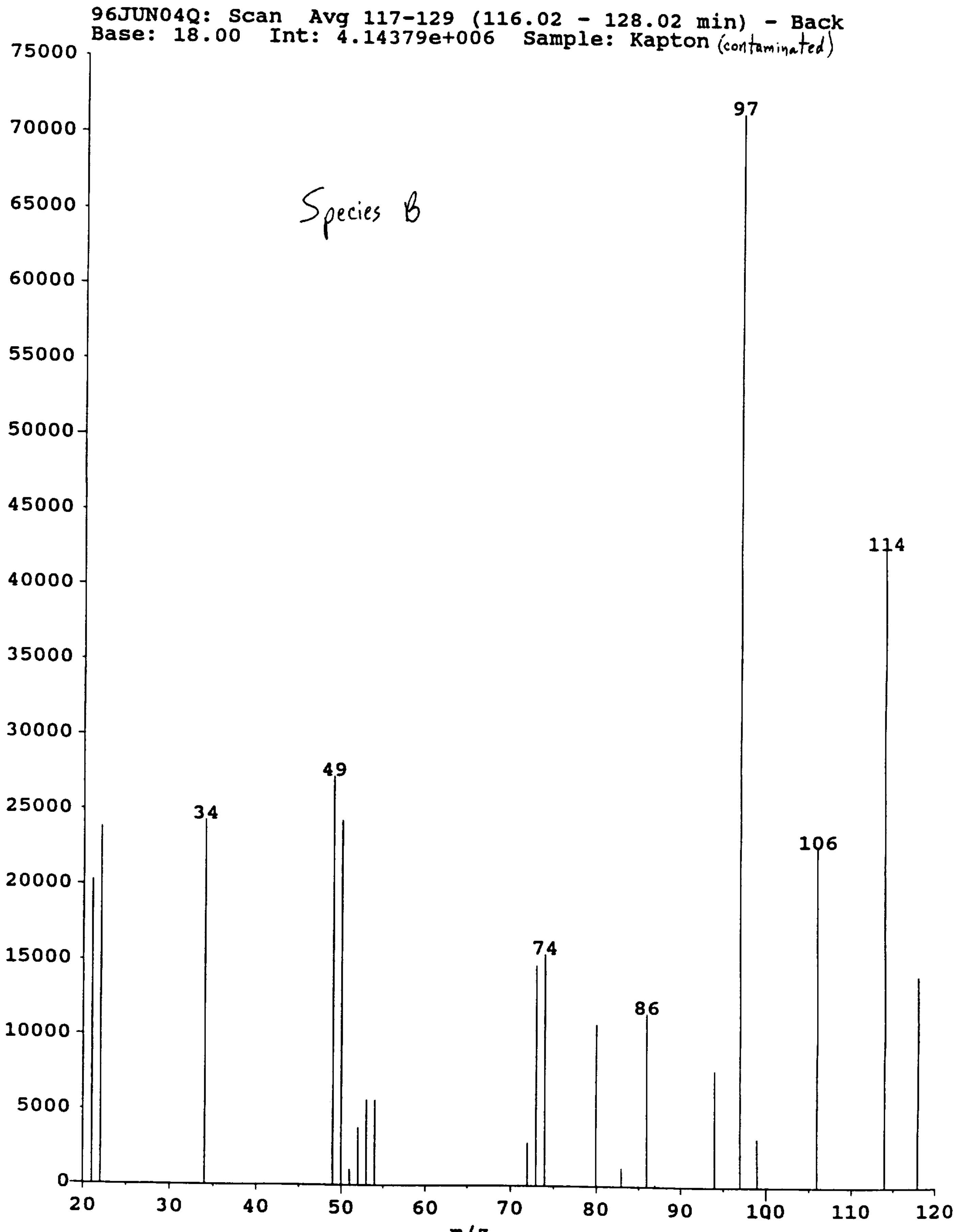


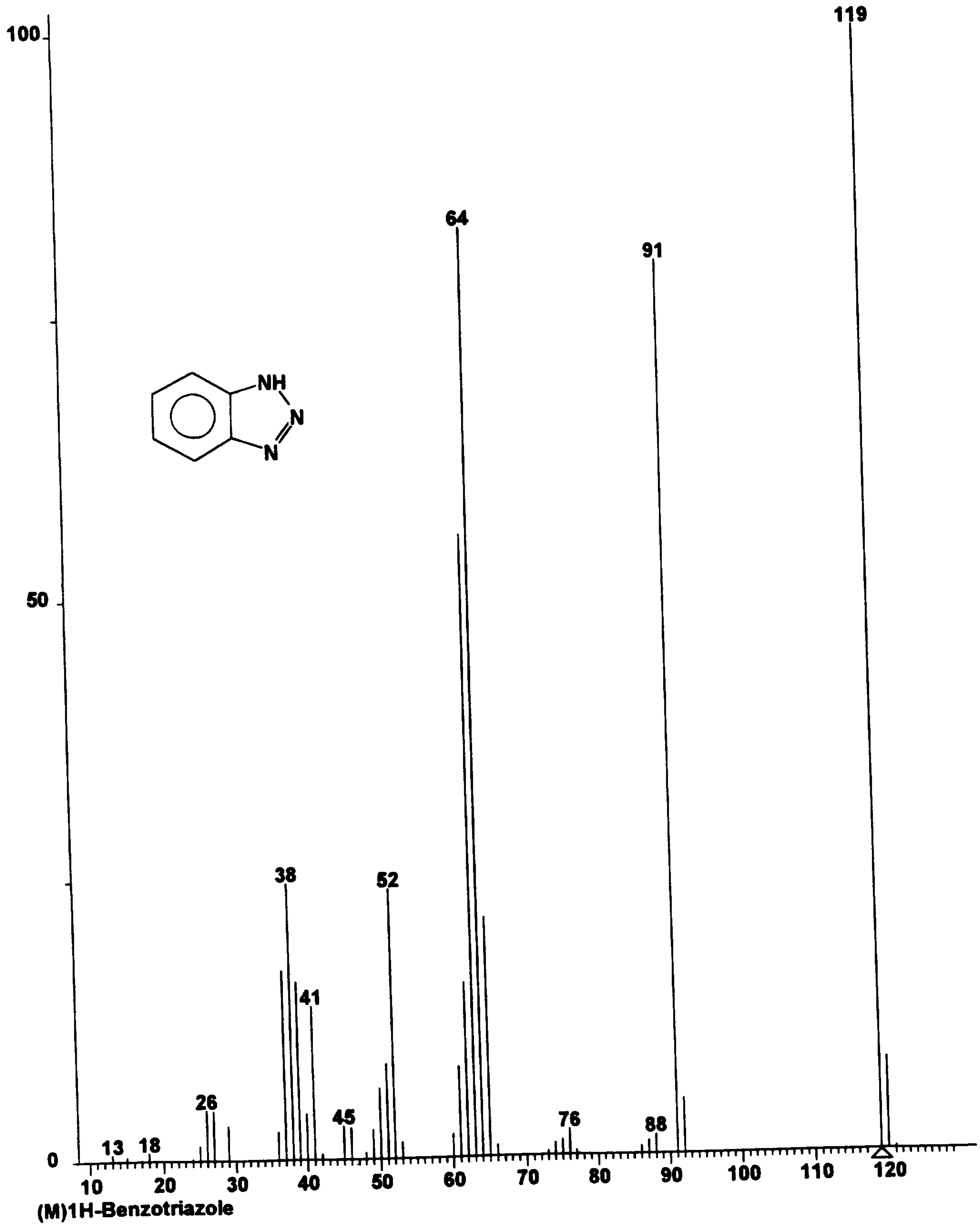
96JUN04Q: QTGA after Kapton (contaminated) at 150°F.



96JUN04Q: QTGA after Kapton (contaminated) at 150°F.

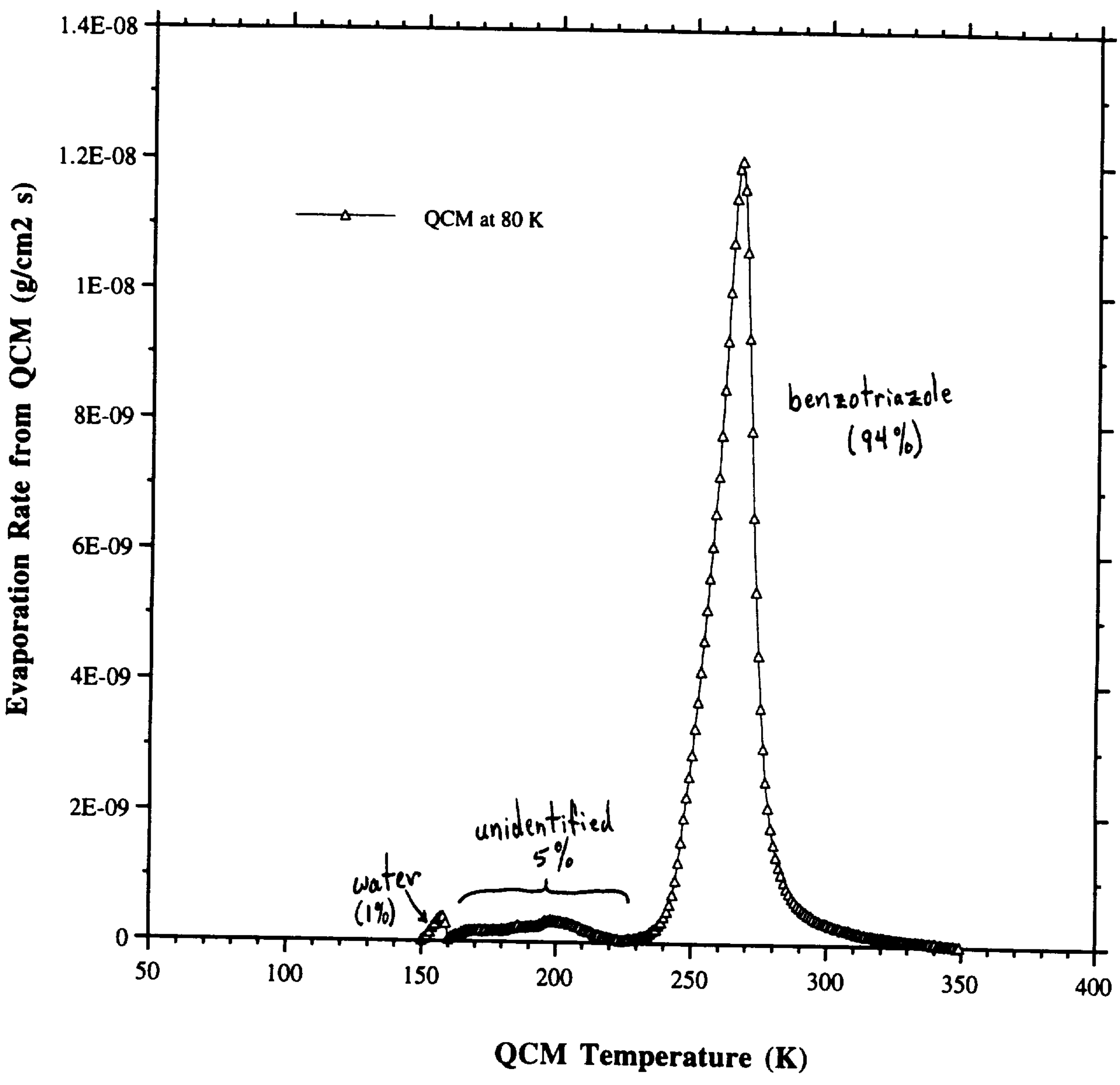



96JUN04Q: Scan Avg 117-129 (116.02 - 128.02 min) - Back
Base: 18.00 Int: 4.14379e+006 Sample: Kapton (contaminated)
Species B
75000
70000
65000
60000
55000
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
97
114
49
34
106
74
86
20
30
40
50
60
70
80
90
100
110
120
m/z



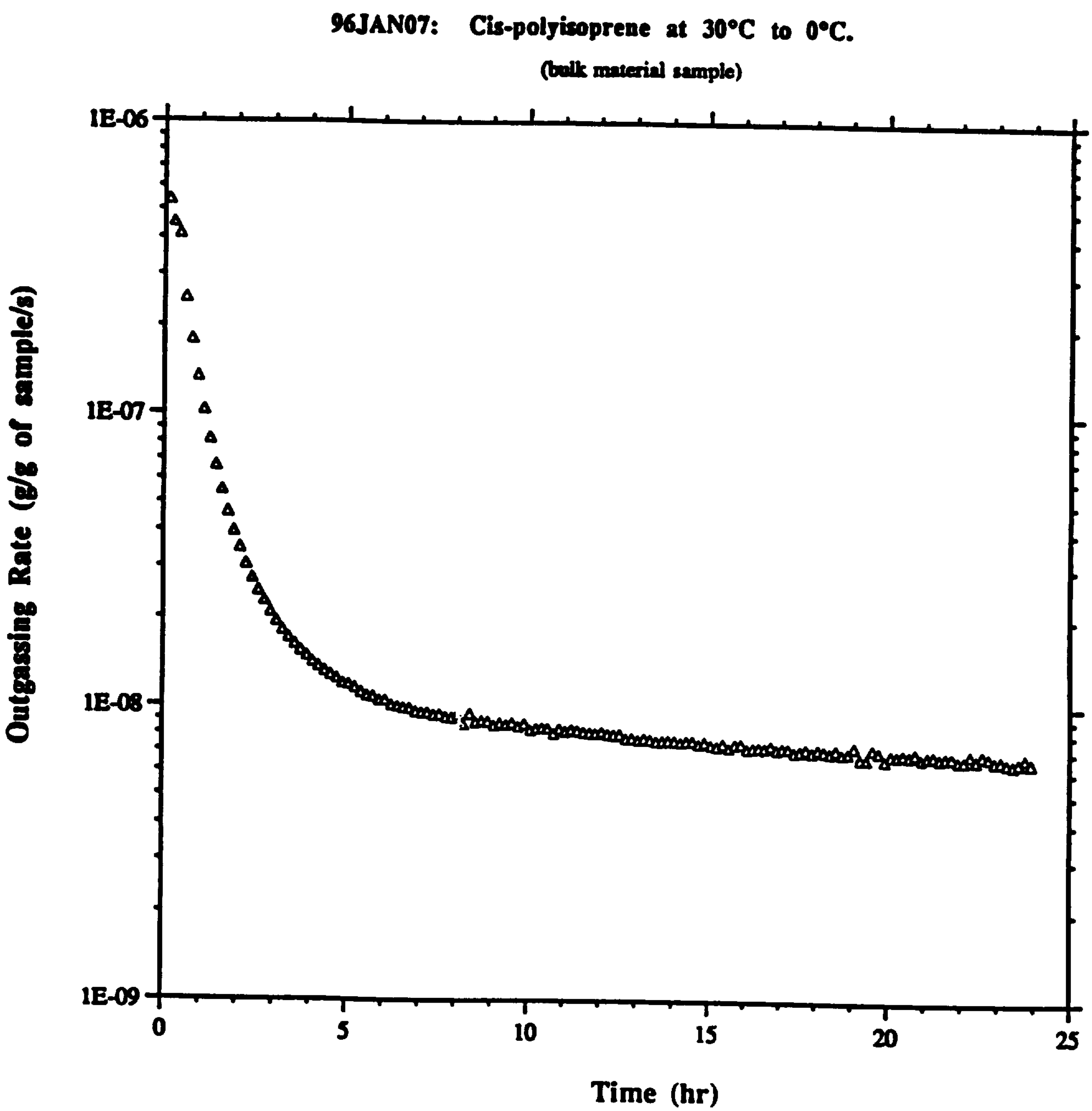
119
100
64
91
NH
N
N
50
38
52
41
26
45
76
88
13
18
0
10
20
30
40
50
60
70
80
90
100
110
120
(M)1H-Benzotriazole

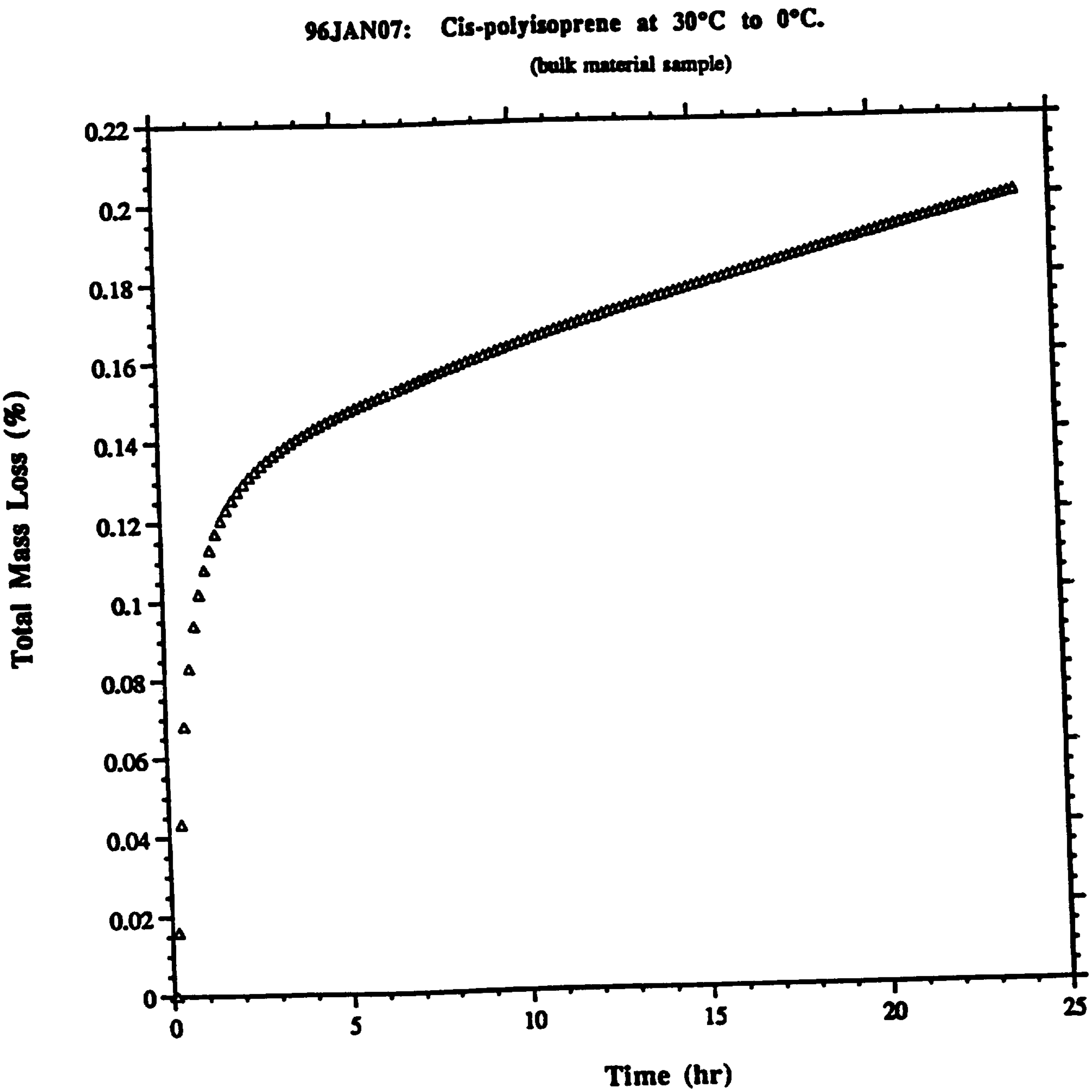
96JUN04Q: QTGA after Kapton (contaminated) at 150°F.

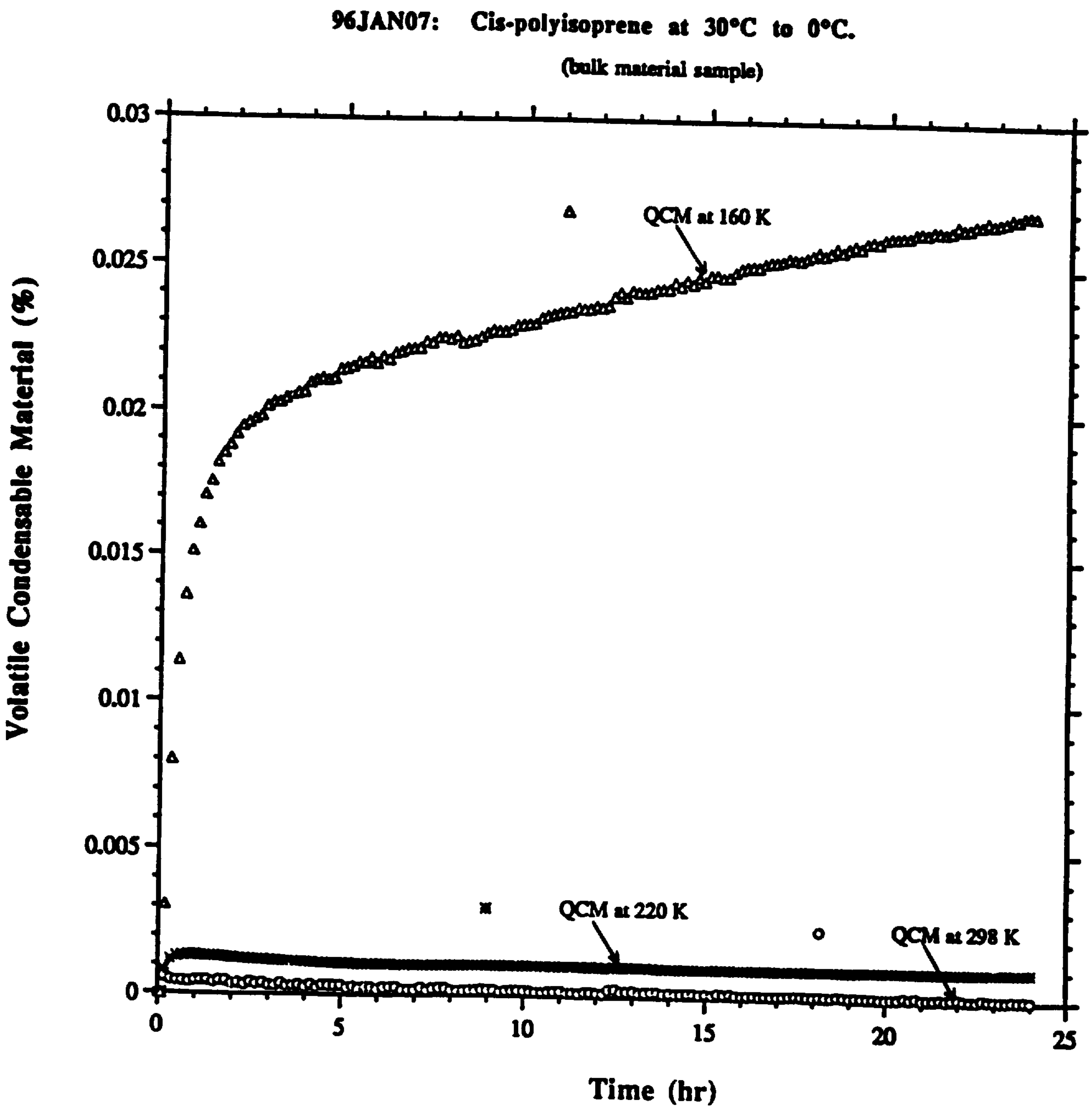


Example #3

Cis-polyisoprene

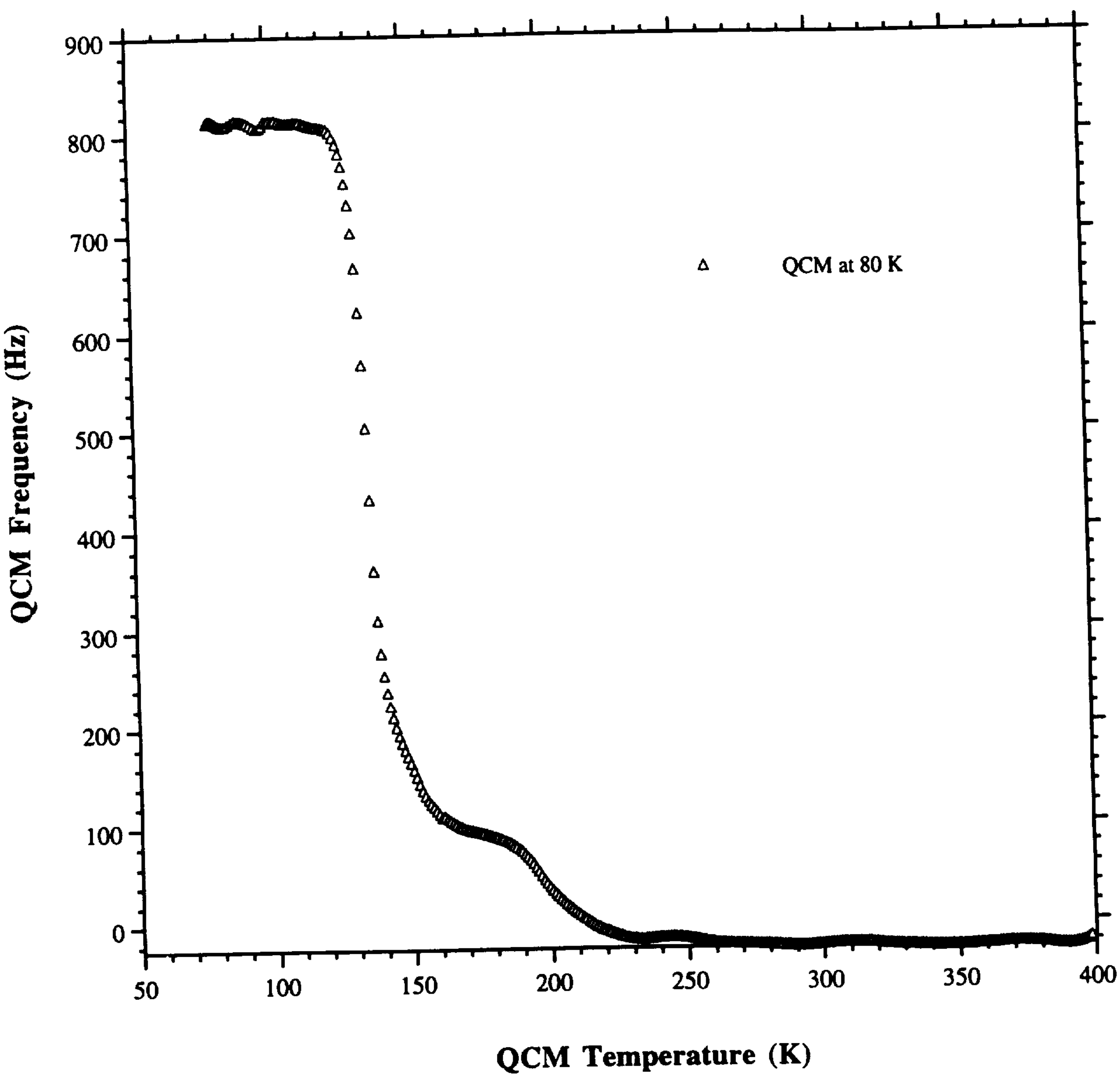

96JAN07: Cis-polyisoprene at 30°C to 0°C.
(bulk material sample)
Outgassing Rate (g/g of sample/s)
1E-06
1E-07
1E-08
1E-09
0
5
10
15
20
25
Time (hr)


96JAN07: Cis-polyisoprene at 30°C to 0°C.
(bulk material sample)
Total Mass Loss (%)
Time (hr)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25

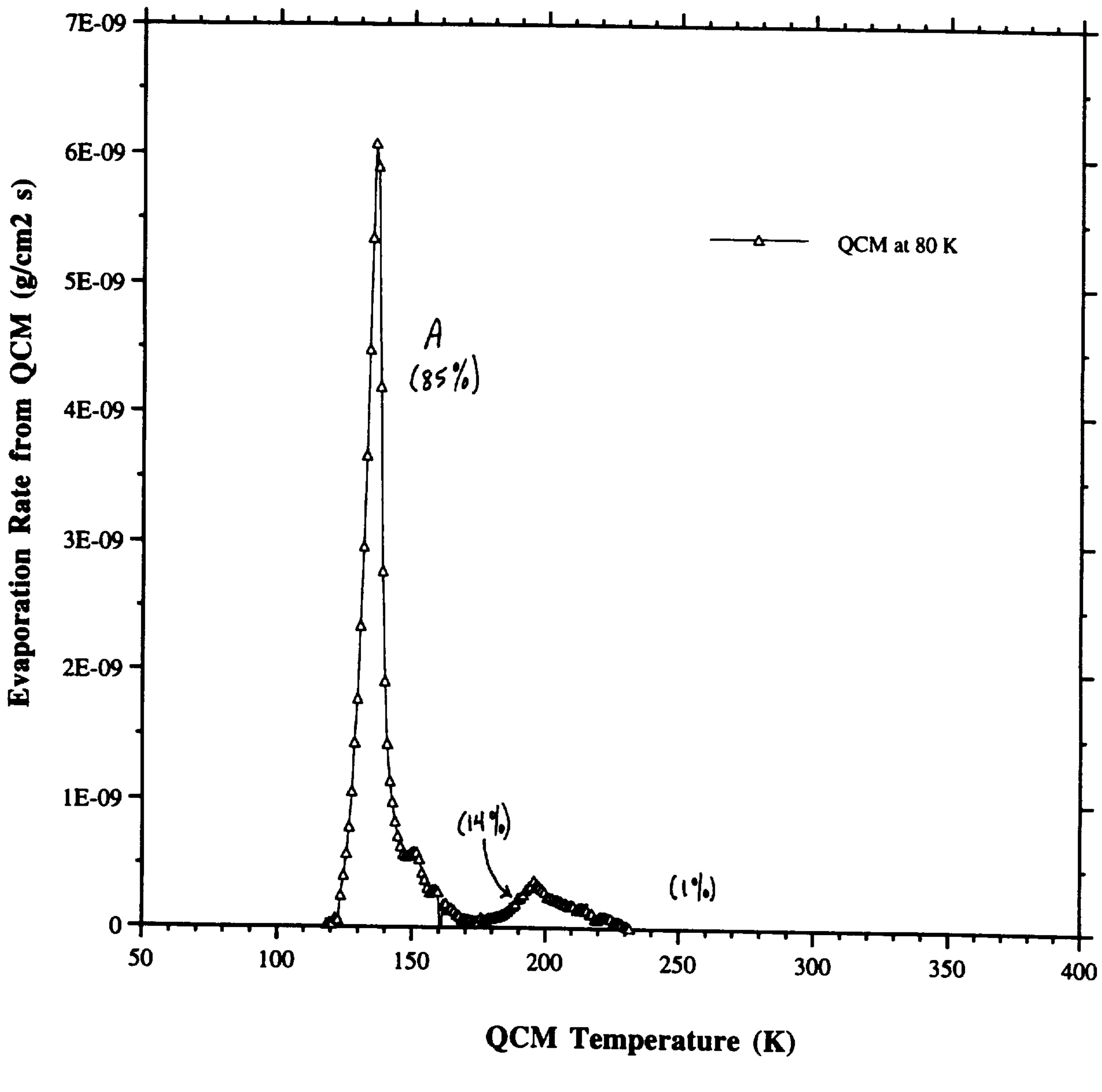


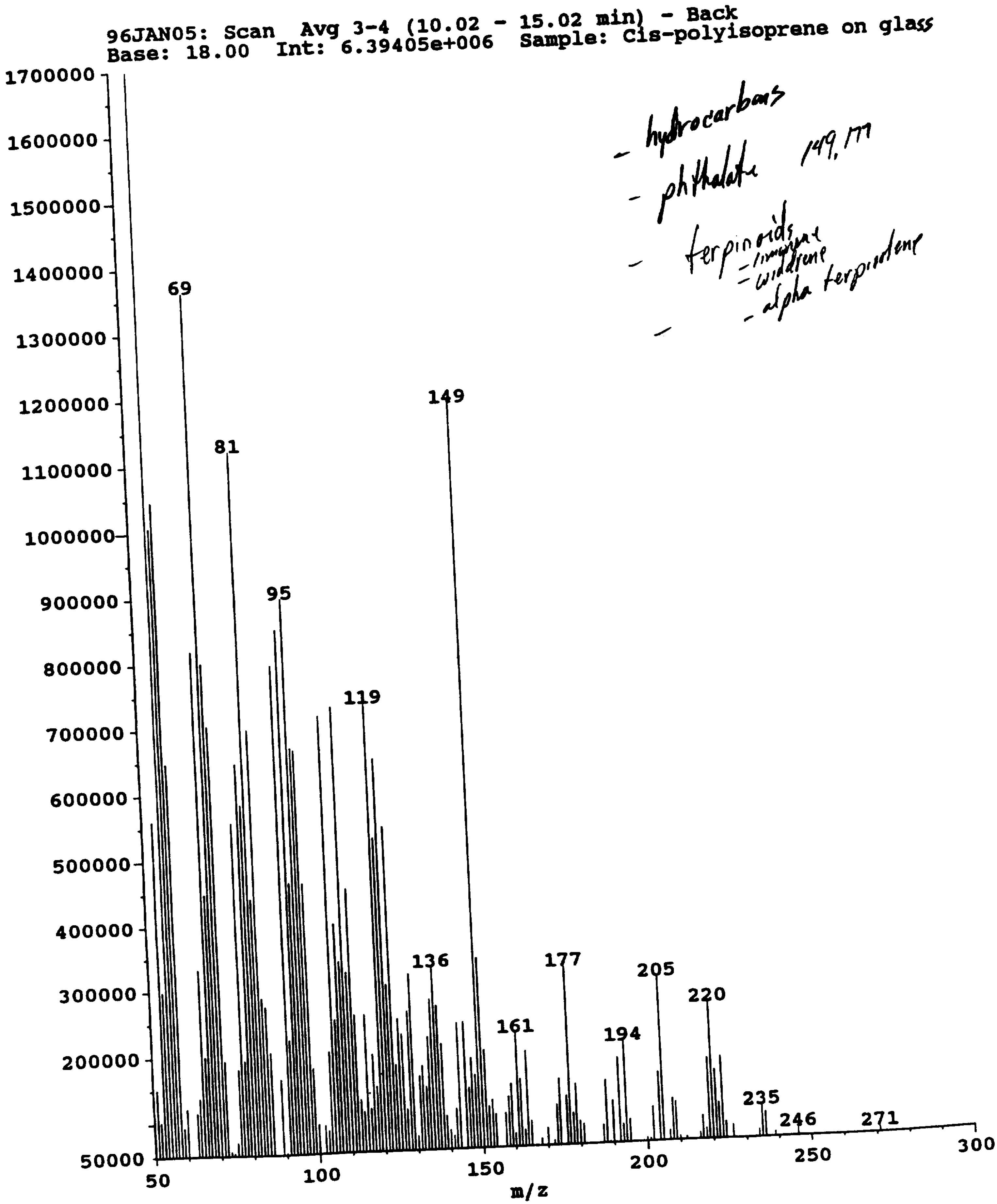
96JAN07: Cis-polyisoprene at 30°C to 0°C.
(bulk material sample)
Volatile Condensable Material (%)
0.03
0.025
0.02
0.015
0.01
0.005
0
QCM at 160 K
QCM at 220 K
QCM at 298 K
0
5
10
15
20
25
Time (hr)

96JAN08Q: QTGA after Cis-polyisoprene at 30°C to 0°C.

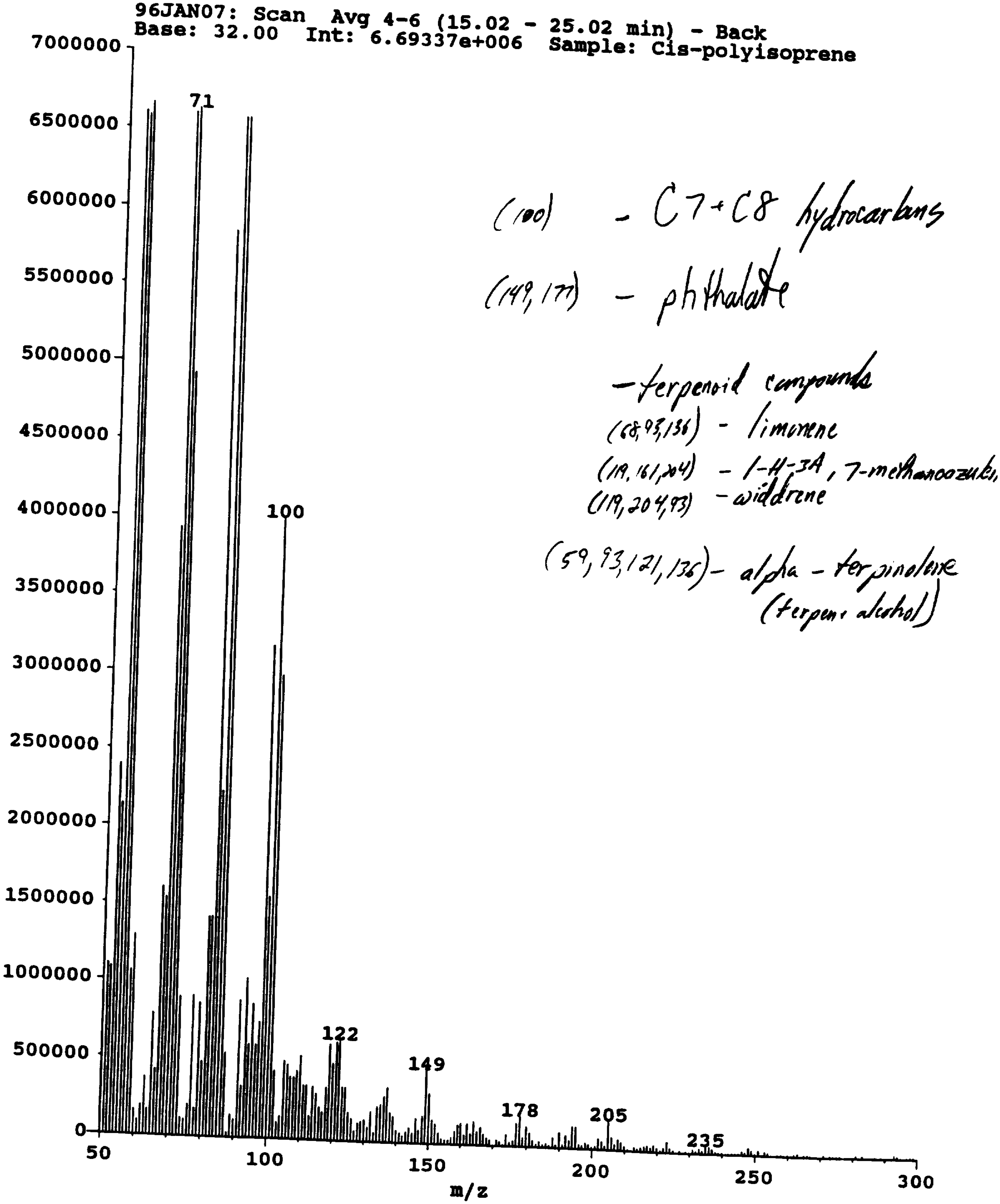


96JAN08Q: QTGA after Cis-polyisoprene at 30°C to 0°C.
(bulk material sample)



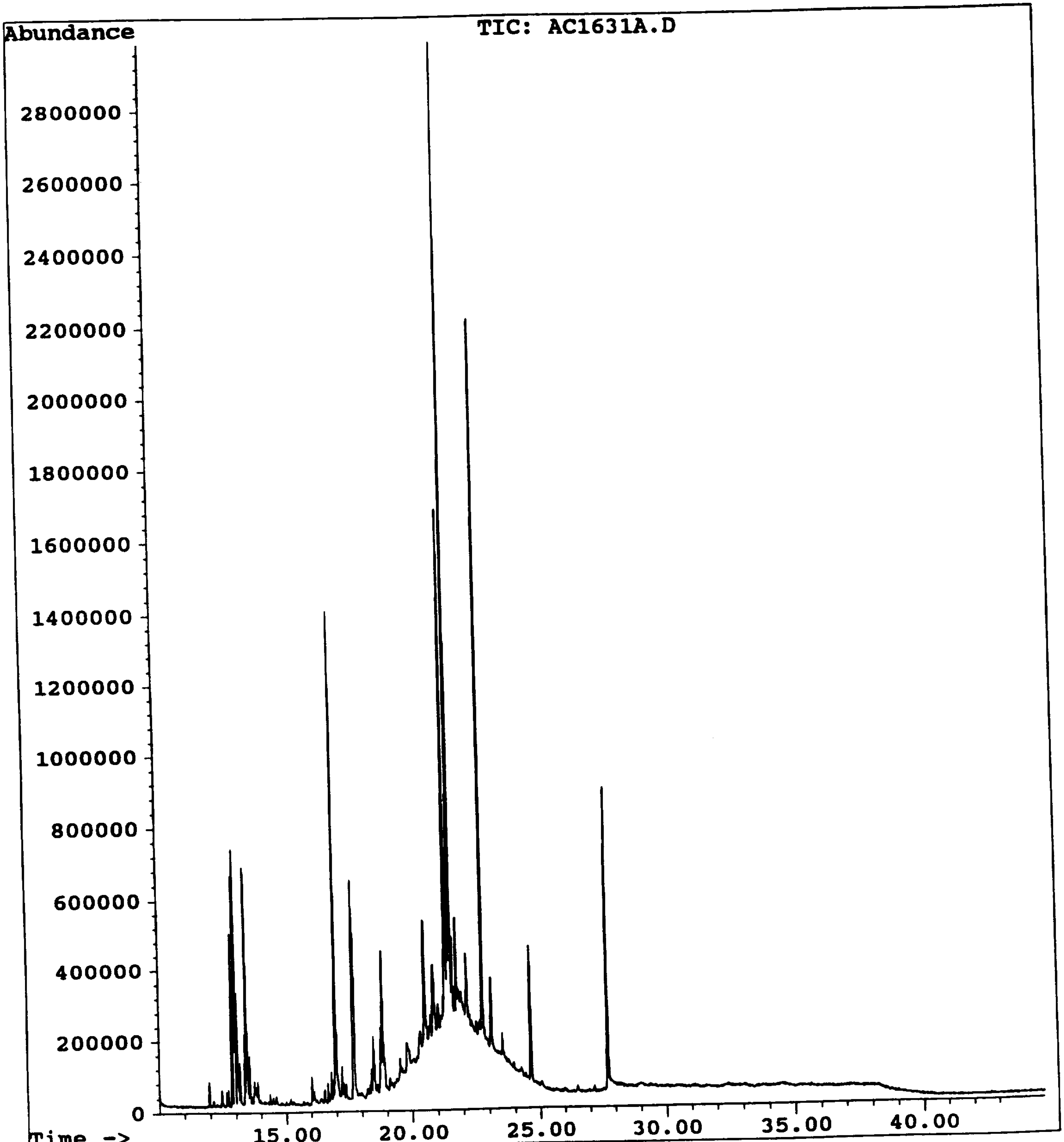


96JAN05: Scan Avg 3-4 (10.02 - 15.02 min) - Back
Base: 18.00 Int: 6.39405e+006 Sample: Cis-polyisoprene on glass
- hydrocarbons
- phthalate 149, 177
- terpinoids
- limonene
- widdrene
- alpha terpinolene
69
81
95
119
149
136
177
205
220
161
194
235
246
271
m/z


96JAN07: Scan Avg 4-6 (15.02 - 25.02 min) - Back
Base: 32.00 Int: 6.69337e+006 Sample: Cis-polyisoprene
7000000
6500000
6000000
5500000
5000000
4500000
4000000
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
71
100
122
149
178
205
235
50
100
150
200
250
300
m/z
(100) - C7 + C8 hydrocarbons
(149, 177) - phthalate
- terpenoid compounds
(68, 93, 136) - limonene
(119, 161, 204) - 1-H-3A, 7-methanoazule
(119, 204, 93) - widdrene
(59, 93, 121, 136) - alpha - terpinolene
(terpene alcohol)

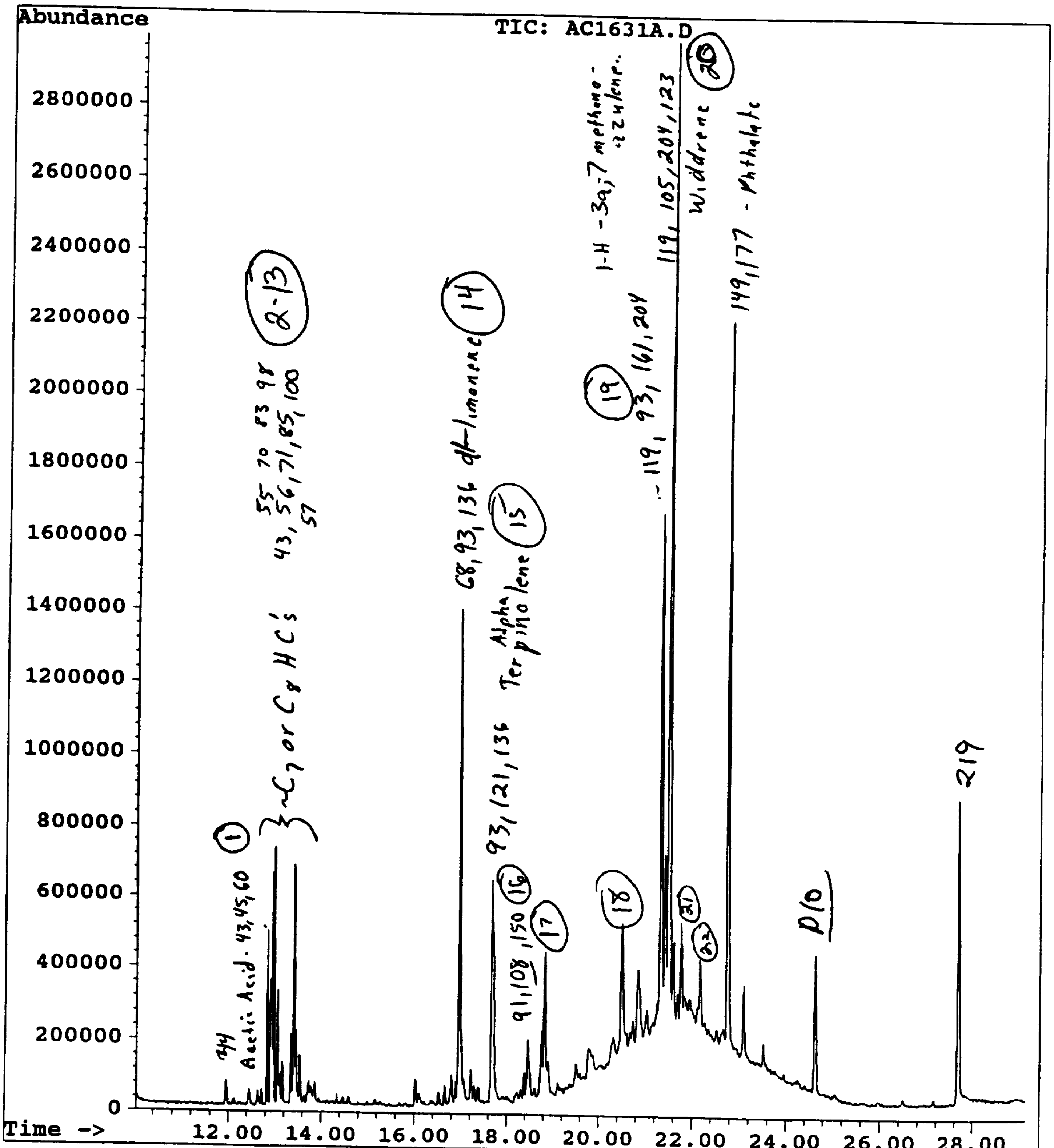
File: C:\CHEMPC\DATA\KATHI\AC1631A.D
Operator: KG
Date Acquired: 12 Jan 96 11:09 am
Method File: TD10DB5.M
Sample Name:
Misc Info: **100FOR10.TCP NZZL-120.CCP**CIS-POLYISOPRENE
ALS vial: 5

GC/MS Data



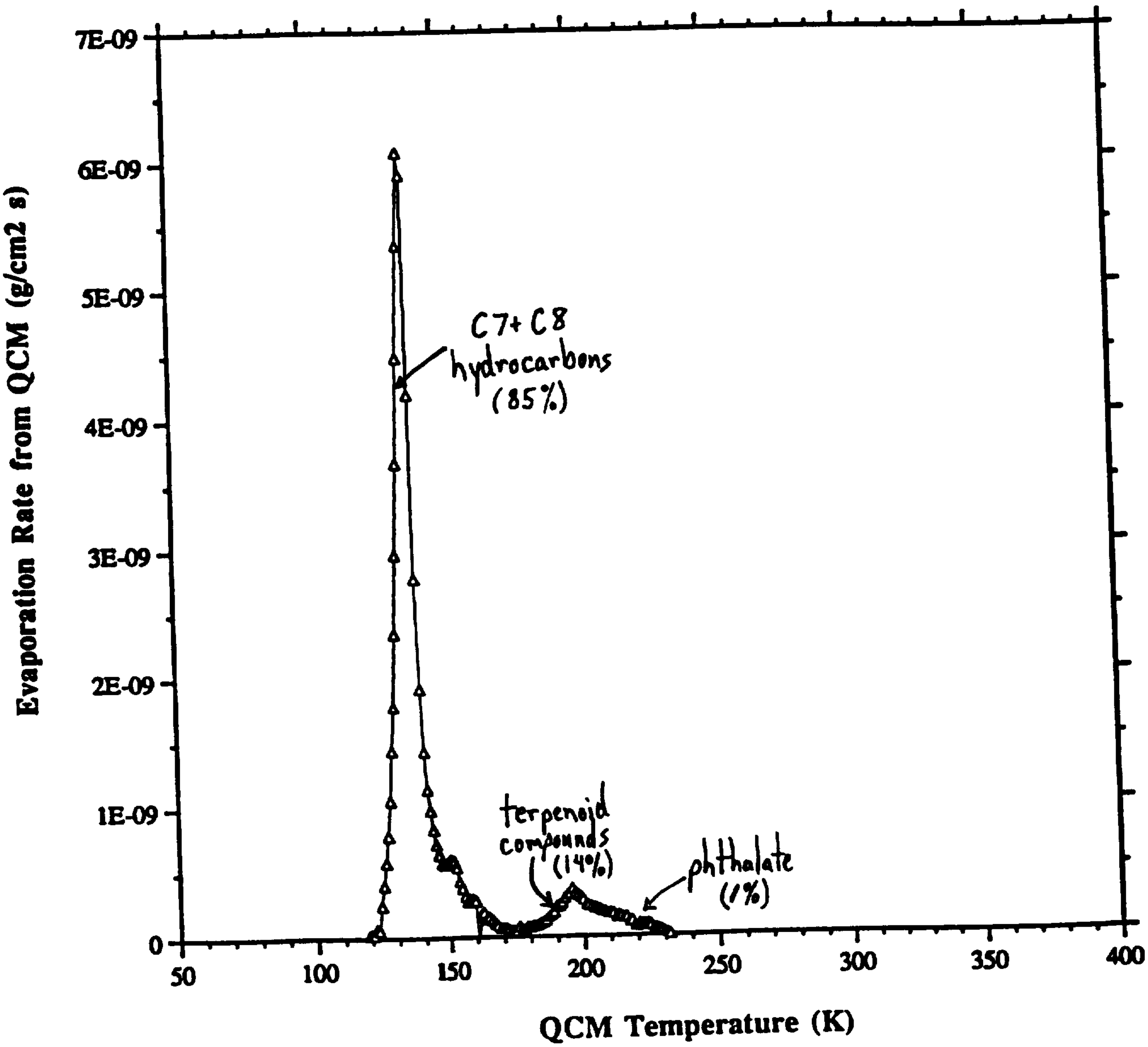
File: C:\CHEMPC\DATA\KATHI\AC1631A.D
Operator: KG
Date Acquired: 12 Jan 96 11:09 am
Method File: TD10DB5.M
Sample Name:
Misc Info: **100FOR10.TCP NZZL-120.CCP**CIS-POLYISOPRENE
ALS vial: 5

GC/MS Data



96JAN08Q: QTGA after Cis-polyisoprene at 30°C to 0°C.

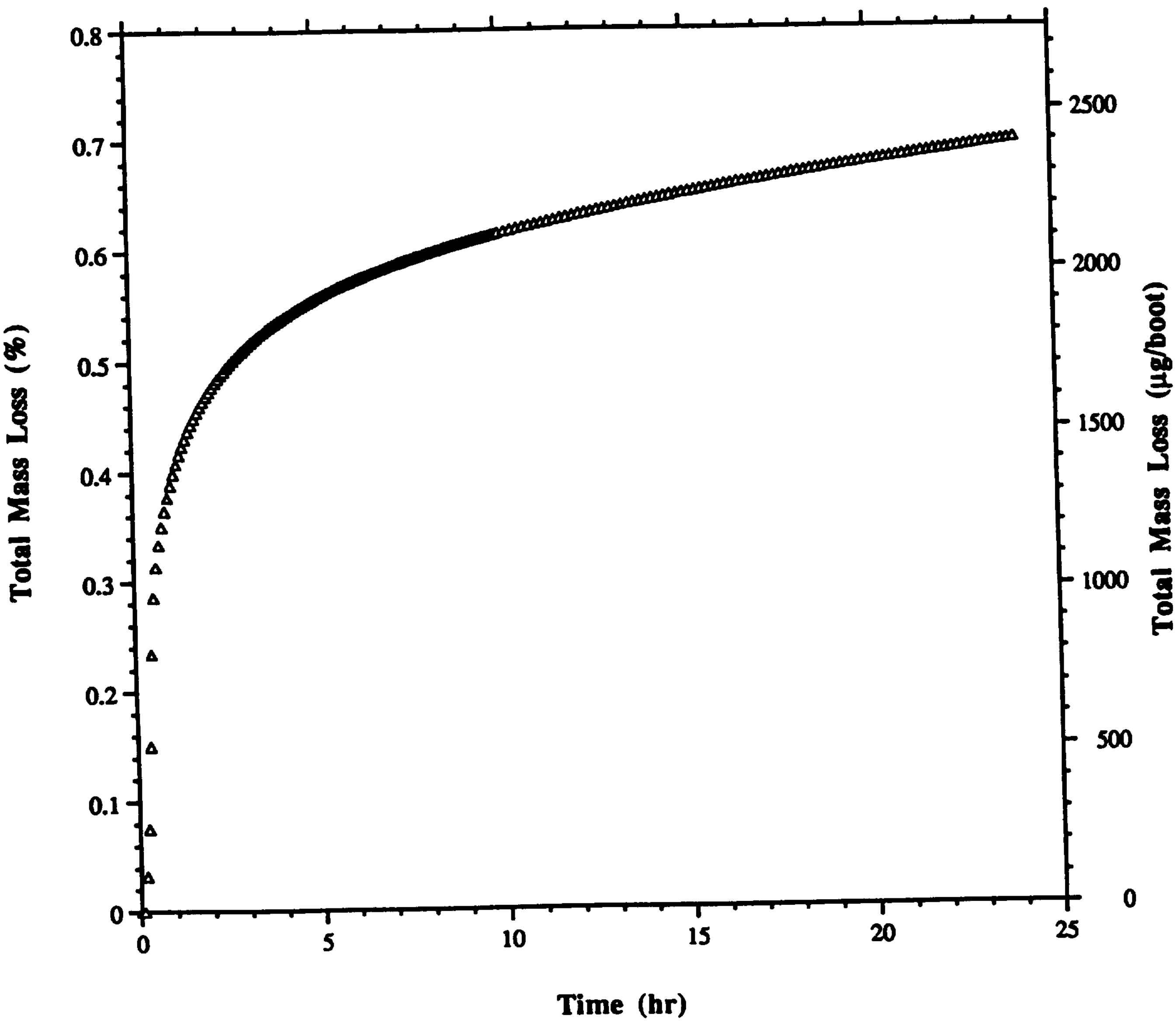
(bulk material sample)



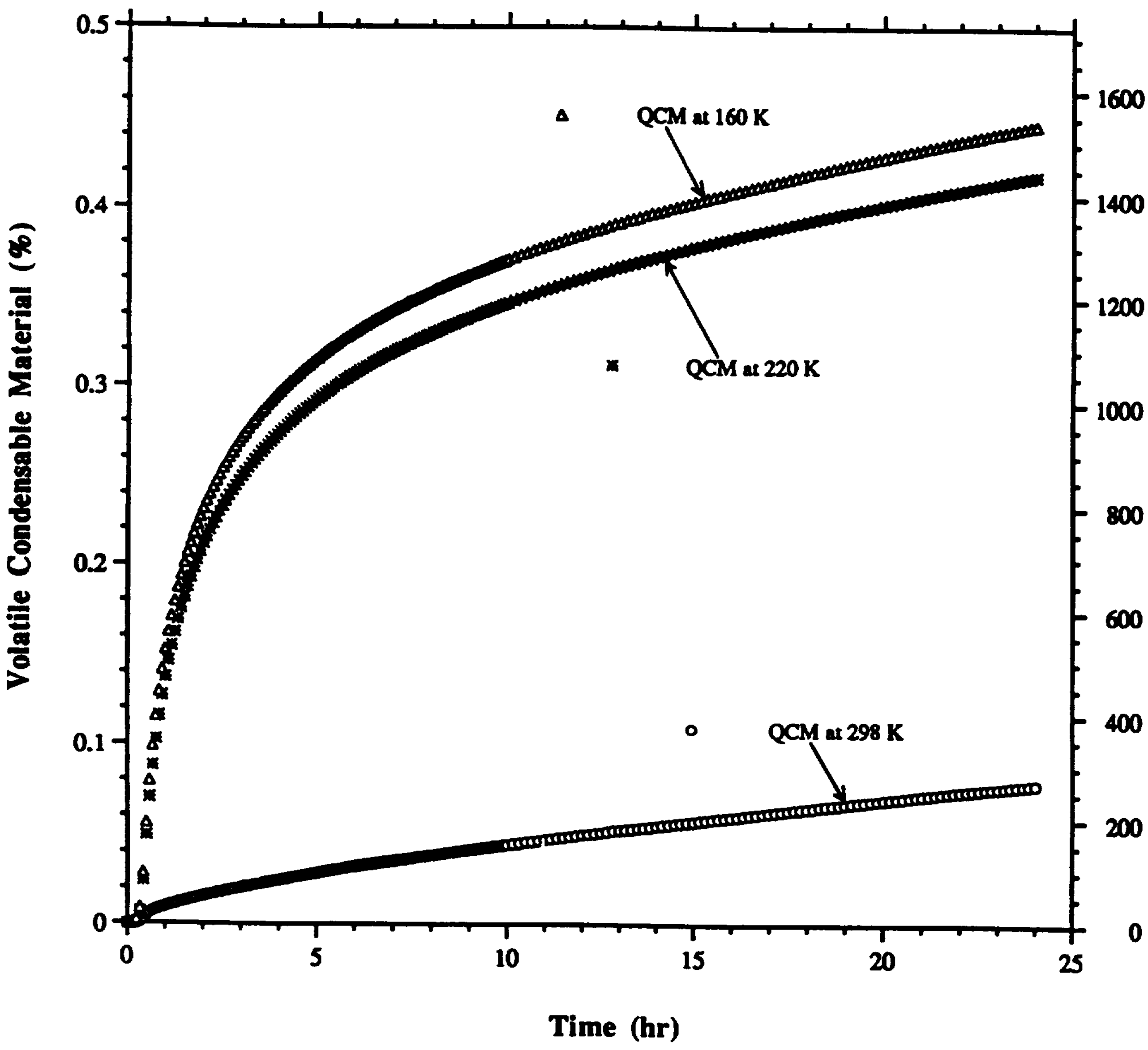
Example #4

Hytrel 8068 Fiber Optic Boot

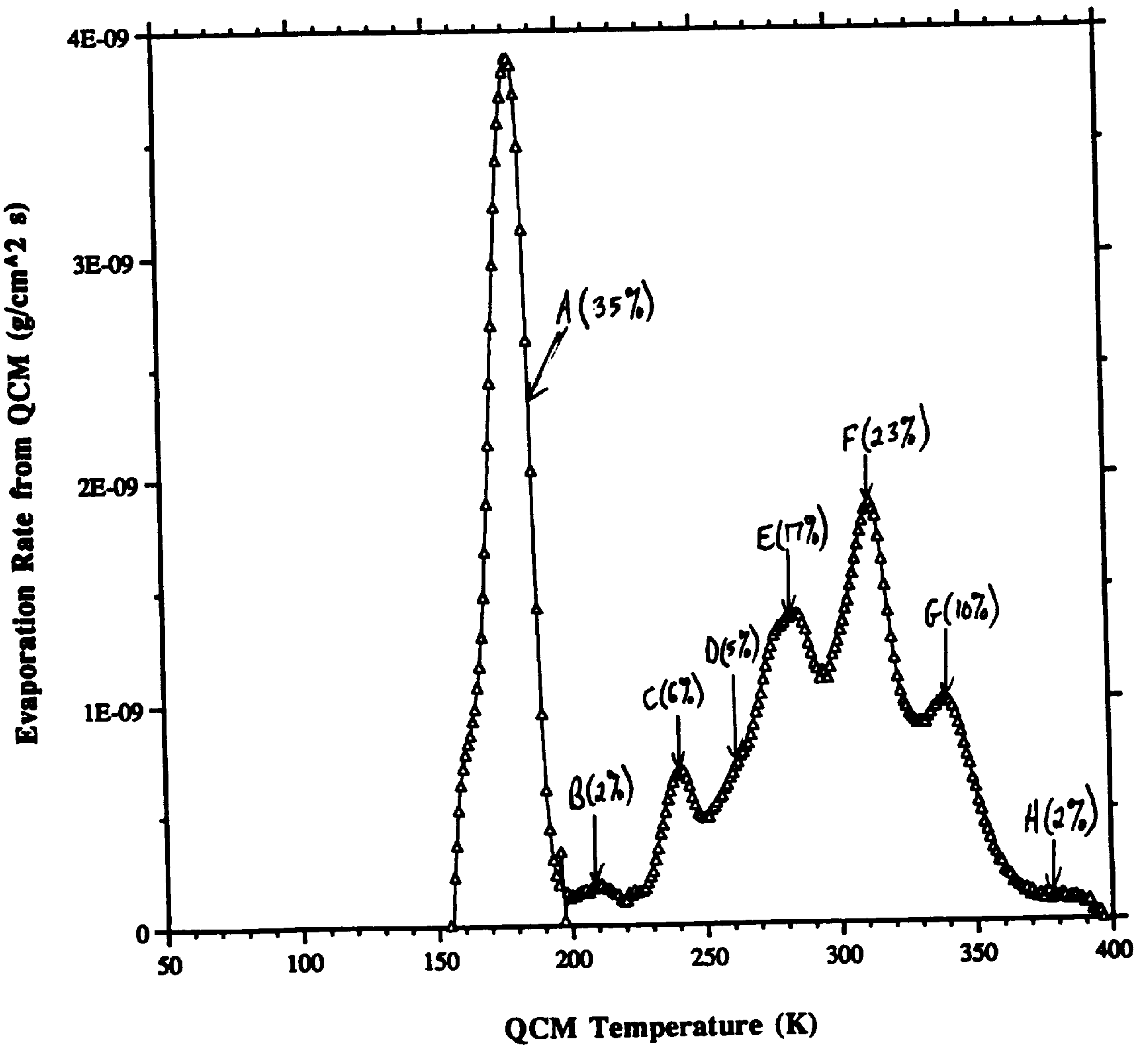
95SEP19B: Hytrel 8068 Black Fiber Optic Boots at 125°C.



95SEP19B: Hytrel 8068 Black Fiber Optic Boots at 125°C.



95SEP20Q: QTGA after Hytrel 8068 Black Fiber Optic Boots at 125°C.



Outgassed Species Determined by OTGA

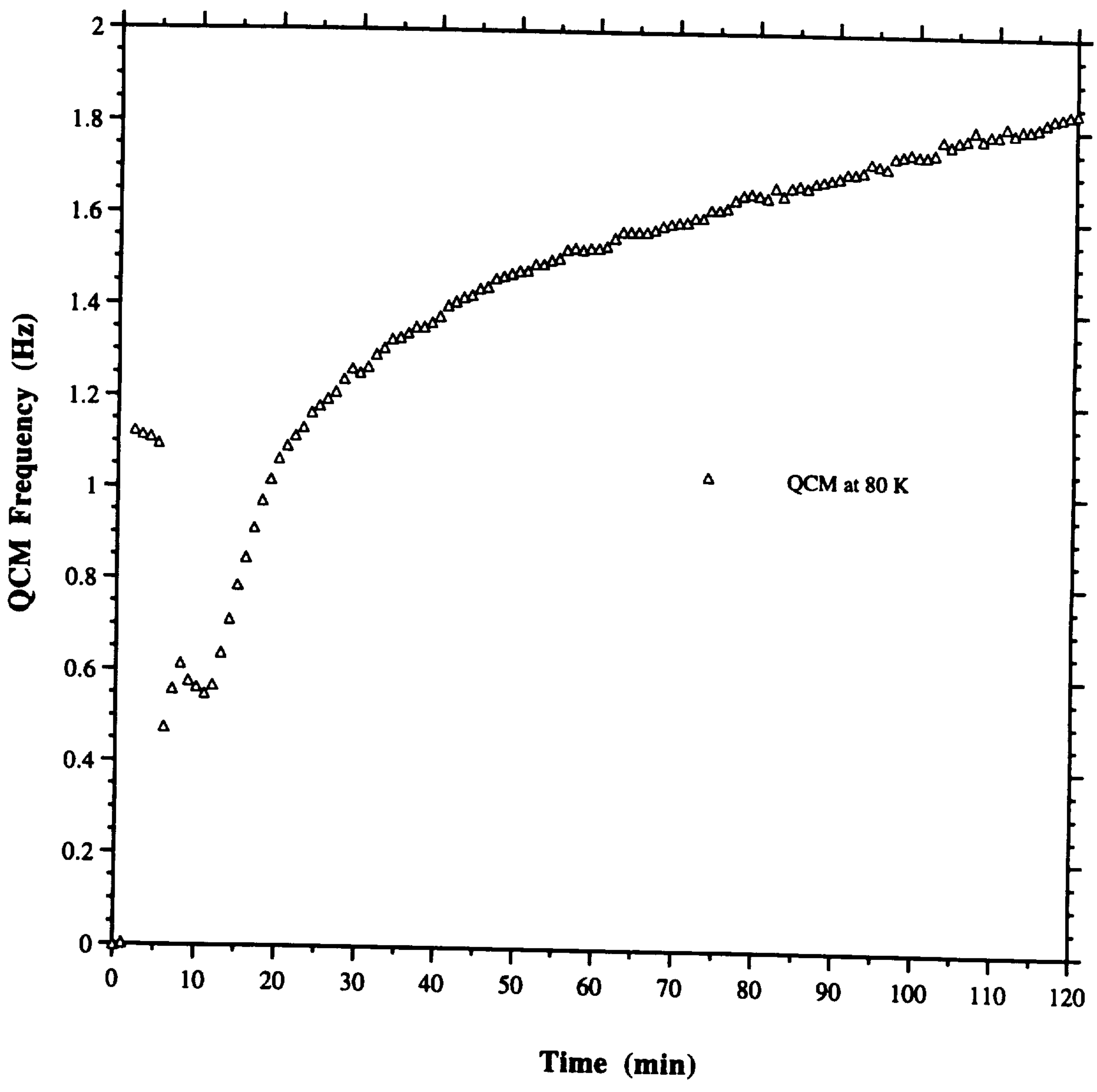
Group	Amount†	Species
A	35 %	water
B	2 %	(1) unidentified aromatics characterized by ions at 77, 91
C	6 %	(1) diethyl biphenyl (2) unidentified species characterized by ions at 181, 210 (3) tetrabromobenzene
D	5 %	(1) unidentified amine characterized by strong ion at 58 (2) small amounts of unidentified species characterized by ions at 135, 137, 149, 151 (3) small amounts of unidentified species characterized by ions at 420, 452
E	17 %	(1) unidentified amine characterized by strong ion at 58 (2) unidentified species characterized by ions at 91, 134
F	23 %	(1) unidentified species characterized by ions at 91, 134 (2) small amounts of unidentified species characterized by ions at 285, 302, 374, 397, 421
G	10 %	(1) unidentified species characterized by ions at 240, 268 (2) unidentified species characterized by ions at 268, 296
H	2 %	unknown

† percentage of the outgassed species (TML) found in this evaporation group

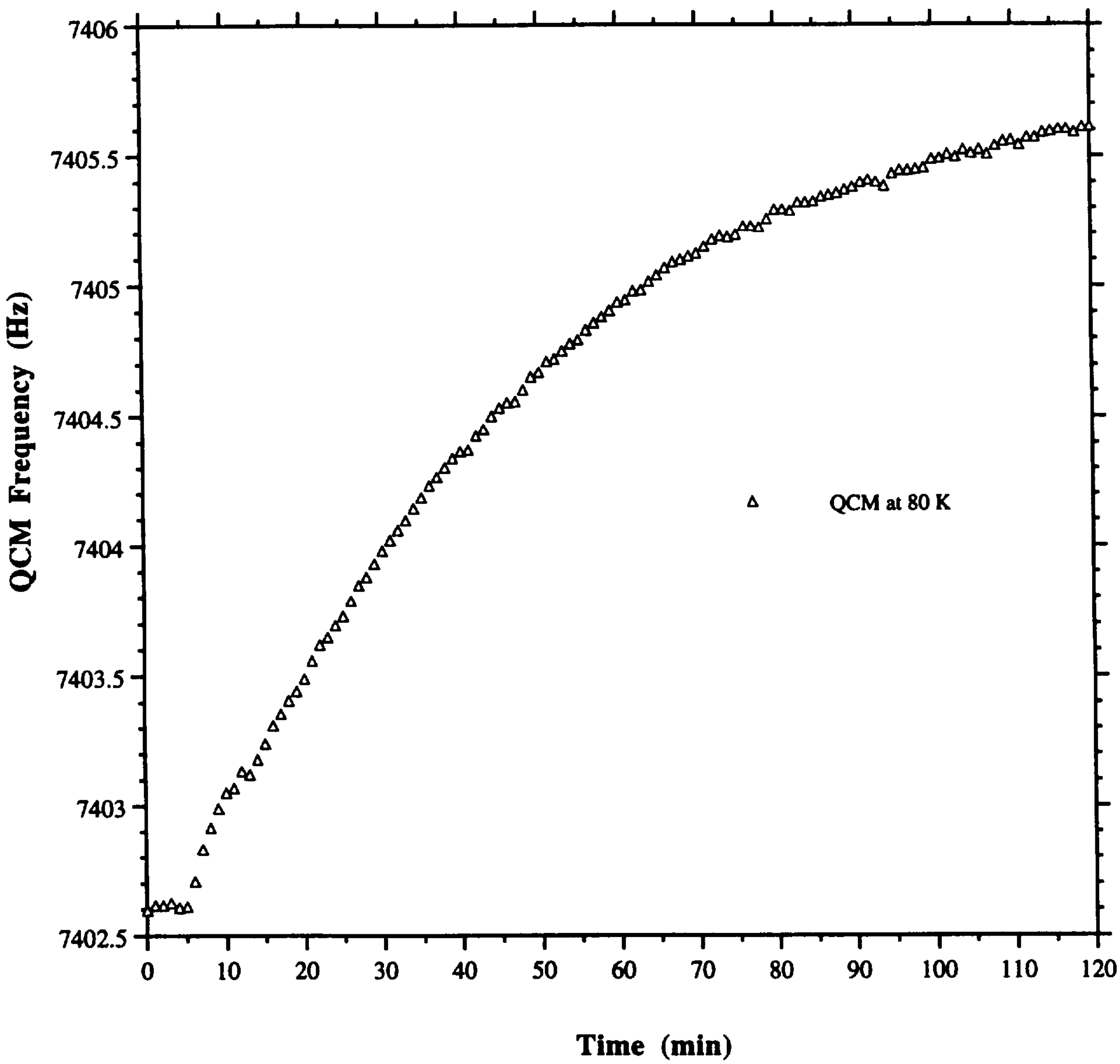
Example #5

Cleanliness Characterization Tests
(Al, Ti, SS... substrates)

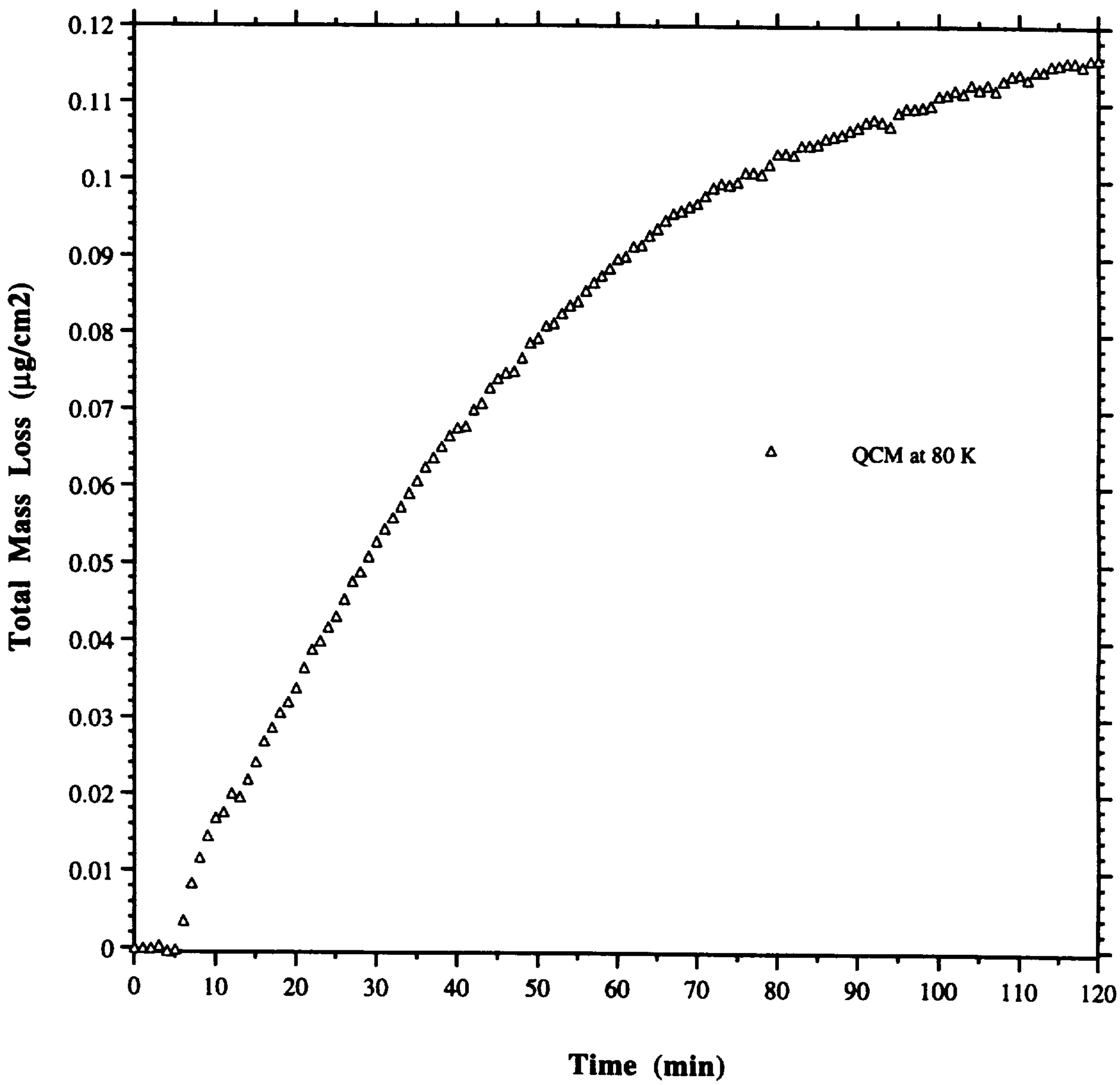
97JUN24A: Empty Cell at 125°C.



97JUN24B: Aluminum Coupon at 125°C.



97JUN24B: Aluminum Coupon at 125°C.



A PRAGMATIC APPROACH TO CONTAMINATION CONTROL PROGRAM MANAGEMENT AND DEVELOPMENT

BY

BARRY GREENBERG

A PRAGMATIC APPROACH TO CONTAMINATION CONTROL PROGRAM MANAGEMENT AND DEVELOPMENT

During this discussion, attendees will be familiarized with how to apply contamination control strategies and technologies in the development and mangement of cleanroom facilities and operations. As an example, the ideal situation of a cleanroom designed and built specifically for large spacecraft projects, the Spacecraft Systems Development and Integration Facility (SSDIF), will be discussed. The operational phase shall be highlighted, reviewing the balance between theoretical approaches and standards versus the limitations found in the "real world". In addition, contamination control strategies developed over the years during the operation and maintenance of cleanrooms shall be reviewed.

BIOGRAPHY

Barry Greenberg is Manager of Cleanroom Operations and MultiProject Support for Mantech SystemsEngineering Corporation. Under his direction, his group is responsible for operating and maintaining all major cleanroom facilities at Goddard Space Flight Center (GSFC) in addition to providing integration and contamination control support to flight projects. Mr. Greenberg has over 24 years experience in contamination control and cleanroom operations management and during his career, he has been responsible for the start-up of many facilities, including a newly constructed cleanroom facility in Japan and the "largest" cleanroom in the world. Mr. Greenberg is a National Director of the Institute of Environmental Sciences and is currently serving on the Executive Board. He was a member of the Working group responsible for the revision of Fed. Std. 209 and is a member of the US TAG for ISO TC/209. He received his Bachelor of Science degree from SUNY in Biology/Chemistry.

OUTLINE

1. GSFC CLEANROOMS

2. SSDIF CLEANROOM

   - DEVELOPMENT
   - CONSTRUCTION
   - UNIQUE FEATURES

3. CONTAMINATION CONTROL STRATEGIES

FLIGHT PROGRAMS

COSMIC BACKGROUND EXPLORER

EXTREME ULTRAVIOLET EXPLORER

BROAD BAND X-RAY TELESCOPE

TOTAL RAINFALL MEASURING MISSION

HUBBLE SPACE TELESCOPE SERVICING MISSION

TOTAL OZONE MAPPING SPECTROMETER

X-RAY TIMING EXPLORER

HITCHHIKER

SMALL EXPLORERS

GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE

MARS OBSERVER LASER ALTIMETER

CONTAMINATION CONTROL STRATEGY

Operational experience has demonstrated that a strong understanding of contamination control theory and a philosophy of consistent review monitoring, and appropriate compromise can result in satisfying flight hardware and cleanroom facility cleanliness standards. In order to facilitate a systematic contamination control approach in response to flight project requirements and issues, a strategy that combines hands-on experience with theoretical concepts has been cultivated. The following list addresses the individual tenets of this approach.

- FLEXIBILITY AND RESPONSIVENESS
- TRAINING
- LEADING BY EXAMPLE
- PRECISION CLEANING AND MATERIAL CONTROL
- FACILITY AND PERSONNEL MONITORING
- OBJECTIVITY
- COMPROMISE
- PROCUREMENT
- TEAMS
- DOCUMENTATION
- COMMUNICATION
- EDUCATION
- SYNERGY

- STRIVE FOR EXCELLENCE

FLEXIBILITY AND RESPONSIVENESS

Adherence to documented contamination control implementation plans is essential. In addition, cleanroom rules, regulations, and procedures need to be enforced. However, a responsible answer to technical and managerial challenges needs to be the order of business. Contamination control professionals need to be flexible in addressing operational issues but must avoid compromising core contamination control requirements. For example, upstream areas need to remain free and clear of ground support equipment and only approved materials should be allowed into the cleanroom.

TRAINING

In order to assure compliance with all operating procedures and maintenance of the cleanroom environment and flight hardware, training must be mandatory for all operations personnel. Attendees should include: managers, engineers, technicians, and maintenance staff. The course should expose the individual to basic cleanroom practices and principles while orienting them to the specific requirements of the facility and resident hardware. The Contamination Control Group should be responsible for the administration of all training activities. When training cannot be scheduled in advance due to logistical issues, an orientation by engineering should be approved.

LEADING BY EXAMPLE

Rules, regulation, and procedures need to be equally applied to all levels of the organization from top management to entry level positions. In many organizations, top management or key personnel feel that they are exempt form following contamination guideline. Such action sends a very negative message to those involved in working in a cleanroom environment. By adherence to published rules and regulations, project management can be a positive force for cleanroom workers instead of just the opposite. It is important that they recognize their influence and take advantage of the opportunity to further the contamination control cause.

PRECISION CLEANING

All materials and equipment should be precision cleaned prior to entering the cleanroom. Allowing uncleaned items into the cleanroom can adversely affect the cleanliness of the facility. In addition, there should be a list of non-approved materials and components. From a molecular contamination viewpoint, materials used on ground support equipment must be evaluated for their outgassing potential. A key philosophy is: "clean as you go along". Time and again, it has been proven that maintaining the cleanliness level of flight hardware and cleaning during integration and testing is more effective than waiting until the final stages. A result of this philosophy has been the cleaning of all cable components prior to harness fabrication.
By doing this, time spent in thermal vacuum chambers has diminished and the level of cleanliness has improved. Since it is extremely difficult to gain access to cable bundles for precision cleaning, this procedure is efficient in getting the job done.

FACILITY AND PERSONNEL MONITORING

A well-thought out facility monitoring plan for the cleanroom is essential. Real time particulate data collection, as opposed to spot checks, is very important. In addition, it has been our experience that continuous monitoring and timely data collection for molecular species and non-volatile residue deposition is effective in controlling contamination. Temperature, relative humidity, and differential pressure data collection are also a necessity. In concert with a well-established monitoring plan, cleanroom employees need to be observed for compliance to cleanroom procedures. Noncompliance should be dealt with by timely notification of the individual's error.

OBJECTIVITY

Although extremely difficult to maintain at times, an objective view of cleanroom operations and contamination control requirements needs to be maintained. A subjective approach may tend to cloud technical issues, resulting in serious ramifications. Contamination control implementation plans need to be objective and pragmatic in their approach. Rather than lobbying for your own point of view or agenda, objective reasoning will, in most cases, result in a satisfactory resolution to all concerns.

COMPROMISE

Although specific adherence to contamination control principles needs to be enforced in a consistent manner, creative compromise is often required when faced with conflicting issues. Experience has shown that, although detailed procedures and implementation plans are necessary, they cannot be applied to every situation or occurrence. However, during the process, the desired goal must always remain in sight; the scope of the goal drives the level of acceptable resolution.

PROCUREMENT

Funds allocated for the procurement of cleanroom equipment should be used to purchase quality instrumentation that responsibly exceeds the technical requirements. It is suggested that by doing so, improvements in servicing the facility and technical improvements in operations will be evident. For example, in order to monitor the presence of airborne molecular contaminants, a continuous IR-based environmental molecular monitor was installed. By not only quantifying contaminants, but also by identifying them, the instrumentation allows for rapid corrective actions and improved analytical capabilities.

TEAMS

The establishment of self-directed work teams is an effective strategy. This team approach, headed by an engineer or lead technician assigned to provide guidance, is very effective. This organization gives technicians a certain degree of autonomy and allows them to develop ownership in their assigned area. In addition, teams provide a rapid response capability and a level of flexibility that is invaluable in supporting flight projects. In a larger sense, we are talking about the employee involvement component of Total Quality Management (TQM).

DOCUMENTATION

Realistic documentation and reporting provides a foundation upon which to build an effective contamination control program. This documentation includes implementation plans, procedures, and work orders. Work orders need to be filled out completely and accurately to assure compliance to the requestor's needs.

COMMUNICATION

Clear, concise, and constant inter- and intra- departmental communication is essential.. Establish a central point of contact for key project hardware and activities Also, make sure that other team members are aware of these major activities so that critical information can flow freely. Continuous information transfer among the group is necessary as each shares responsibility for the maintenance of the contamination control program. Of all the components of an effective strategy, this may be the most critical to success.

EDUCATION

The entire group of professionals needs to develop and maintain expertise and exposure to advancements in contamination control technology, equipment, and applications. It is recommended that areas deserving involvement include:

- molecular contamination monitoring
- particulate monitoring advances
- changes in ISO documents and Mil.Std.. 1246
- involvement with **Cleanrooms** and IEST sponsored events
- precision cleaning and changes in the use of CFCs .
- particulate fallout and NVR monitoring

SYNERGY

It is very difficult to support the belief that every procedural violation directly generates a contamination event. Rather, it is suggested that equal validity be given to the enforcement of all rules and regulations. Whether the individual steps in any program contribute to the success of the effort is arguable at best. One thing is clear, though, and that is that a systematic approach needs to be taken.

STRIVE FOR EXCELLENCE

Although commitment to time frames and milestones is a primary concern, protecting the hardware, especially in our industry, ranks above all else. Job performance should be directed to performing all tasks in a manner complementing the quality issues. Never sacrifice quality for speed. Verbalize major changes to project personnel--you'll find that more times than not, quality issues will command precedence. Strive for excellence!

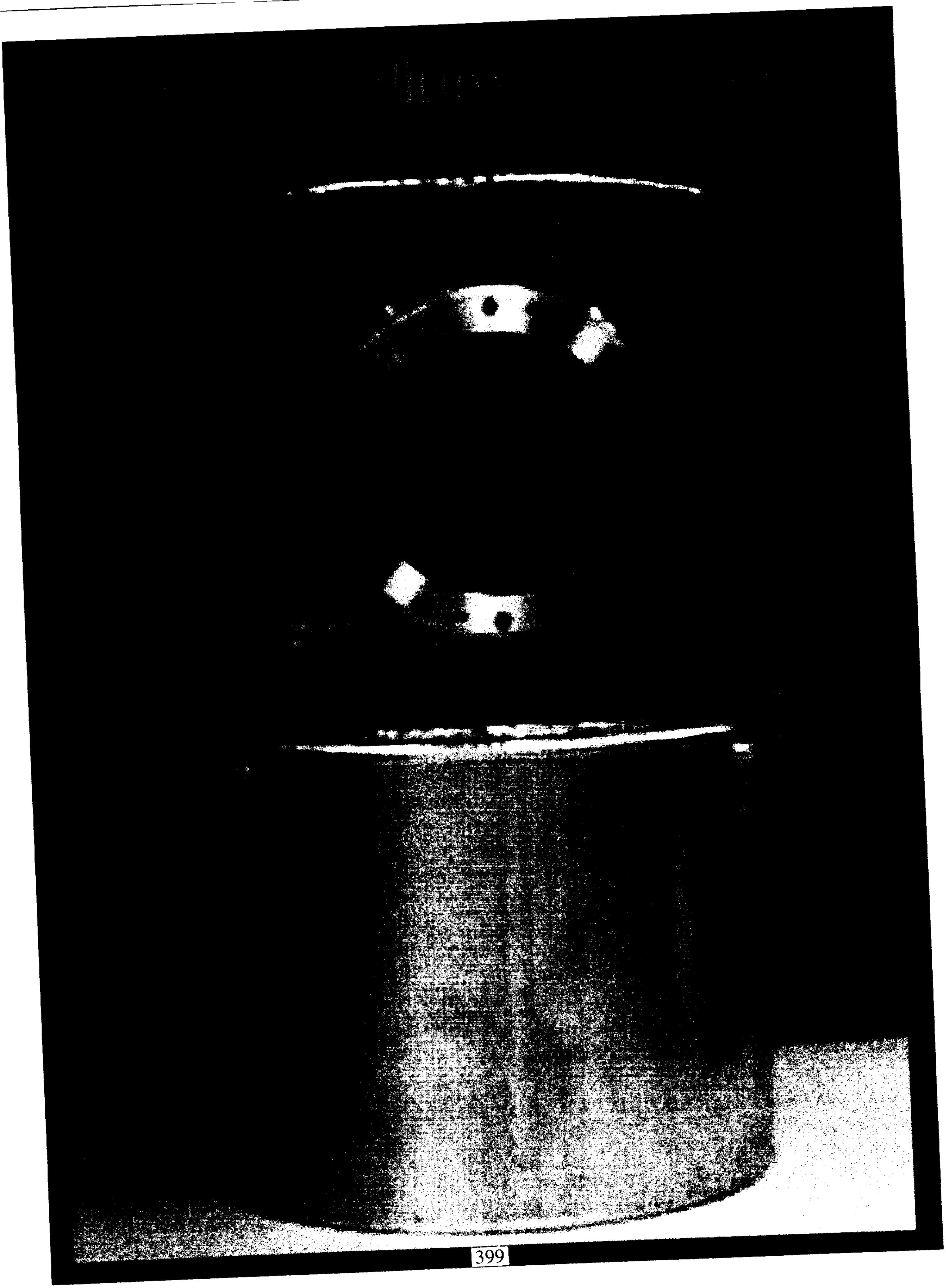
Experience has demonstrated; contamination control programs and policies managed using standard principles and techniques as **guidelines** rather than gospel and then applying in a pragmatic fashion, are the most successful. At the same time, all appropriate issues and considerations must be taken into account. There is no substitute for pragmatism and appropriate compromise during the development and implementation of these programs. Over the years, projects such as EUVE, TRMM, and the HST Servicing Mission have supported this approach, resulting in budgets being met and projects exceeding their initial goals. Adherence to the recommended contamination control strategy allows all functional groups in operations, quality assurance, and project management to successfully satisfy major requirements.

GSFC
Calorimetric Emittance Facility

CALORIMETRIC EMITTANCE FACILITY

Purpose:	**Determine the Total Hemispheric Emittance of Thermal Control Coatings**
Temp Range:	**40°K - 340°K**
Sample Size:	**1.5" diameter Aluminum Substrate**


Calorimetric Emittance Facili



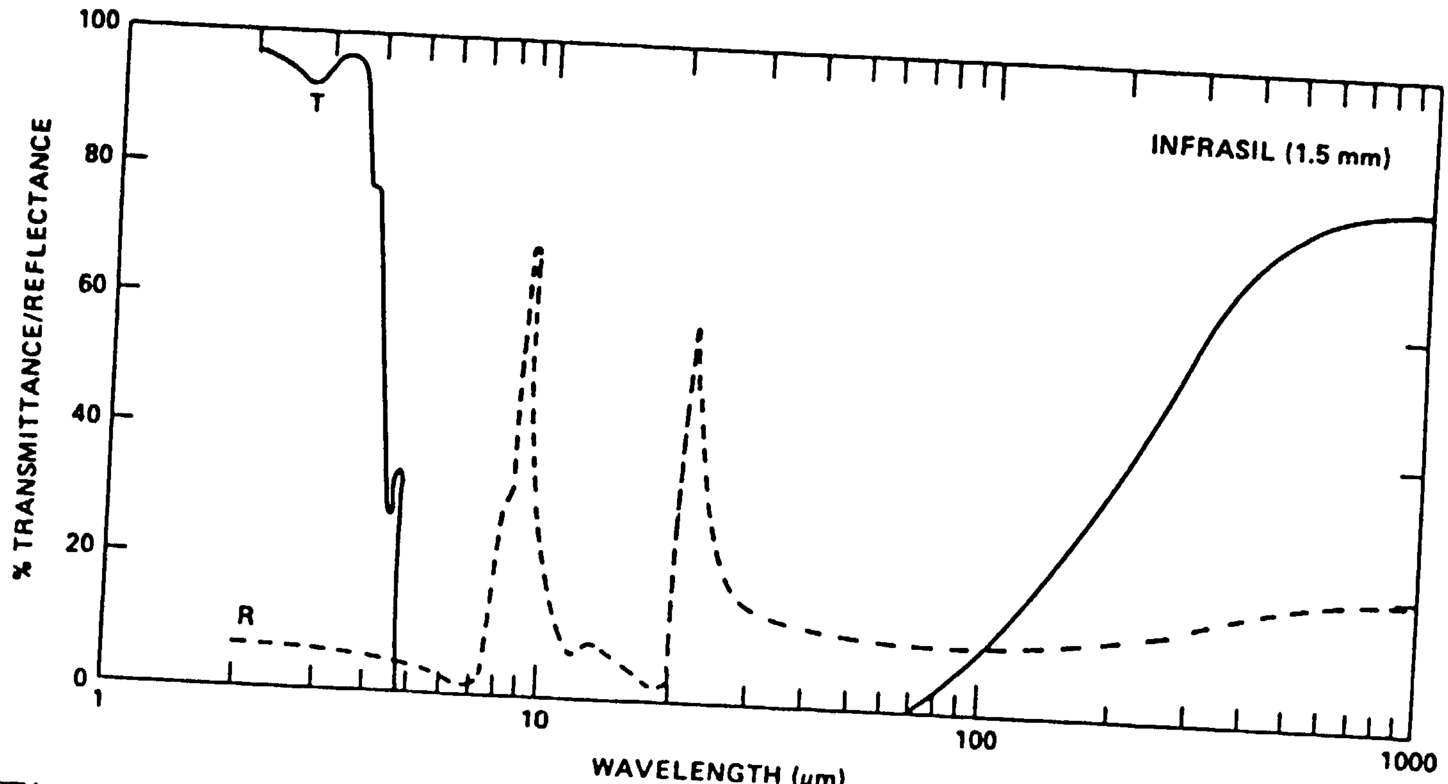
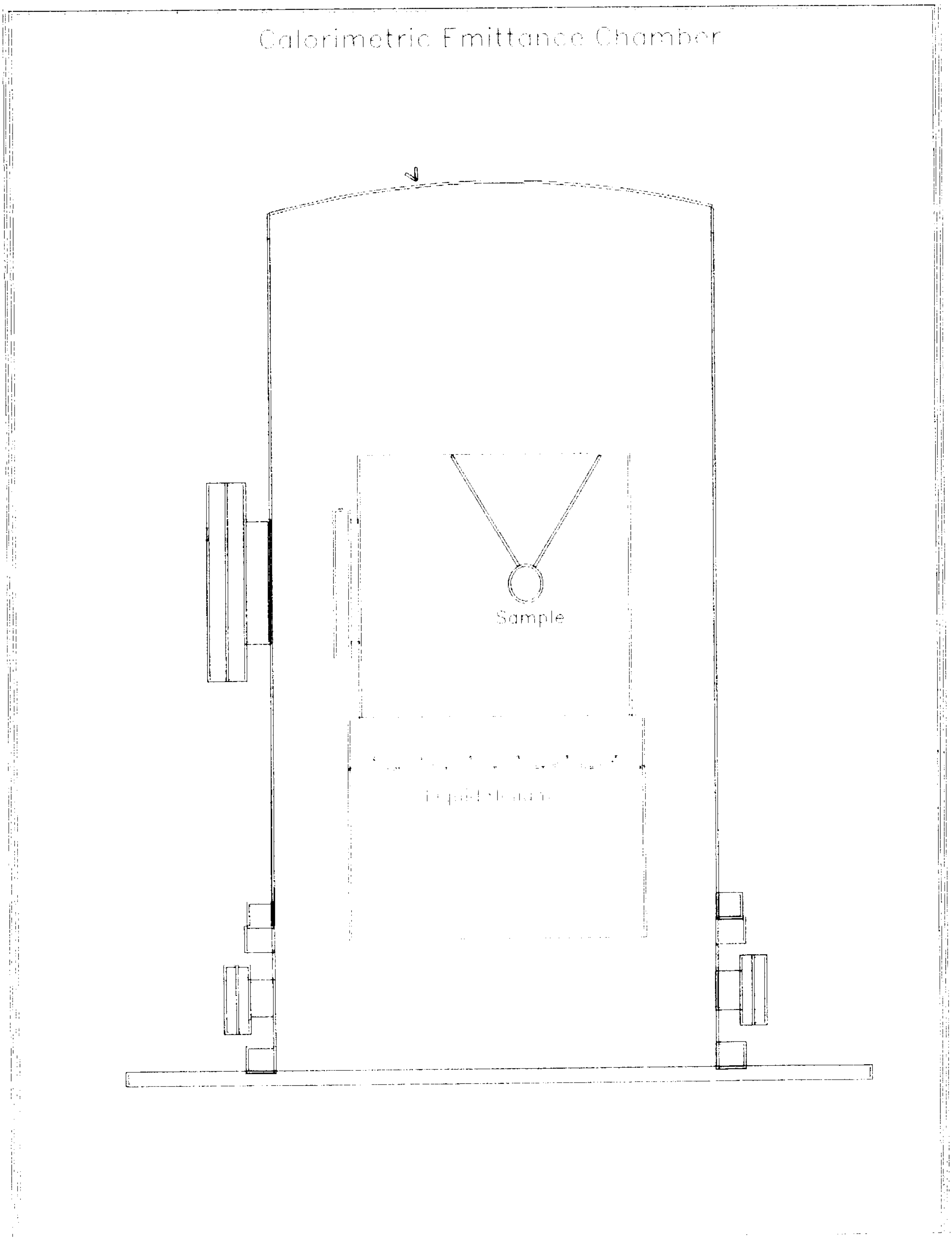


Fig. 7. Transmittance and reflectance of Infrasil, 1.5 mm thick, over the wavelength range from 2 to 1000 μm.

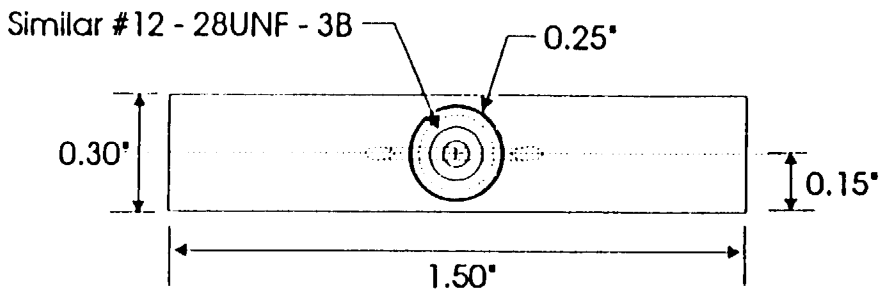

Calorimetric Emittance Chamber
Sample

1.50" Diameter Cylindrical Sample

Material: Aluminum
99.9% pure or better
TOLERENCE 0.01"

Highly Polished Aluminum

For use with Flat Head Screw
#12 - 28UNF - 3A



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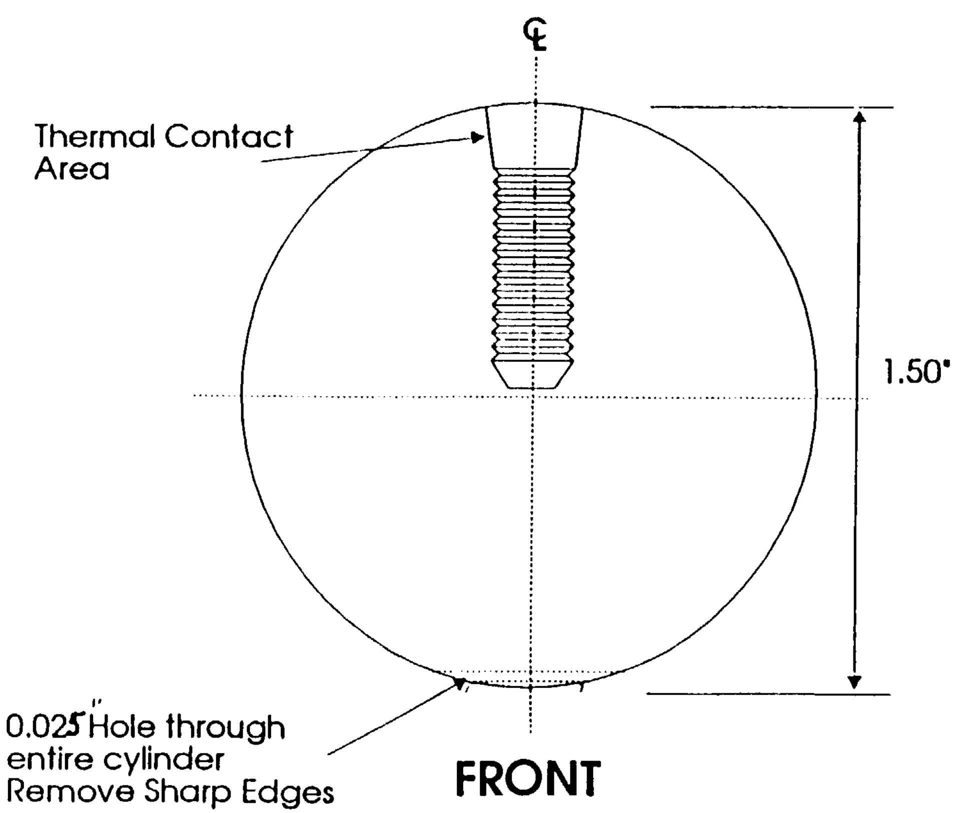
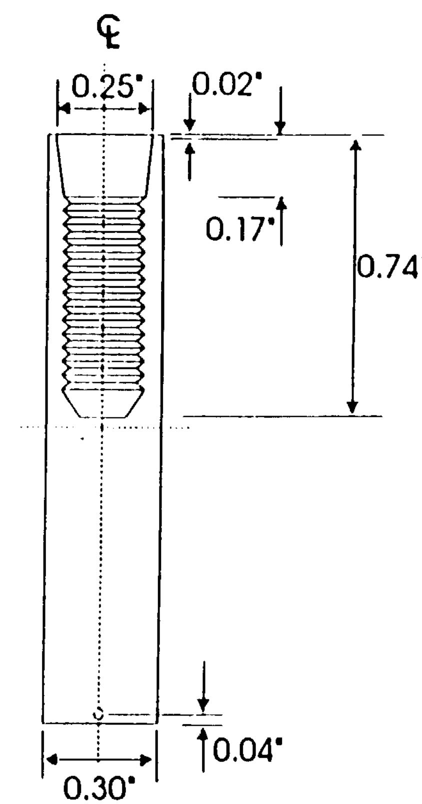
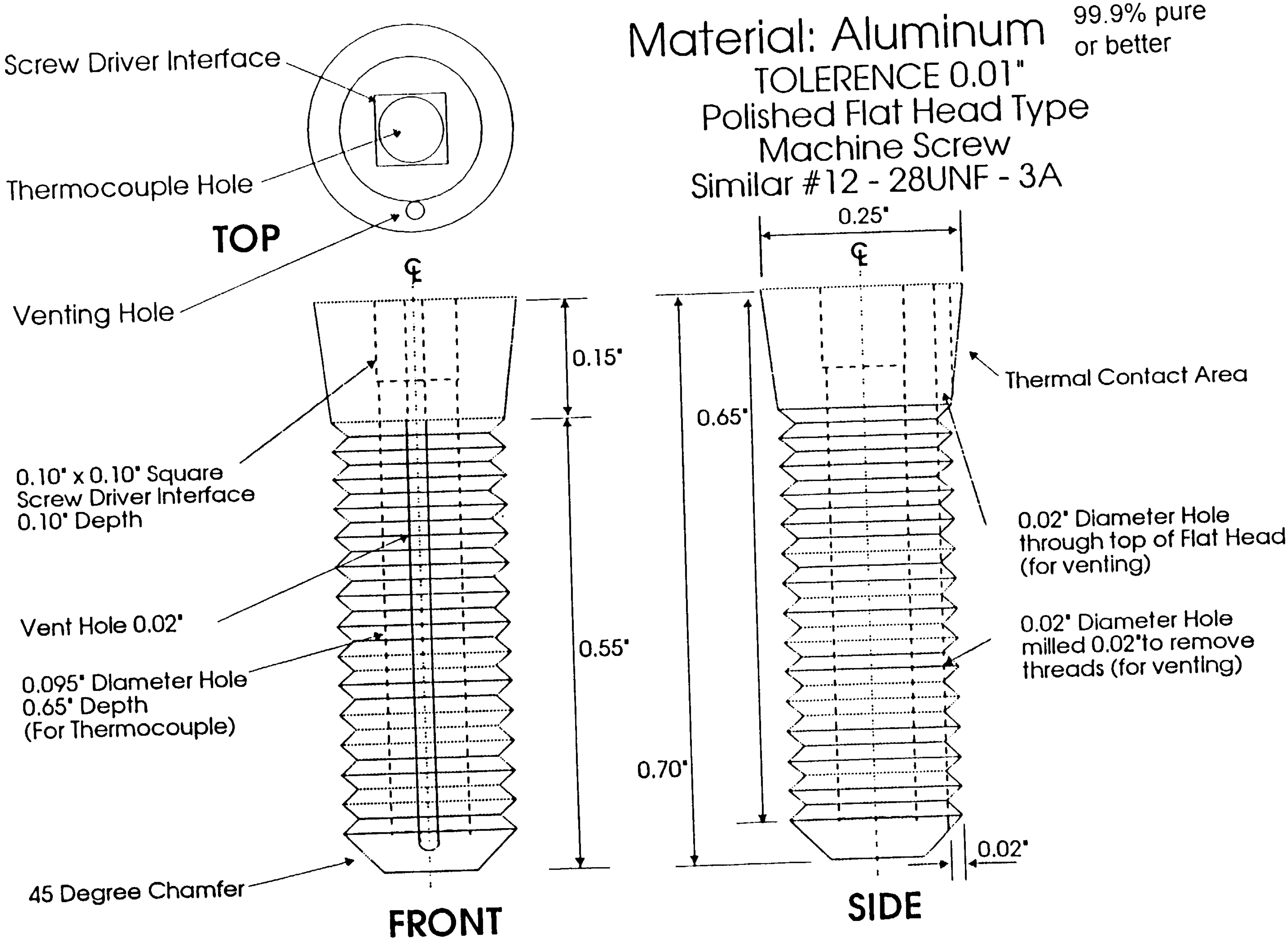


FRONT

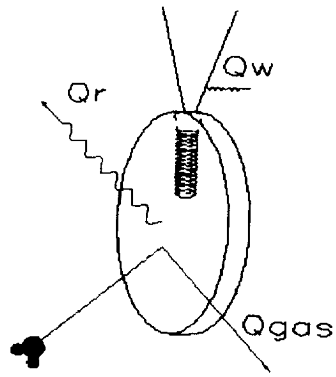


SIDE

Flat Head Machine Screw For Embedded Thermocouple



Calculation of Emittance



$$-m\cdot Cp\cdot\frac{\Delta T}{\Delta t} = a\cdot\sigma\cdot\varepsilon\cdot\left(T^4 - Ts^4\right) + Q_w + Q_{gas} - Q_{sd}$$

$$\varepsilon_k = \frac{-m_{al}\cdot Cp_{al_k}\cdot\frac{\Delta Tv_k}{\Delta t_k} - m_p\cdot Cp_{c_k}\cdot\frac{\Delta Tv_k}{\Delta t_k} - a_s\cdot\sigma\cdot\varepsilon_r\cdot\left[\left(T_k\right)^4 - \left(Ts_k\right)^4\right] - Q_{w_k} - Q_{gas_k} + Q_{sd_k}}{a_k\cdot\sigma\cdot\left[\left(T_k\right)^4 - \left(Ts_k\right)^4\right]}$$

Where:

m_{al} = mass of Aluminum
m_p = mass of coating
a = total emitting area of coating
a_s = area of sensor screw
T = Temperature of Sample
Ts = Temperature of Shroud
σ = Setefan-Boltzman constant
ε = emittance of sensor screw head
Δt = time for sample change temp
ΔT= Temperature interval
Cp_{al} = Specific heat of Aluminum
Cp_c = Specific heat of coating
Q_w = Heat loss due to Heat Radiation from Sensor Leads
Q_{gas} = Heat loss due to Residual Gas in Chamber
Q_{sd} = Heat input due to resistive heating from Silicon Diode Sensor

Heat Losses

Heat loss due to residual Gas in Vacuum Chamber:

$$Qgas = \Lambda \cdot \alpha \cdot \sqrt{\frac{273}{Ts}} \cdot (T - Ts) \cdot P \cdot a$$

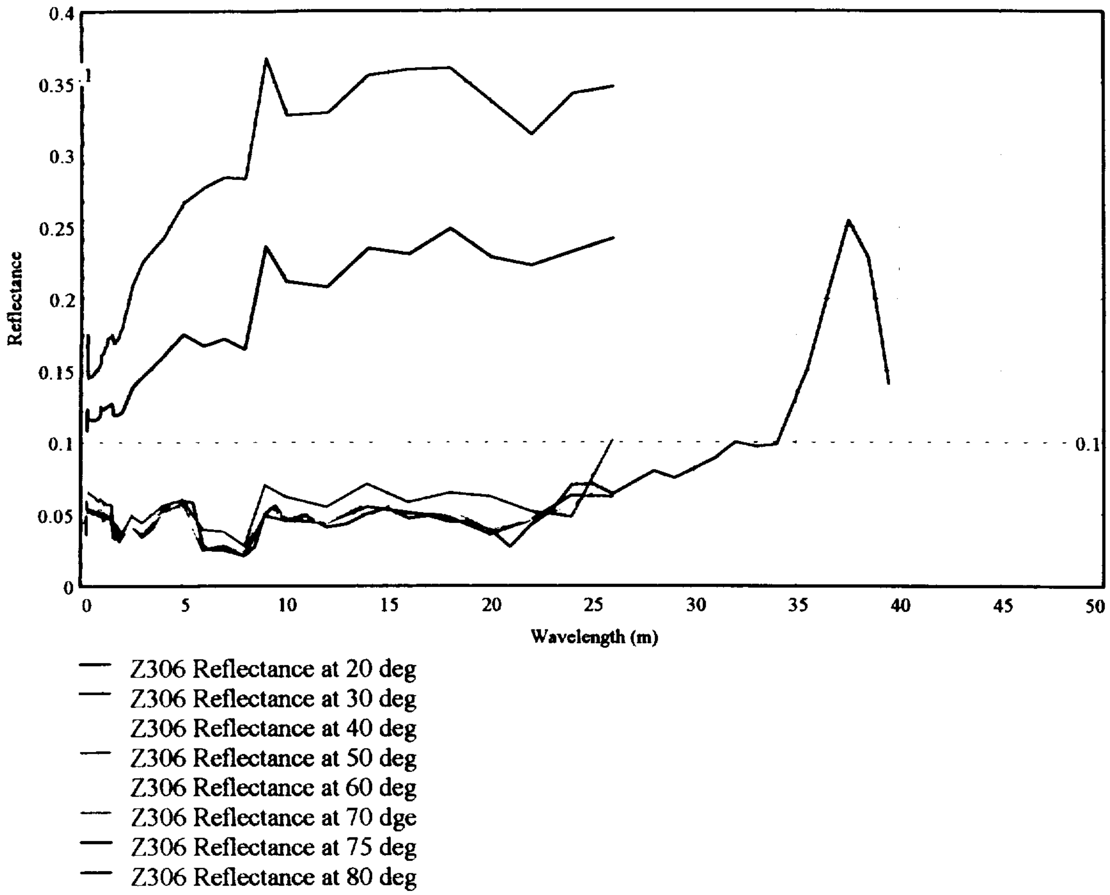
Heat flow through sensor wire:

$$qw = -\pi \cdot \left[k \cdot D^3 \cdot \varepsilon \cdot \sigma \cdot \left(\frac{T^5 - 5 \cdot Ts^4 \cdot T + 4 \cdot Ts^5}{10} \right) + k \cdot \Lambda_o \cdot D^3 \cdot \alpha \cdot \left(\frac{273}{Ts} \right)^{0.5} \cdot \left(\frac{T^2 - 2 \cdot Ts \cdot T - Ts^2}{4} \right) \cdot P \right]^{\frac{1}{2}}$$

Where:

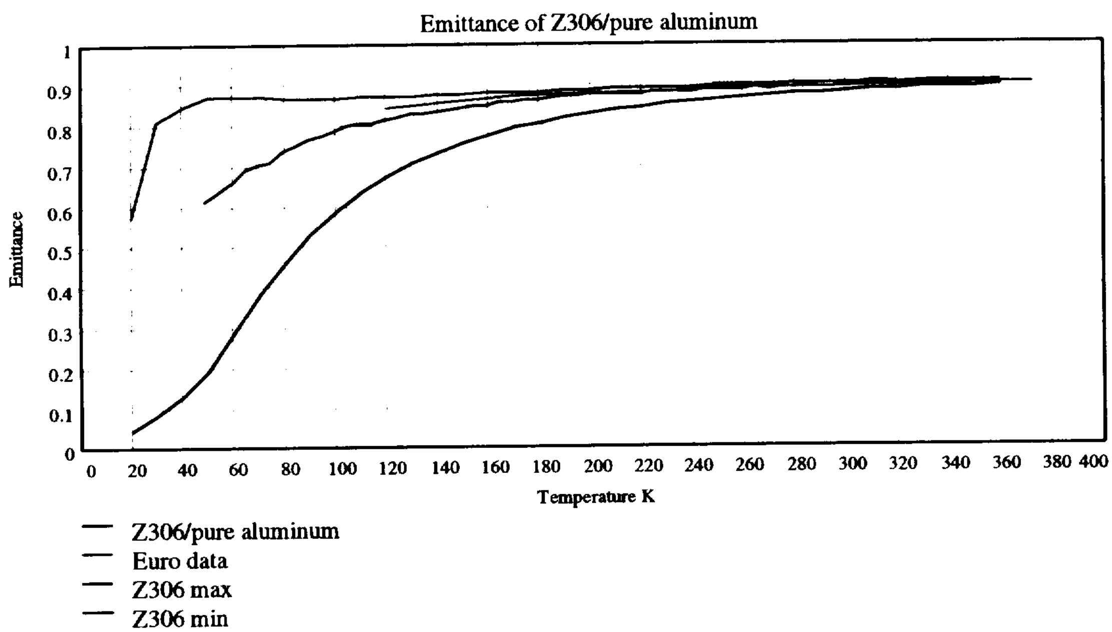
D = diameter of wire m
k = thermal conductivity of wire
T = temperature of sample (K)
Ts = temperature of shroud (K)
ε = emittance of wire coating
σ = Stefan- Boltzman constant W/m^2K^4
P = Pressure in torr
α = accommodation coefficient
Λ_o = free molecular conductivity at 0°C

Reflectance of Z306 as a function of angle of incidence

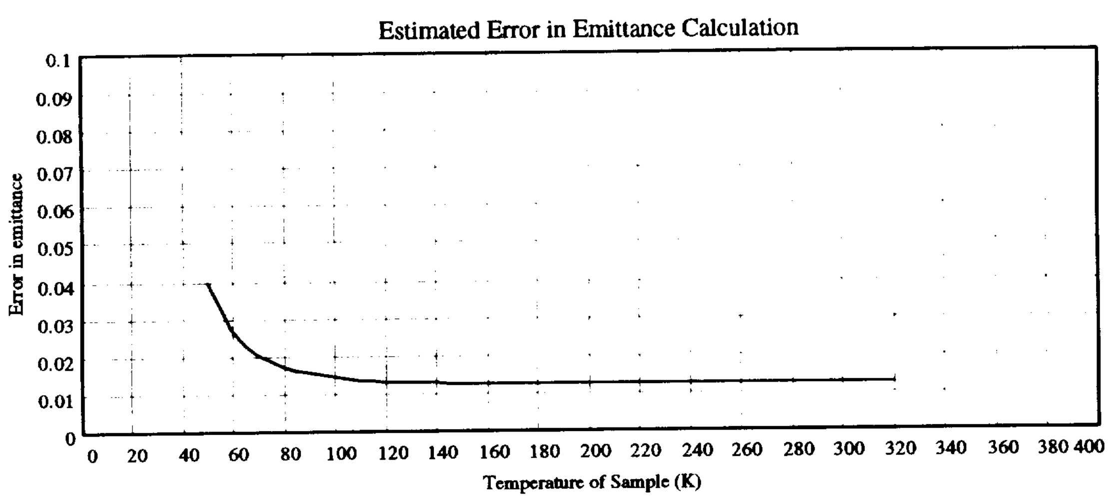


$$\varepsilon_H(T) \equiv 2 \cdot \int_0^{\frac{\pi}{2}} \varepsilon_t(\theta, T) \cdot \sin(\theta) \cdot \cos(\theta)\, d\theta$$

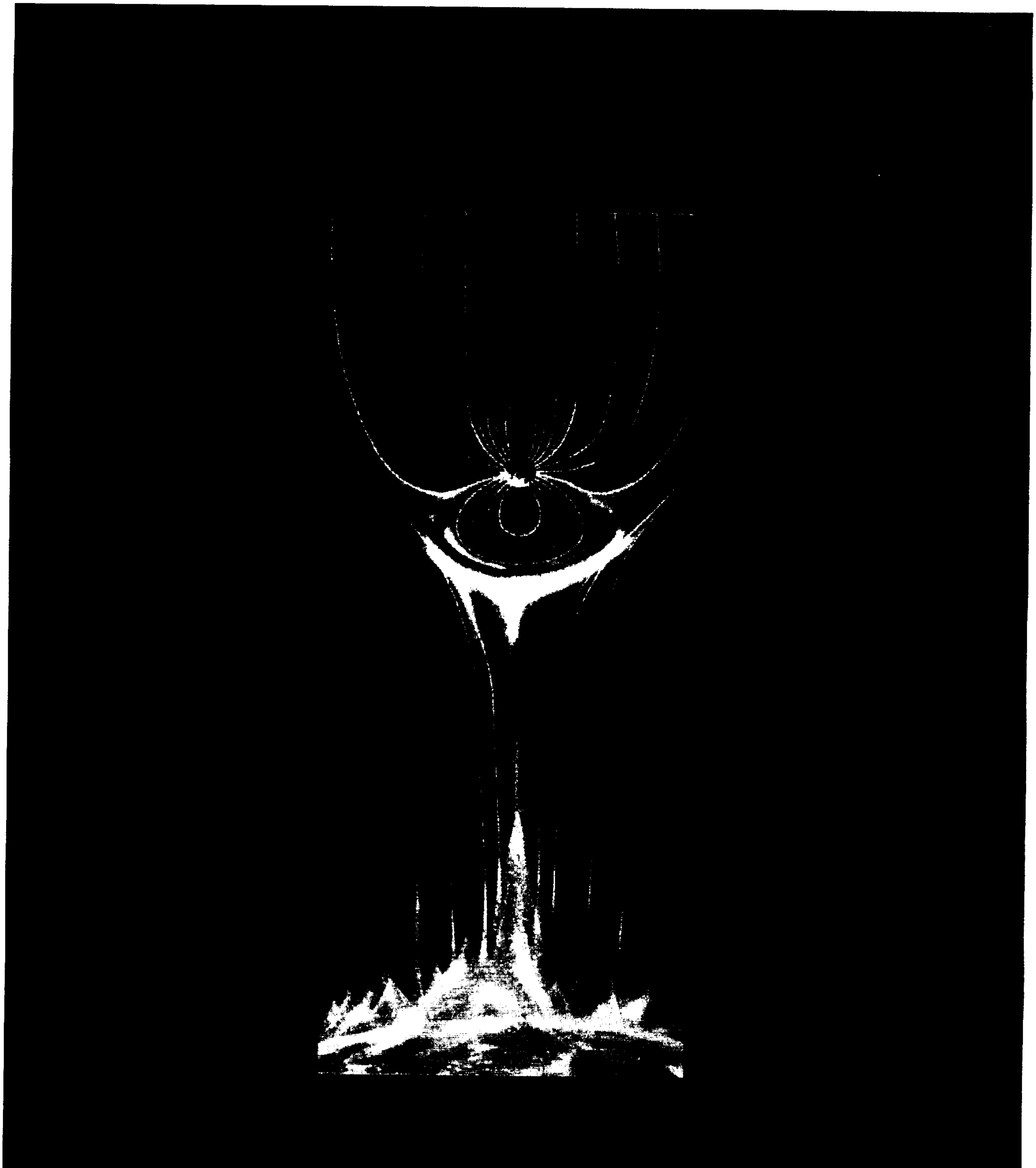
$$\varepsilon_t(\theta, T) \equiv 1 - \frac{\displaystyle\int_{\lambda 1}^{\lambda 2} \rho(\lambda) \cdot \frac{8 \cdot \pi \cdot h \cdot c}{\lambda^5 \cdot \left(e^{\frac{h \cdot c}{\lambda k T_i}} - 1 \right)}\, d\lambda}{\displaystyle\int_{\lambda 1}^{\lambda 2} \frac{8 \cdot \pi \cdot h \cdot c}{\lambda^5 \cdot \left(e^{\frac{h \cdot c}{\lambda k T_i}} - 1 \right)}\, d\lambda}$$

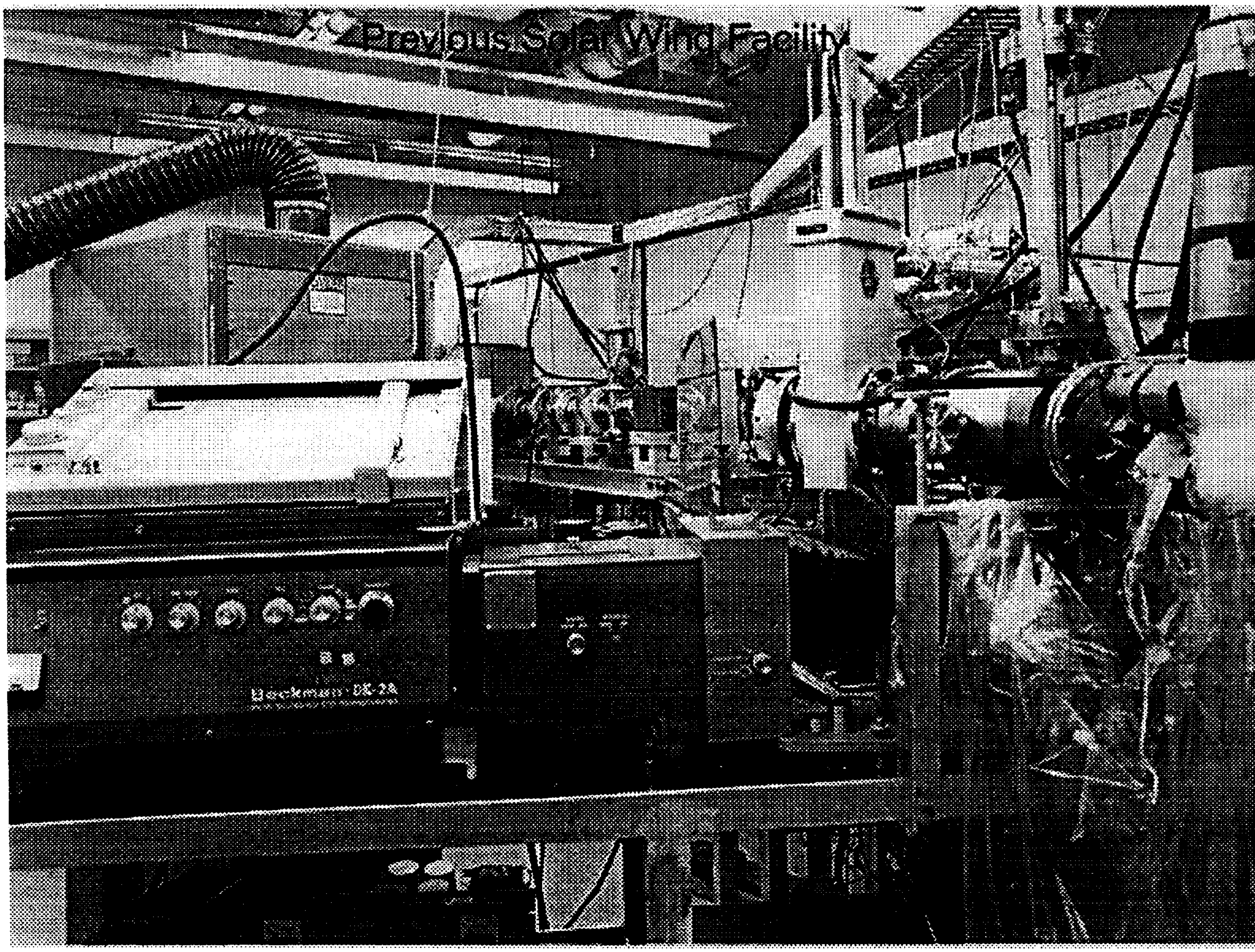


Emittance of Z306/pure aluminum
Emittance
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Temperature K
Z306/pure aluminum
Euro data
Z306 max
Z306 min



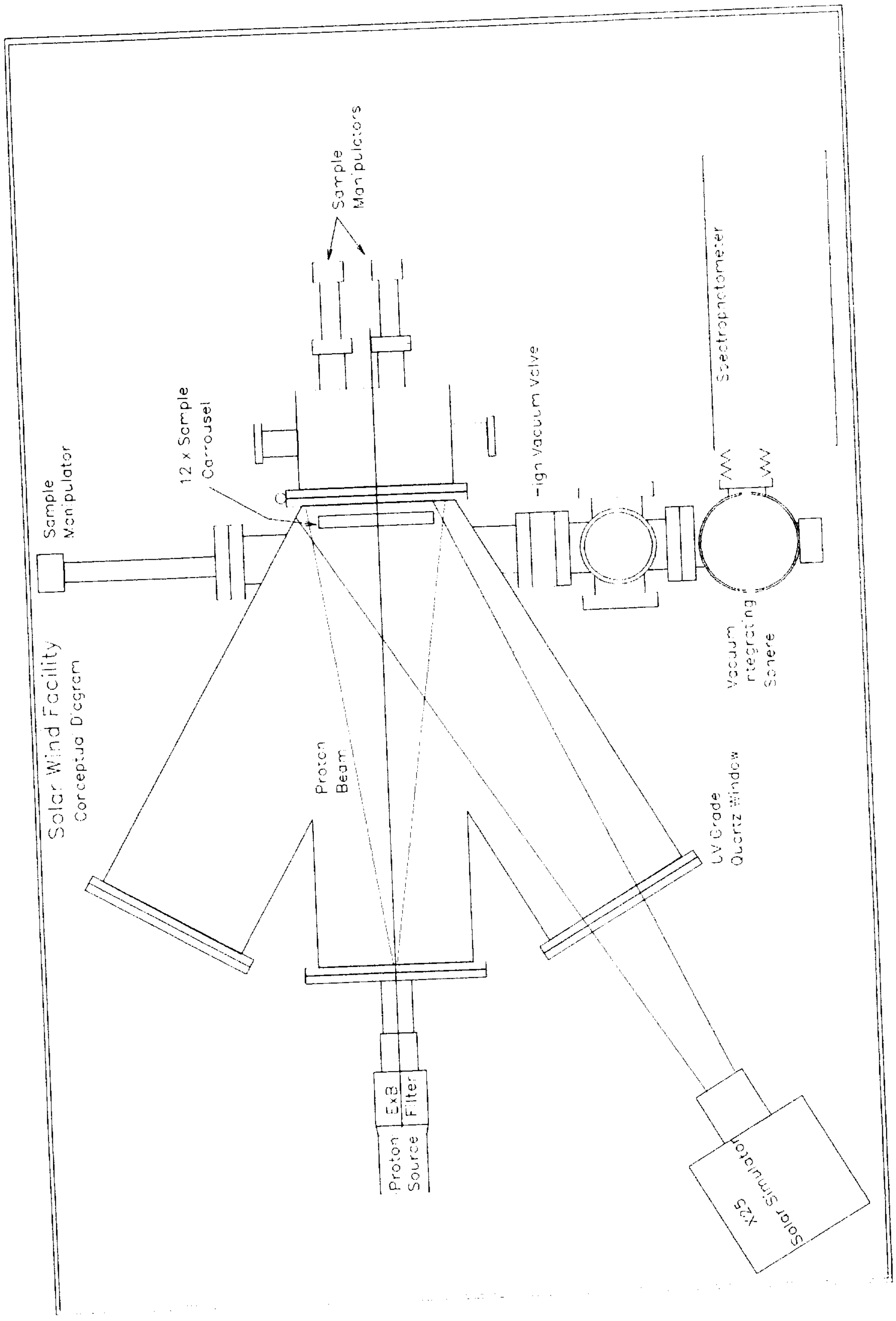
Estimated Error in Emittance Calculation
Error in emittance
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Temperature of Sample (K)


NASA

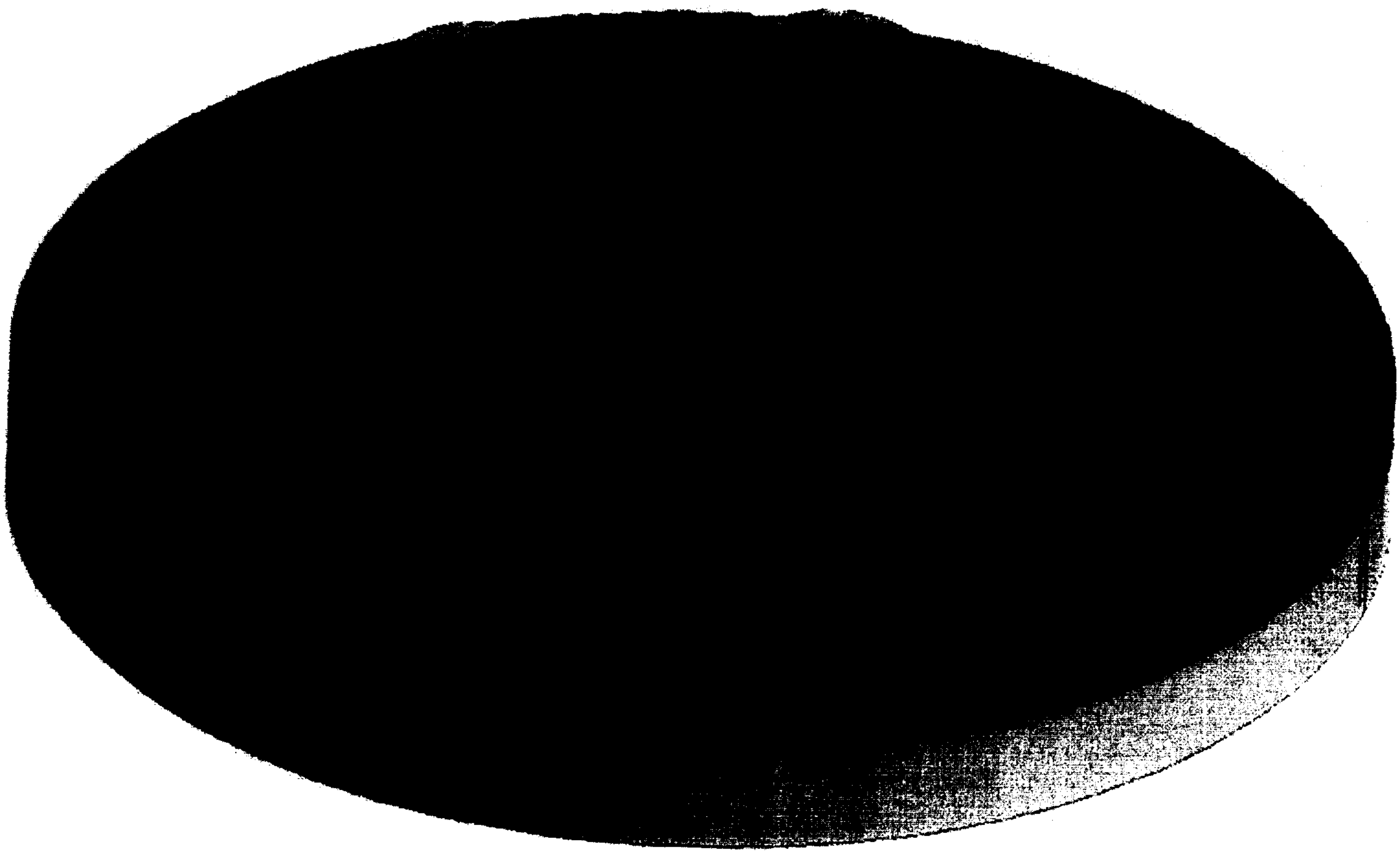

Previous Solar Wind Facility
Beckman DK-2A

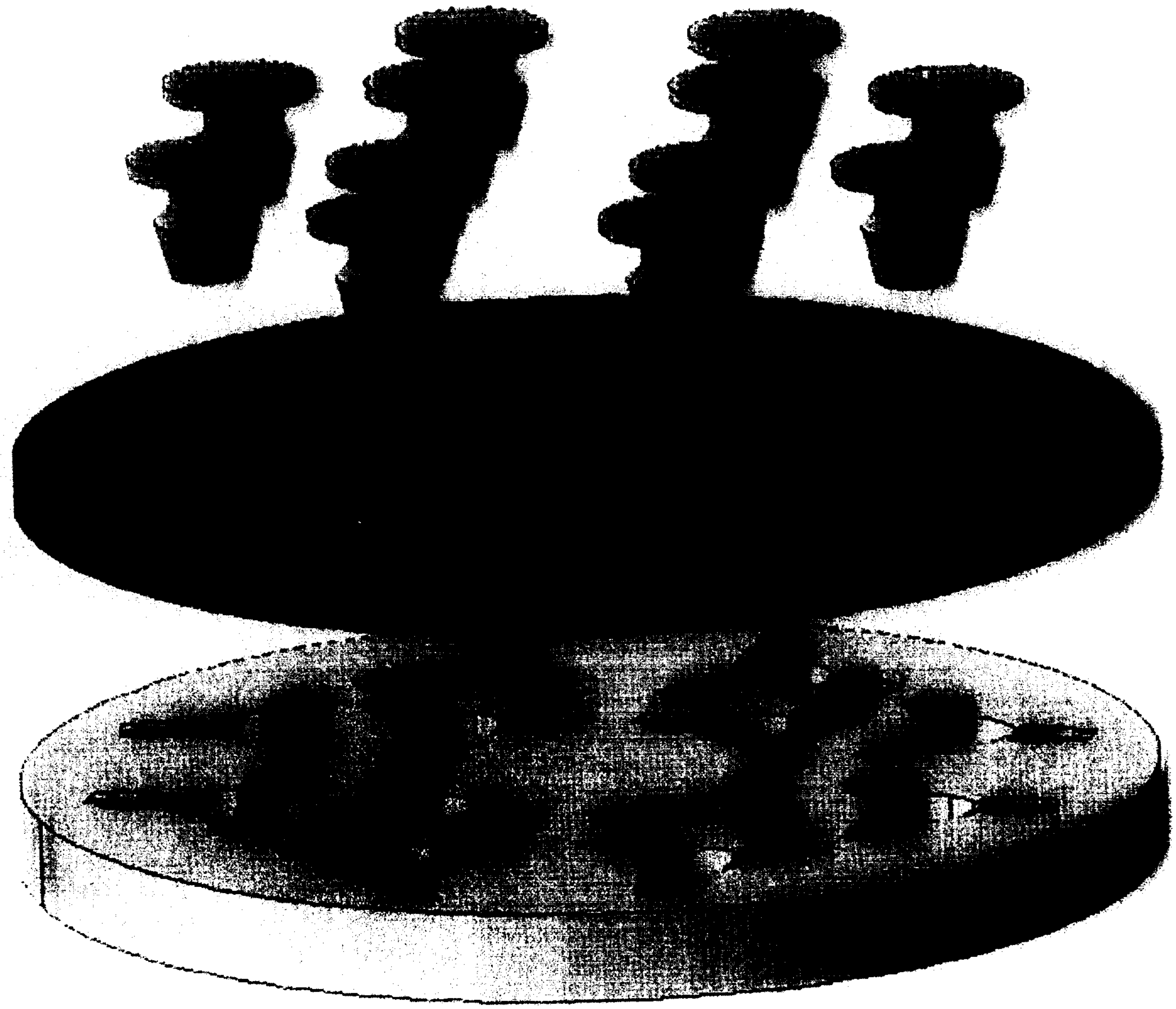
SOLAR WIND FACILITY

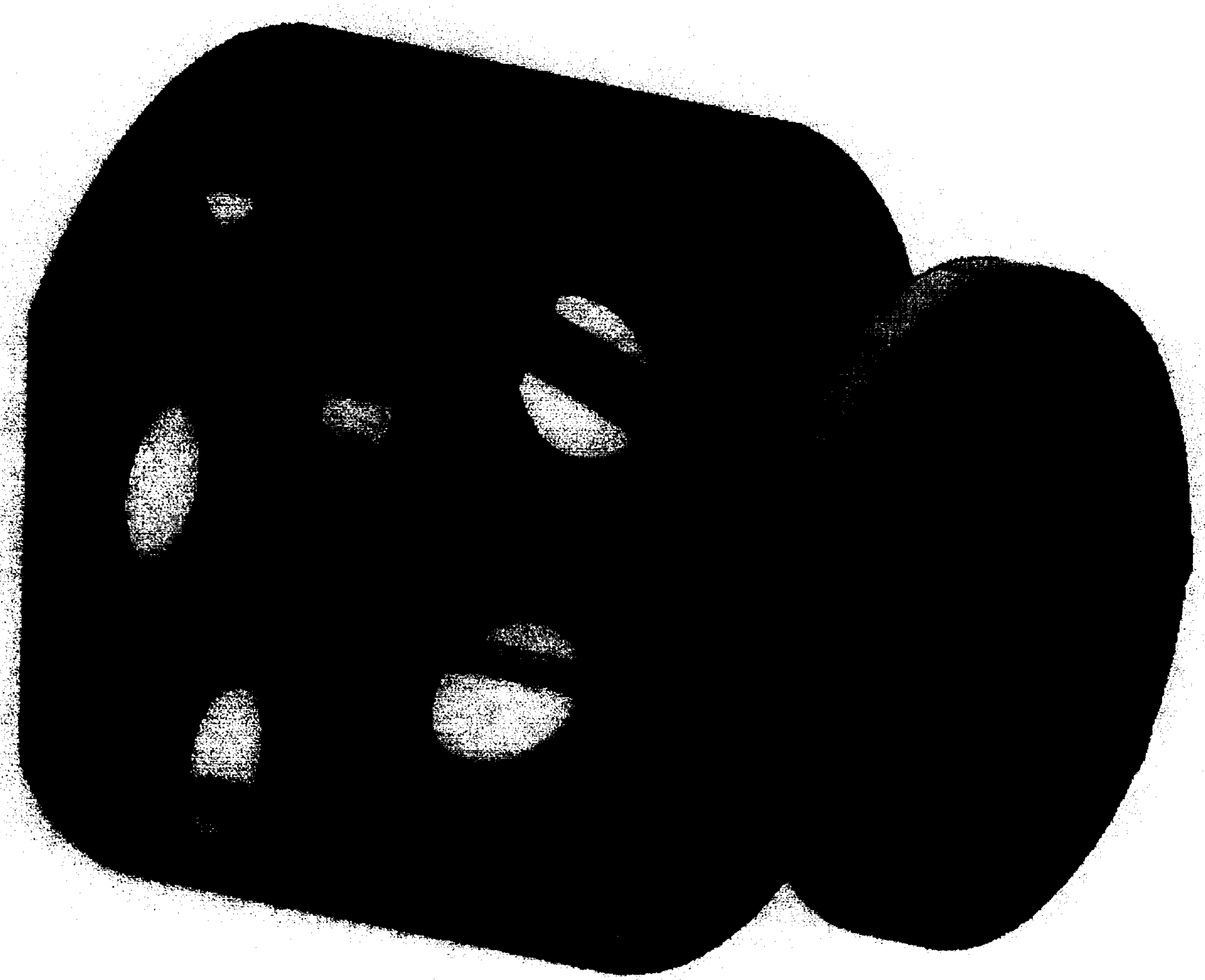
Purpose:	**Simulate Solar Wind & measure degradation of Thermal Control Coatings cause by UV & p^+**
Sample Size:	**12 samples 2cm dia**
Beam Energy:	**500eV - 10KeV ±50eV**
Current Density:	**$2.7nA/cm^2$**
Beam Size:	**12cm**
Design Criteria:	**Exposure time significantly less than old facility**
	UV simulation more complete
	Absolute In-Situ Reflectance measurement
	Integrating Sphere independent from main chamber
	Minimum of 12 samples

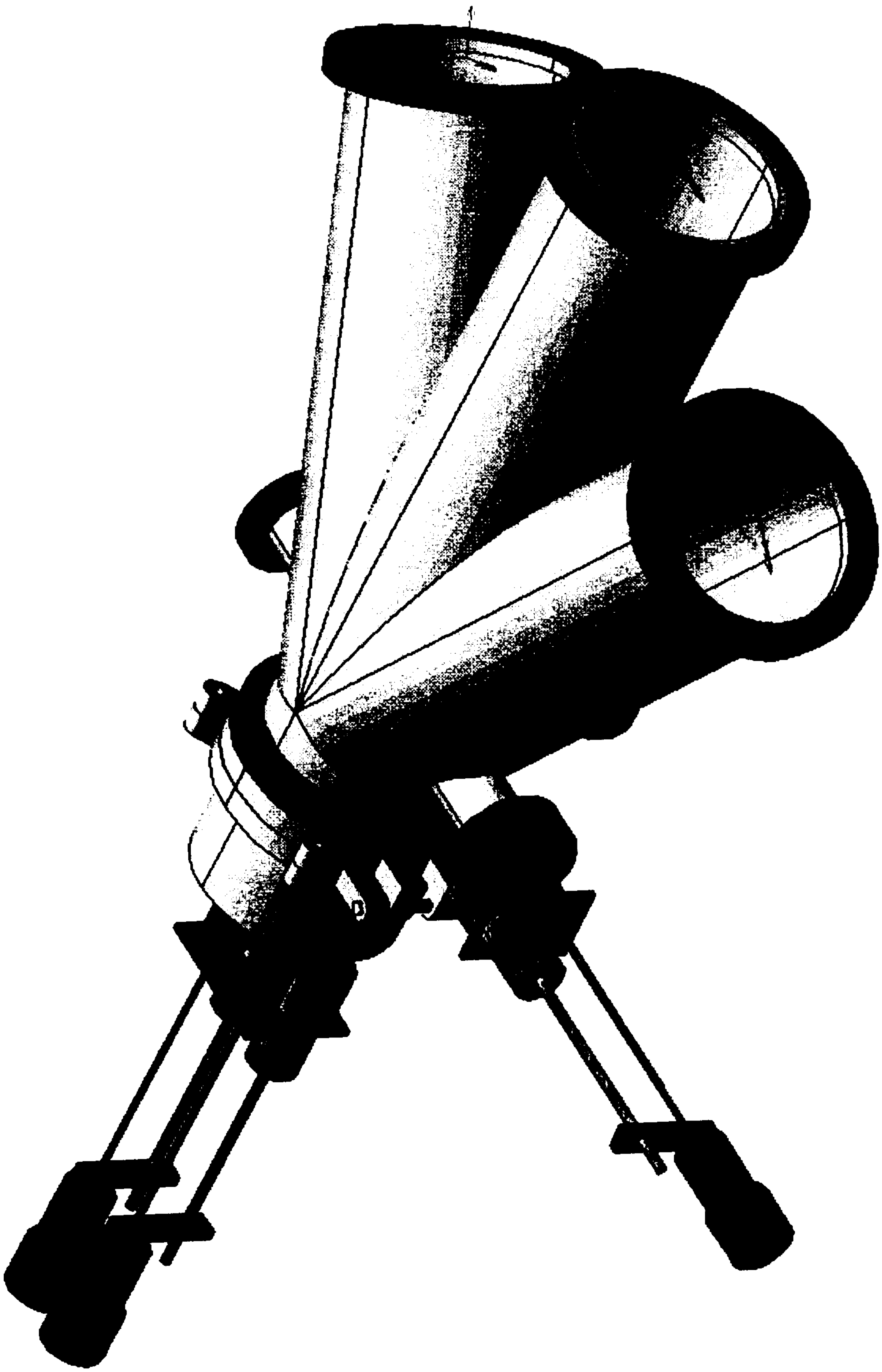


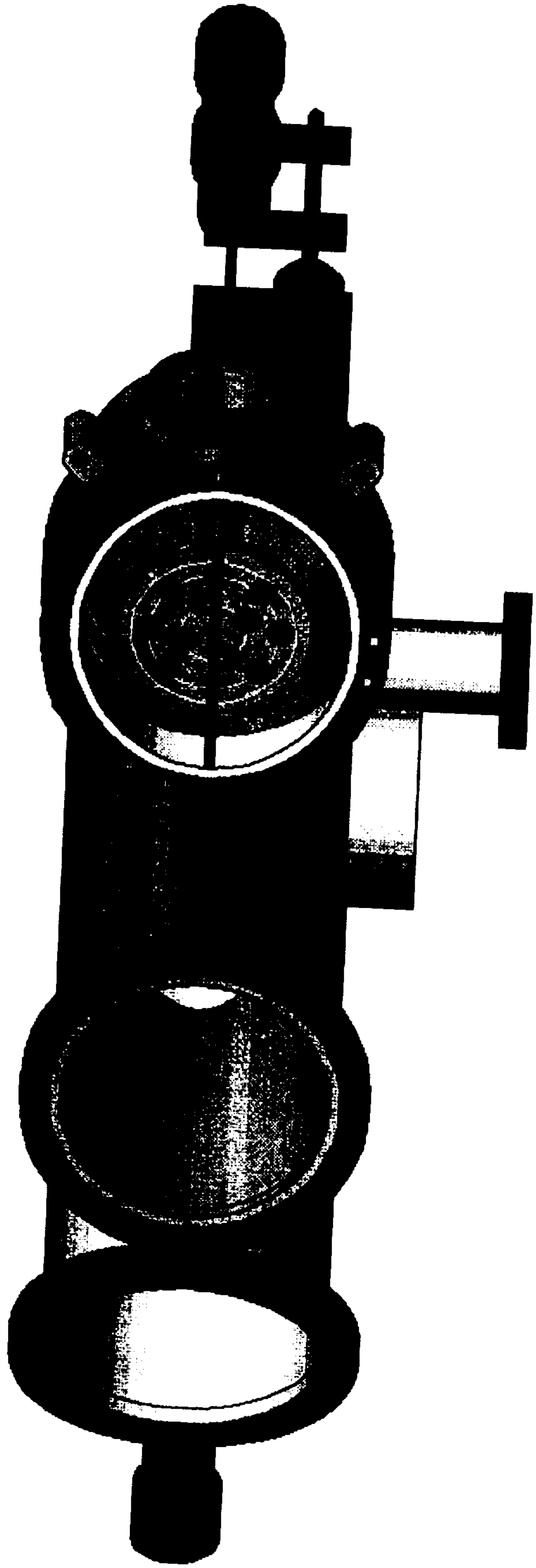
Solar Wind Facility
Conceptua Diagram
Sample Manipulator
12 x Sample Carousel
Sample Manipulators
Vacuum Valve
Spectrophotometer
Vacuum Integrating Sphere
Proton Beam
UV Grade Quartz Window
Proton Source
ExB Filter
X25 Solar Simulator

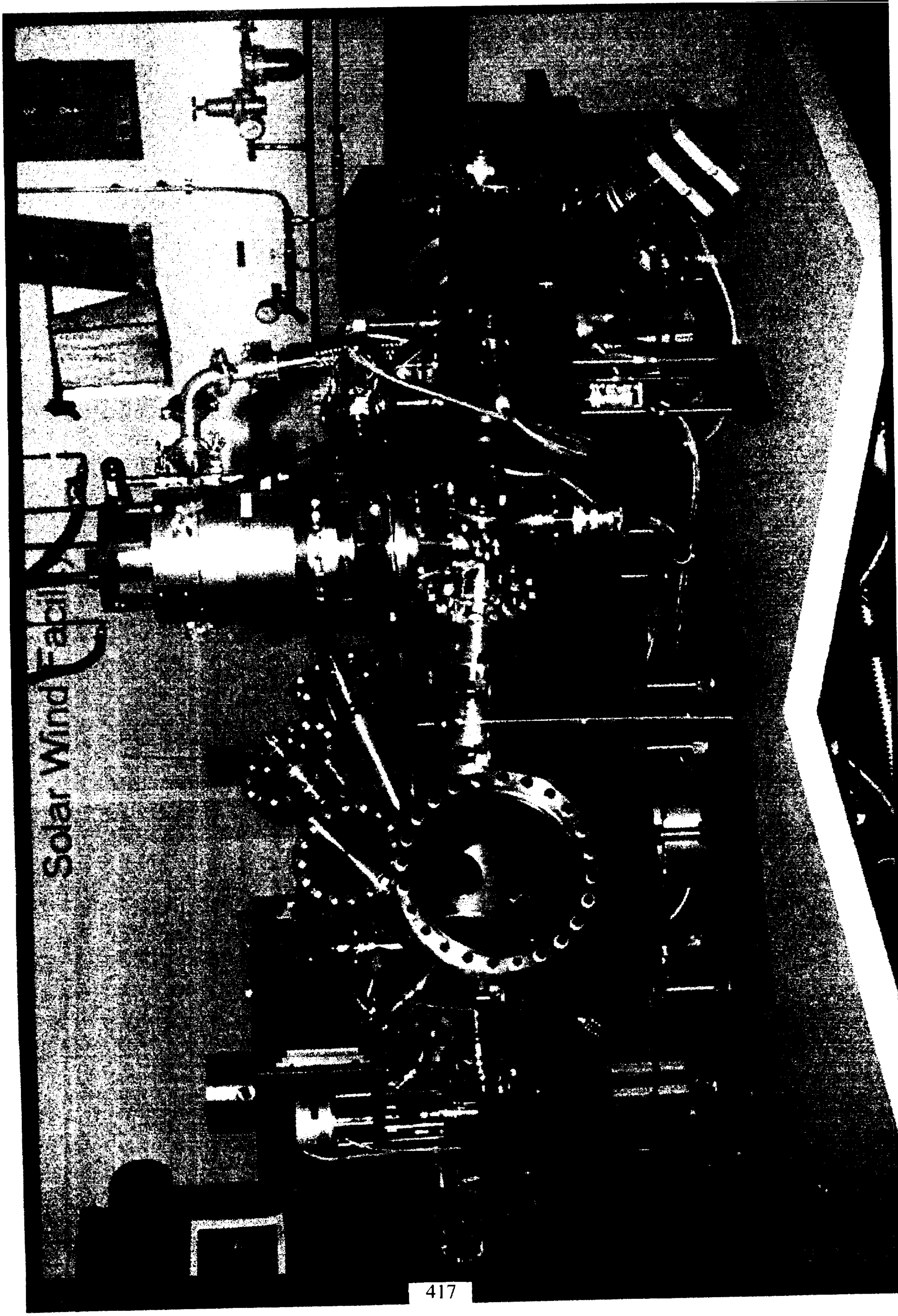


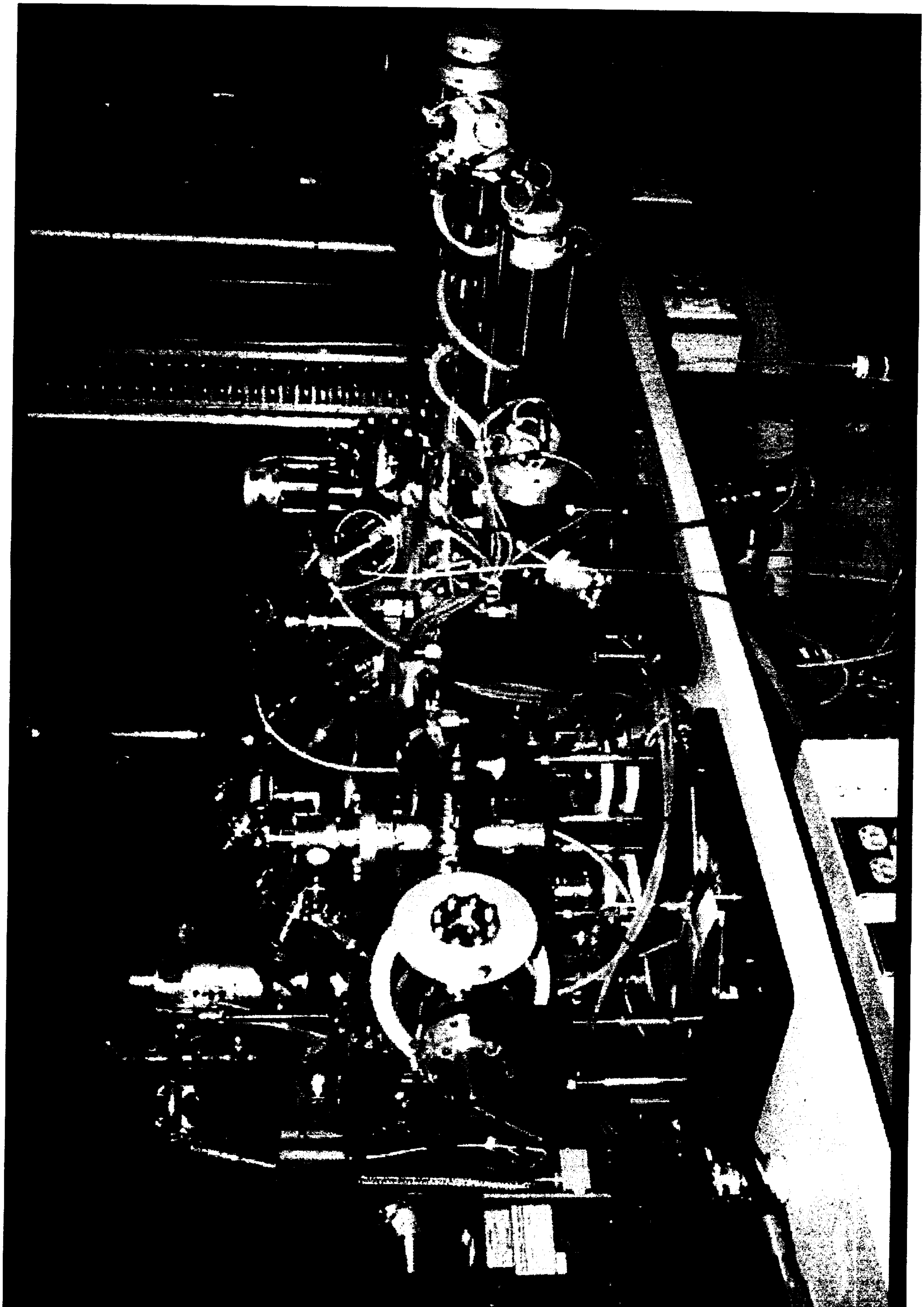









Solar Wind



GSFC Solar Wind Facility
Planned Testing

Initial Test

1. MS74
2. S13GPLO
3. NS43G
4. Ag Teflon 5mil FEP
5. Ag Teflon 2mil FEP
6. VDA/Kapton 5mil
7. ITO/VDA/Kapton 2mil
8. NS43C
9. A276
10. GSFC Composite Coating
11. Z93P
12. VDA (degrading reference)

Second Test

1. AZ174
2. Z306
3. Z307
4. Z93SC55
5. AZ4301
6. L300
7. H322
8. Spectrally Selective Coating
9. Z93SC1655
10. A276
11. Dark Mirror Coating
12. VDA (non degrading reference)

THERMAL COATINGS

Coatings Measurement Facility

The reflectance and transmittance of thermal control surfaces are measured over the wavelength range 0.25μm to 2.5 μm. From this data the solar absorptance is calculated via ASTM-E903-82. The normal emittance (e_n) is also calculated from normal reflectance data of surfaces from 5 to 40 μm.

MULTISEEDES UV Degradation Chamber

This facility is designed to provide long term full spectrum solar exposure for 14 thermal coatings test samples under vacuum. A dedicated spectrophotometer is capable of measuring degradation of reflectance of the test samples in-situ.

Calorimetric Emittance Chamber

The Calorimetric Emittance facility has been designed to measure the total hemispheric emittance of thermal control surfaces via a calorimetric technique over a temperature range of 40°K - 350°K.

Electrostatic Facility

The Electrostatic Charge Facility is designed to determine charging of thermal control surfaces under electron current densities and energies found on orbit. Surface conductivity can be determined for a coating from -150°C to 100 °C.

Solar Wind Facility

The Solar Wind Facility is a combined effects chamber design to simulate the effects of low energy protons in combination with ultra violet light on thermal control coatings. This facility has the capability of accommodating twelve 2 cm diameter sample simultaneously. These samples can be exposed to protons with energy ranging from 0.5Kev to 10Kev with flux densities of $3x10^8$ cm^2. This intensity is sufficient to allow the equivalent of one year of on orbit exposure to be simulated in approximately 3 weeks. Degradation in that the total hemispherical reflectance of each sample can be measured in-situ over the wavelength range 0.25-2.4 μm.

Bell Jar Vapor Deposition System I

This facility is a fully automated resistance evaporation system. Utilizing a programmable logic controller, capable of depositing a series of up to 6 different materials in a single run. This system is currently dedicated to coating astronaut visors exclusively

72 inch diameter Vapor Deposition System &Thermal Vacuum System

This system can deposit a series of up to 4 different materials via resistance evaporation plus four additional materials via electron beam, in a single run with optional substrate rotation and optical monitoring capabilities. This system also has an available shroud that can be installed to convert the chamber for thermal vacuum test purposes

Bell Jar Vapor Deposition System II	**A resistance evaporator with automatic valve sequencing and deposition control, capable of depositing a series of up to 5 different materials in a single run. It also has substrate rotation and optical monitoring capabilities.**
Bell Jar Vapor Deposition System III	**A resistance evaporator with substrate rotation, capable of depositing a series of up to 4 different materials in a single run.**
Thermal Vacuum Chamber	**A thermal vacuum cycling chamber capable of achieving temperatures from ~ +150°C to -190°C. This chamber can be fitted with cold plates, 21 by 21 inch maximum. The available shroud in 12 inch diameter by 15 inch height.**

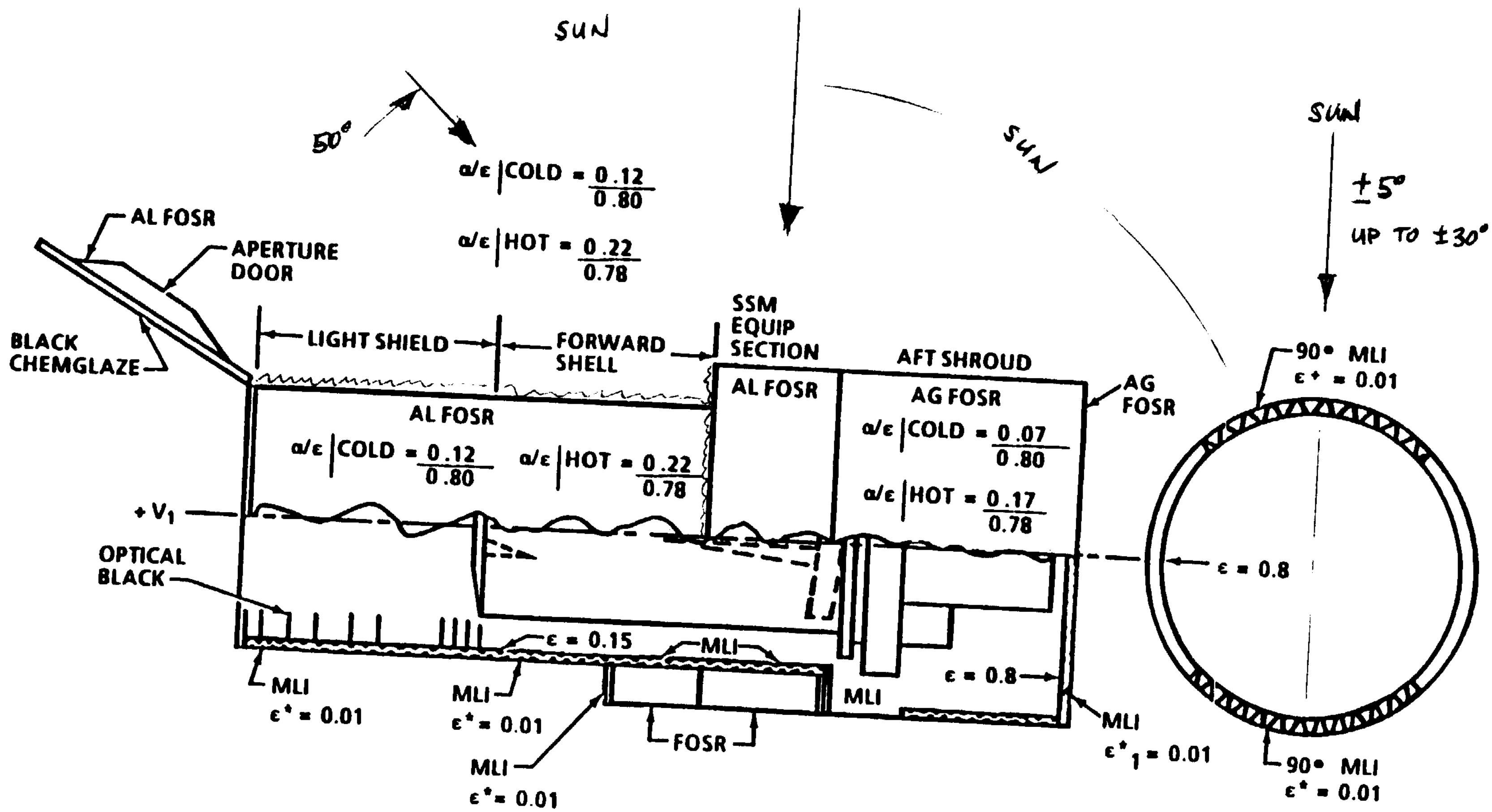
DEGRADATION OF HST EXTERNAL MULTI-LAYER INSULATION MATERIAL

Yukio Yoshikawa, Lockheed Martin Technical Operations
Jack J. Triolo, Swales & Associates, Inc.
Patricia A. Hansen, GSFC, NASA
Larry Dell, Lockheed Martin Technical Operations

PRESENTATION OUTLINE

- HST THERMAL DESIGN
- HST HISTORY
- FSM RETURNED MATERIALS
- SM2 MLI DAMAGE SURVEY
- LIGHT SHIELD MLI DAMAGE & REPAIR
- SSM ES MLI DAMAGE & REPAIR
- SM2 MATERIALTESTING
- FLIGHT TEMPERATURES
- CANDIDATE MATERIALS
- EVALUATION TEST PROGRAM

HST BASELINE THERMAL DESIGN

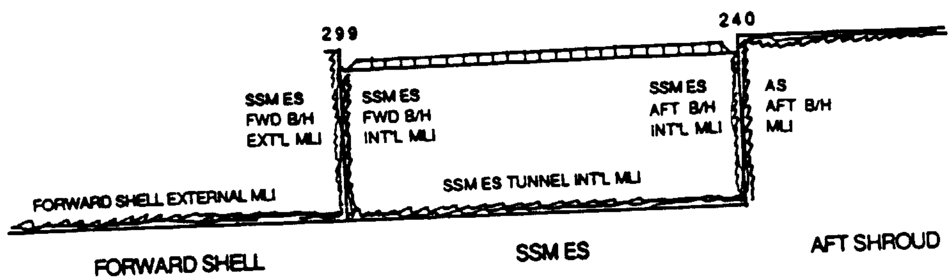


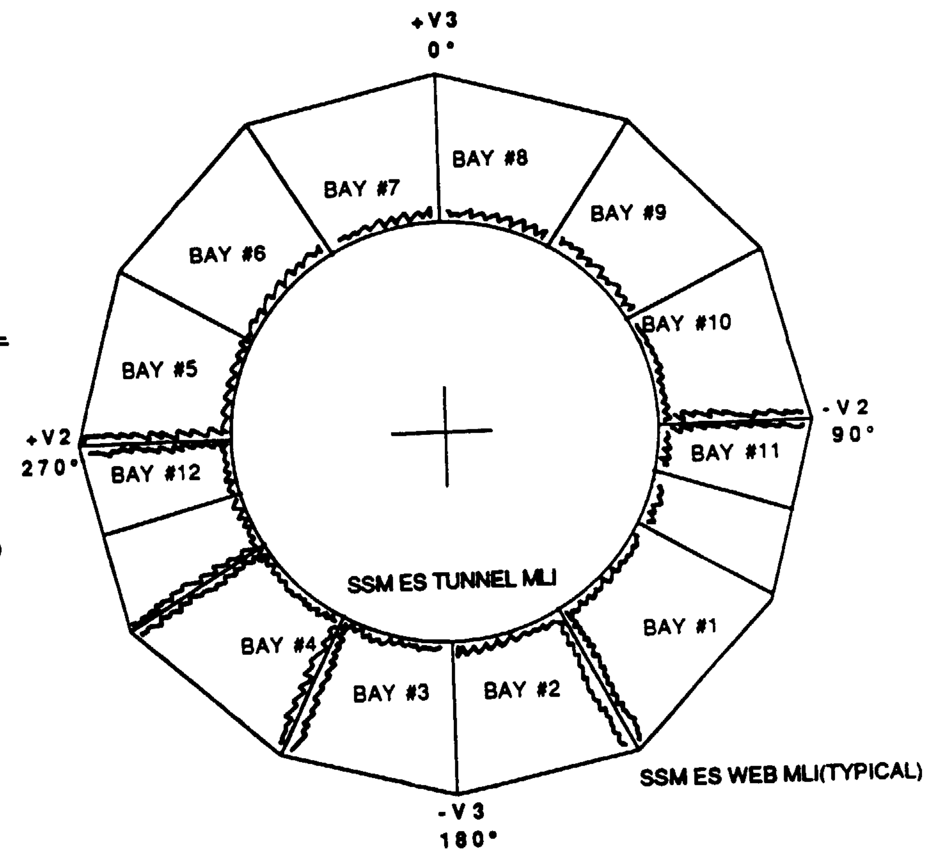
ORBIT ALTITUDE 600 KM

ORBIT INCLINATION 28.5°

BETA ANGLE RANGE ± 52.0°

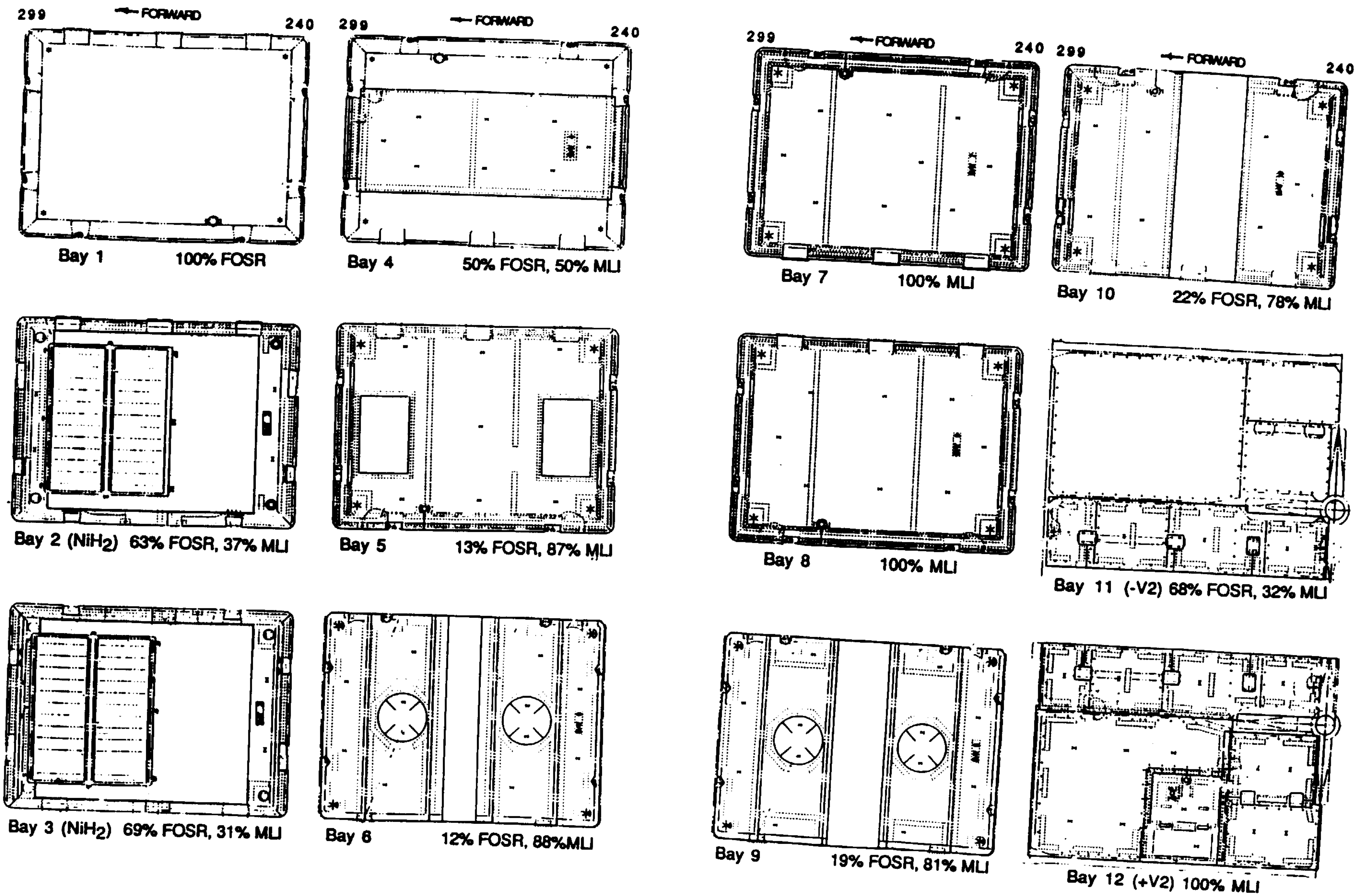
SSM EQUIPMENT SECTION





STA 238-299
LOOKING FORWARD

SSM ES DOOR MLI



HST MLI CONFIGURATION

- HST MLI CONFIGURATION
  - Outer Layer - 5 mil Teflon Aluminized backside
  - 15 layers - 1/3 mil Embossed Double Aluminized Kapton
  - Inner Layer - 1 mil Single Aluminized Kapton (Kapton out)
- HST RADIATOR & AFT SHROUD
  - 5 mil Teflon Silver backside - Acrylic adhesive
- HST APERTURE DOOR
  - 5 mil Teflon Alumunized backside - Acrylic adhesive

HST HISTORY

- MLI FABRICATION & INSTALLATION ~1980
- HST SYSTEM TV/TB TEST ~60 DAYS - 1985
- HST DEPLOYMENT - APRIL 1990
- FIRST SERVICING MISSION (FSM) - DEC 1993 (3.7 YRS)
- SECOND SERVICING MISSION (SM2) - FEB 1997 (6.8 YRS)
- THIRD SERVICING MISSION(SM3) - 1999 - SCHEDULED
- FOURTH SERVICING MISSION (SM4) - 2002 - SCHEDULED
- HST RETRIEVAL MISSION ~2009 - SCHEDULED

HST RETURNED H/W PROPERTIES

Table 5: Magnetometer MLI FEP Layer Optical Properties

ESH Value	α_s	ε_n	$\epsilon_{Hem'l}$ $.96\epsilon_m$
16,670	0.215	0.812	.78
11,339[1]	0.223	0.827	.79
11,339[2]	0.188	0.838	.80
9,193, or 6,324	0.180	0.820	.79
6,324, or 9,193	0.223	0.823	.79
4,477	0.173	0.825	.79
Literature Value (Ref. 8)	≤ 0.14	≥ 0.75	
Literature Value (Ref. 9)	0.13	0.81	

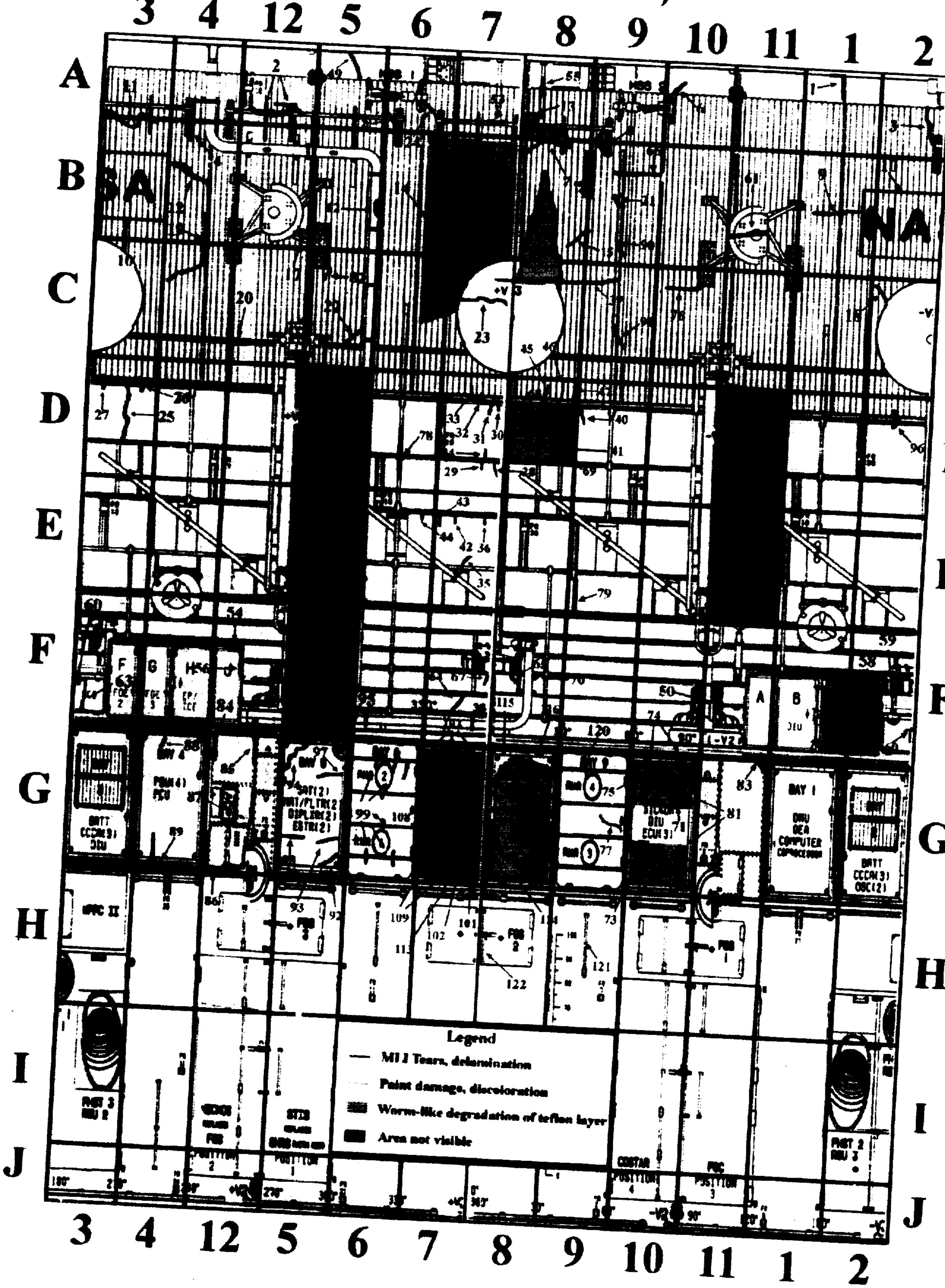
Table 6: SA-I drive arm MLI FEP Layer Optical Properties

ESH Value	α	ε_n	
Highest	0.101	0.792	.76
Middle Value	0.097	0.807	.78
Lowest	0.102	0.803	.77
Literature Value (Ref. 8)	≤ 0.09	≥ 0.75	
Literature Value (Ref. 9)	0.08	0.81	

Note: Because the ESH values for the areas of the SA-I MLI have not been calculated, only relative values, when compared to the solar pointing surface can be used.

Reference 1, Degradation of FEP Thermal Control Materials Returned from the Hubble Space Telescope, T. M. Zuby (NASA GSFC), K. K. de Groh (NASA LeRC), and D. C. Smith (Cleveland State University)

HST MLI Damage
(Damage Identified)



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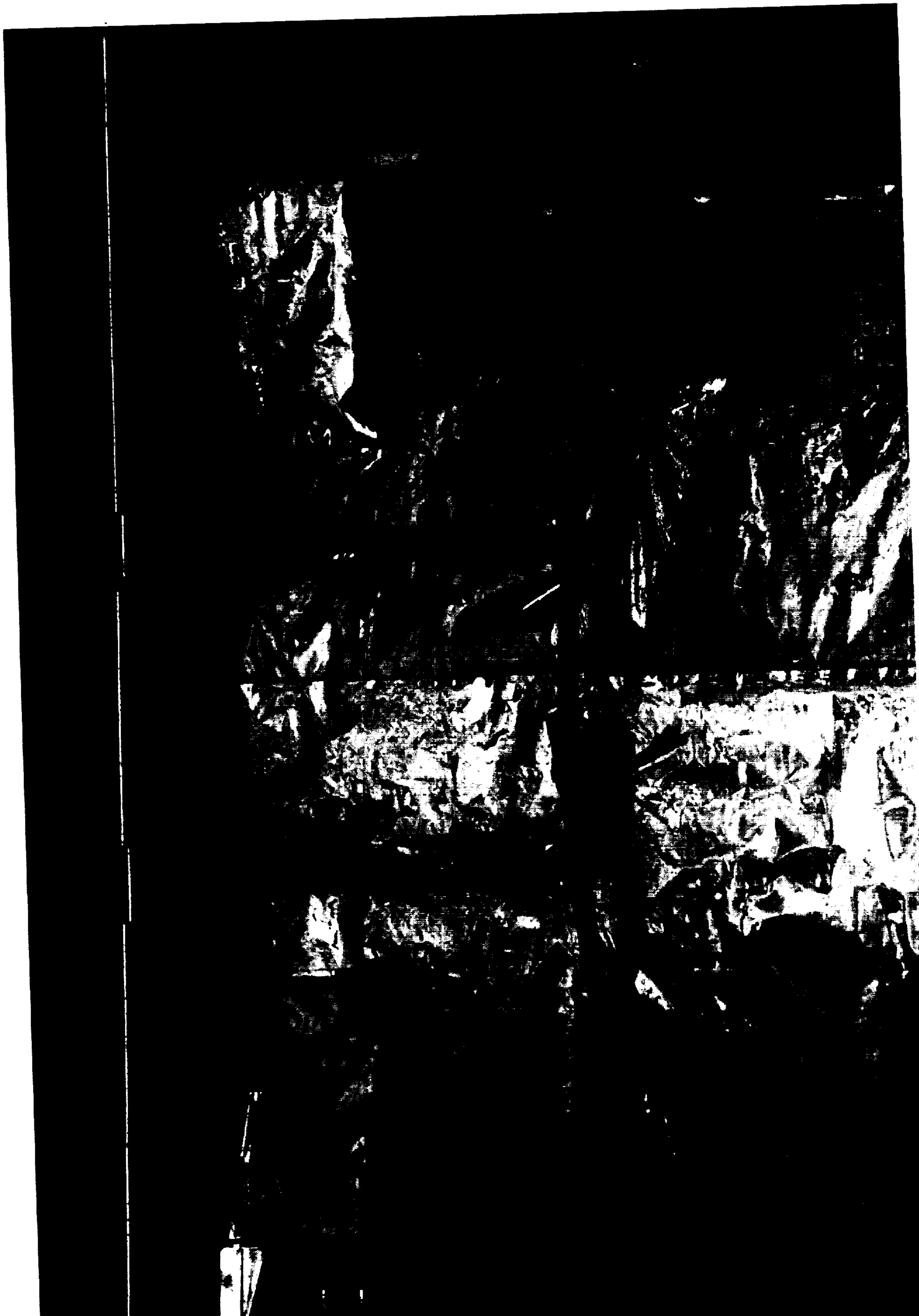
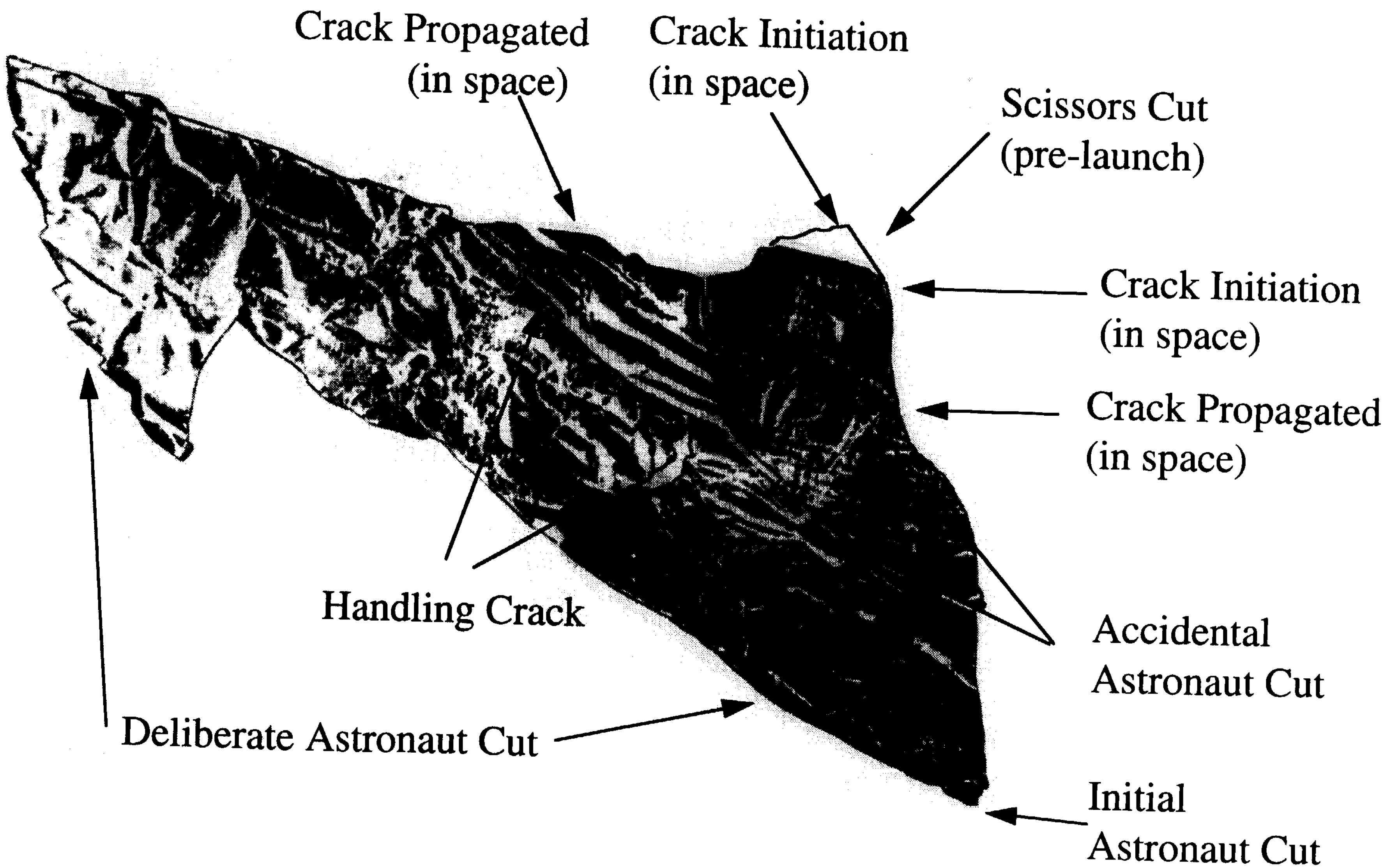
S82E5442 1997:02:15 11:17:06



S82E5440 1997:02:15 11:16:47

HST MLI SM2
Light Shield Specimen Re-assembled



S82E5890 1997:02:18 08:14:01

This photograph, taken with an electronic still camera (ESC) on February 15, shows a tear in the thermal insulation of the Hubble Space Telescope Bay #8.

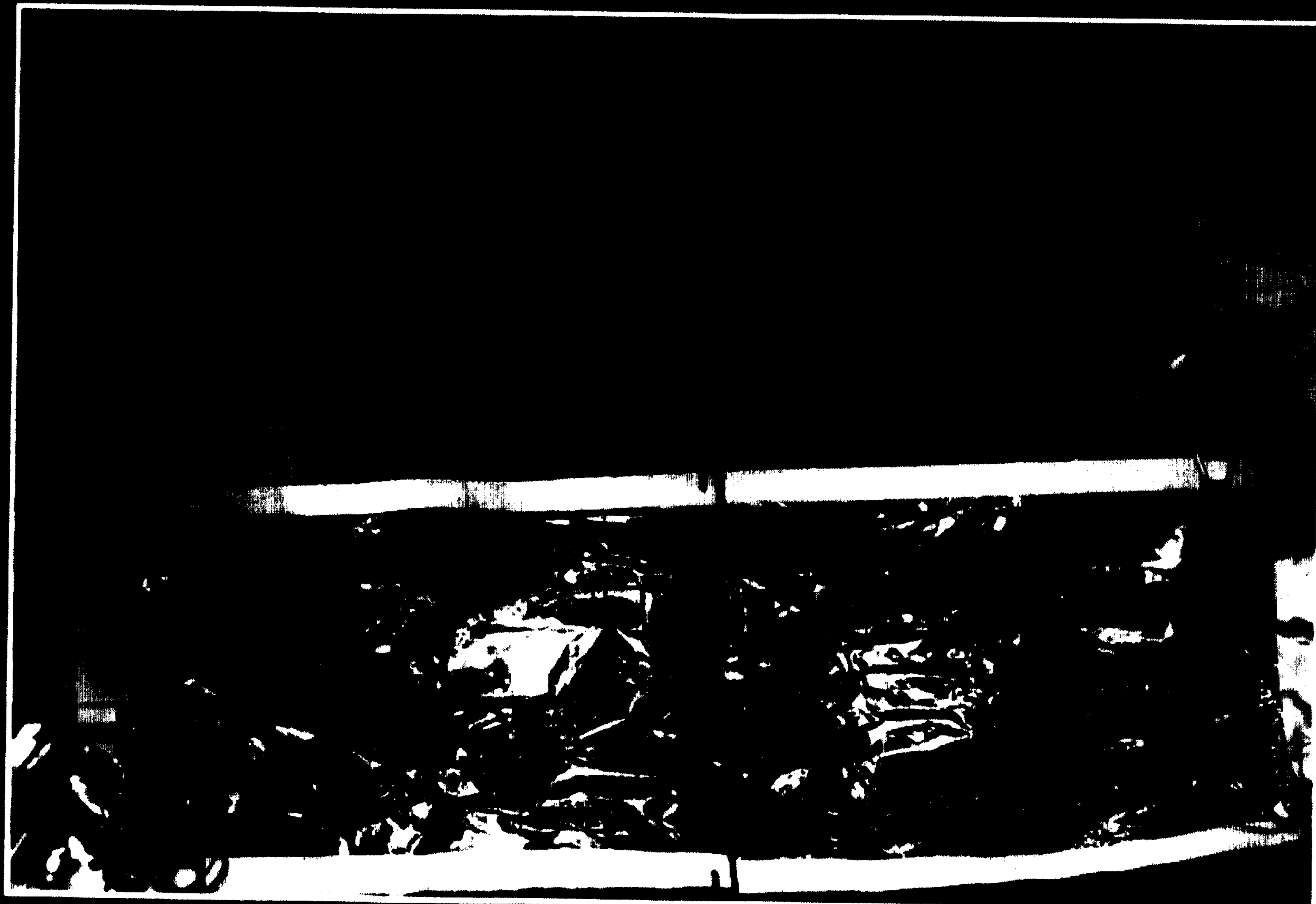
FIGURE 8 EQUIPMENT SECTION BAY 7 & 8 REPAIR

S82E5892 1997:02:18 08:15:25

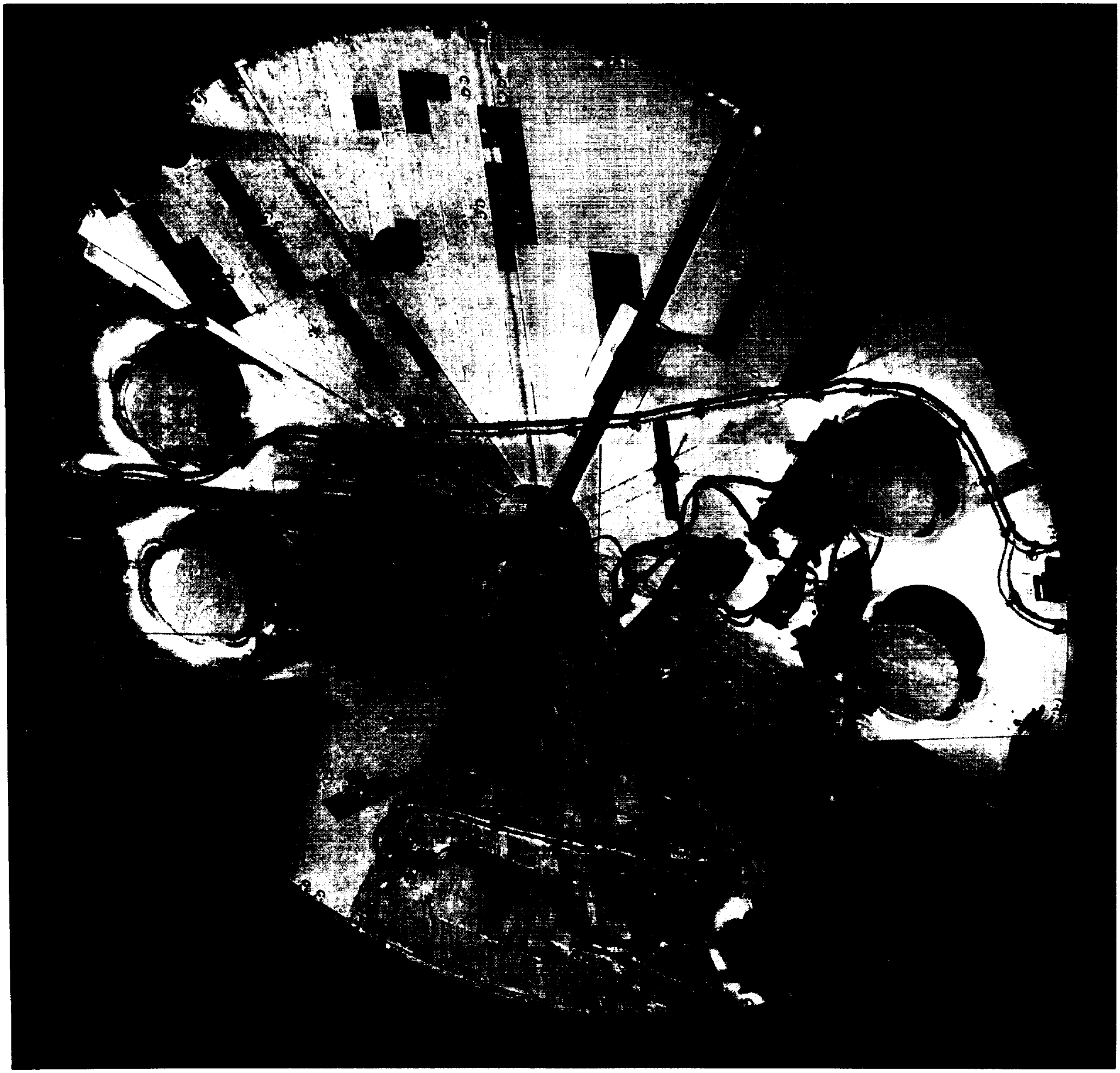
EQUIPMENT SECTION BAY 7 & BAY 8 REPAIR

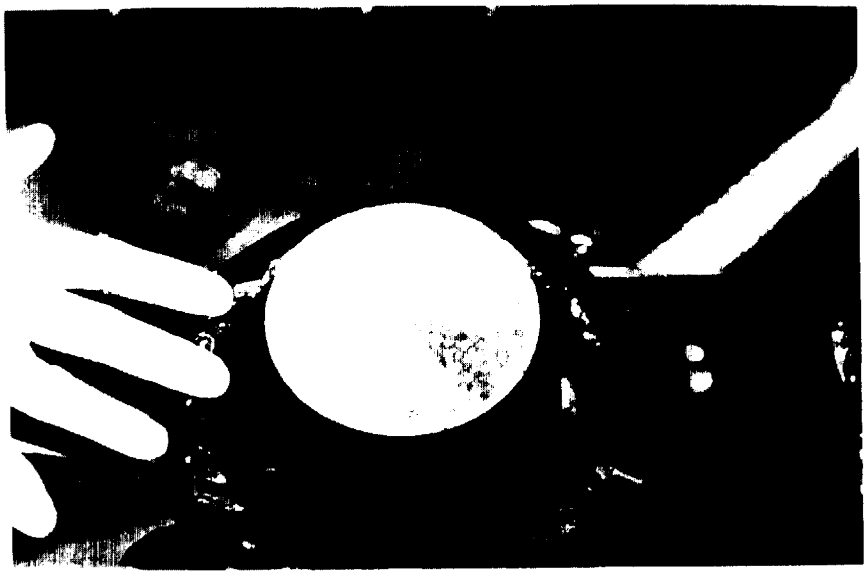
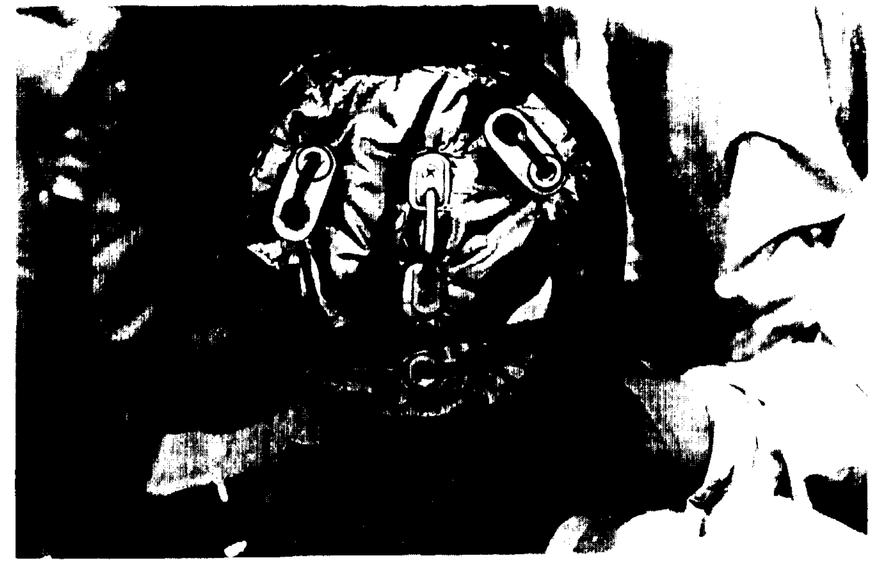
S82E5895 1997:02:18 08:21:36

EQUIPMENT SECTION BAY 10 REPAIR (TOP)

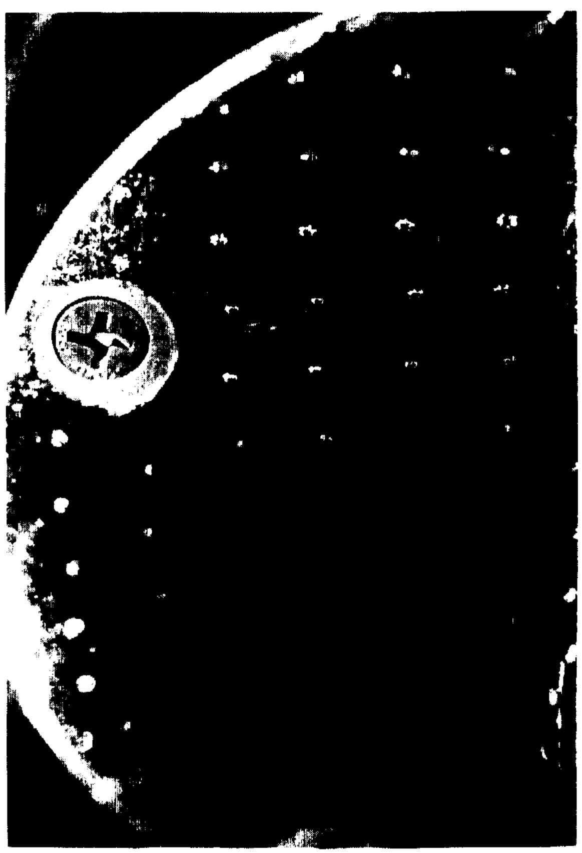


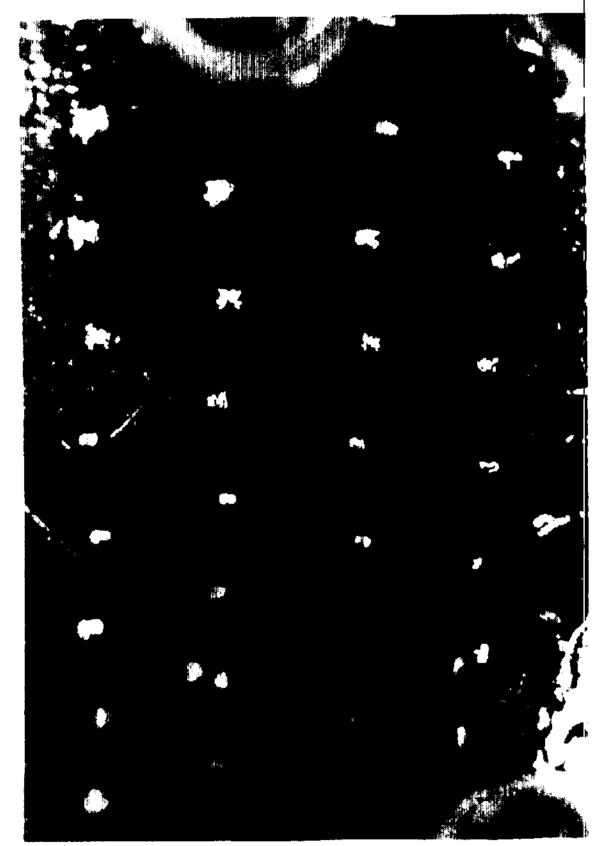
Astronaut Scott J. Horowitz. pilot. shows the hand-crafted thermal insulation blanket to support the goal of the final spacewalk to cover tears in HST's insulation caused by changes in thermal conditions.



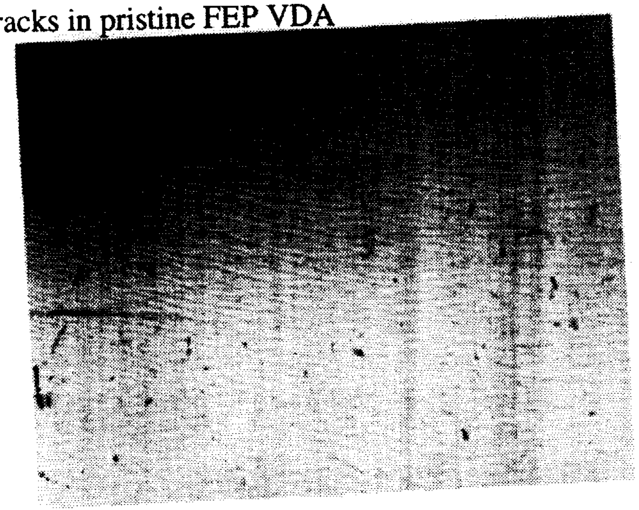
CRYO VENT COVER AG TEFLON



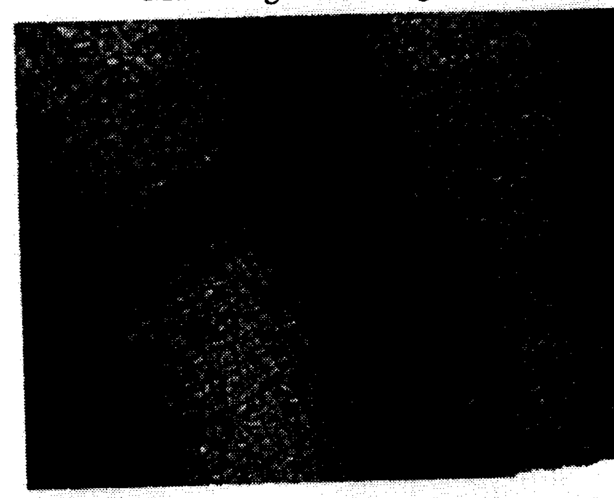


Mud Tiling of Metallized Layer

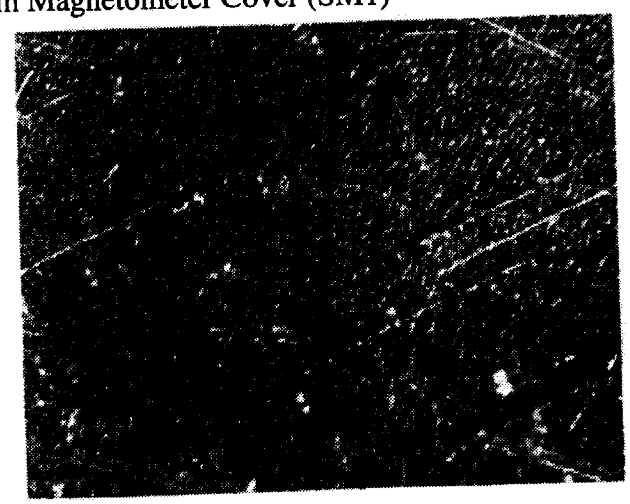
Handling cracks in pristine FEP VDA



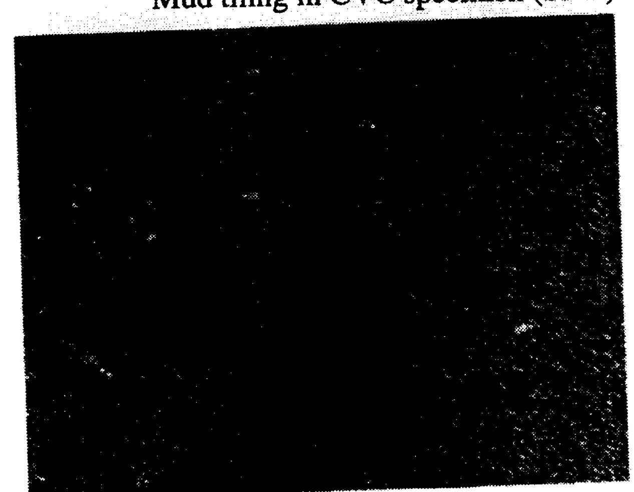
Mud tiling in MLI Light Shield specimen (SM2)



Mud tiling in Magnetometer Cover (SM1)



Mud tiling in CVC specimen (SM2)



HST RETURNED TEFLON PROPERTIES

- HST DEPLOYED - 24 April 1990

- FIRST SERVICING MISSION - 2 Dec 93 (3.7 yrs)
  - Solar Array I - (Ag Teflon) a = 0.10
  - MSS MLI - (Al Teflon) a = 0.17 - 0.22

- SECOND SERVICING MISSION - 11 FEB 97 (6.8 yrs)
  - Light Shield MLI - (Al Teflon) a = 0.20
  - Cryo Vent Cover - (Ag Teflon) a = 0.14

HANDBOOK TEFLON DATA

Metalized Teflon Degradation

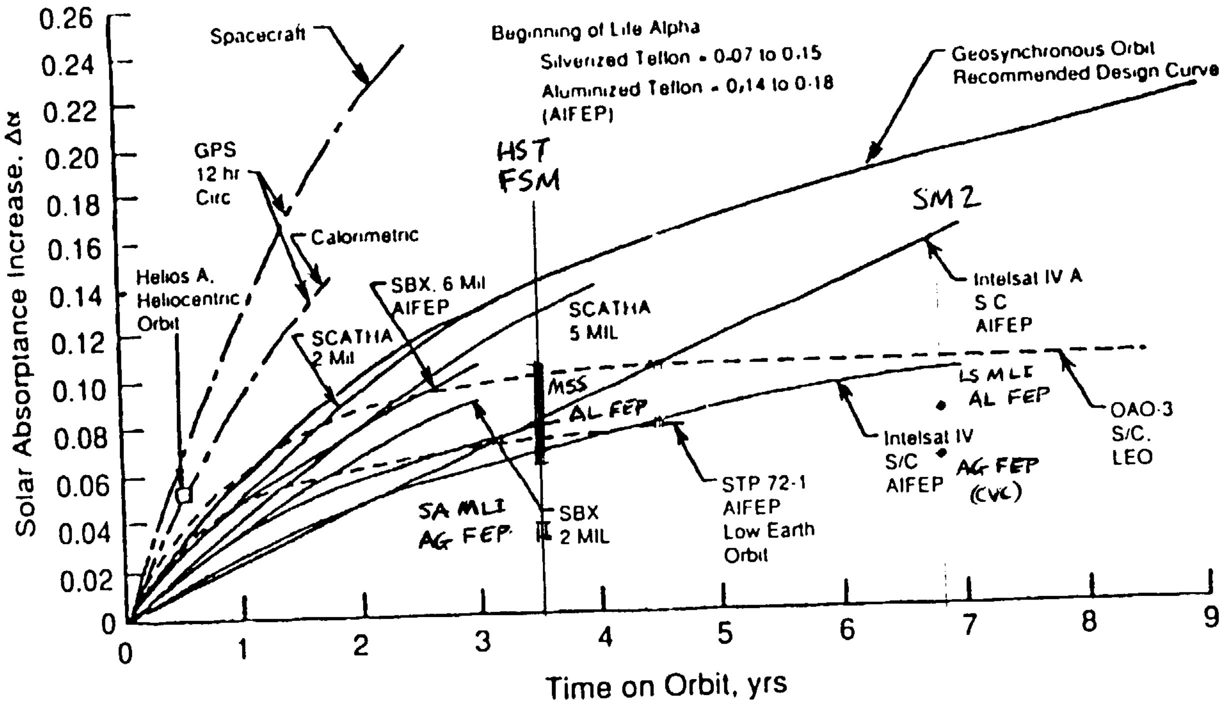


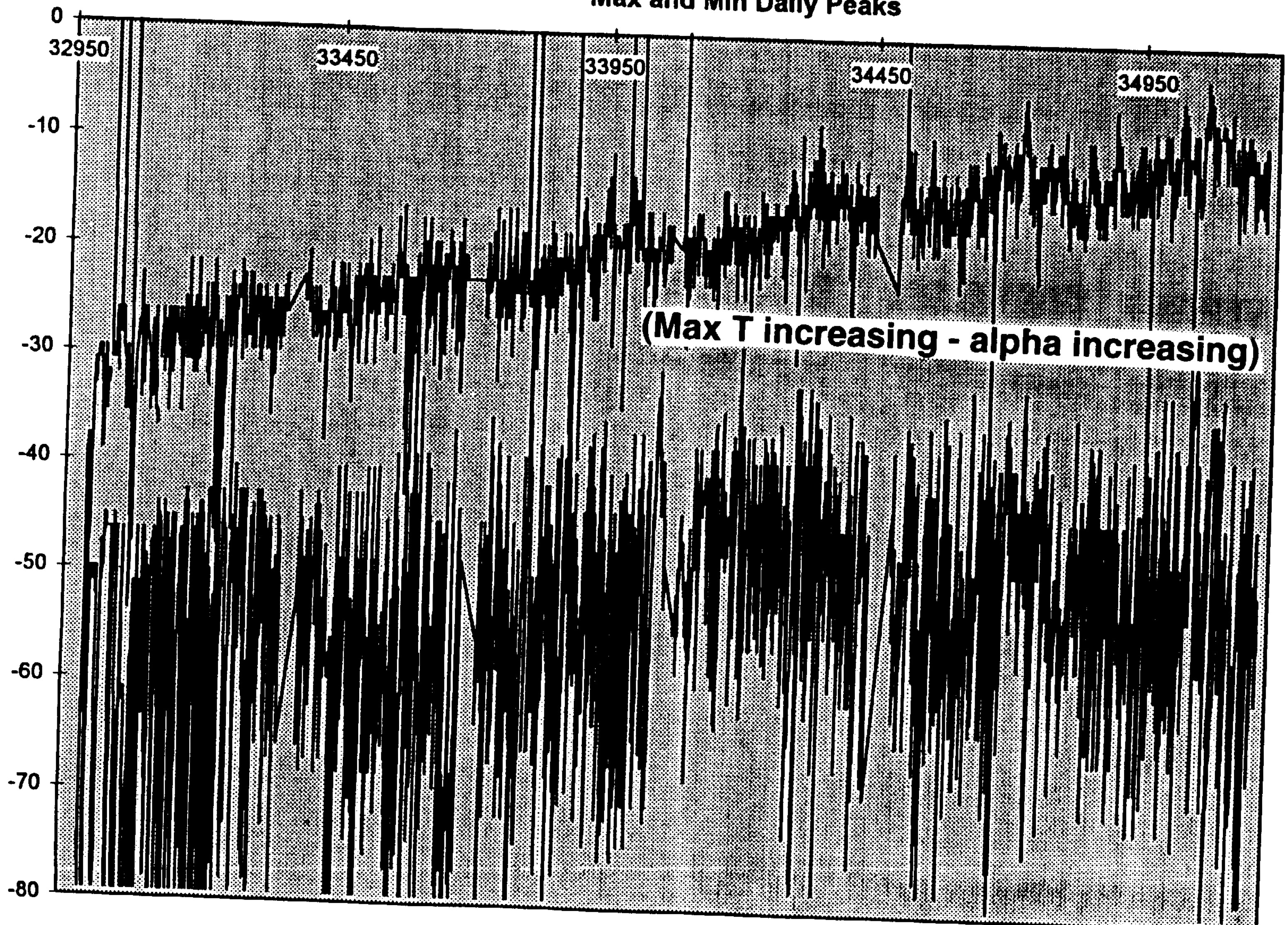
Figure 8. Metalized Teflon degradation (in geosynchronous orbit unless otherwise indicated)

Reference: "Satellite Thermal Control Handbook", D. G. Gilmore, Editor, Aerospace Corporation

HST AFT SHROUD TEFLON FLIGHT TEMPERATURES

T383 1990 - 1996

Max and Min Daily Peaks



AFT SHROUD TEFLON FLIGHT TEMPERATURES

FAILURE REVIEW BOARD FINDINGS

- FINDINGS (to date)
  - TEFLON EMBRITTLEMENT DUE TO UV, X-RAYS AND/OR CHARGED PARTICLES
  - "MUD TILING" DUE TO THERMAL CYCLING
  - TEFLON TEARS ALL STARTED AT STRESS POINTS
    - CUTS, STITCHES, EDGES, ETC.
  - FEP ALONE SOLAR ABSORPTANCE INCREASES IN SPACE (Most of the a increase)

CANDIDATE MATERIALS

- 10 mil FEP/Ag/Inconel/adhesive/Nomex scrim
- 5 mil FEP/Ag/Inconel/Fiberglass scrim in adhesive/2 mil Kapton
- 10 mil FEP/Al/adhesive/Nomex scrim
- 5 mil FEP/Al/Fiberglass scrim in adhesive/2 mil Kapton
- 5 mil FEP/Ag/Inconel/Nomex in adhesive
- 5 mil FEP/Al/Nomex in adhesive
- TRMM OCLI Tedlar
- 5 mil FEP/VDA

Adhesive - non - UV darkening

MATERIAL TEST PROGRAM

4 - 3in.x0.5in. 5 mil FEP/Al to SM2 charged particles/AO

1 each - 2in.x0.5in. Candidates to SM3 charged particles/AO/TC/NUV

1 each - 2in.x2in. Candidates to SM3 charged particles/x-ray/VUV/TC

1 each - 3in.x1.5in. Candidates to SM3 charged particles/x-ray/VUV/TC

1 each - 3in.x1.5in. Candidates to SM3 charged particles

1 each - 1in.x1in. Candidates to NUV (1000 esh)

1 each - 8in.x10in. Candidates to 5000 cycles TC to determine twist or "potato chip" deformation

Measure solar absorptance after each test and final emittance

SEM, DMA, TMA, Density, Thermography, and Bend Tests

CONCLUSIONS

- SOLAR ABSORPTANCE IS INCREASING
- TEFLON IS EMBRITTLED WITH MANY TEARS
- MLI FRB TESTS HAVE ESTABLISHED CAUSES
- CANDIDATE MATERIALS IDENTIFIED
- EVALUATION TEST PROGRAM STARTED
- DESIGN TEAM ASSEMBLED FOR SM3 REPAIR
- STANDBY FOR SM3 FINDINGS/PAPERS

SWALES AEROSPACE

Thermal Control Coatings Development at NASA - GSFC

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Thermal Control Coatings Development

Swales Aerospace

Jack Triolo -- Thermal Coatings Development

George Harris -- Thin Film Application Development

Grace Miller -- Lacquer Application

John Petro -- Lacquer Application

Bob Gorman -- BRDF Measurements

Wanda Peters -- Thermal/Optical Measurements

NASA - Goddard Space Flight Center

Lon Kauder -- Thermal Coatings Development

Background

- Thin film coatings have the capabilities of obtaining a wide range of thermal radiative properties.
- Thin film coatings' thermal radiative properties can be tailored to suit the thermal control requirements of a given situation (i.e., specific solar absorptance and/or emittance).
- Surface coatings can be spectrally selective to enhance radiative coupling and decoupling.
- Predictable thermal properties require specular surfaces, which can be difficult and costly to achieve.

Approach to Coatings Development

- Utilization of different metals to vary the solar absorptance value of the coating.
- Variation of dielectric thickness to alter the normal emittance value of the coating. (The thicker the dielectric layer, the higher the normal emittance value.)
- Utilization of a lacquer applied to surfaces to provide suitable specularity for thin film application.

Current Coatings Development at GSFC

- Spectrally Selective Coatings

- Lacquer Coatings

Spectrally Selective Coatings

- Application
  - GOES Cooler Patch and Astromast Structure

- Goal
  - Develop a pair of selective coatings to reduce the radiative coupling (solar and IR absorbed energy) of a sunlit object to a cooler patch at 100K.

Spectrally Selective Coatings

- Approach
  - Reduce the mast thermal emittance without raising the mast temperature while keeping the a_s/e ratio at about 1.0.
  - Reduce the patch solar absorptance, a_s.
  - Lower the patch IR (200-300K) absorptance, a_{IR}.
  - Keep the patch thermal emittance (100K) as high as possible.

Spectrally Selective Coatings

- Mast Coating:
  - Non-Specular Coating (1500 grid cloth finish)

    Ag/Al_2O_3 (2000A)/SiO_2(6000A)

    $a_s = 0.18$

    e(300K) = 0.18
  - Specular Coating (1500 grid finish overcoated with lacquer)

    Ag/Al_2O_3 (1000A)

    $a_s = 0.07$

    e(300K) = 0.07

Spectrally Selective Coatings

- Patch Coating: (All coatings have been applied to glass slides)
  - **SSC2**: Al/Al_2O_3 (16,000A) /TiO_2 (6,000A) /Al_2O_3(16,000A)

    $a_s = 0.15$ e(100K) = 0.82 a_{IR}(200K) = 0.79 a_{IR}(300K) = 0.69
  - **SSC3**: Al/Al_2O_3 (14,000A) /TiO_2 (6,000A) /Al_2O_3(14,000A)

    $a_s = 0.15$ e(100K) = 0.82 a_{IR}(200K) = 0.78 a_{IR}(300K) = 0.65
  - **SSC4**: SSC3/MgO (6,000A)

    $a_s = 0.15$ e(100K) = 0.82 a_{IR}(200K) = 0.68 a_{IR}(300K) = 0.60
- When Al is replaced with Ag in the SSC Patch Coating

  $a_s = 0.09$ on glass (no change in IR spectra)

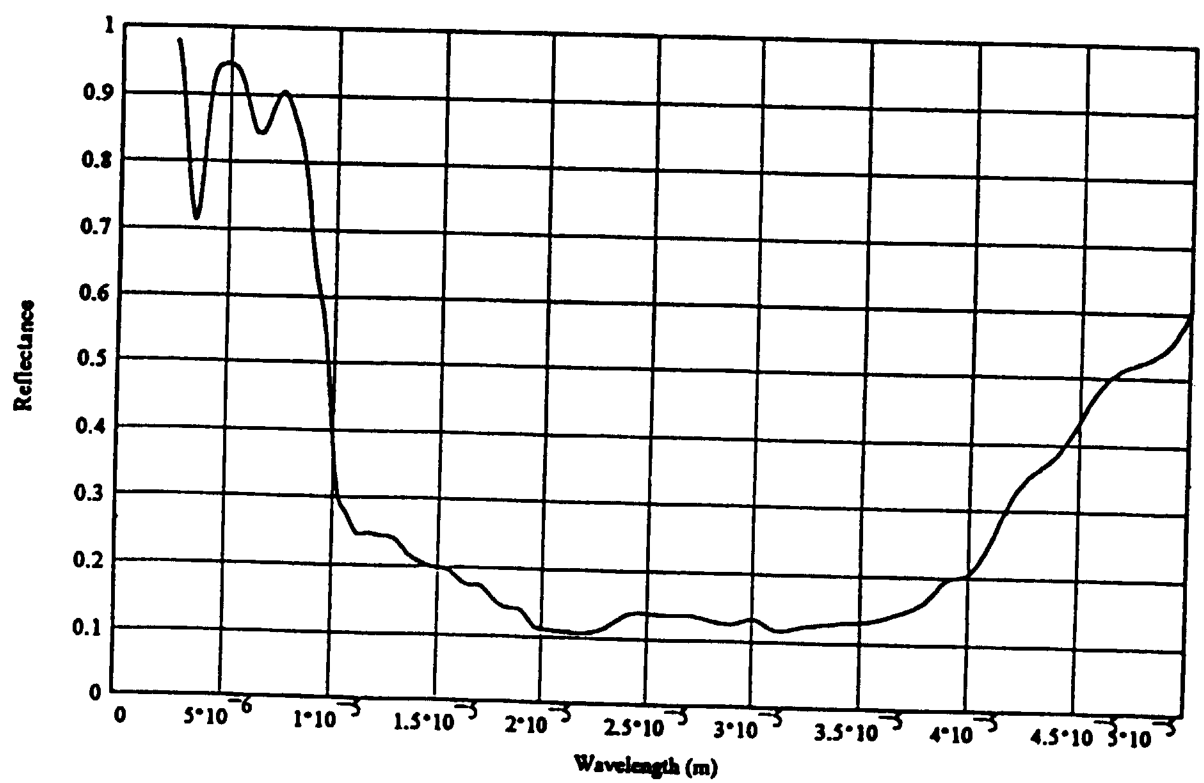
Spectrally Selective Coatings

Thermal Radiative Properties
Reflectance Curve

PATCH SELECTIVE COATING PROPERTIES - SSC3/Ag

	SUNSHIELD TEMP K	ϵ PATCH	α_S SOLAR	α SUNSHIELD	α ASTROMAST
SS EOL	250	0.8	0.09	0.72	0.65
SS BOL	230	0.8	0.09	0.74	0.65
WS	170	0.8	0.09	0.82	0.65

SPECTRAL REFLECTANCE OF GOES PATCH COATING - SSC3/Al



Lacquer Coatings

- Application
  - GOES Astromast surfaces
  - Cooler Shields

- Goal
  - Develop a coating process applicable to a surface making the surface highly specular without polishing and suitable for thin film application.

Lacquer Coatings

- Process
  - Spray lacquer coating on substrate.
  - Bakeout lacquer coating. (Specularity of the surface is influenced by the cleanliness of the bakeout.)
  - Apply thin film as needed (i.e., vacuum deposited aluminum for cooler shields).

Lacquer Coatings

- Vapor Deposited Aluminum (VDA)

  [on an aluminum substrate]

  $a_s = .09$ $e_n = .02$

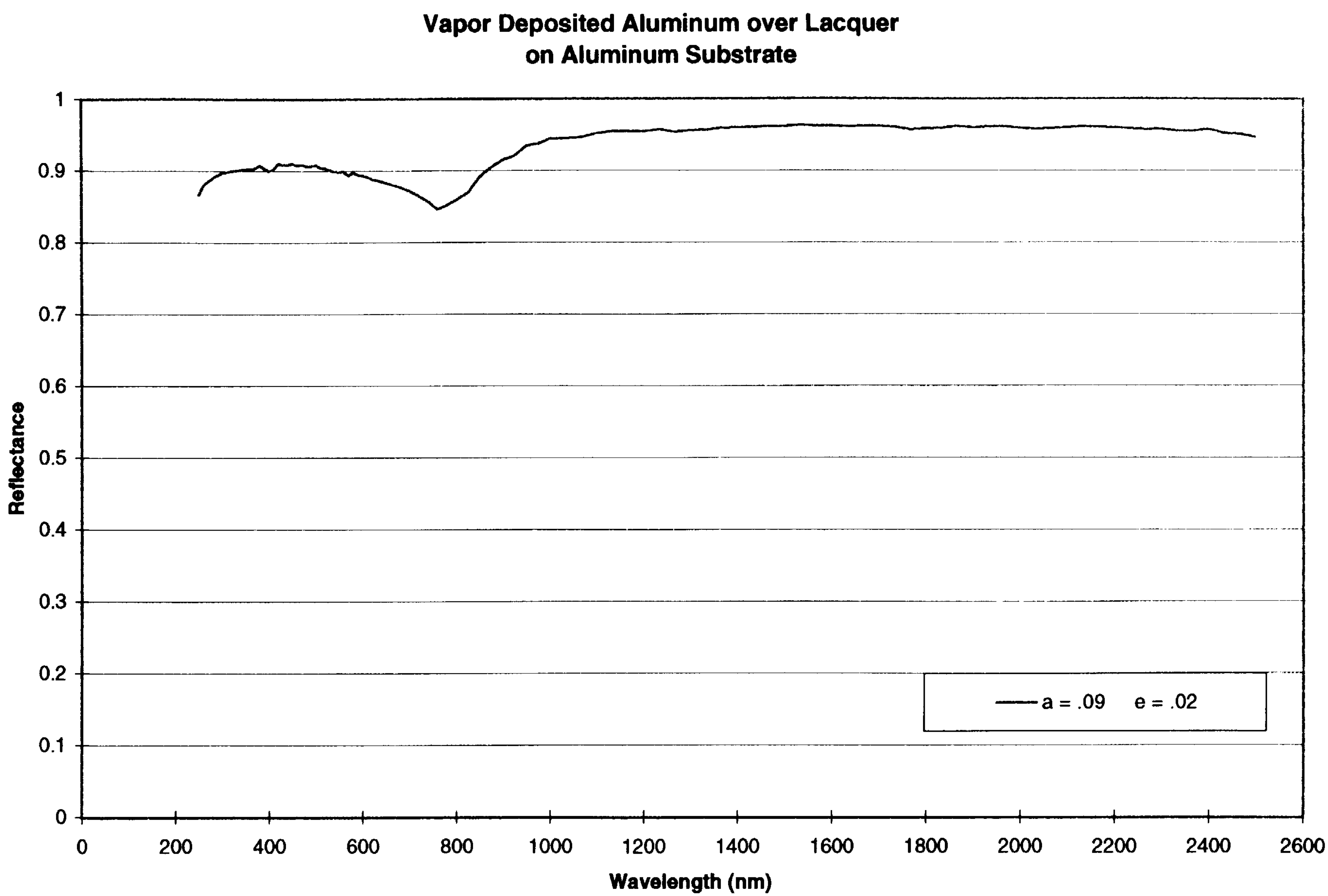
- Vapor Deposited Gold (VDG)

  [on an aluminum substrate]

  $a_s = .18$ $e_n = .01$

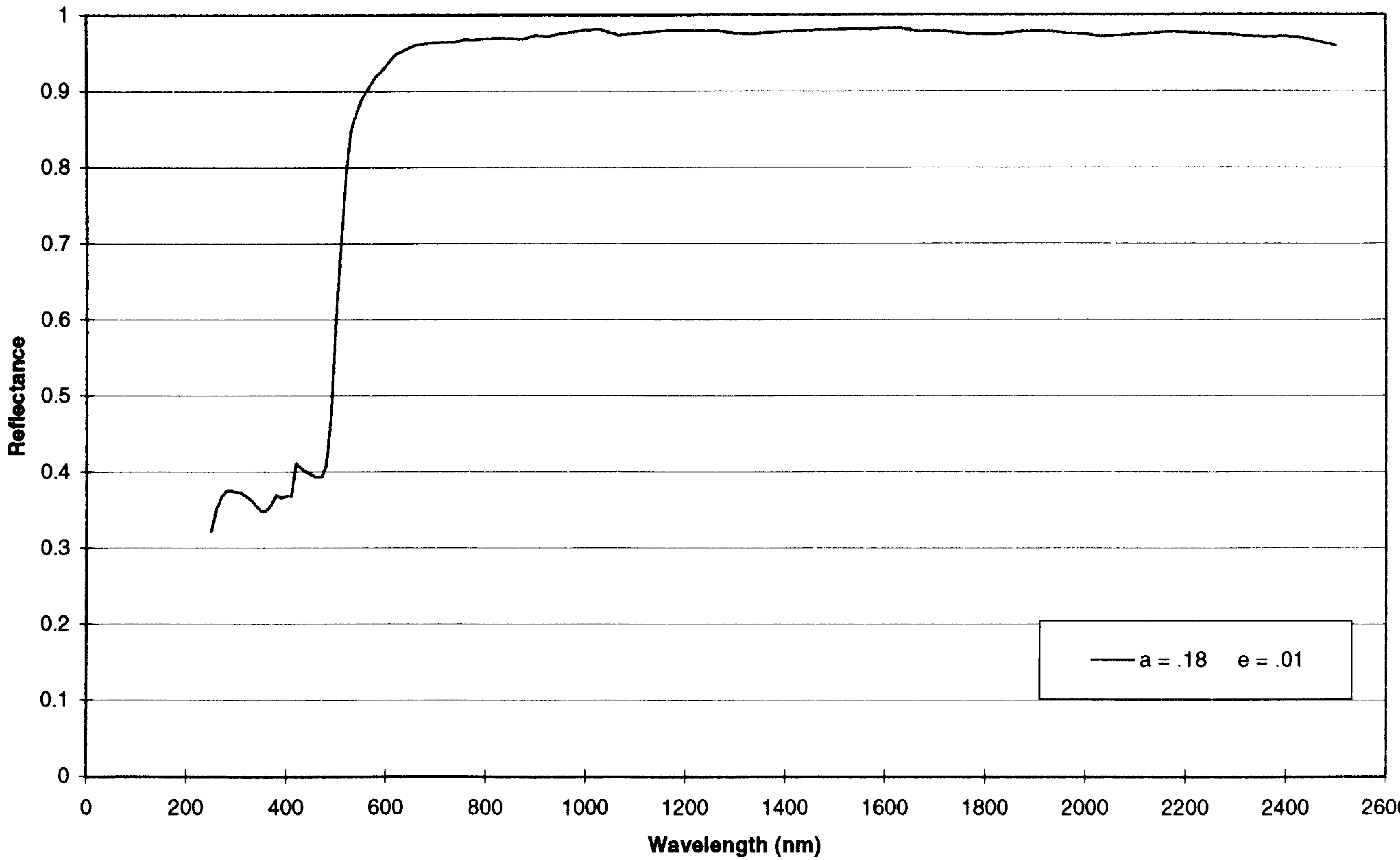
Lacquer Coatings

VDA Reflectance Curve
VDG Reflectance Curve
Light Scattering (Specularity) Plot

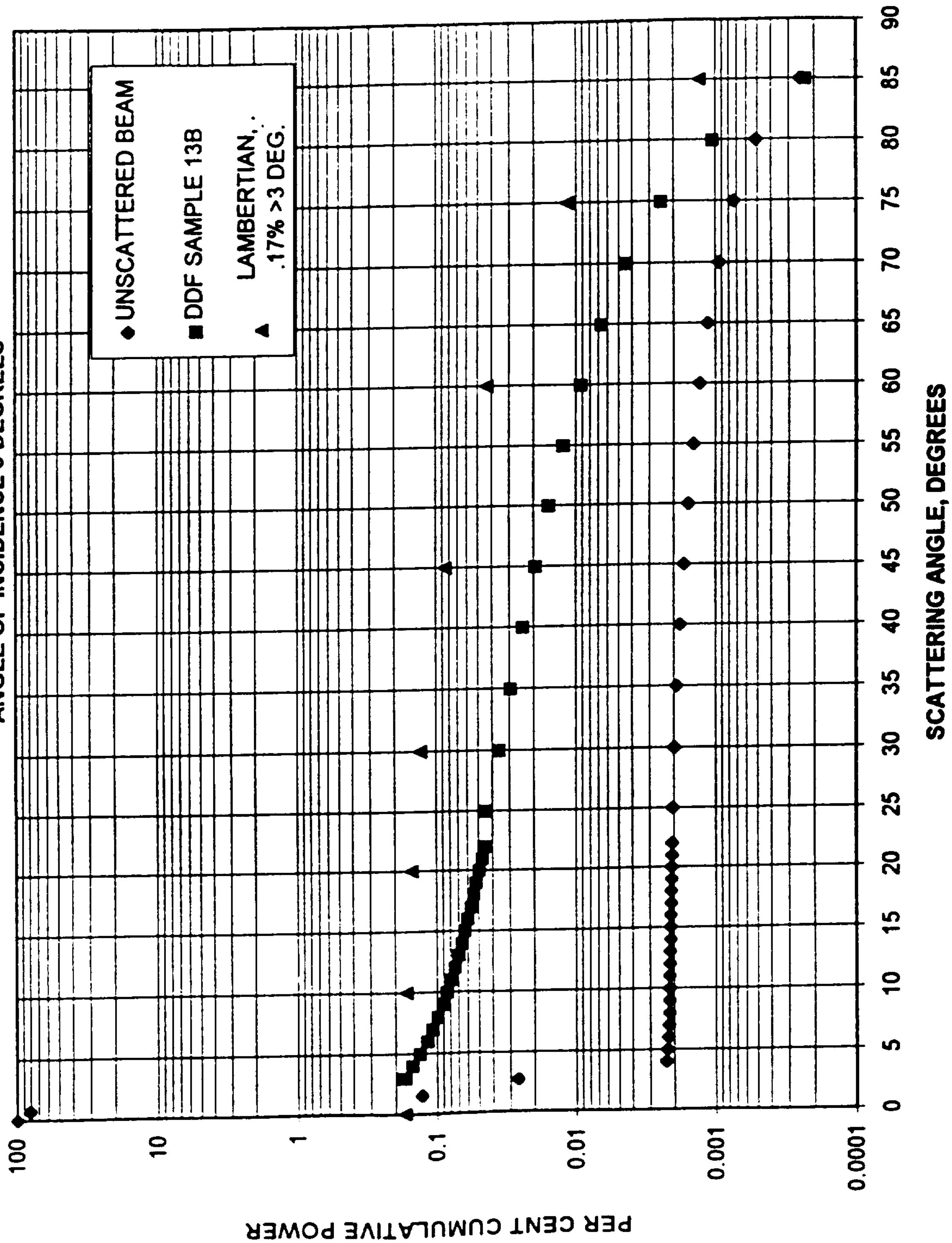


Vapor Deposited Aluminum over Lacquer
on Aluminum Substrate
Reflectance
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Wavelength (nm)
a = .09 e = .02

Vapor Deposited Gold over Lacquer
on Aluminum Substrate



CUMULATIVE POWER DISTRIBUTION
DDF SAMPLE 13B, HORIZONTAL ORIENTATION
ANGLE OF INCIDENCE 5 DEGREES



Conclusion

- Spectrally Selective Coatings
  - This coating can be tailored to meet thermal radiative property requirements by varying the dielectric type and layer thickness to achieve the required solar absorptance and emittance values.
- Lacquer Coatings
  - This is a simple coating process that can be used to make a surface highly specular and suitable for thin film application at an economical cost.

Electrochromic Coatings:

Thermal Emittance and Solar Absorptance Control

presented at the

Space Coatings and Contamination Workshop

Annapolis, Maryland

July 10, 1997

by

EIC Laboratories, Inc.

Norwood, Massachusetts 02062

Overview

- Electrochromic Materials and Devices
- Device Design for IR Emittance and Solar Absorptance Control
- Characteristics and Performance
- Technical Challenges
- Future Work

EIC Laboratories, Inc.

About EIC Laboratories

- Small business concern founded in 1971
- Conducts research and development in the physical sciences (electrochemistry, materials science, spectroscopy)
- Approximately 60 employees, primarily B.Sc., MS., or Ph.D. level
- Research sponsored by DoD, NASA, DoE, NIH, NSF, and corporate (typically large aerospace companies)

Major Research Programs

- secondary lithium batteries (part of USABC)
- optical coating (electrochromic coatings for solar and infrared modulation)
- Raman spectroscopy for chemical detection
- biomedical electrodes and materials for functional electrical stimulation
- other areas
    - conductive polymers (aircraft transparencies)
    - process control (plasma emission spectroscopy)
    - corrosion, polymers, polymers, fuel cells

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Electrochromic R&D History

- began in 1982 with DoE sponsorship of solar control coatings for architectural glass
- ongoing with collaborative effort with OCLI, Cardinal IG, and Andersen Windows
- variable emittance applications funded by NASA, DoD, beginning in 1986
- corporate support for DoD and consumer applications (8 non-government funded programs)

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Results of Previous Work

- at least 25 technical publications
- 6 patents awarded, 1 pending
- technology licensed to a Fortune 500 company

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Electrochromic Switching

optical modulation caused by change in oxidation state:

$$\text{c-}WO_3 + xLi^+ + xe^- \Longleftrightarrow \text{c-}Li_xWO_3$$

transparent — reflective

- reflective or absorptive modulation
- reversible (large number of switching cycles)
- continuously adjustable (function of x)

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Reflective and Absorptive Modulation

Crystalline:

- transparent to reflective
- 2 μm to >25 μm wavelength range

Amorphous:

- transparent to absorptive
- 0.4-1.5 μm wavelength range
- 3-5 μm and >8 μm also possible

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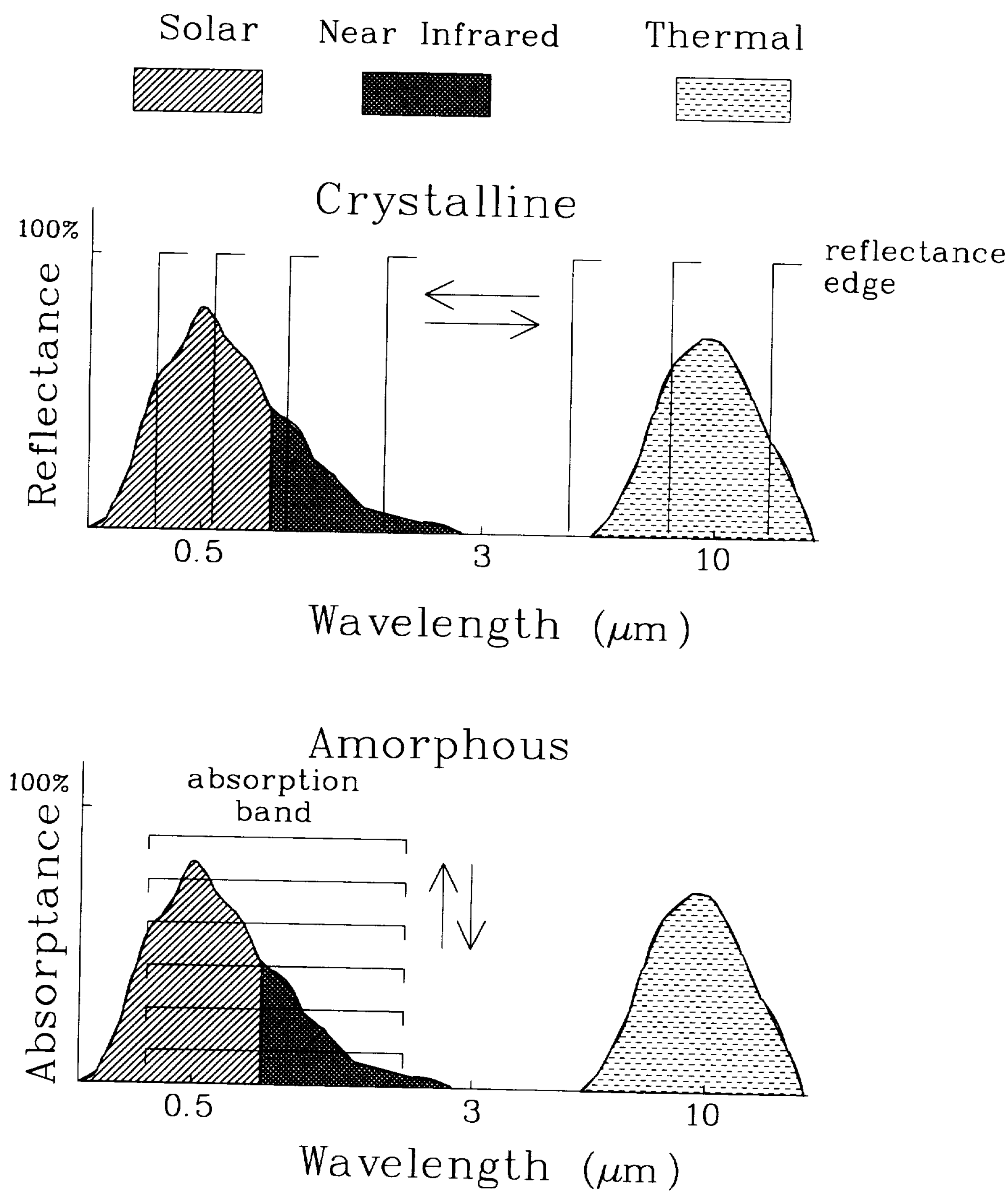
Spectral Modulation with Li_xWO_3



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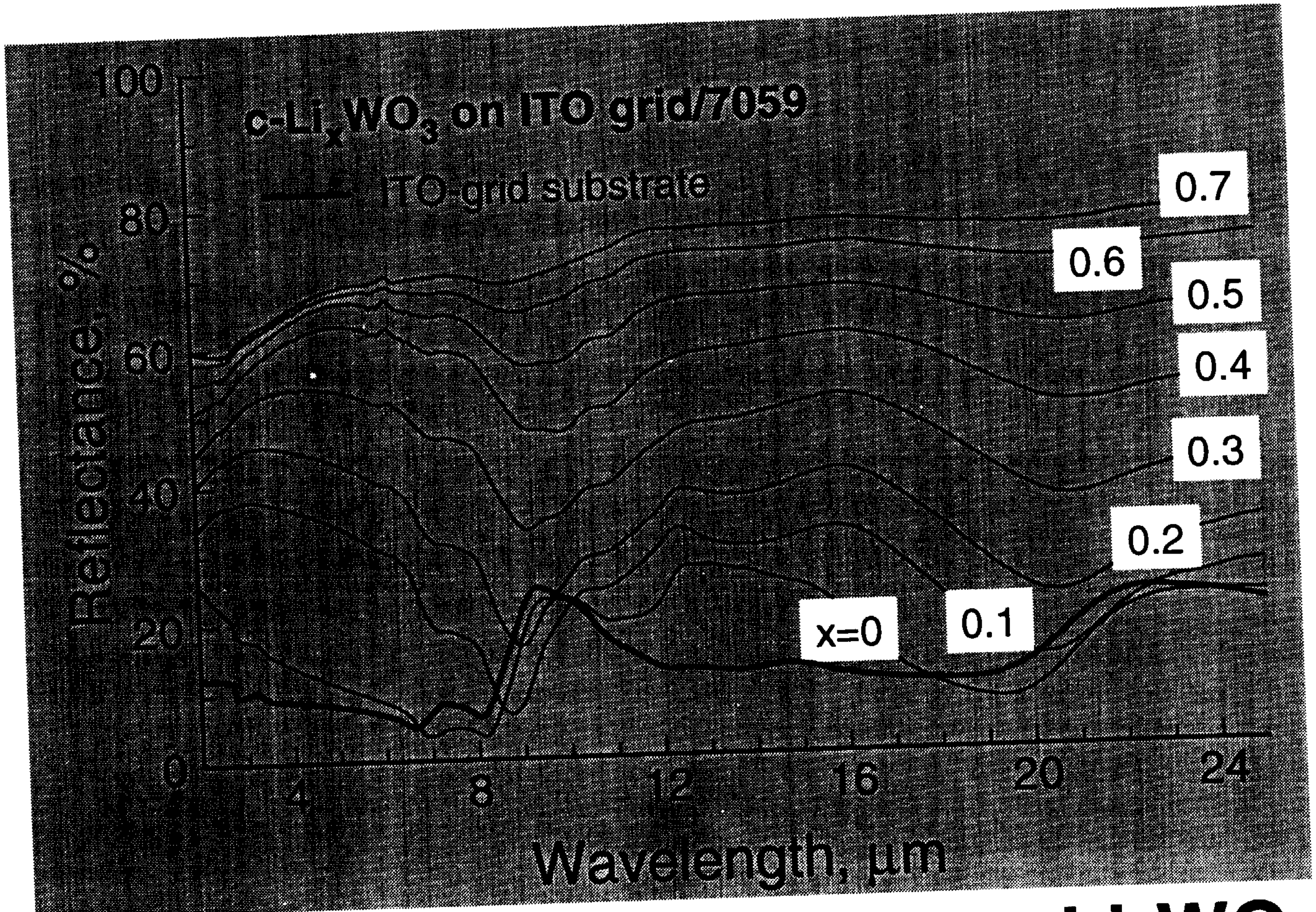
Infrared Modulation in c-Li_xWO_3



c-WO_3 + xLi^+ + xe^- <=> c-Li_xWO_3

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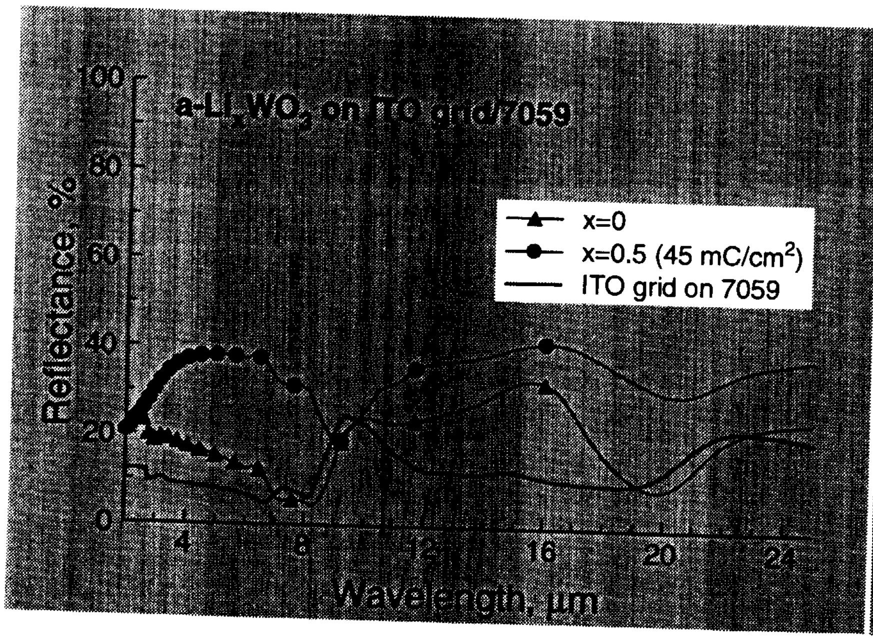
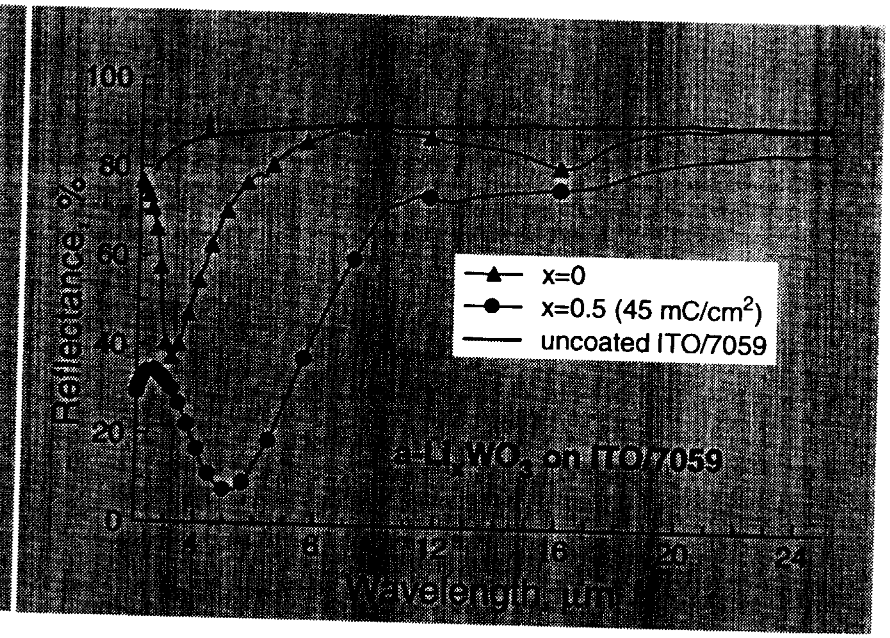
Infrared Modulation in a-Li_xWO_3



Reflectance of a-Li_xWO_3 deposited on an emissive, ITO-grid electrode



Reflectance of a-Li_xWO_3 deposited on a reflective, ITO-film electrode

$$a\text{-}WO_3 + xLi^+ + e^- \Leftrightarrow a\text{-}Li_xWO_3$$

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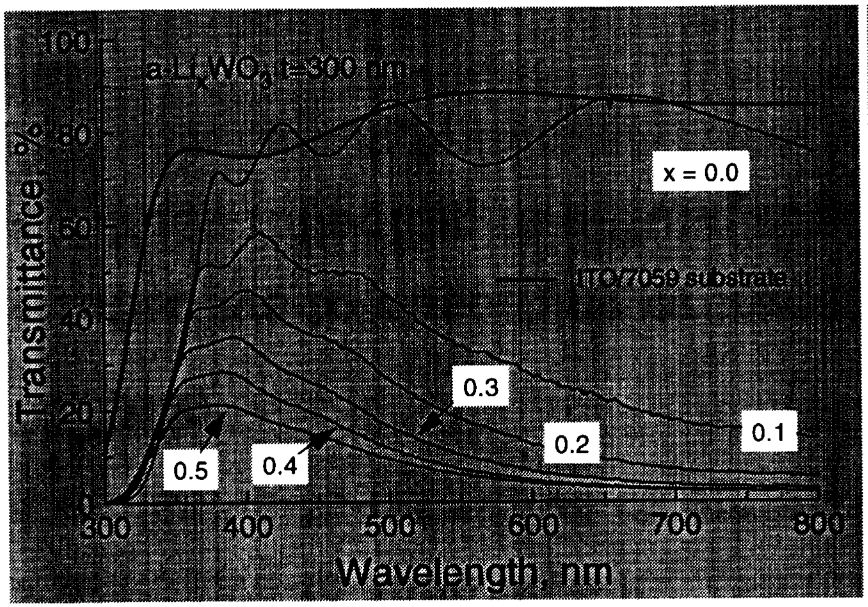
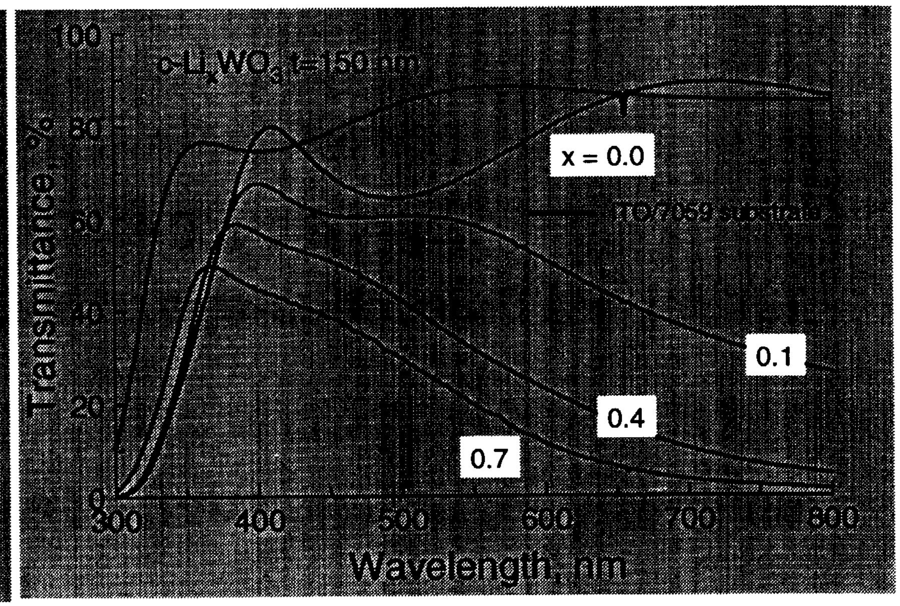
Solar Modulation in Li_xWO_3

amorphous



absorption band centered at 0.9 μm

crystalline



mixture of reflectance in the near-infrared and absorption in the visible

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Electrochromic Device Switching

Infrared

- emissive-to-reflective for $\lambda > 5\ \mu m$
- emissive-to-reflective or emissive-to-transmissive for $3 < \lambda < 6\ \mu m$

Solar

- reflective-to-absorbing or transmissive-to-absorbing 0.4-1.5 μm
- diffuse reflecting to diffuse absorbing 0.4-1.5 μm

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Device Requirements for Emittance Control

- emittance modulation in the 6-30 μm wavelength range
- low solar absorptance ($a_s < 0.2$)
- tolerates temperature extremes (<-50°C and >100°C)
- at least 10,000 switching cycles
- tolerates space environment (AO, VUV, energetic particles)
- switching speed of a few minutes
- tolerates earth environment before launch

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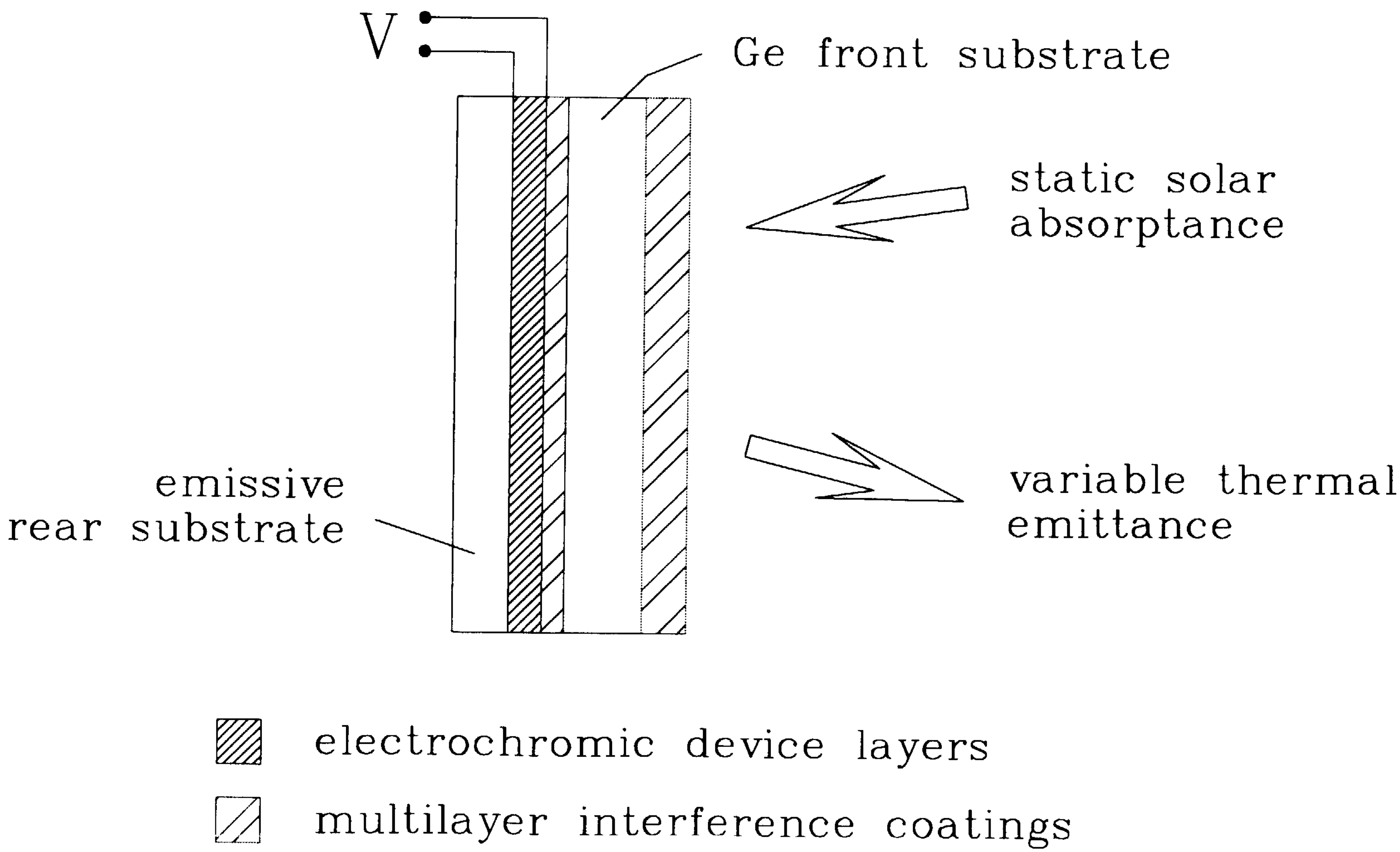
BASIC DEVICE CONFIGURATION



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TWO DEVICE CONFIGURATIONS

1. Devices with a polymeric ion conductor separating the c-Li_xWO_3 and counter electrode

2. Devices with an "all-solid-state" structure

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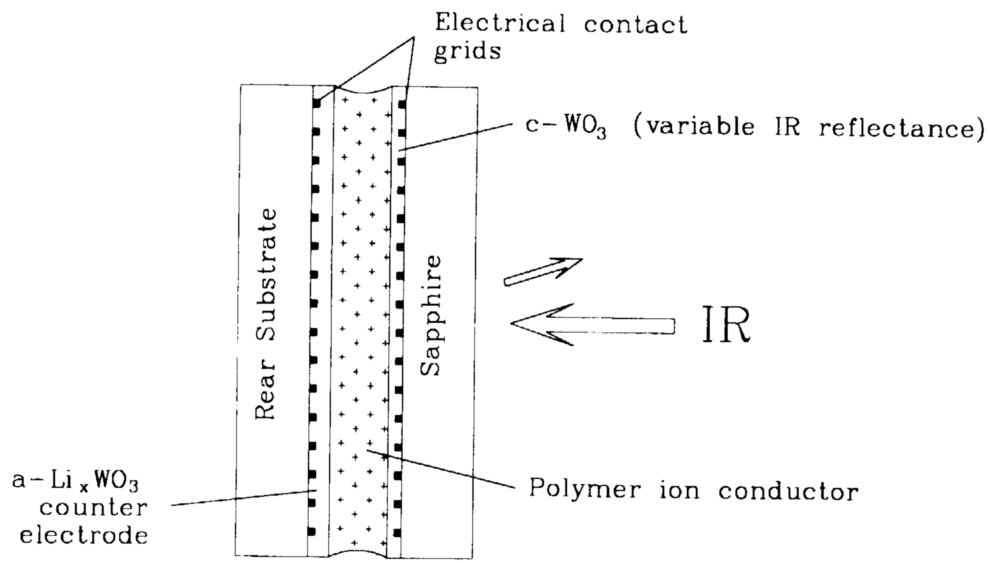
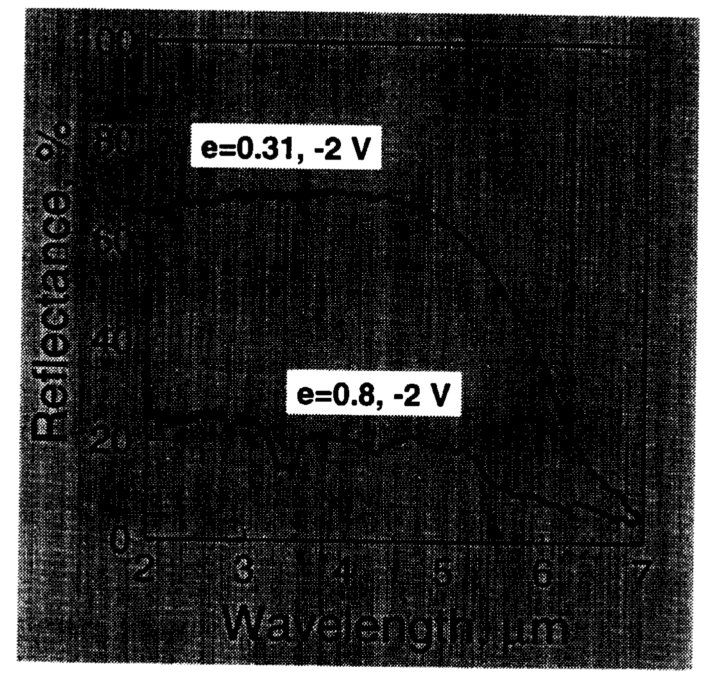
Device with Polymeric Ion Conductor
3-5 μm Modulation

sapphire substrate - high transmittance 3-5 μm





- contrast reflectance of c-Li_xWO_3 against pigmented polymer background
- wide emittance modulation without antireflection coatings

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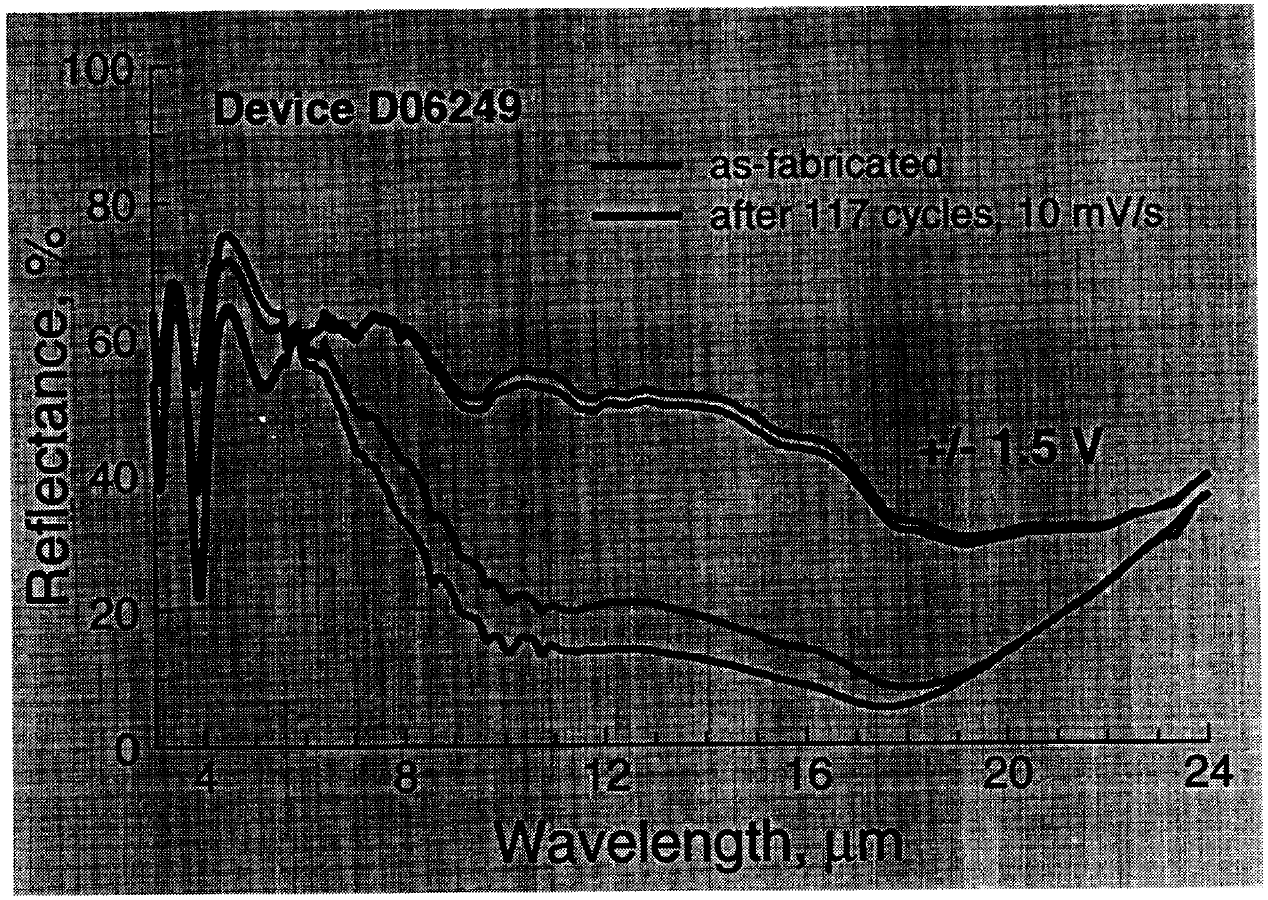
Current Li^+ Polymer Devices 6-24 μm Modulation



- switched for 117 cycles
- emittance range limited by the Ge substrate

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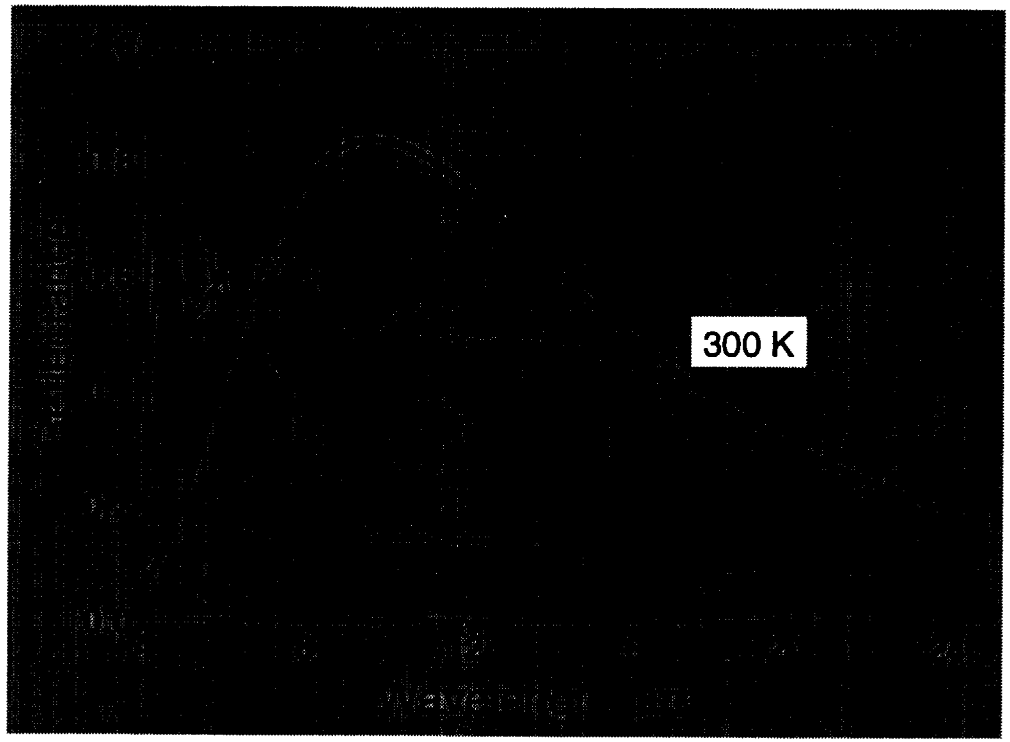
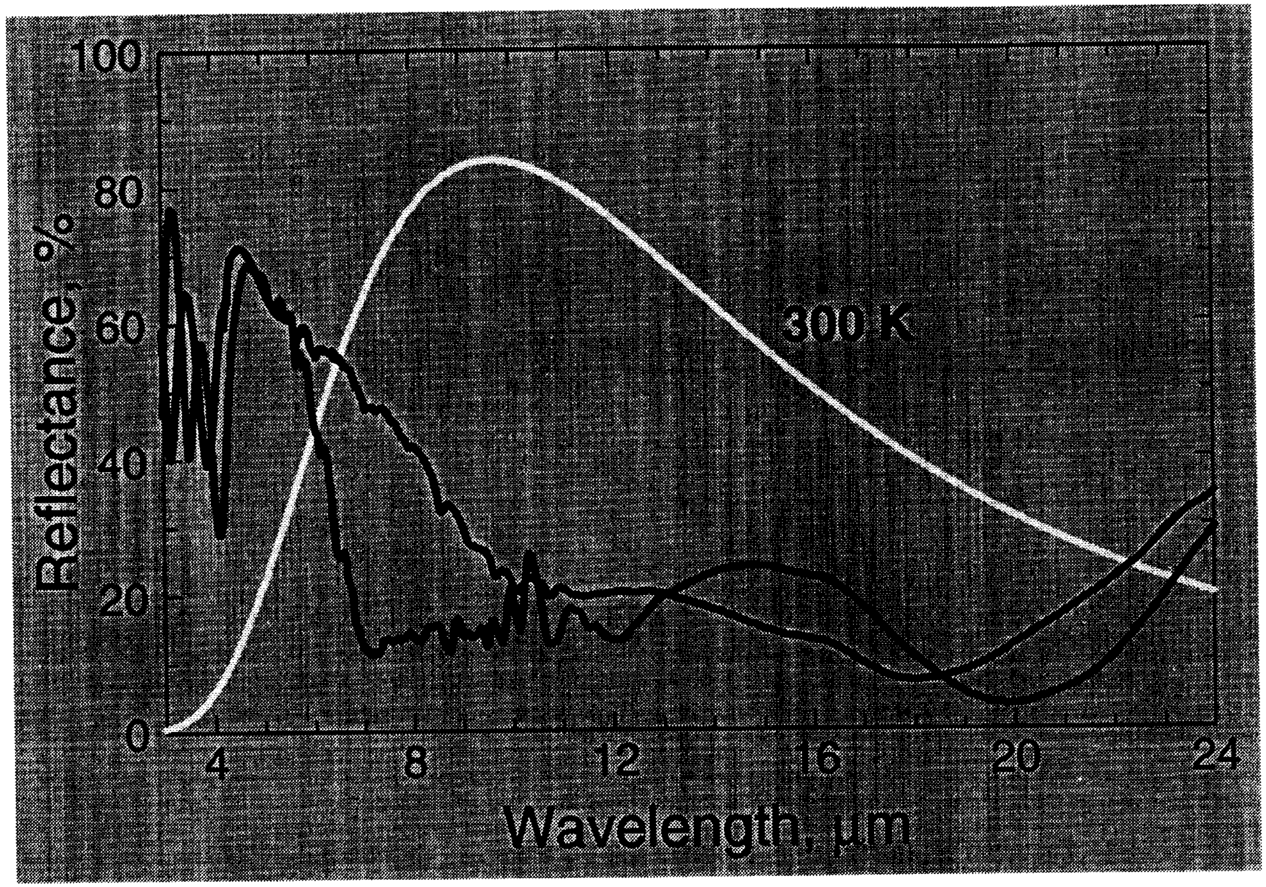
Comparison with the Planck Distribution



Improve AR coating

- increase overall throughput
- shift high energy edge to shorter wavelengths

Modifying the AR Coating



high energy edge shifted, but further shift desirable

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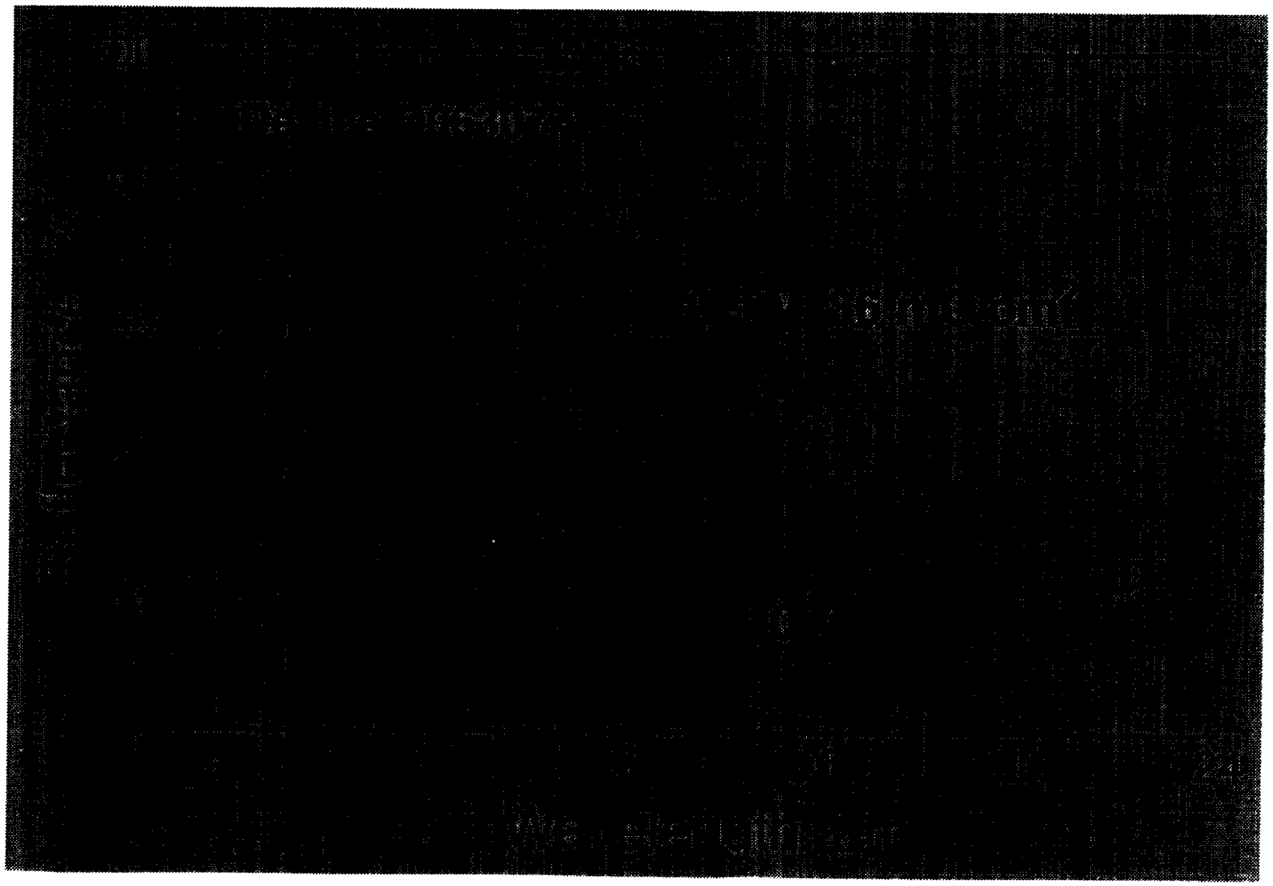
Device with Modified AR Coating



- absorption band at 10 μm due to interfacial reactions

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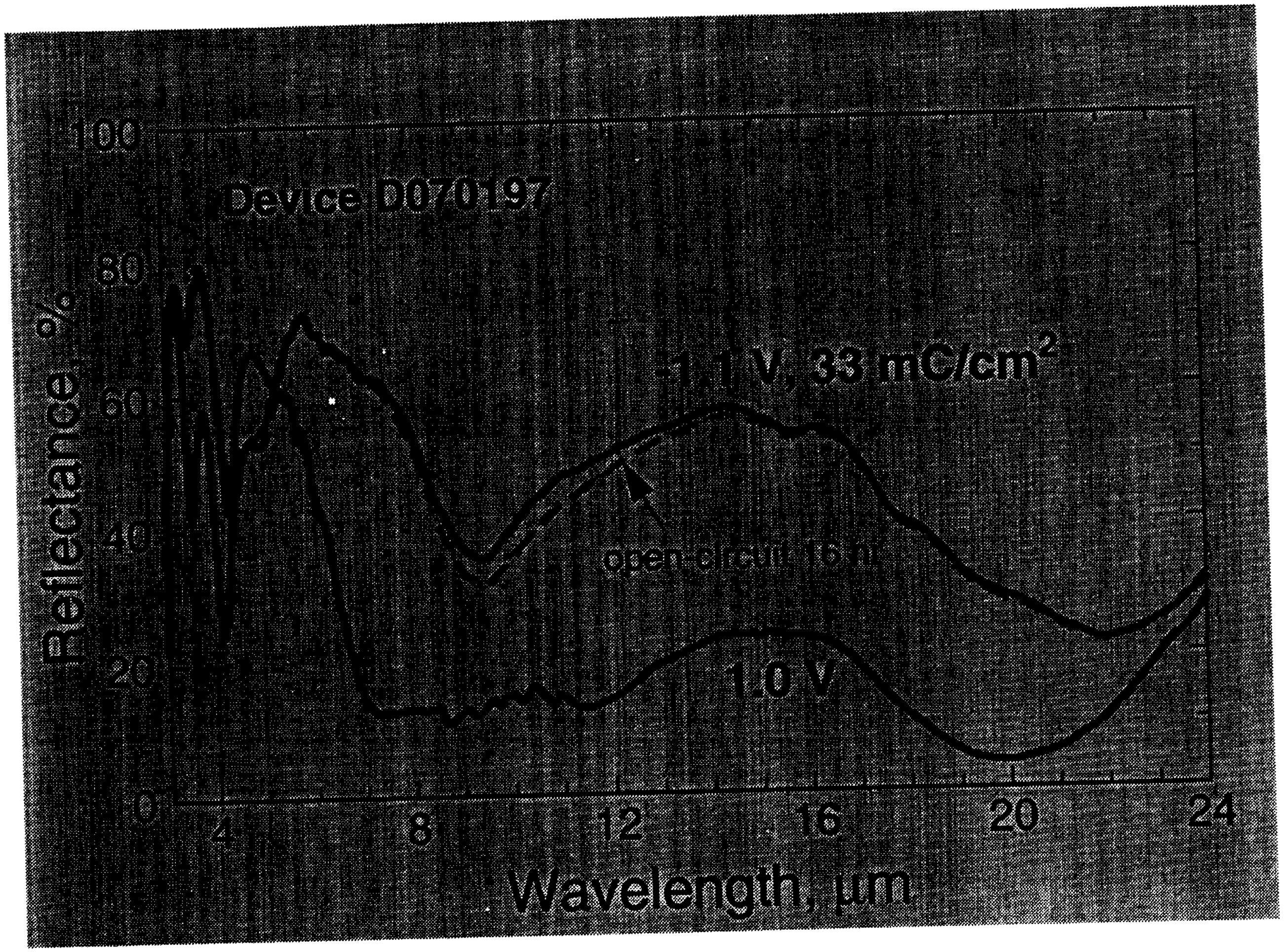
Open-Circuit Memory



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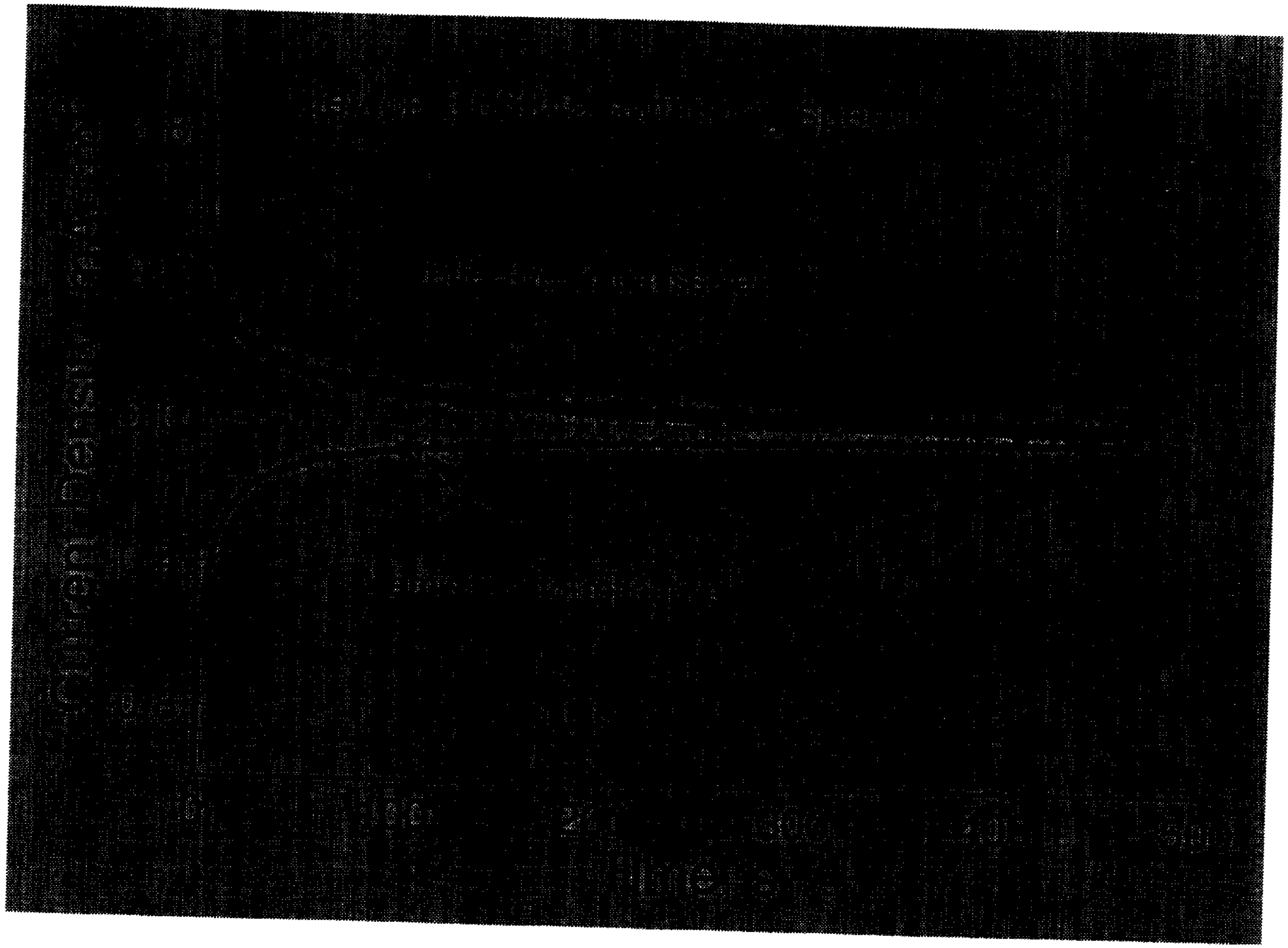
Switching Speed



current transient in response to a step (1.5 V) voltage: switching complete in ~300 s

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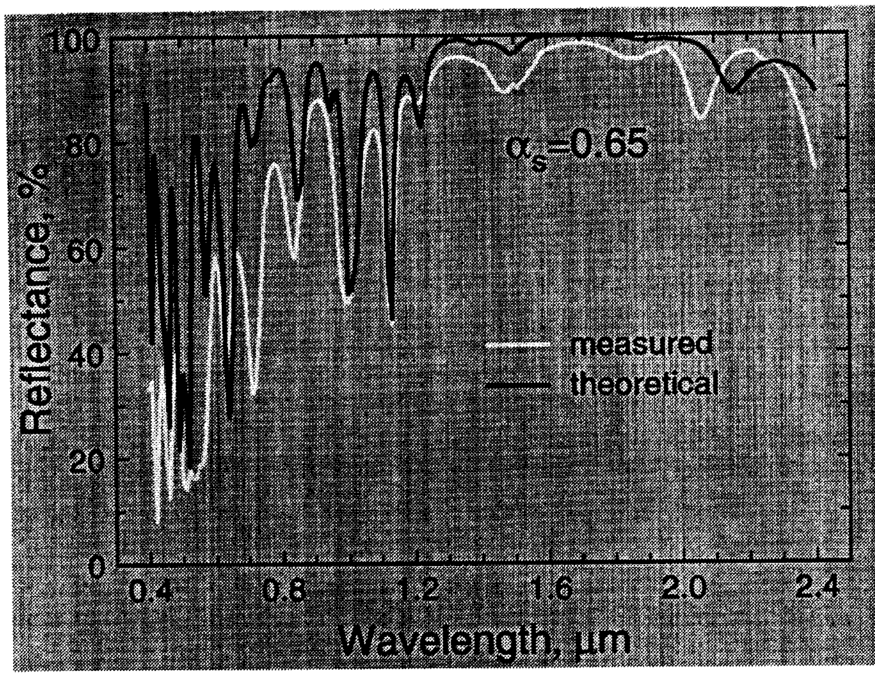
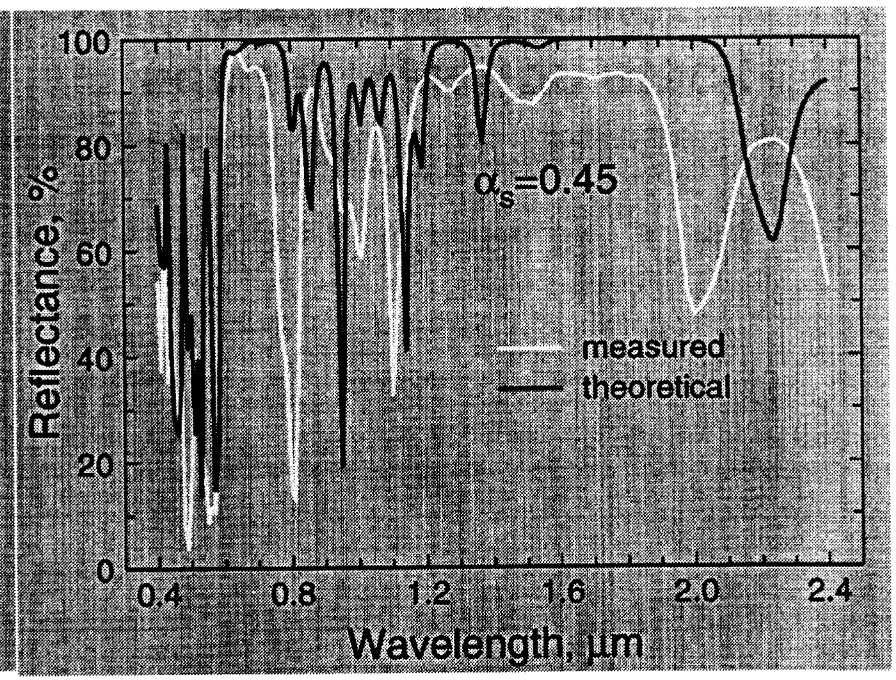
Solar Absorptance

should be <0.2 for practical devices



AR-coated Ge with no solar rejection stack



first solar reflectance stacks in coating

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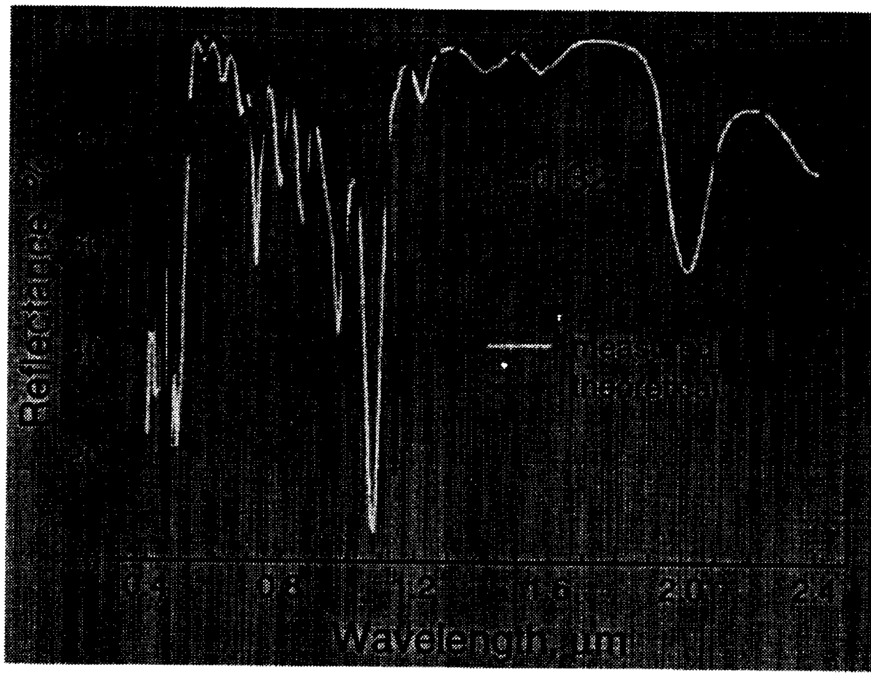
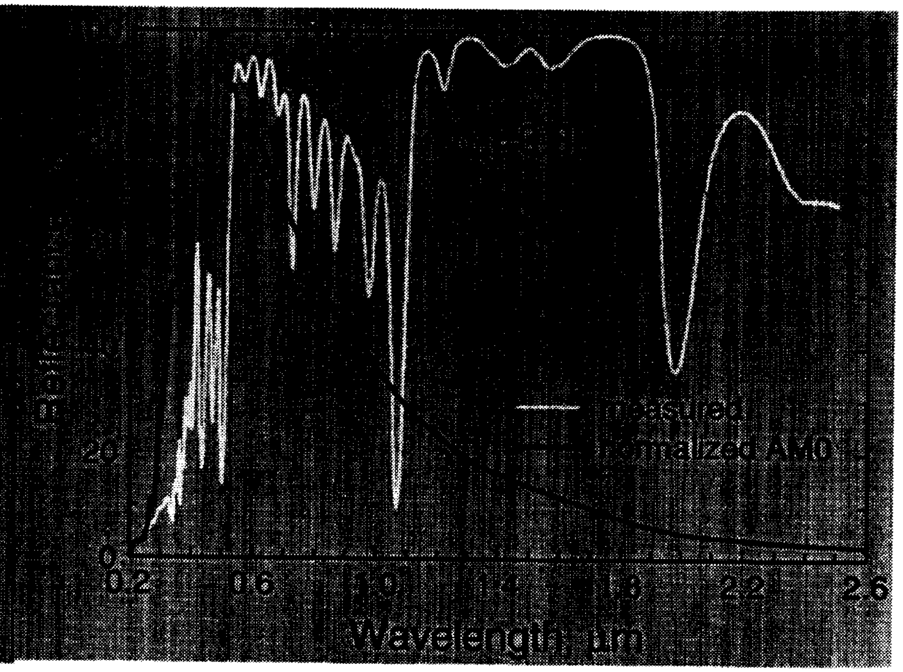
Refinement in Low α_s Coatings



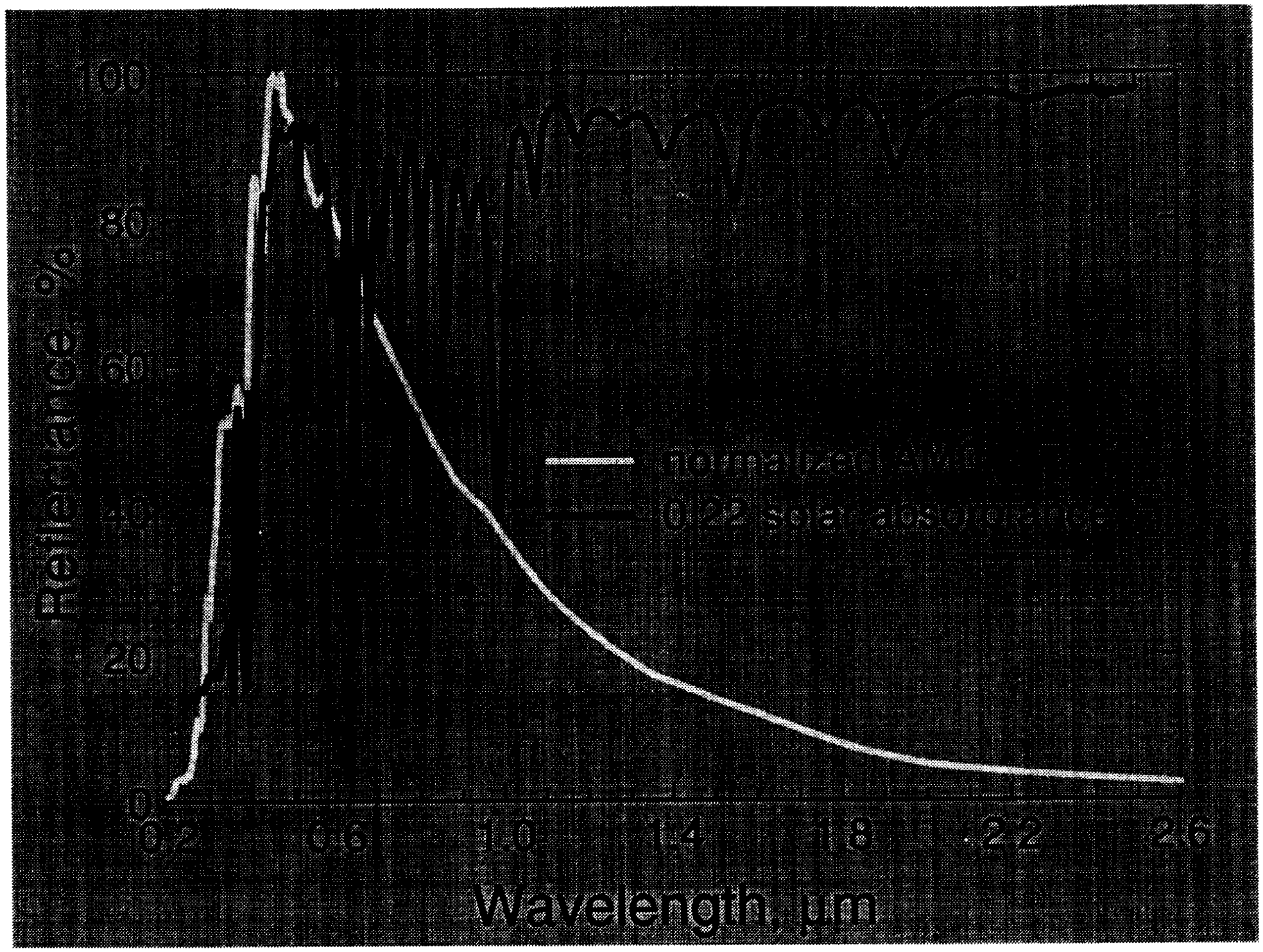
rejection stack at 0.55 µm
reduces α_s from 0.45 to 0.32



need a rejection stack
centered at lower
wavelength 0.4-0.5 µm

EIC Laboratories, Inc.

Low α_s Coating



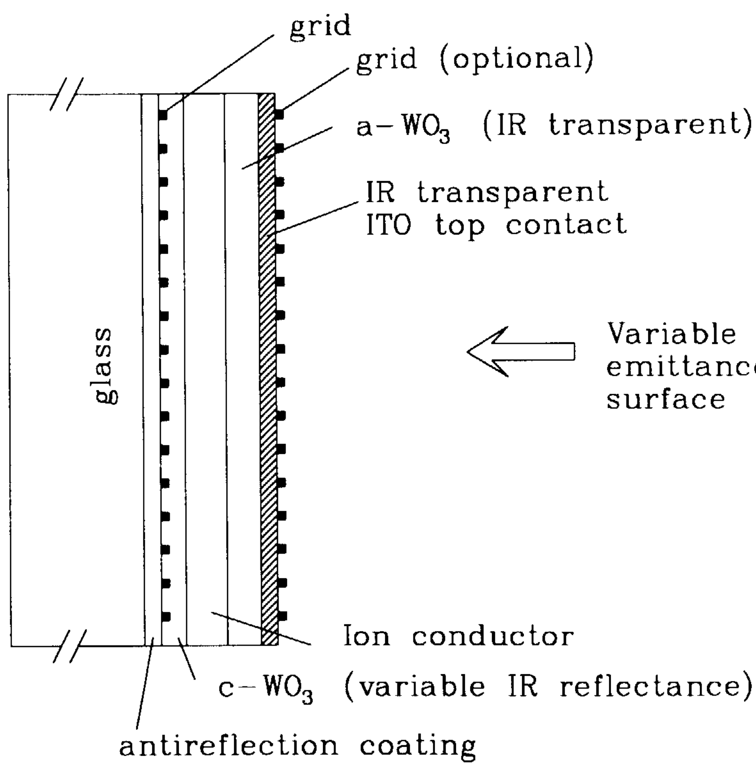
need more reflectance at short wavelengths

EIC Laboratories, Inc.

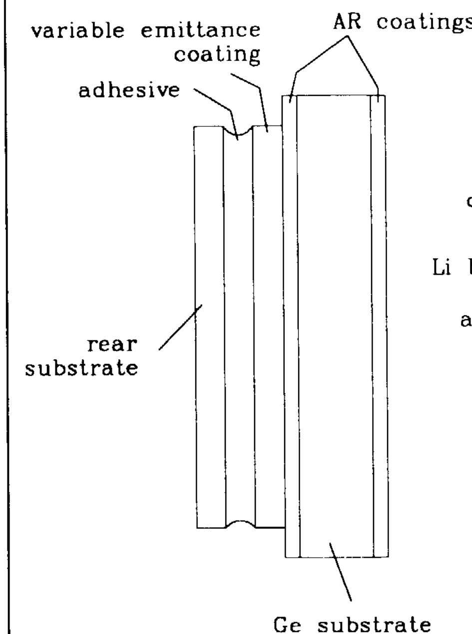
Solid State Variable Emittance Devices

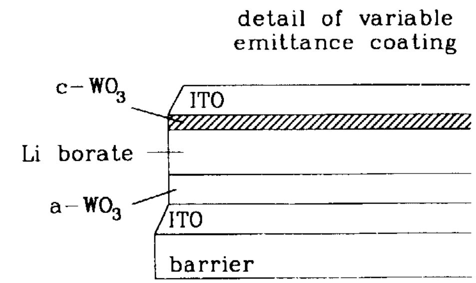
- advantages:
  - minimal outgassing
  - better environmental stability
- status:
  - recent redesign to facilitate low α_s
  - redesigned coatings by July 1997

Design of Solid-State Variable Emittance Coatings



Old: Electrochromic films exposed to space environment

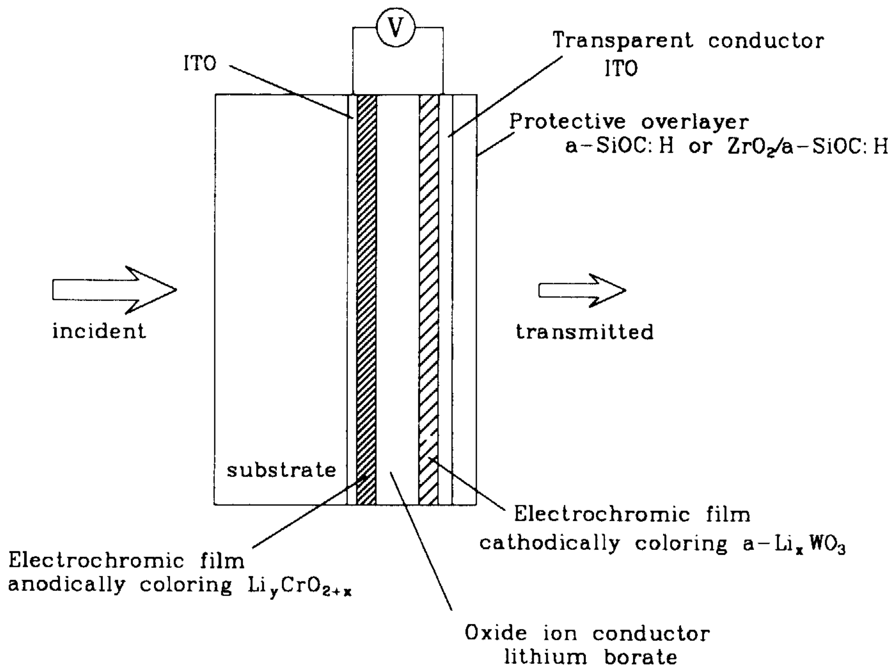




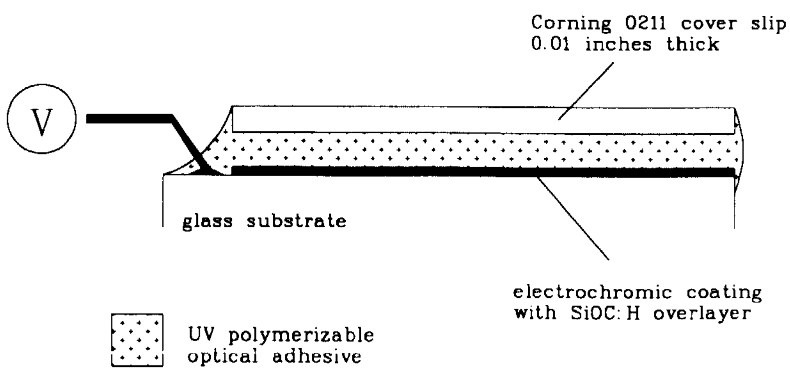
New: AR-coated Ge used as front substrate

EIC Laboratories, Inc.

Solar Absorptance Coatings



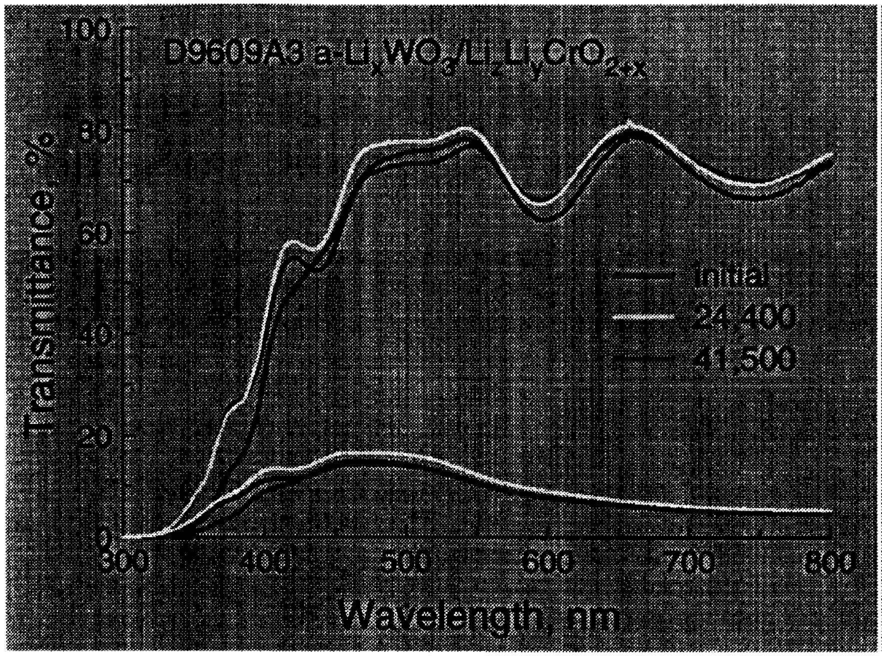
- Coatings typically design to modulate between absorbing and transmitting.
- Solar transmittance range 6-60% (AM1)
- Obtain variable reflectance by replacing one ITO film with Al

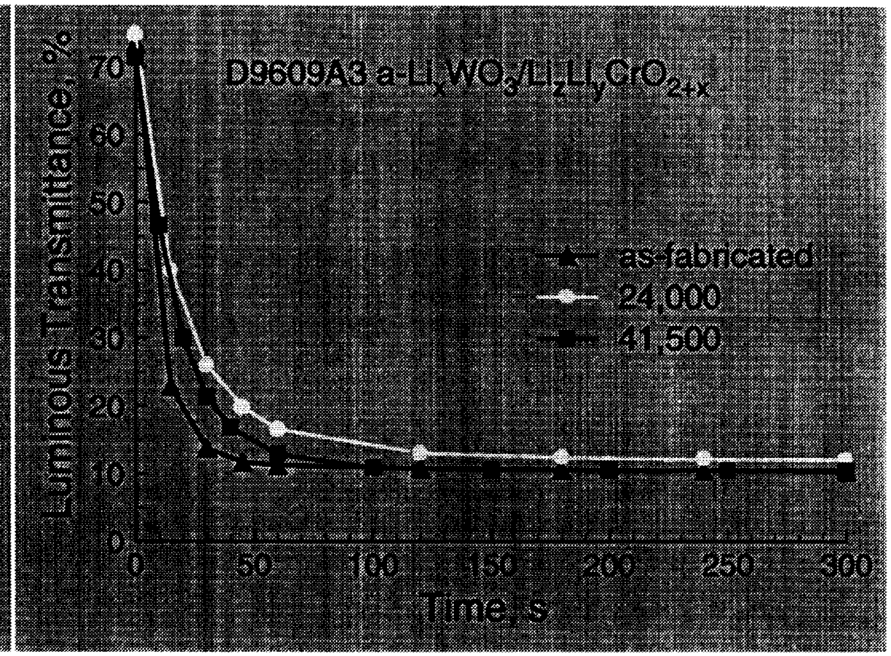


- Laminated structure used to protect against moisture and mechanical damage

EIC Laboratories, Inc.

Performance of Variable Solar Absorptance Coatings
long-term switching at room temperature



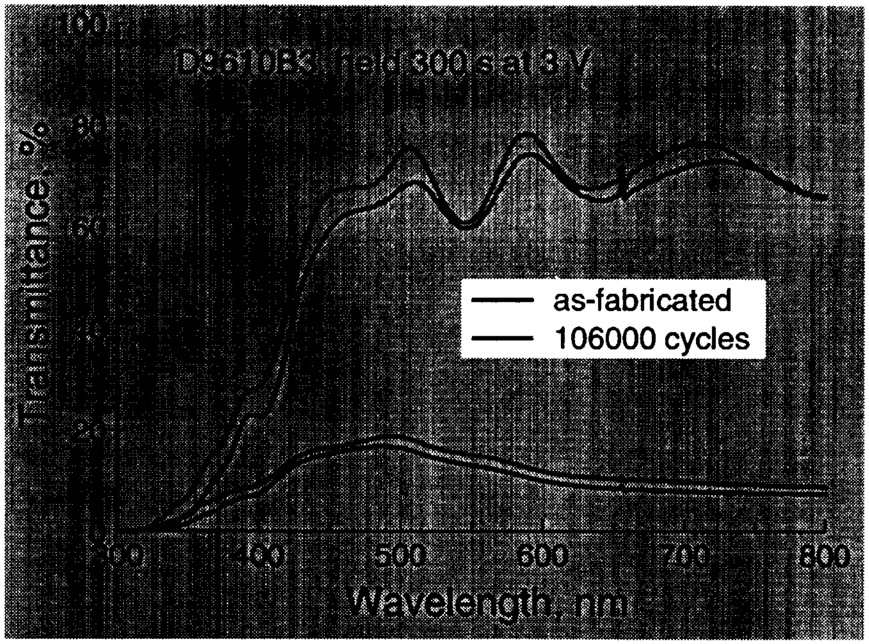


spectral transmittance after 41,500 cycles at room temperature (~3 months of continuous switching)

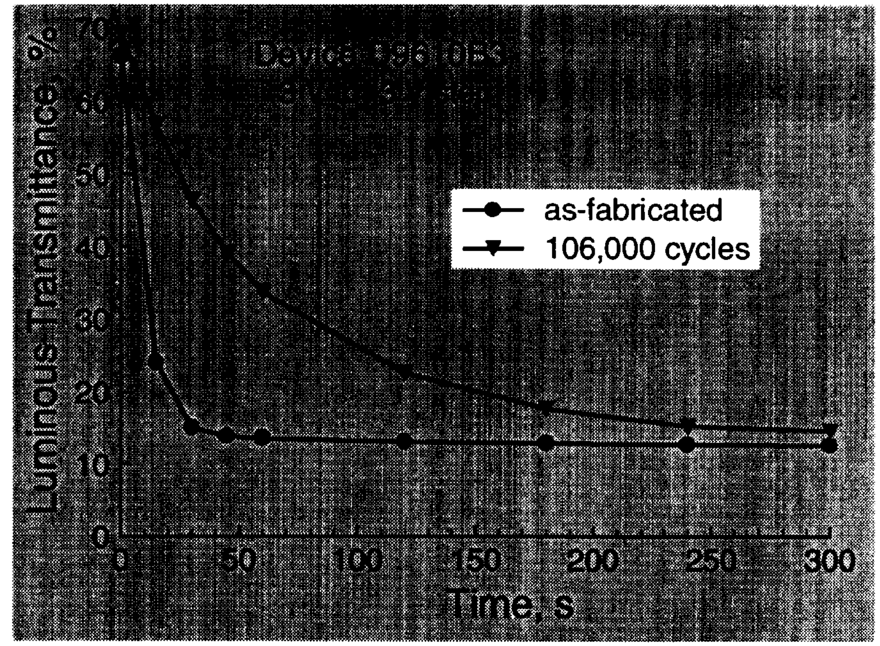
switching speed after 41,500 cycles at room temperature - some decrease in speed is observed over the first 5,000 cycles

EIC Laboratories, Inc.

Switching at 60°C



no significant change in spectral response after >10^5 switching cycles at 60°C



slower switching speed after cycling at 60°C

EIC Laboratories, Inc.

Solid State Coatings

- long-term, multicycle switching demonstrated
- limited use of higher voltages (<10 V) for more rapid switching possible
- can be switched at elevated temperatures (>100°C)

EIC Laboratories, Inc.

Anticipated Performance of Optimized Coatings

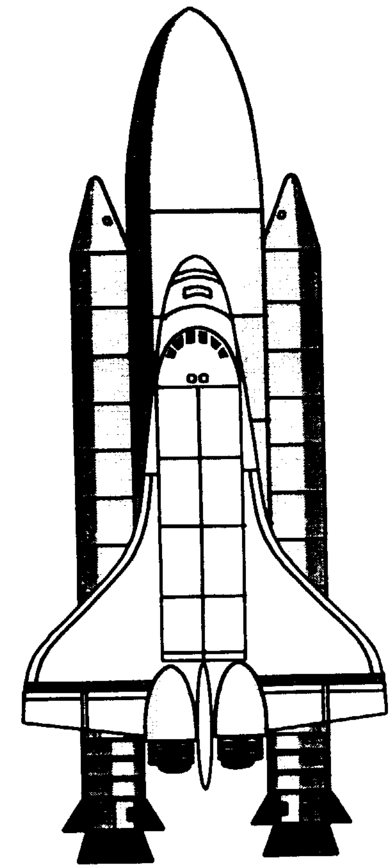
maximum emittance	>0.8	depends on use of finer grids or optimized electrode coatings
minimum emittance	<0.3	depends on c-WO_3 and coating design
solar absorptance	<0.2	0.22 for current coatings
switching speed	<300 s	for small area coatings (<25 cm^2)
switching cycles	>50,000	42,000 at RT and 10^5 at 60°C demonstrated in variable transmittance coatings
thermal stability	-130°C to 100°C	limited by adhesives?

EIC Laboratories, Inc.

Near Term Objectives

- **Fabricate polymer-laminated and solid-state variable emittance devices under a subcontract from Physical Sciences Inc. (Phase I SBIR, *Space Validation of Variable Absorptivity and Emissivity Thermal Control Materials*)**
- **Fabricate a solid-state demonstration device for December 1997 delivery to NASA Goddard (Phase II SBIR, *Thermal Control Coatings for Satellites*)**

AZ Technology



SPACECRAFT CONTAMINATION & COATINGS WORKSHOP

AZTek

Randell Thompson
July 10, 1996

see0797.ppt

4901 Corporate Drive, Suite 101, Huntsville, Alabama 35805
205 837-9877 Main 205 837-1155 Fax

AZ Technology, Inc.

AVAILABLE COATING PRODUCTS AND DEPOSITION CAPABILITY

- COATINGS
  - White Thermal Control Coatings
  - Optical Black Coatings
  - Marker Coatings
  - Tailorable Coatings
  - Overcoats & Sealants

AVAILABLE COATING PRODUCTS AND DEPOSITION CAPABILITY (cont'd.)

- DEPOSITION CAPABILITIES
  - 12 X 15 Ft. HEPA Filtered Coatings Application Booth
  - 12 X 12 Spray Coatings Deposition Room With Filtered Air Supply
  - Controlled Air Flow
  - Temperature & Humidity Controlled & Monitored Air Systems
  - Large Variety Of Spray Gun Types & Sizes Available
  - Many Qualified Individuals For Coating Flight Hardware

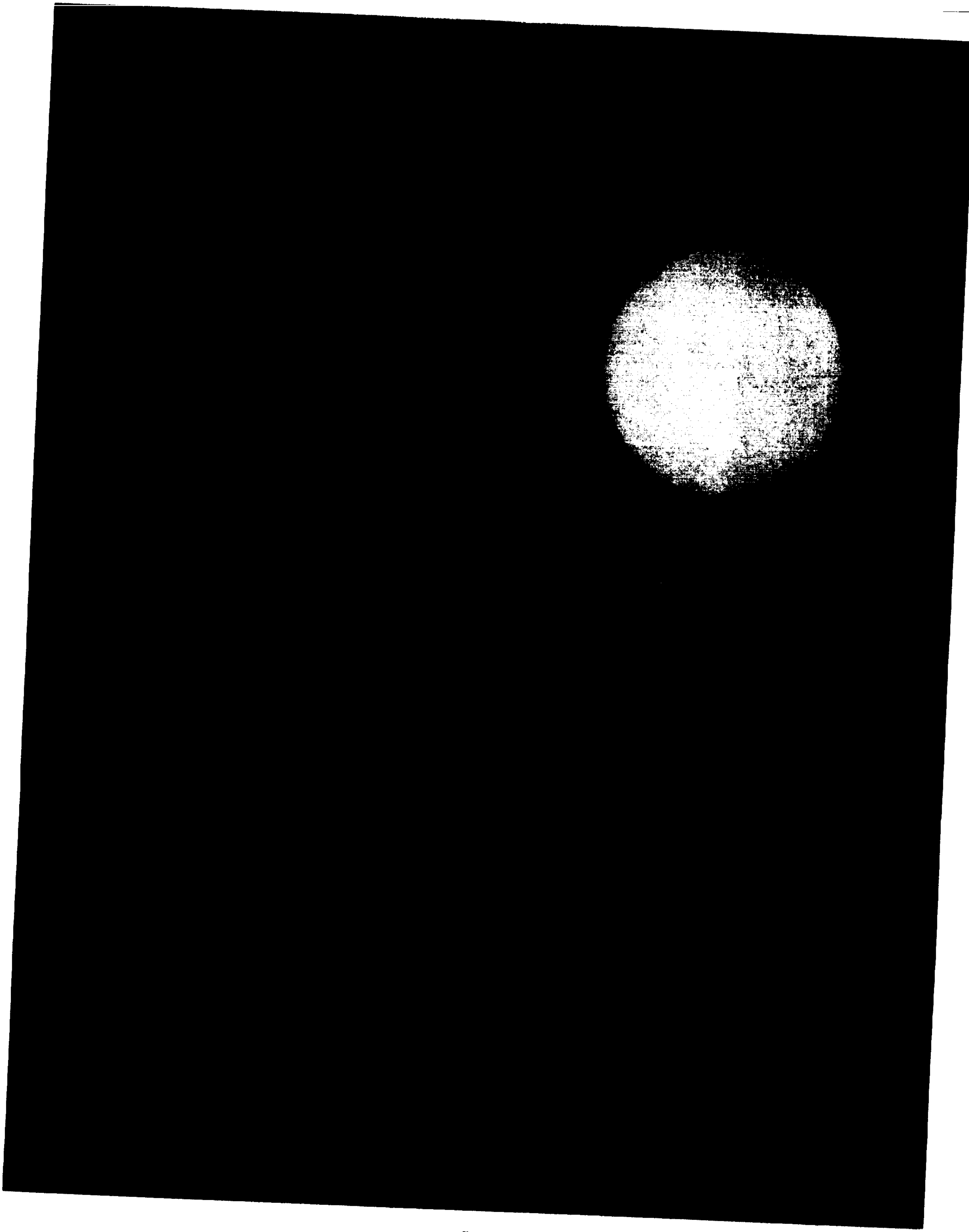
AZTek

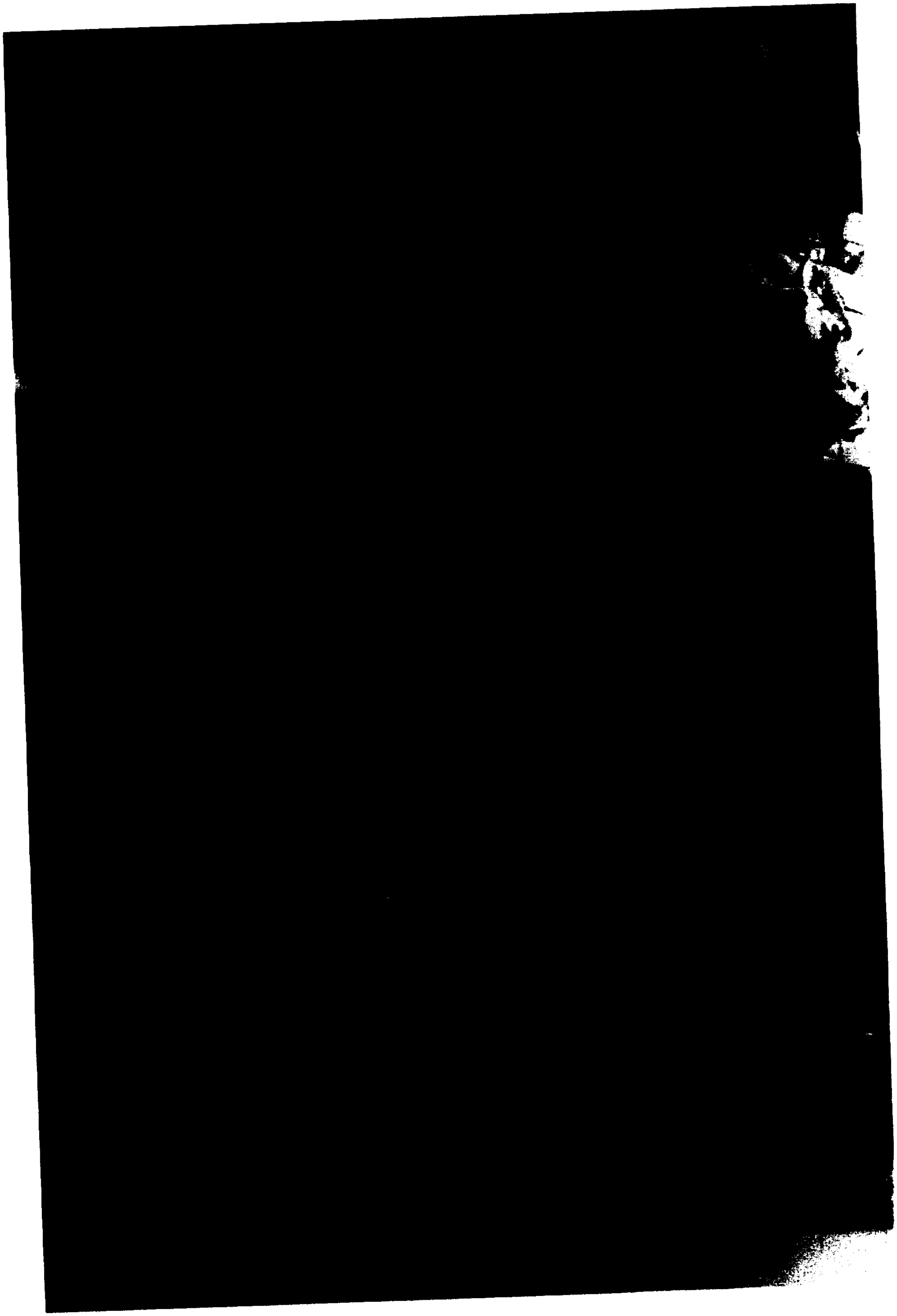
AZ TECHNOLOGY HAS DEVELOPED-WITH NASA-THIS UNIQUE SERIES OF SPACECRAFT COATINGS

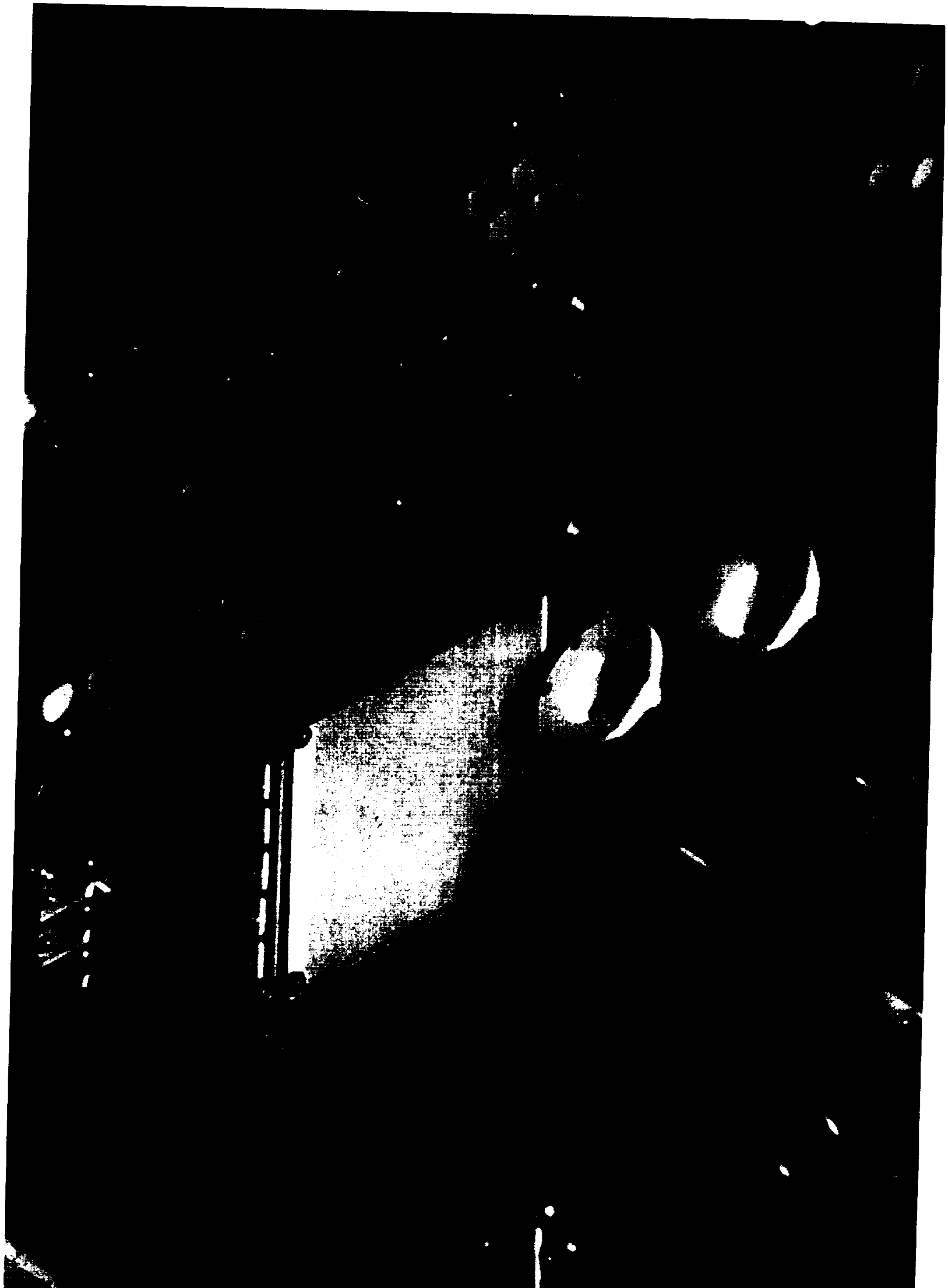
- CURRENTLY TESTED AND FLOWN COLORS
  - White
  - Black
  - Yellow
- COLORS CURRENTLY UNDER DEVELOPMENT
  - Red
  - Blue
- COATINGS ARE TAILORABLE TO A RANGE OF PROPERTIES
  - Mechanical
  - Physical
  - Optical

AZ Technology, Inc.

see0797.ppt



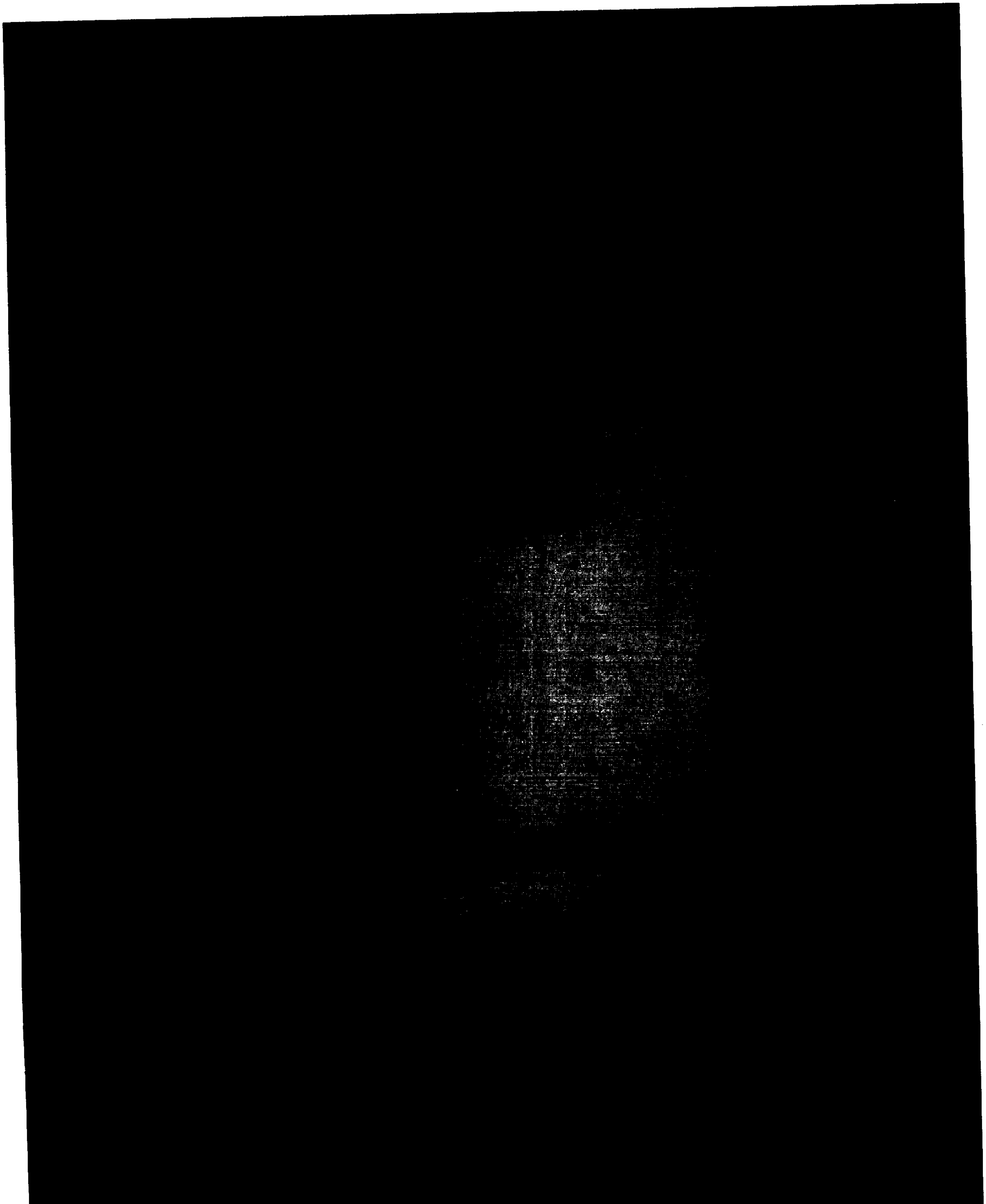


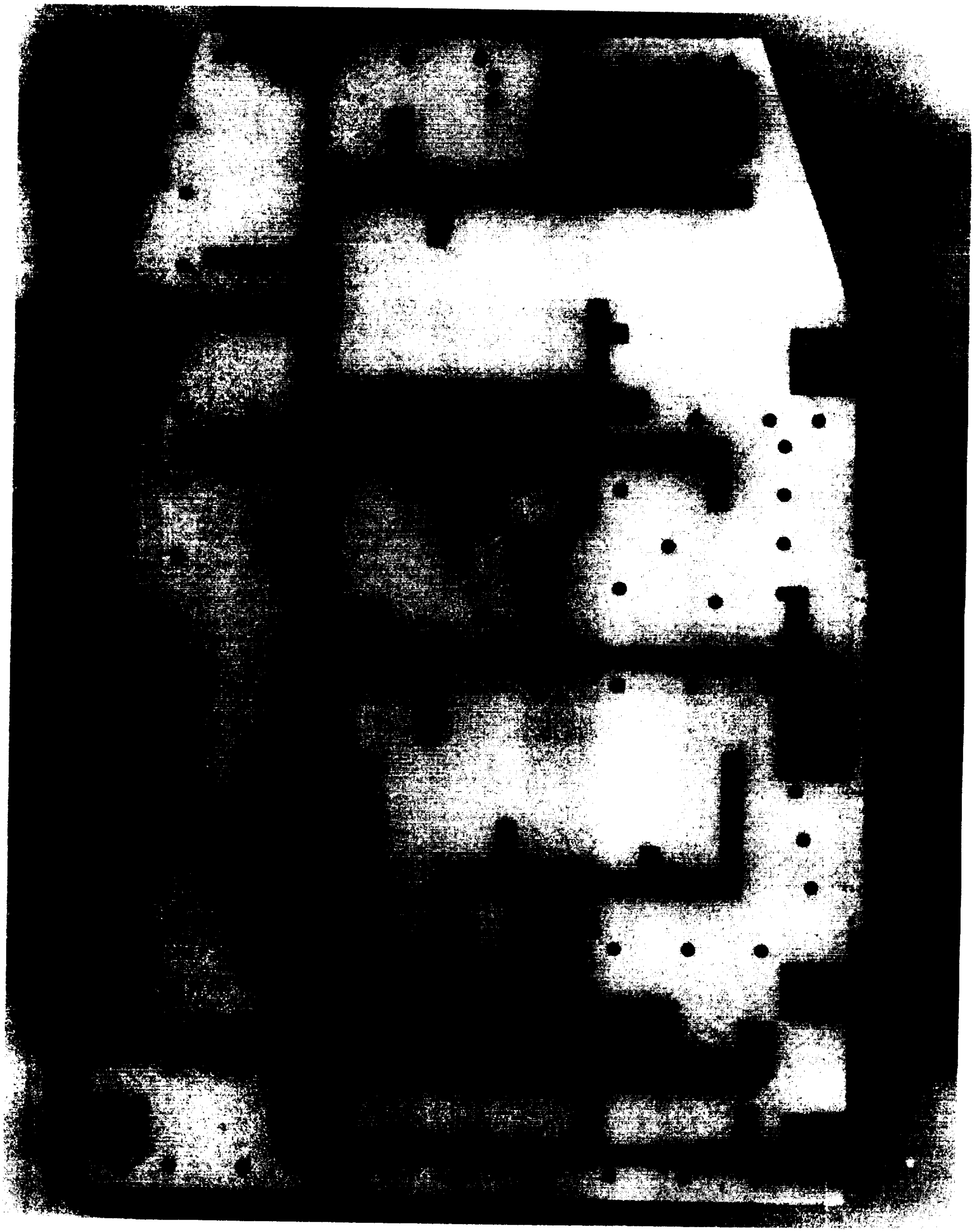



OPM

PRIMERS

- DEVELOPMENT OF PRIMERS THAT ALLOW SILICATE COATINGS TO BE DEPOSITED ON A VARIETY OF SUBSTRATES
  - Cyanate Ester/Graphite Composites
  - Epoxy/Graphite Composites
  - Epoxy/Carbon Composites
  - Carbon/carbon Composites
  - Anodized Aluminum
- NO SILICONE OR SILANES USED
- USED ON SEVERAL FLIGHT HARDWARE PROGRAMS
  - ISS
  - AXAF
  - Military Surveillance Programs
- CURRENTLY DEVELOPED IN TWO VERSIONS
  - RF Transmissive MLP-300AZ
  - RF Reflective MLP-100AZ

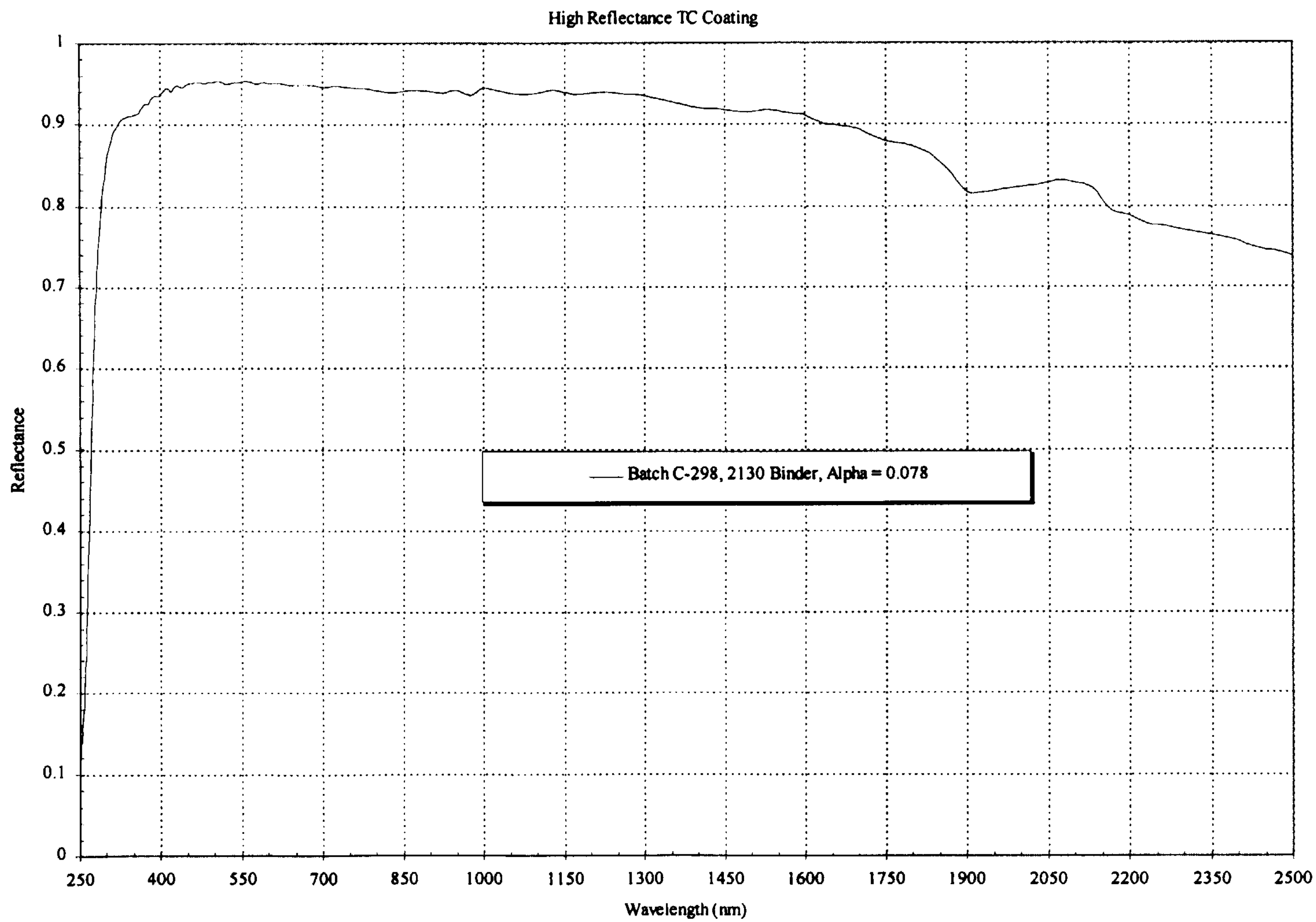




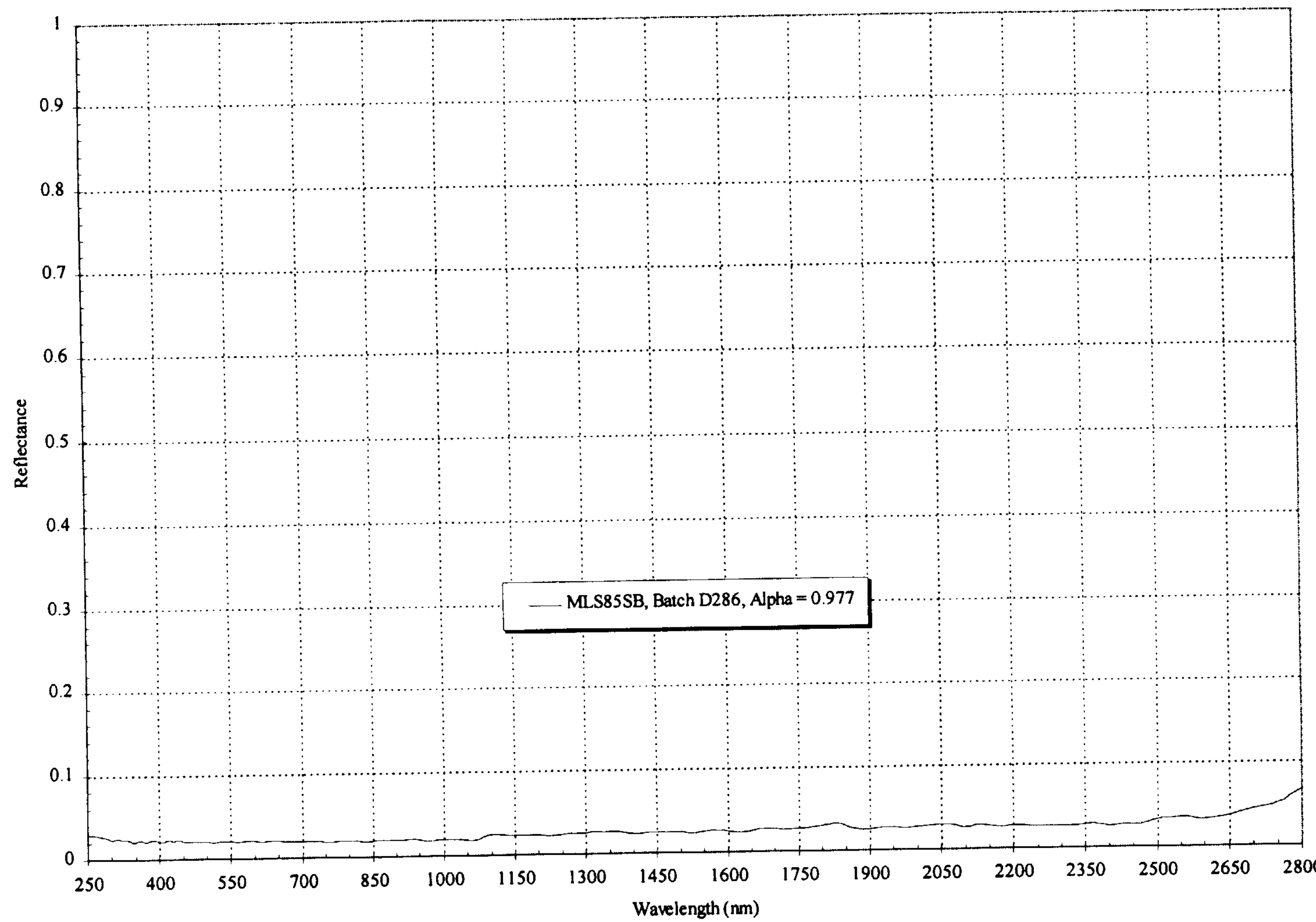
AZTek

MATERIALS & COATINGS RESEARCH AND DEVELOPMENT AREAS

- Electrically conductive thermal control coatings
- Ultralow/ultrahigh solar absorptance thermal control coating
- Tailored solar absorptance or thermal emittance coatings
- Primers
- Specialty marker coatings for use on spacecraft
- Space stable screen printing inks
- Electrochromic materials and coating
- Thermally conductive coatings and adhesives
- Space grade polymers
- Space stable ceramic powders


High Reflectance TC Coating
Reflectance
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
250
400
550
700
850
1000
1150
1300
1450
1600
1750
1900
2050
2200
2350
2500
Wavelength (nm)
Batch C-298, 2130 Binder, Alpha = 0.078

Silicone Optical Black Thermal Control Coating

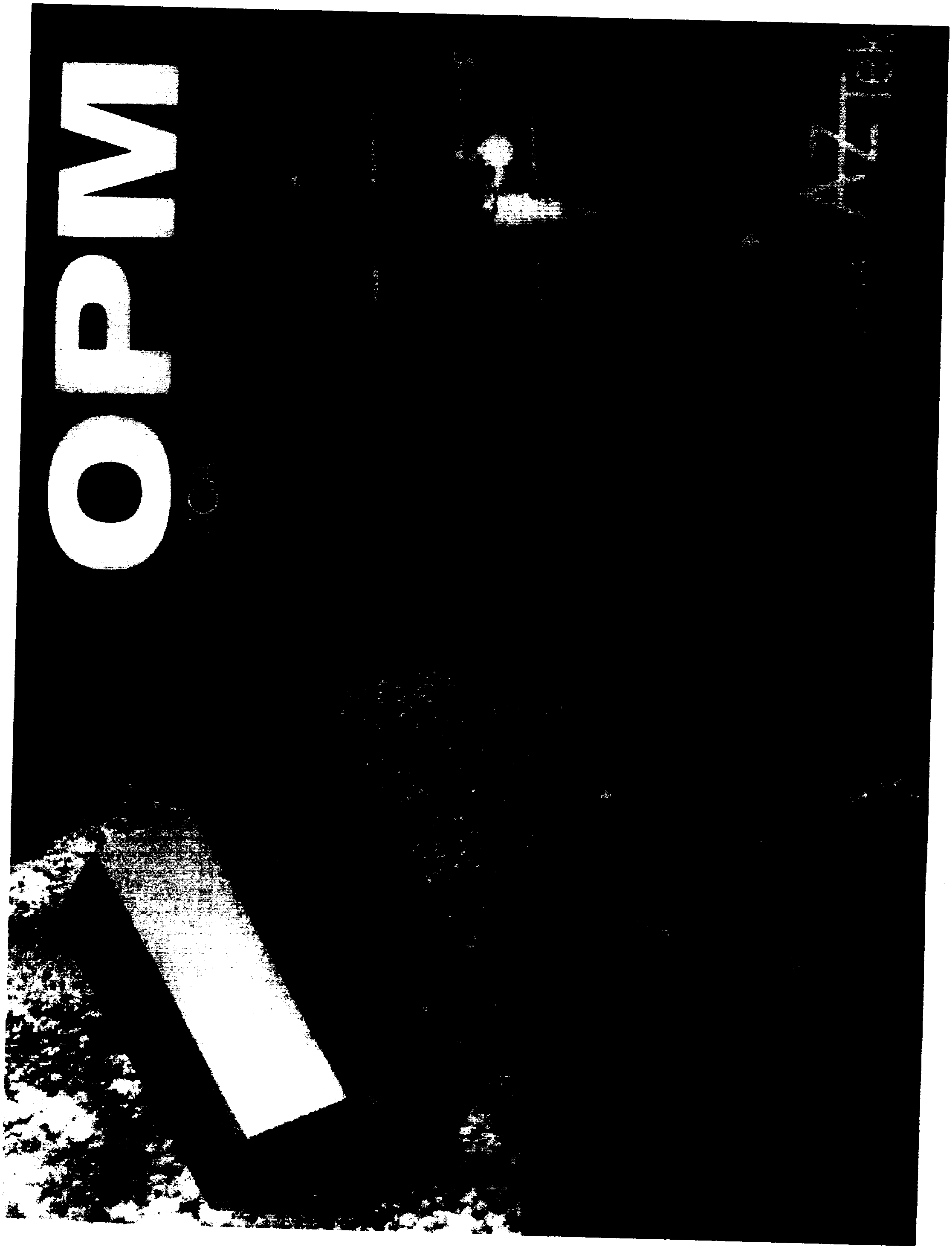


MATERIALS & COATINGS SERVICES

- Expert coating of hardware
- Material synthesis, coating development and sales
- Expert consulting
- Development and production of custom coatings
- Coating testing and evaluation

CUSTOMER LIST

- McDonnell Douglas Aerospace
  - St. Louis, MO
  - Huntington Beach, CA
- SPAR Aerospace Limited
- Lockheed-Martin
  - Camden, NJ
  - Houston, TX
- Boeing
  - Huntsville, AL
  - Seattle, WS
  - Houston, TX
- University of Colorado Laboratory for Atmosphere and Space Physics
- NASA
  - MSFC
  - LARC
  - JSC
  - LERC
  - GSFC
- TRW
- Symetrics/Parker-Hannifin
- Johns Hopkins Research Institute
- Harris Corporation
- EG & G Judson
- Ball Aerospace


OPM

OPTICAL PROPERTIES MONITOR

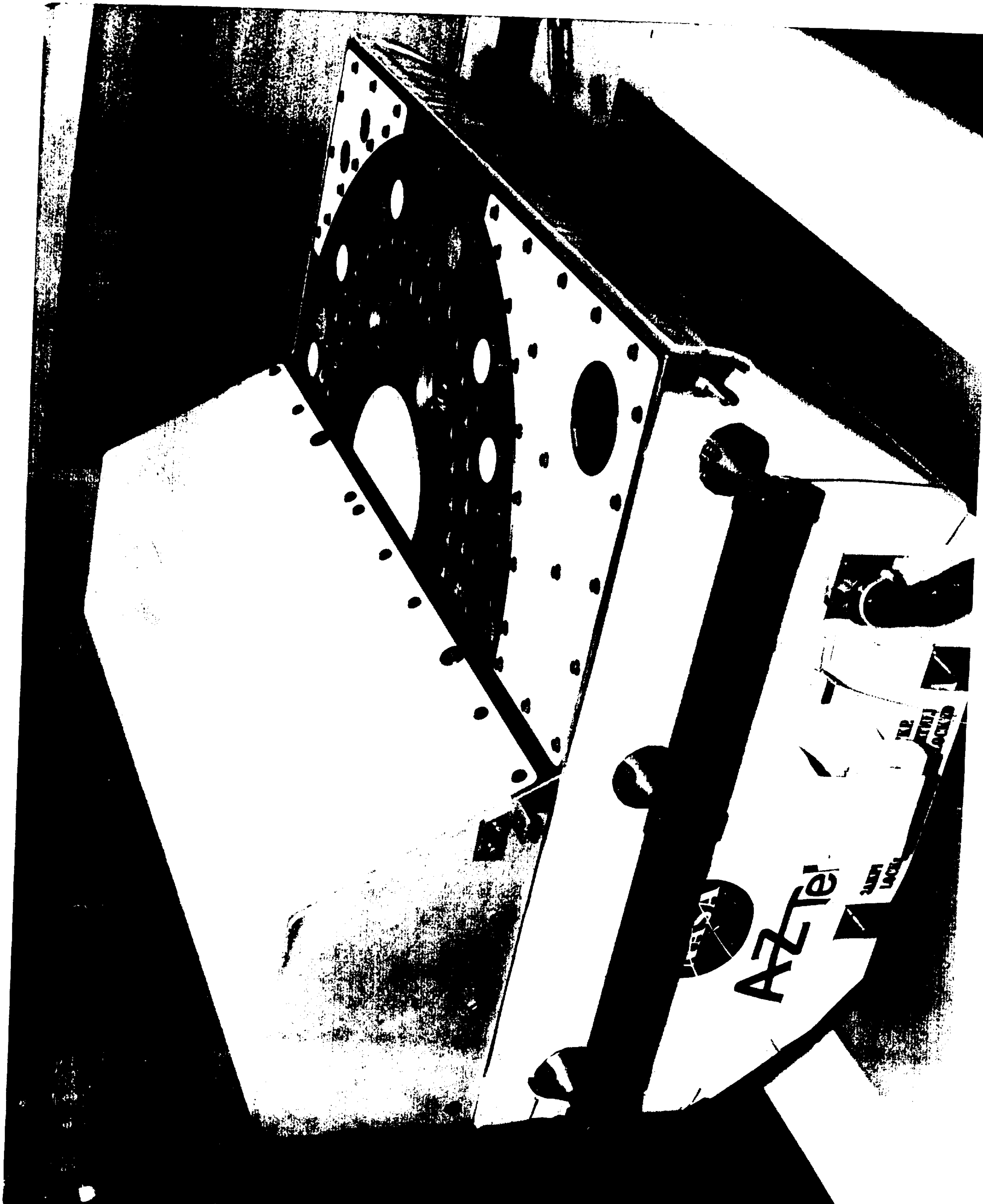
Experiment Summary

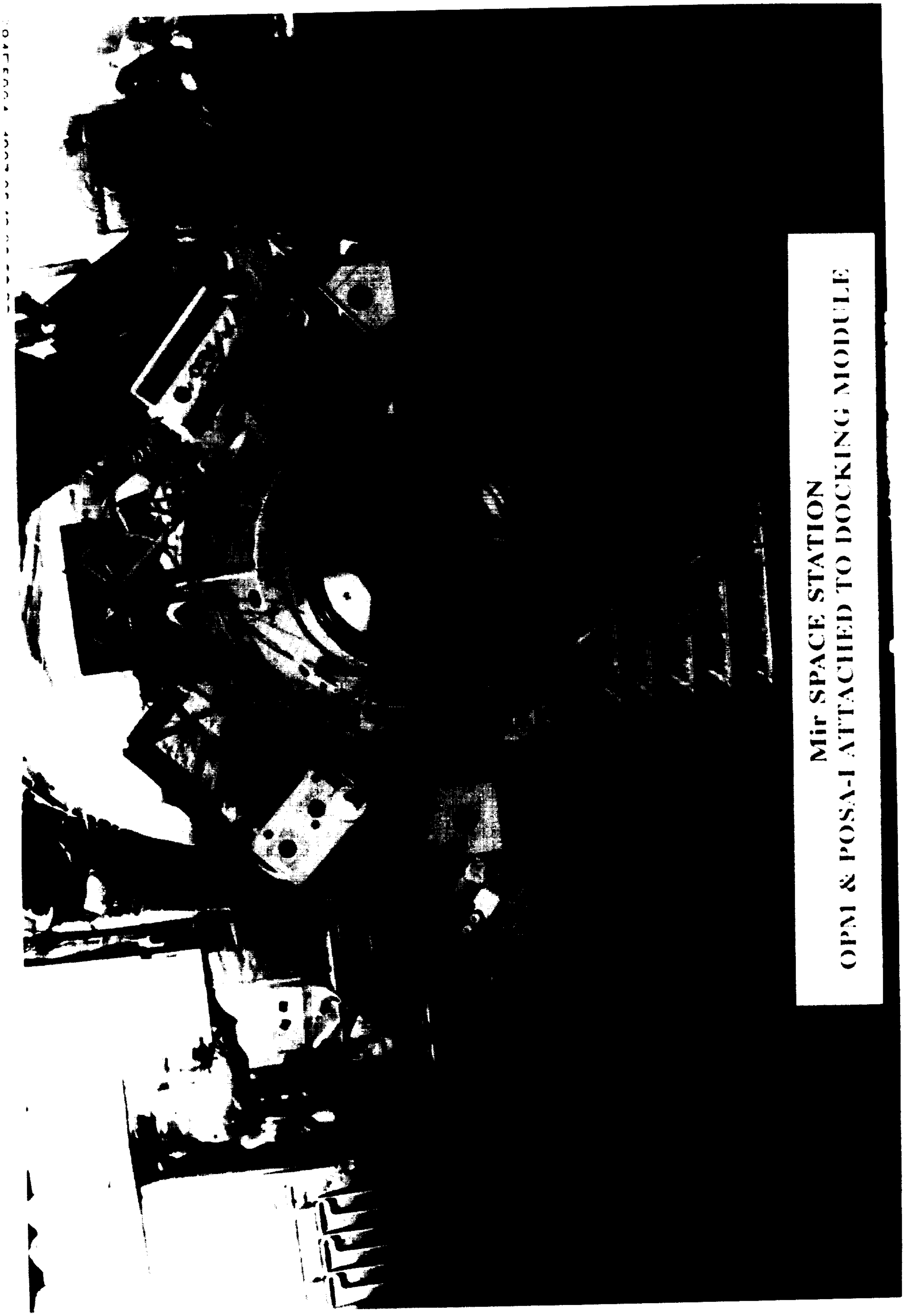
The OPM is a multifunctional, reusable in-flight laboratory for the in-situ study of materials. Selected materials will be exposed to the low earth orbit space and Mir induced environment and their effects measured through in-situ measurements and post-flight analyses.

- Optical and thermal properties are measured by in-situ measurement subsystems.
  - Spectral total hemispherical reflectance
  - Total Integrated Scatter (TIS)
  - Vacuum Ultraviolet (VUV) reflectance/transmittance
  - Total emittance

- Environmental monitors measure selected components of the exposure environment.
  - Solar/earth irradiance
  - Molecular contamination
  - Atomic oxygen

- Detailed optical and thermal properties, surface degradation, and contamination are determined by post-flight analyses.





Mir SPACE STATION
OPM & POSA-I ATTACHED TO DOCKING MODULE

AZ Tek AZ TECHNOLOGY

OPTICAL PROPERTIES MONITOR

OPM Status

- Deployed on the exterior of the Mir Docking Module
  - Joint US/Russian EVA
  - Powered up at 02:21 CDT (07:21 GMT) on April 29, 1997
  - Planned movement of OPM carousel observed during EVA

- OPM data received from April 29, 1997 to June 11, 1997

- More detail about the OPM is available at http://see.msfc.nasa.gov and at http://www.azhsv.com

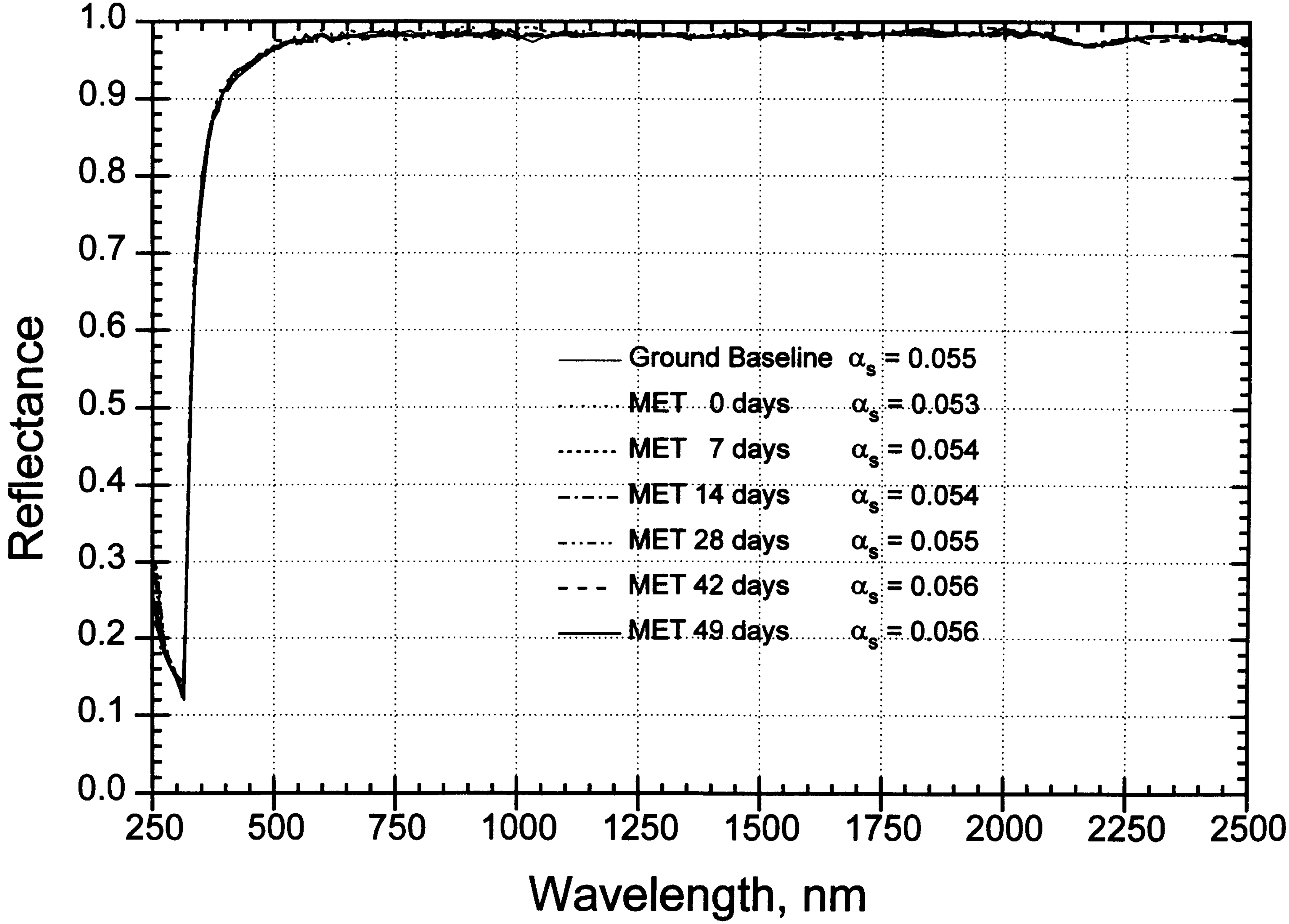
gsfc797.pr4-7/7/97

OPM Status
(continued)

- Analysis of initial OPM data indicates:
  - Most OPM systems are working extremely well including:
    - The flight sample array survived launch, storage, and deployment intact and without significant contamination
    - Optical reflectometer
    - Total Integrating Scatter (TIS) instrument
    - Calorimeter measuring system
    - TQCM molecular contamination monitors
    - Atomic oxygen monitor system
    - Irradiance monitor system
    - OPM support systems
  - A few anomalies or unexpected conditions have been observed:
    - The VUV instrument is not operating properly
    - The Mir attitudes and thermal environment are somewhat different than planned

OPM Reflectometer Measurements - (preliminary)

Optical Solar Reflector



ADVANCED CONDUCTIVE THERMAL CONTROL MATERIAL SYSTEMS

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Senior Engineer
Advanced Materials
and Coatings Laboratory
Energy and Environmental Systems

IIT RESEARCH INSTITUTE

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Prepared for Presentation at:

1997 Spacecraft Contamination
and Coatings Workshop
Annapolis, MD

July 10, 1997

M. S. Deshpande
and Y. Harada
IIT Research Institute
Chicago, Illinois

J. Vaughn
NASA-Marshall Space
Flight Center
Huntsville, Alabama

*Sponsored by IR&D and NASA-SEE Program: Contract No. NAS8-405080
IITRI Project No. C06804

ORGANIZATION

- Program goal
- Concepts
- Progress made and results
- Closure and future

IIT Research Institute

PROGRAM GOAL

Task A: Black Thermal Control Coatings

- $\alpha_S \geq 0.90$ $\varepsilon_N \geq 0.90$
- Adhesion, thermal shock – satisfactory for long-term use
- Space environment stability – satisfactory for long-term use
- Study 1000 ESH UV-vac. (Aerospace Corp./GSFC)
- $\rho_S = 10^4\text{-}10^9\ \Omega/\square \approx 10^4\text{-}10^9\ \Omega\text{-cm}^2\ (\rho v \times t)$ tailorable
- ESD measurement (GSFC)

PROGRAM GOAL

Task B: White Thermal Control Coatings (low α_S/ε_T)

- α_S – Achieve minimum ($\leq$0.18; comparable to Z-93P)
- ε_N – $\geq$0.88
- Adhesion, thermal shock – satisfactory for long-term use
- Space environment stability – satisfactory for long-term use
- Study 1000ESH UV-vac. (Aerospace Corp./GSFC)
- $\rho_S = 10^6 - 10^{10}\ \Omega/\square = 10^6 - 10^9\ \Omega \cdot cm^2$ ($\rho v \times t$) tailorable
- ESD measurements (GSFC)

BINDER DEVELOPMENT
IR&D: C 46007C002

- SS-55: Sodium Silicate Sol. with Carbonate Formation Inhibitor

  TYPICAL PROPERTIES

pH	11.0 - 11.5
% solids	35%
Na_2O: SiO_2	1:3.33

- Doped Hybrid Potassium/Sodium Silicate Sol.

  DHS-1

  DHS-2

BINDER DEVELOPMENT (cont'd)

- DHS ⇒
  - 50:50 mixture of Kasil 2130 and SS-55
  - Addition of required dopant precursor
  - Mixing/warming
- DHS-1: Maximum dopant level to achieve the highest resistivity of desired range
- DHS-2: Minimum dopant level to achieve the highest resistivity of desired range

PIGMENT DEVELOPMENT
IR&D: C46007C003

Doped Black Glass Development:

Motivation: Conductive additions forces to compomise α_s

Dopant: Indium

Target Resistivity: ?

Process/Precursor Selection:

- Carbosil + carbowax + In precursor salt and carbonization

or

- Si backbone resin + In precursor salt and carbonization

SUMMARY OF BLACK THERMAL CONTROL/OPTICAL COATINGS AT AMCL/IITRI

Coating System	Pigment	Binder	α_x	ϵ_T	Comments
D-111	Carbon black WB-225	Kasil 2130	≃0.95	0.90 ± 0.02	Stable, LDEF data. Not recommended for AO resistance.
MH11-Z	WB-225 Graphite	Kasil 2130	0.89 to 0.91	0.90 ± 0.02	Electrically conductive $\leq 10^6$ Ω•cm stable. (JPL)
MH21-IP	Black glass	Kasil 2130	0.95 to 0.98	0.90 ± 0.02	AO-resistant; stable.
MH55-IC	Black glass graphite	Kasil 2130	0.90 to 0.93	0.90 ± 0.02	Electrically conductive 10^6-10^9 Ω/□
MH21S/LO	Black glass	Silicone MHS/LO	0.95 to 0.98	0.90 ± 0.02	Stable, NASA-TM-100768, recommended for AO resistance.
MH21SC/LO	Black glass graphite fiber	Silicone MHS/LO	0.90 to 0.93	0.90 ± 0.02	Electrically conductive 10^4-10^9 Ω/□

OPTICAL, PHYSICAL AND ELECTRICAL MEASUREMENTS FOR BLACK COATINGS

Coating	Batch No.	α_S †	ϵ_T ‡	Resistivity ($\rho \times t$) (Ω cm cm)*	Surface Resistivity ($\Omega/\square$)*
MH21SC/LO-1	T-302	0.93	0.87	10^{10} - 10^{7}	10^{10} - 10^{6}
MH55-IC	S-204	0.94	0.87	10^{9} - 10^{7}	10^{9} - 10^{6}
MH41SCB/LO	S-235	0.95	0.88	10^{9} - 10^{7}	10^{10} - 10^{7}
D21SC/LO	T-026	0.96	0.85	10^{9} - 10^{7}	10^{7} - 10^{5}
D36SCB/LO	T-027	0.95	0.91	10^{10} - 10^{7}	10^{10} - 10^{9}

† Measured using Lambda 19
‡ Measured using DB-100
* Measured using HP-4339A High Resistance Meter

BLACK COATINGS			
Non-conducting Black Baseline Coatings:			
MH21-IP	Black glass	Kasil 2130	2:1
MH21S/LO	Black glass	MHS/LO stripped polydimethyl siloxane	2:1
D21S/LO	Cosmic black, WB-500	MHS/LO stripped polydimethyl siloxane	2:1
Conductive Black Coatings:			
DBG-IP	Doped black glass (Indium doped)	Kasil 2130	2:1
DBG/DHS-1	Doped black glass	DHS-1	2:1
MH55IC	Black glass, Graphite 9035, ZnO	Kasil 2130	5.5
MH21SC/LO	Black glass, graphite fiber, Graphite 9035	MHS/LO stripped polydimethyl siloxane	2.1
MH41SCB/LO	Black glass/B_4C	MHS/LO stripped polydimethyl siloxane	4:1
D21SC/LO	Cosmic black-WB-500, Graphite 9035	MHS/LO stripped polydimethyl siloxane	2:1

BLACK COATINGS

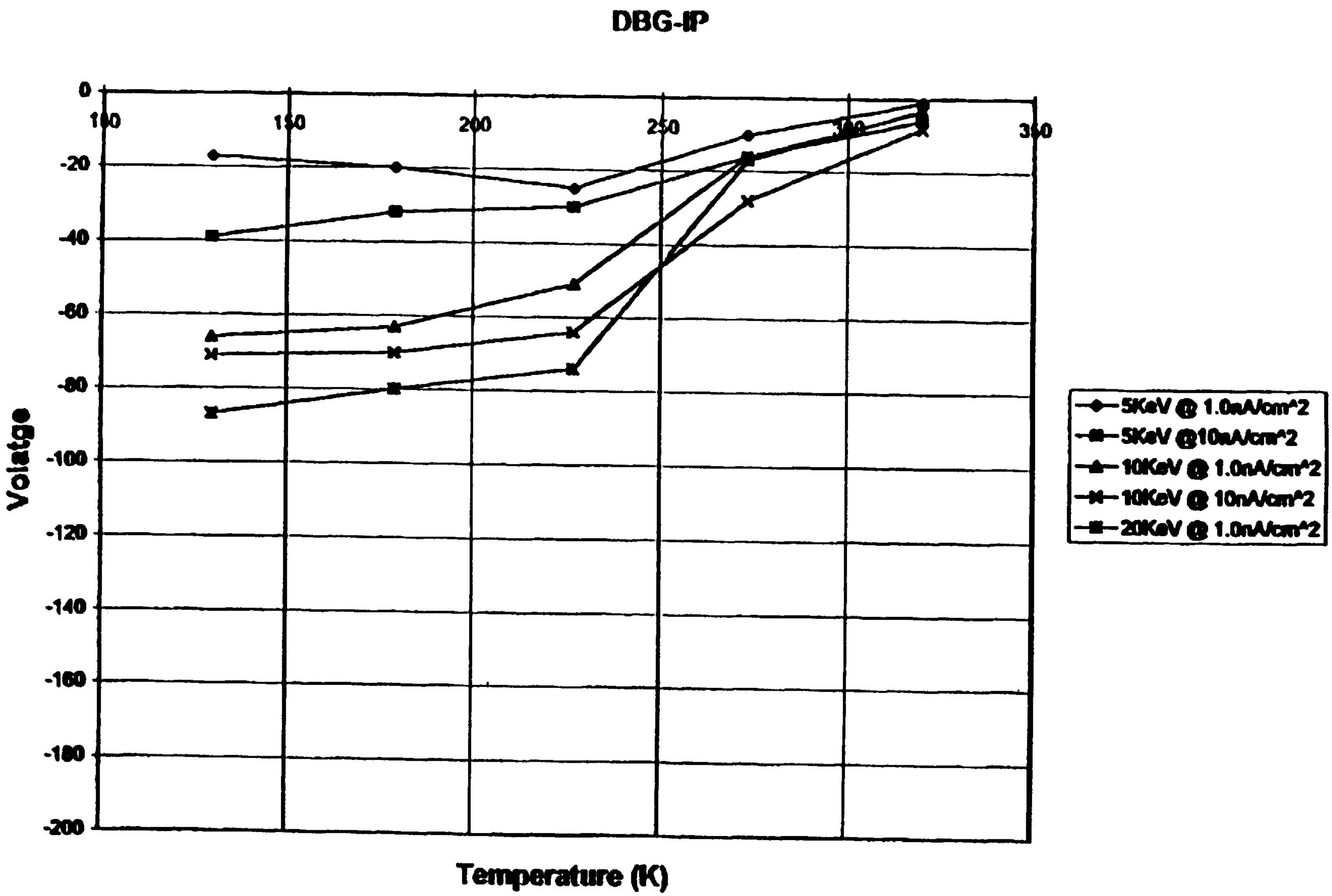
Material	Batch No.	Alpha	Emittance	Resistivity Ω/□ HP4329A	Resistivity Ω/□ HP4339A
Non Conducting Base Line Coatings					
MH21-IP	U-284/289(GZ)	0.98	0.90	1.00E+14	
MH21S/LO	U-360(HZ)	0.98	0.90	1.00E+14	
D21S/LO	T-023(BA)	0.98	0.91	1.00E+10	2.00E+10
Conductive Black Coatings					
DBG-IP	U-021(EO)	0.97	0.90	2.00E+08	1.00E+08
MH55-IC	S-204(Z)	0.94	0.88	1.00E+09	1.00E+09
DBG/DHS	U-283(GU)	0.96	0.90	8.00E+08	1.00E+09
MH21SC/LO	U-166(FD-1)	0.96	0.86	1.00E+06	7.00E+05
MH41SCB/LO	U-053(FD)	0.96	0.87	1.00E+09	1.00E+09
D21SC/LO	T-026(BJ)	0.95	0.88	1.00E+06	C/M

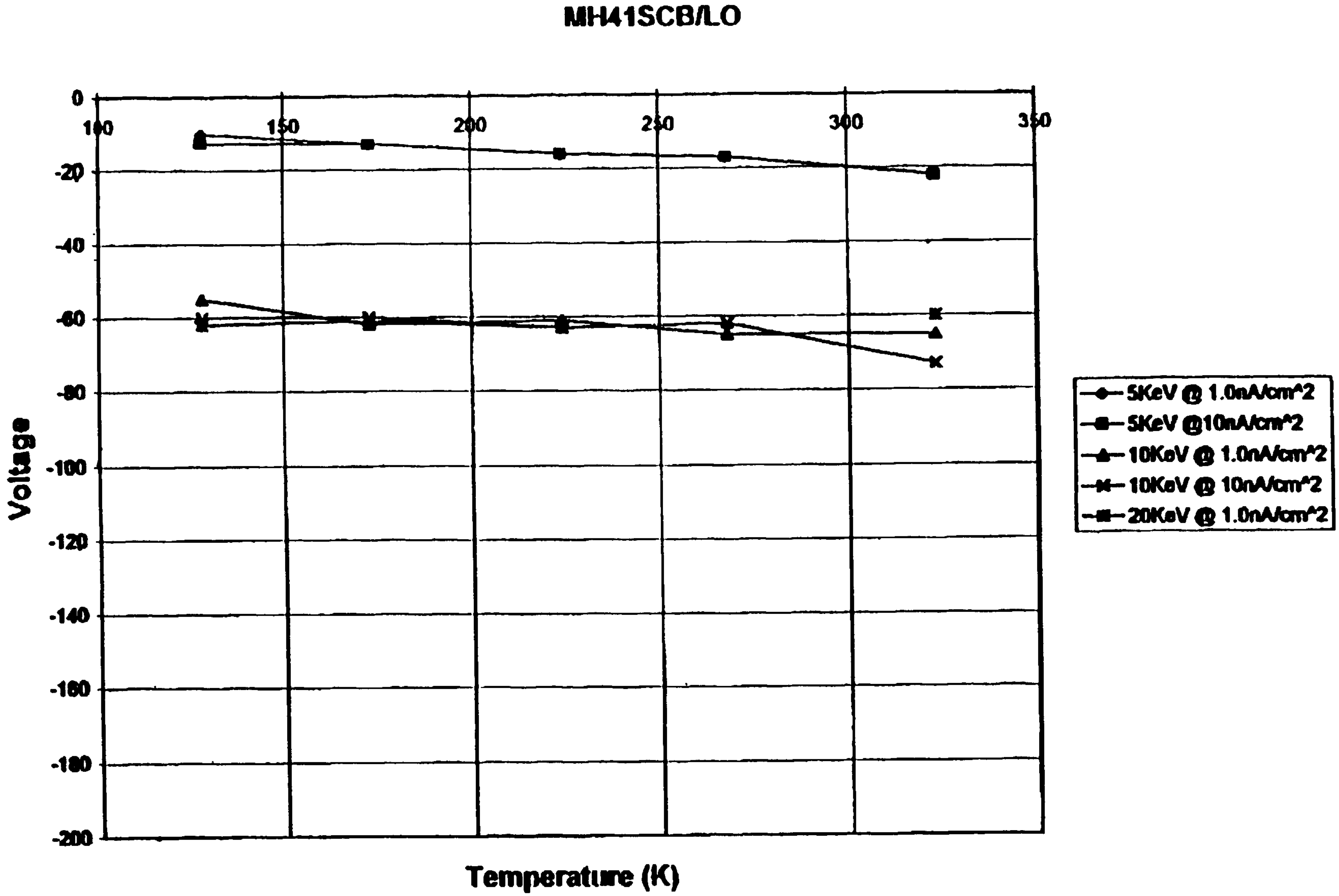
Typical Performance of Promising Conductive Absorber Optical Coatings in Low Earth Orbit (LEO)				
Material	Pre-exposure α_S	Post-exposure α_S	$\Delta\alpha$	Tested By
Inorganic-Conductive				
MH55-IC	0.940	0.939	-0.001	Aerospace Corp.
MH55-IC	0.942	0.941	-0.001	Aerospace Corp.
MH55-IC	0.928	0.938	0.010	GSFC
DBG-IP	0.974	0.975	0.001	Aerospace Corp.
DBG-IP	0.973	0974	0.001	Aerospace Corp.
DBG-IP	0.957	0.951	-0.006	GSFC
DBG-DHS	0.958	0.957	-0.001	Aerospace Corp.
DBG-DHS	0.956	0.956	0	Aerospace Corp.
Organic-Flexible-Conductive				
D21S/LO	0.980	0.980	0	Aerospace Corp.
D21SC/LO	0.956	0.957	0.001	Aerospace Corp.
D21SC/LO	0.955	0.956	0.001	Aerospace Corp.
MH21SC/LO	0.963	0.964	0.001	Aerospace Corp.
MH21SC/LO	0.965	0.965	0	Aerospace Corp.
MH41SCB/LO	0.951	0.950	-0.001	Aerospace Corp.
D36SCB/LO	0.962	0.967	0.005	GSFC
MH41SCB/LO	0.939	0.947	0.008	GSFC
MH21SC/LO	0.951	0.955	0.004	GSFC

All tests at GSFC involved exposure to 1000 ESH of UV and vacuum.

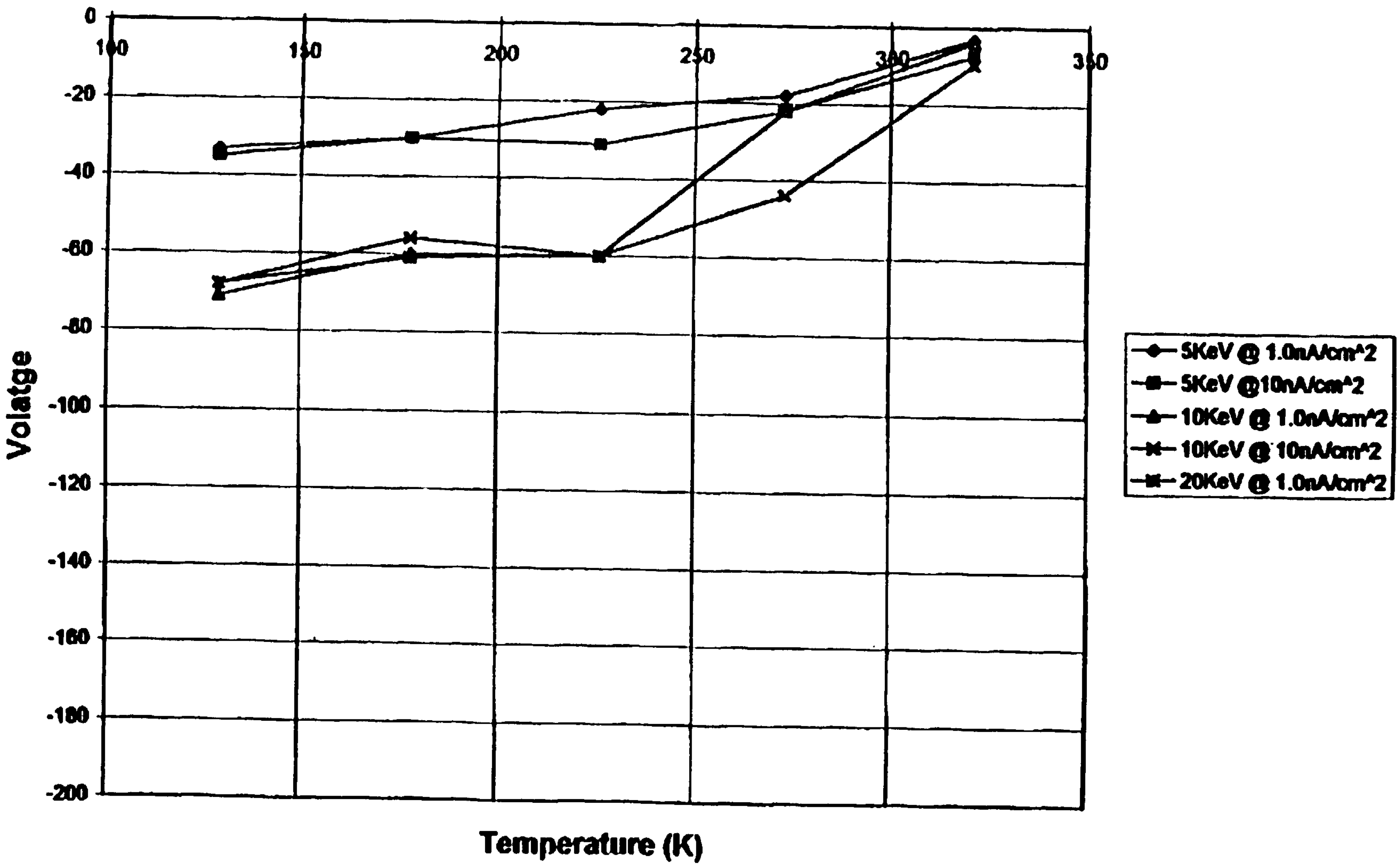
All tests carried out at Aerospace Corporation involved exposure to 2000 ESH of UV + 8.26 x 10^{13} e^-/cm^2 [100 KeV] + 5.18 x 10^{13} e^-/cm^2 [35 KeV] (typical DMSP orbit) and vacuum.

C06804-TB.MD

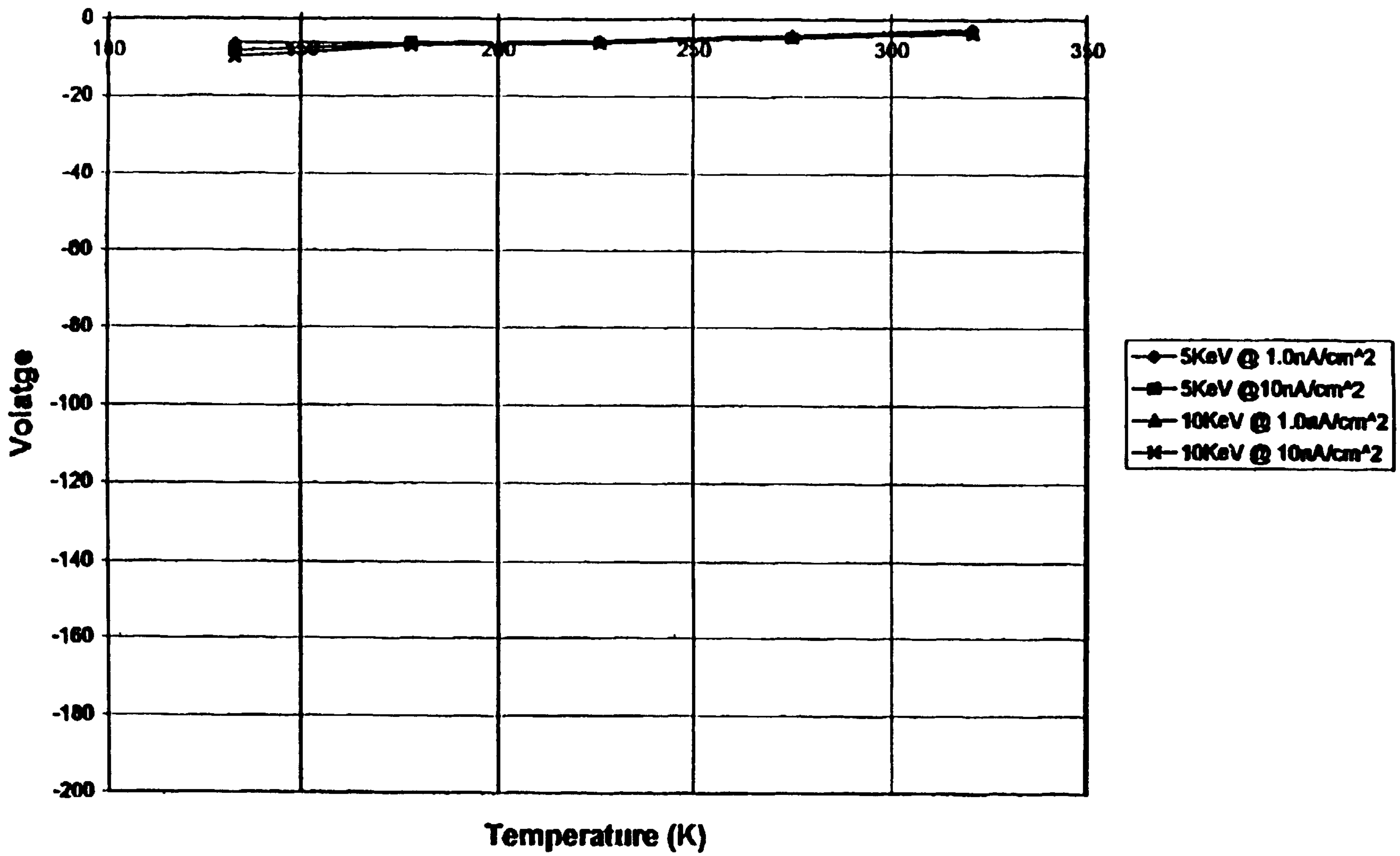

DBG-IP
Volatge
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
100
150
200
250
300
350
Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2
20KeV @ 1.0nA/cm^2


MH41SCB/LO
Voltage
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
100
150
200
250
300
350
Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2
20KeV @ 1.0nA/cm^2

MH55IC


0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Volatge
100
150
200
250
300
350
Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2
20KeV @ 1.0nA/cm^2

D36SCB/LO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Volatge
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300
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Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2

CANDIDATE Z-93CXY COATING PROCESSING ROUTE

A. Adjust Zn interstitial concentration in ZnO matrix to tailor different grain resistivity.

B. Choose process parameters: temperature, time to adjust required morphological details via flash calcination.

C. Choose pigment-to-binder ratios to evaluate electrical, optical, spray, and adhesion properties.

D. Select candidate concepts.

Advantage: Better control, cost effective.

CONDUCTIVE THERMAL CONTROL MATERIAL SYSTEMS

- Z-93SCXY: Z-93C08, Z-93C06, Z-93C55, Z-93C05 treated ZnO/Kasil 2130 (proprietary treatment)

  $\Delta \alpha_s$ - Per IITRI-C207-25 (Z-52/Z-36)

Exposure, ESH	Solar Factor	Reflectance, %	
		440 nm	600 nm
0	-	89.0	95.5
270	3	85.5	94.0

CONDUCTIVE CONCEPT

Z-93CXY: Flash calcined: control of Zn interstitials for required conductivity in silicate binders and doped silicate binders			
ZnO(FC)/2130	ZnO Flash Calcined (FC)	Kasil 2130	5.5
ZnO(FC)/SS-55	ZnO(FC)	SS-55	5.5
ZnO(FC)/DHS-1	ZnO(FC)	DHS-1	5.5
ZnO(FC)/DHS-2	ZnO(FC)	DHS-2	5.5

				Resistivity Ω/□	
Material	Batch No.	Alpha	Emittance	HP4329	HP4339
ZnO(FC)/2130	U-321(HM)	0.14	0.92	1.00E+14	
ZnO(FC)/SS-55	U-322(HF)	0.14	0.91	1.00E+08	6.00E+08
ZnO(FC)/DHS-1	U-323(HG)	0.15	0.92	2.00E+09	2.00E+08
ZnO(FC)/DHS-2	U-327(HL)	0.15	0.91	1.00E+09	1.00E+09

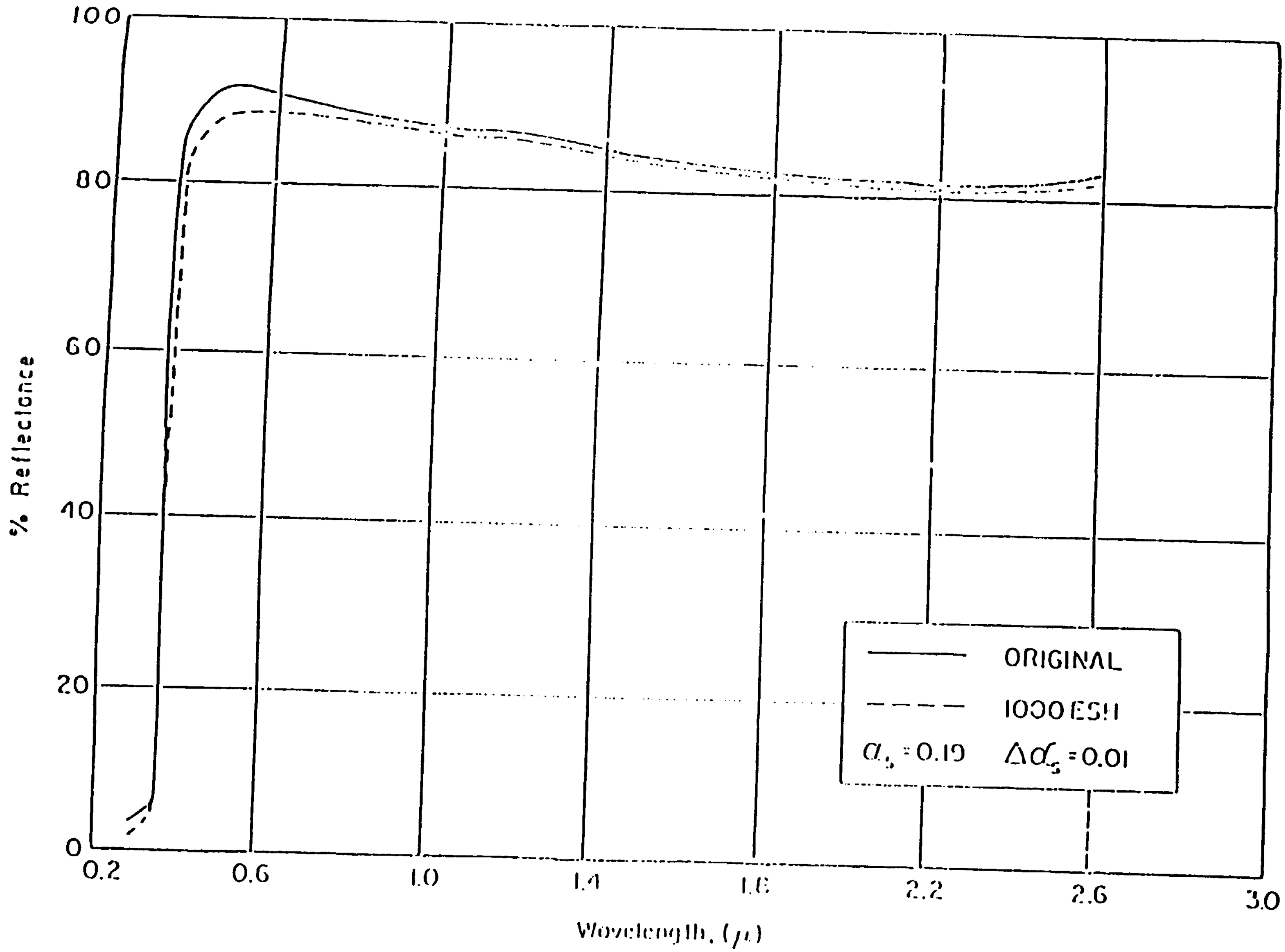
CANDIDATE Z-93SCXY COATING PROCESSING ROUTES

A. Process 50 lb batches of S13GP pigment

B. Assume ZnO/K_2SiO_3 ratio for S13G/S13GP pigment ~ 20

C. Prepare candidate formulation with candidate binder

D. Spray samples for evaluation following Z-93P process specifications

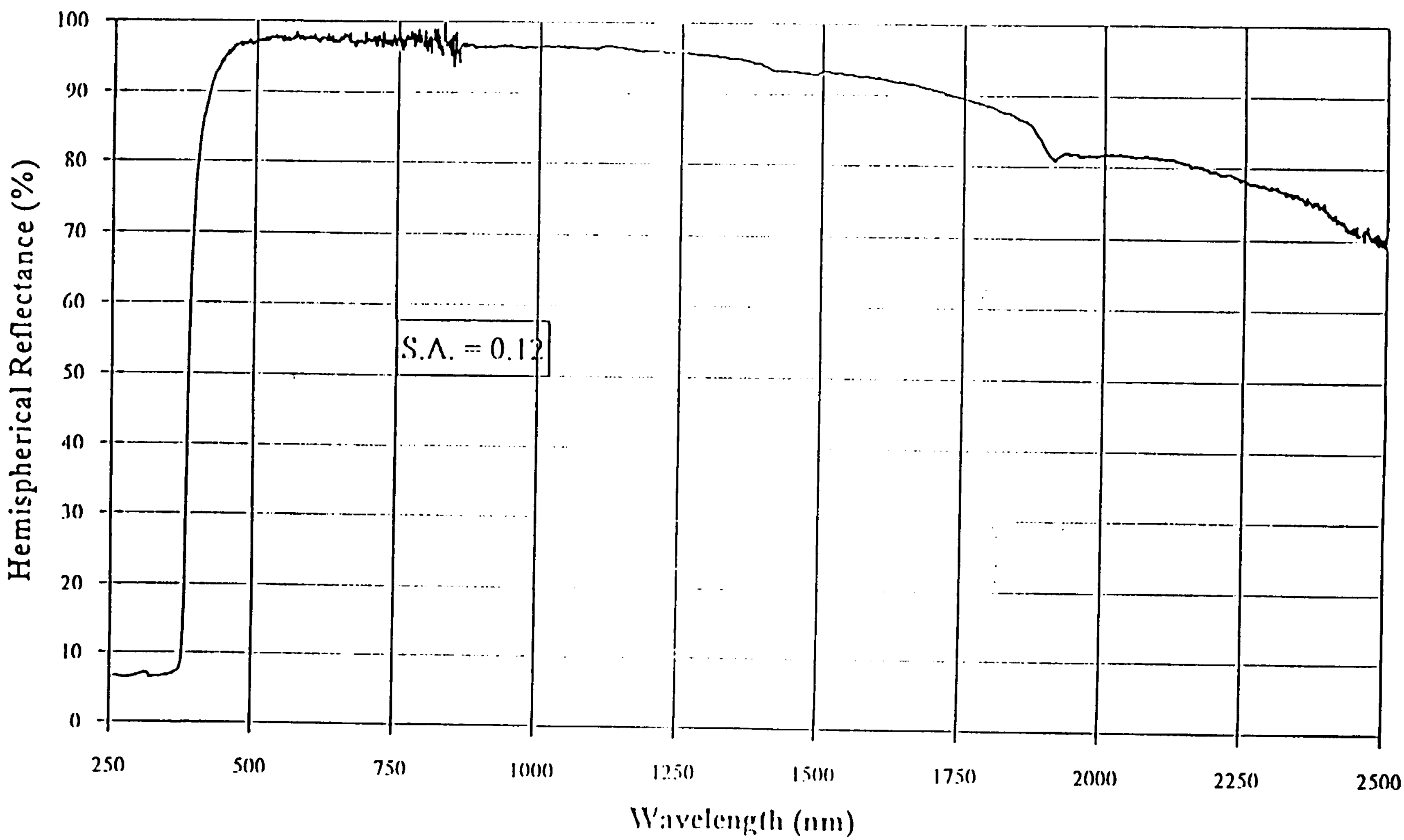


1,000 ESH UV-VAC Stability of Z-93SC55

Use of disclosure of data contained on this sheet is subject to the restriction on the title page of this document.

Z93SCXY: Microencapsulated pigments in silicate binders and doped silicate binders			
S13GP/2130	S13GP	Kasil 2130	5.5
S13GP/SS-55	S13GP	SS-55	5.5
S13GP/DHS-1	S13GP	DHS-1	5.5
S13GP/DHS-2	S13GP	DHS-2	5.5
S13N /SS-55	S13N	SS-55	5.5
S13N/DHS-1	S13N	DHS-1	5.5
S13N/DHS-2	S13N	DHS-2	5.5

Solar Absorptance of Z-93SC55



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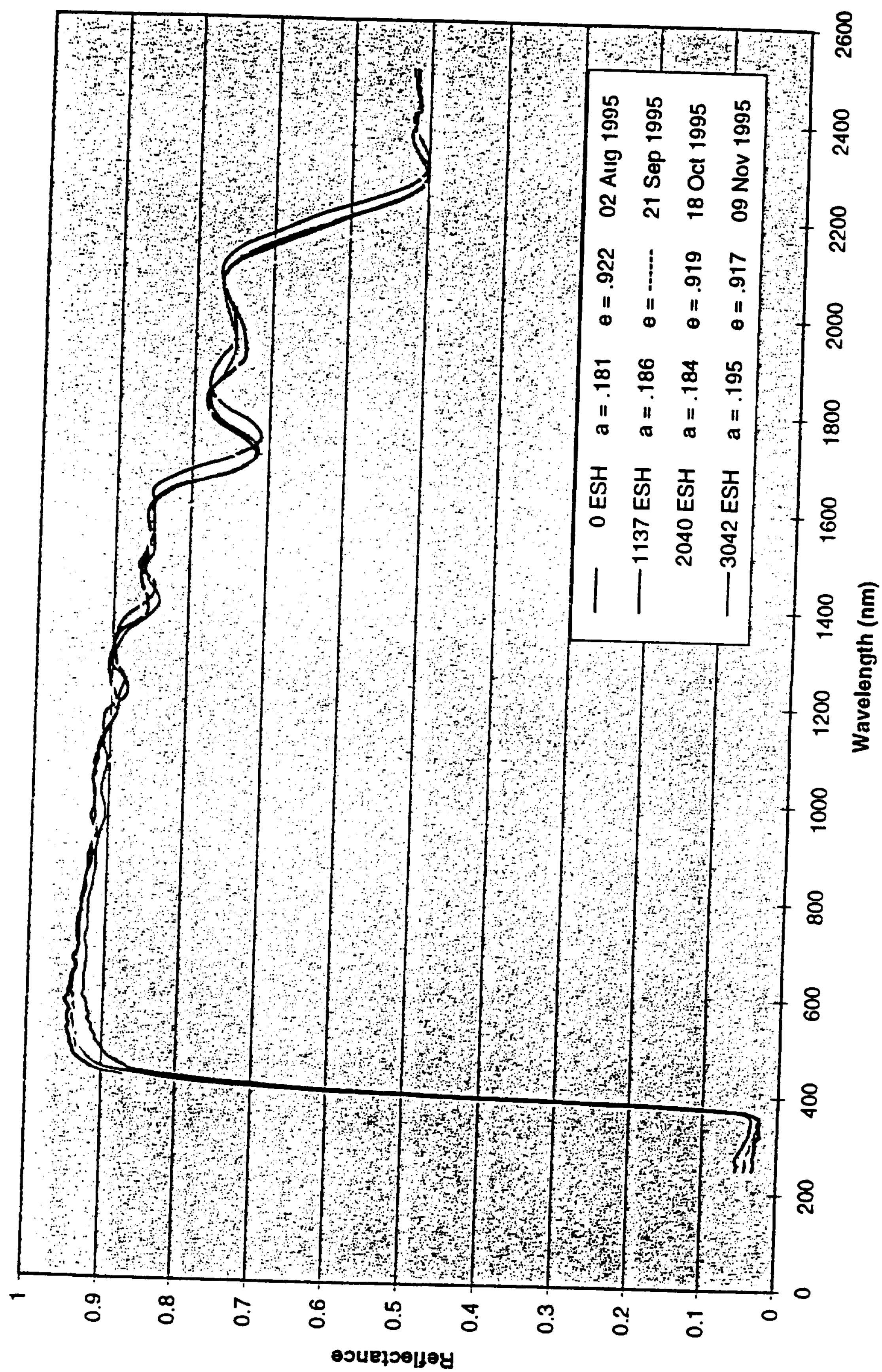
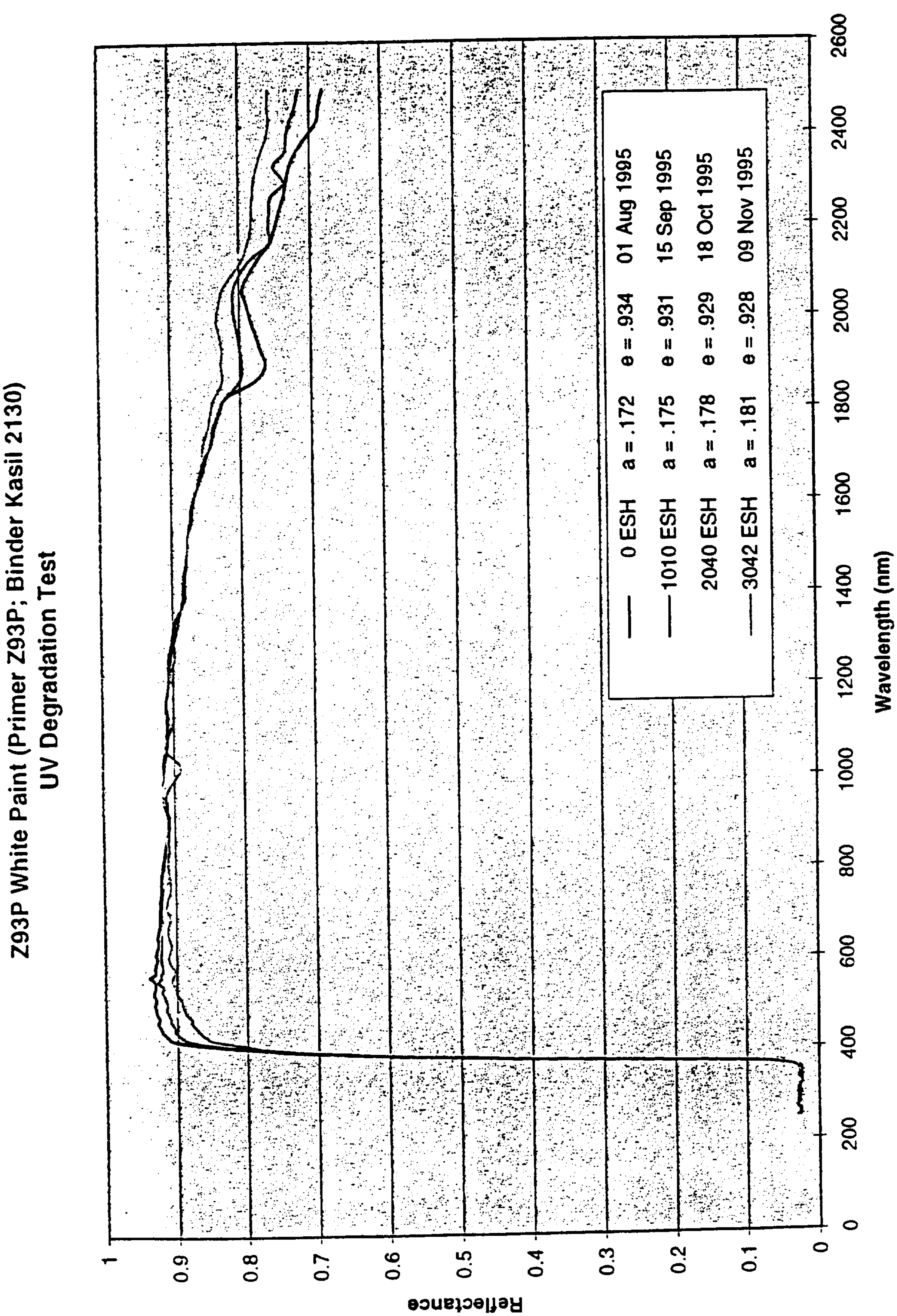
Z-93SCXY

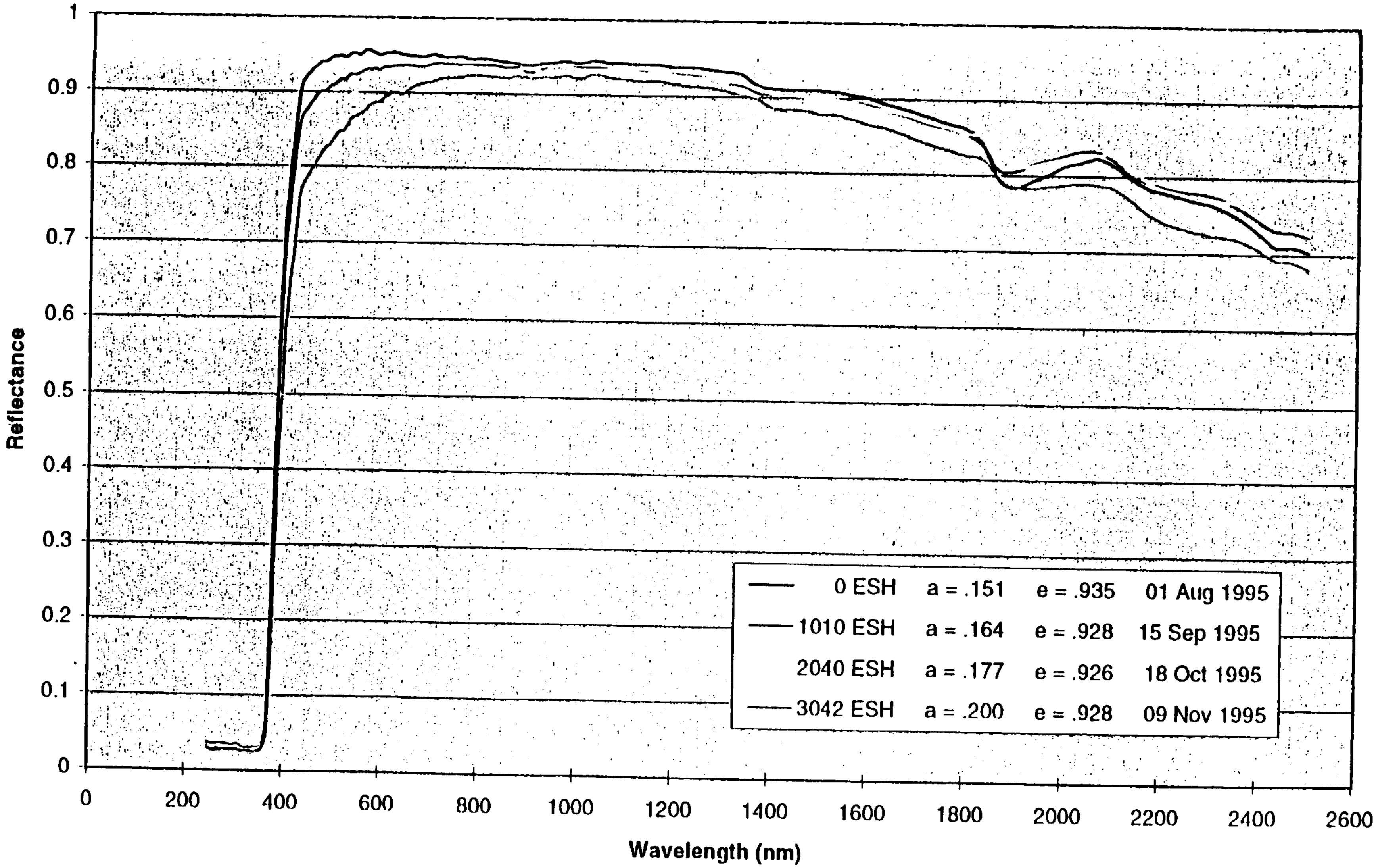
Material	Batch No.	Alpha	Emittance	Resistivity Ω/□	
				HP4329A	HP4339A
S13GP/2130	(FM)	0.13	0.92	1.00E+09	5.00E+09
S13GP/SS-55	U-405(IU)	0.13	0.91	8.00E+09	5.00E+09
S13GP/DHS-1	U-279(GS)	0.14	0.92	8.00E+07	1.00E+09
S13GP/DHS-2	U-328(HH)	0.13	0.92	4.70E+08	1.00E+09
S13N/SS-55	U-260(GR)	0.12	0.90	2.00E+08	1.00E+09
S13N/DHS-1	U-317(HE)	0.14	0.92	4.00E+08	1.00E+09
S13N/DHS-2	U-329(HI)	0.13	0.92	5.60E+08	5.00E+09

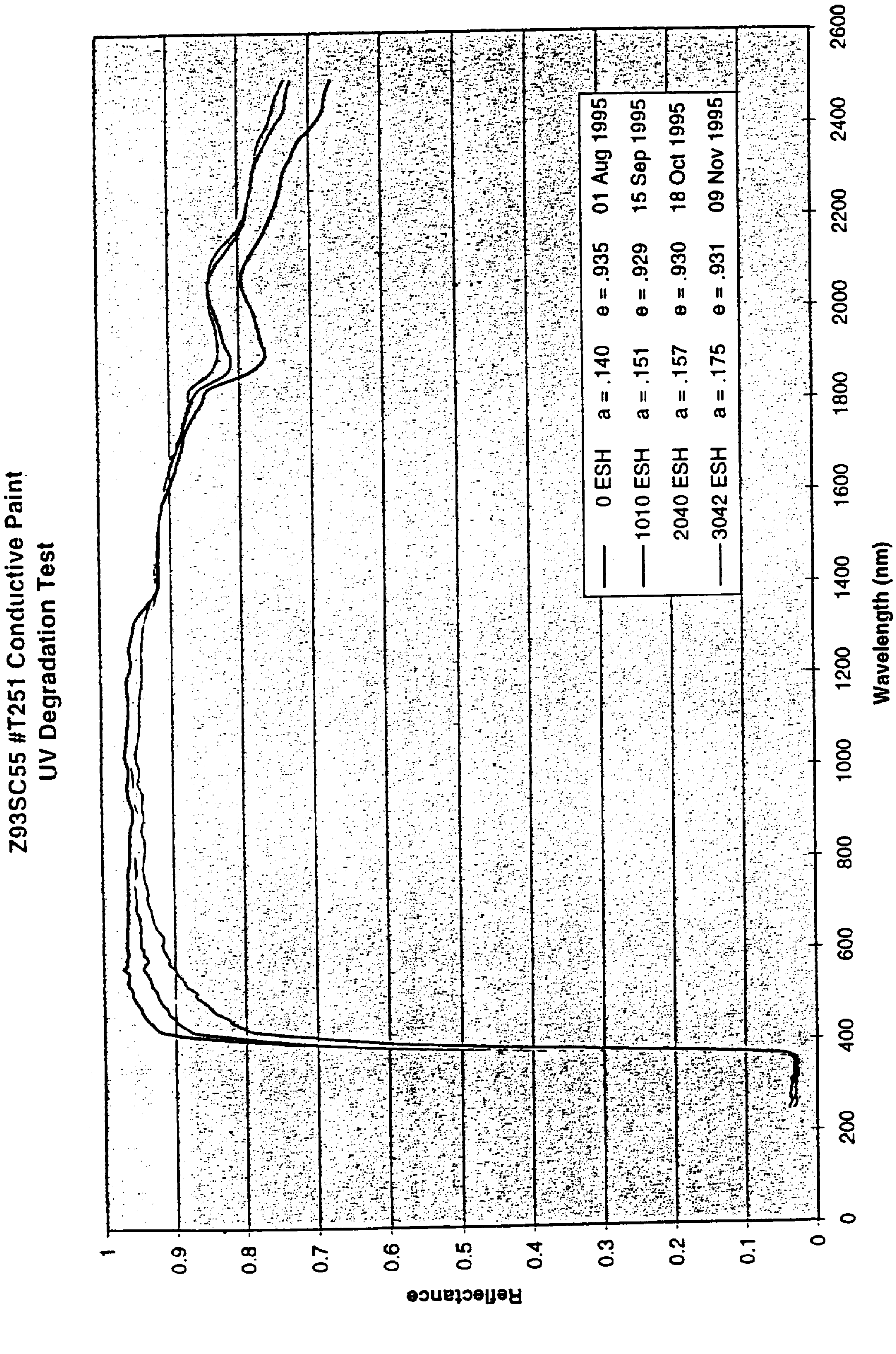
S13GP/LO-1 White Paint (Primer S13GP/LO-1; Binder Kasil 2130)
UV Degradation Test




Z93P White Paint (Primer Z93P; Binder Kasil 2130)
UV Degradation Test
Reflectance
Wavelength (nm)
0 ESH a = .172 e = .934 01 Aug 1995
1010 ESH a = .175 e = .931 15 Sep 1995
2040 ESH a = .178 e = .929 18 Oct 1995
3042 ESH a = .181 e = .928 09 Nov 1995
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600

Z93SC55 #EI-2 Conductive Paint
UV Degradation Test




Z93SC55 #T251 Conductive Paint
UV Degradation Test
Reflectance
Wavelength (nm)
0 ESH a = .140 e = .935 01 Aug 1995
1010 ESH a = .151 e = .929 15 Sep 1995
2040 ESH a = .157 e = .930 18 Oct 1995
3042 ESH a = .175 e = .931 09 Nov 1995
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600

Z-93SCLMXY

Goal: Dope S13GP pigment with indium

High Temp. Doping (DZS)

- Doped (In doped) ZnO containing silicate glass
- High temperature causes Zn_2SiO_4 formation
- Dopant loss was evident
- Resultant dopant level (?)
- Expensive route

LOW TEMPERATURE DOPING OF S13GP PIGMENT

- 900 gm batchers processed
- (SP-500) ZnO reactively encapsulated with Doped SS-55
- In precursor salt need minimized
- Micro encapsulation parameters same as S13GP
- Several batches produced with good consistency

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Z-93SCLMXY

Material	Batch No.	Alpha	Emittance	Resistivity Ω/□ HP4329A	Resistivity Ω/□ HP4339A
DZS/2130	T-244(DK)	0.08	0.93	1.00E+14	
DZS/SS-55	U-207(FO)	0.07	0.90	2.00E+10	1.00E+09
DZS/DHS-1	U-278(GQ)	0.07	0.93	6.00E+07	2.00E+08
DZS/DHS-2	U-331(HK)	0.07	0.93	1.00E+08	7.00E+08
DS13N/SS-55	U-315(P)	0.13	0.92	9.00E+08	1.00E+08
DS13N/DHS-1	U-316(S)	0.12	0.93	2.00E+08	6.00E+08
DS13N/DHS-2	U-330(HJ)	0.13	0.93	3.00E+08	1.00E+09

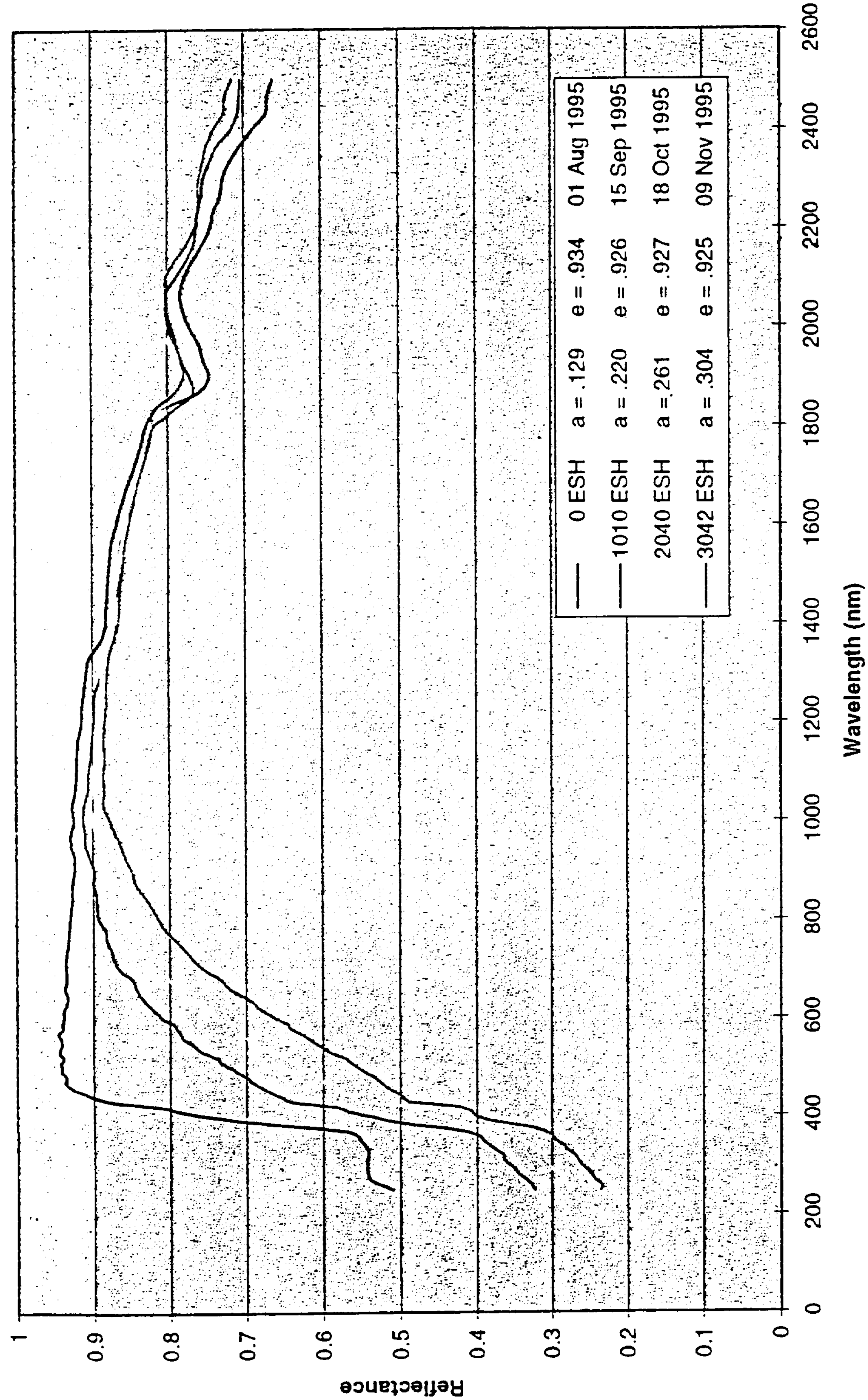
Z-93SCLMXY: Doped zinc silicate (high temperature doping) in silicate binders and doped silicate binders; and doped microencapsulated pigments (low temperature doping) in silicate binders and doped silicate binders.

DZS /2130	DZS	Kasil 2130	5.5
DZS/SS-55	DZS	SS-55	5.5
DZS/DHS-1	DZS	DHS-1	5.5
DZS/DHS-2	DZS	DHS-2	5.5
DS13N /SS-55	DS13N	SS-55	5.5
DS13N/DHS-1	DS13N	DHS-1	5.5
DS13N/DHS-2	DS13N	DHS-1	5.5

95QV01 USAF WL/MLBT SCEPTRE TEST OF IITRI EXPERIMENTAL MATERIALS

	Pretest-in-air (PRIA)	Posttest-in-air (POIA)	Change in Solar Absorptance
Z-93SC1655 (batch T-244) DK-12 (2.2 EUVS)	0.082	0.321	0.239
Z-93SC1655 (batch T-344) EM-11 (2.3 EUVS)	0.103	0.306	0.203

Z93SC1655 #EK-20 Conductive Paint
UV Degradation Test



OTHER WHITE CONDUCTIVE COATINGS
IR&D: C44007C003

PIGMENT DEVELOPMENT

- Sb: Doped Zn_2SnO_4
- Eu_2O_3 (Process per AFML-TR-71-246)

BINDER FOR ZOT

- Phos. Sol.

Other White Conductive Coatings:			
ZOT/Phos sol	ZOT # 98790	Phos sol	5.5
ZOT/SS-55	ZOT # 98790	SS-55	5.5
ZOT/DHS-2	ZOT # 98790	DHS-2	5.5
Eu_2O_3/SS-55	Eu_2O_3	SS-55	5.5
Eu_2O_3/DHS-2	Eu_2O_3	SS-55	5.5
Ta_2O_5 /2130 (RT cured)	Ta_2O_5	2130	5.5
Ta_2O_5/SS-55 (RT cured)	Ta_2O_5	SS-55	5.5
Ta_2O_5/2130 (HT cured)	Ta_2O_5	2130	5.5
Ta_2O_5/SS-55 (HT cured)	Ta_2O_5	SS-55	5.5
Composite White Conductive Coating:			
Sb Doped	ZnO + Sb doped Zn_2SnO_4	2130	5.5

Other White Conductive Coatings:			
ZOT/Phos sol	ZOT # 98790	Phos sol	5.5
ZOT/SS-55	ZOT # 98790	SS-55	5.5
ZOT/DHS-2	ZOT # 98790	DHS-2	5.5
Eu_2O_3/SS-55	Eu_2O_3	SS-55	5.5
Eu_2O_3/DHS-2	Eu_2O_3	SS-55	5.5
Ta_2O_5 /2130 (RT cured)	Ta_2O_5	2130	5.5
Ta_2O_5/SS-55 (RT cured)	Ta_2O_5	SS-55	5.5
Ta_2O_5/2130 (HT cured)	Ta_2O_5	2130	5.5
Ta_2O_5/SS-55 (HT cured)	Ta_2O_5	SS-55	5.5
Composite White Conductive Coating:			
Sb Doped	ZnO + Sb doped Zn_2SnO_4	2130	5.5

OTHER WHITE CONDUCTIVE COATINGS

Material	Batch No.	Alpha	Emittance	Resistivity Ω/□ HP4329A	Resistivity Ω/□ HP4339A
ZOT/SS-55	U-379(IN)	0.12	0.87	2.10E+08	8.90E+08
ZOT/DHS-2	U-378(IO)	0.13	0.88	2.40E+08	2.20E+09
Eu203*/SS-55	U-353(ID)	0.07	0.92	8.50E+09	1.50E+09
Eu203*/DHS-2	U-381(II)	0.08	0.91	2.10E+07	1.50E+09
ZOT/Phos. Sol.	U-377(HT)	0.14	0.89	1.40E+11	5.00E+09
Ta205*/2130 (RT Cure)	U-358(IG)	0.18	0.90	1.70E+09	4.30E+09
Ta205*/SS-55 (RT Cure)	U-359(IH)	0.17	0.88	5.60E+09	2.20E+09
Ta205*/2130 (HT Cure)	U-358(IG)	0.16	0.90	3.00E+09	3.00E+09
Ta205*/SS-55 (HT Cure)	U-359(IH)	0.15	0.88	1.60E+10	5.00E+09
Composite CTG White Conductive Concept					
Sb Doped	U-252(GE)	0.13	0.90	8.50E+10	1.50E+09

FLEXIBLE WHITE CONDUCTIVE COATING

Flexible White Conductive Coating:			
DS13NSC/LO-41	DS13N	MHS/LO stripped polydimethyl siloxane	4.0
Composite Flex. Ctg.	DS13N+Sb:Zn_2SnO_4	MHS/LO stripped polydimethyl siloxane	4.0

Material	Batch No.	Alpha	Emittance	Resistivity Ω/□	
				HP4329A	HP4339A
DS13NSC/LO-51 41 (5 mils)	U-334(HV)	0.16	0.91	NA	3.00E+10
Composite Flex.	U-489	0.18	0.91	NA	2.00E+10

Typical Performance of Promising Conductive White Thermal Control Coatings in Low Earth Orbit (LEO)				
Material	**Pre-exposure α_S**	**Post-exposure α_S**	**$\Delta\alpha$**	**Tested By**
Concept: **Z-93CXY** - Flash calcination of ZnO (SP-500) to retain controlled Zn interstitials, and stabilization with doped hybrid, silicate binder.				
ZnO(FC)/DHS-2	0.139	0.141	0.002	Aerospace Corp.
ZnO(FC)/DHS-2	0.146	0.146	0.000	Aerospace Corp.
ZnO(FC)/DHS-2	0.158	0.168	0.010	GSFC*
Concept: **Z-93SC55** - Stabilization of Zn interstitials via microencapsulation and incorporation in hybrid silicate and doped hybride silicate binders.				
S13GP/DHS-1	0.147	0.153	0.006	Aerospace Corp.
S13/GP/DHS-1	0.142	0.148	0.006	Aerospace Corp.
S13GP/SS-55	0.125	0.140	0.015	Aerospace Corp.
S13GP/SS-55	0.127	0.137	0.010	Aerospace Corp.
S13GP/SS-55	0.140	0.177	0.037	GSFC**
S13GP/SS-55	0.151	0.206	0.055	GSFC**
Concept: **Z-93SCLMXY** - Stabilization of Zn interstitials via microencapsulation using doped hybrid silicate binder and incorporation in hybrid silicate binder or doped hybrid silicate binder.				
DS13N/SS-55	0.136	0.173	0.035	Aerospace Corp.
DS13N/SS-55	0.137	0.153	0.016	Aerospace Corp.
DS13N/DHS-2	0.124	0.161	0.037	Aerospace Corp.
DS13N/DHS-2	0.122	0.128	0.006	Aerospace Corp.
DS13N/DHS-2	0.148	0.154	0.006	GSFC*

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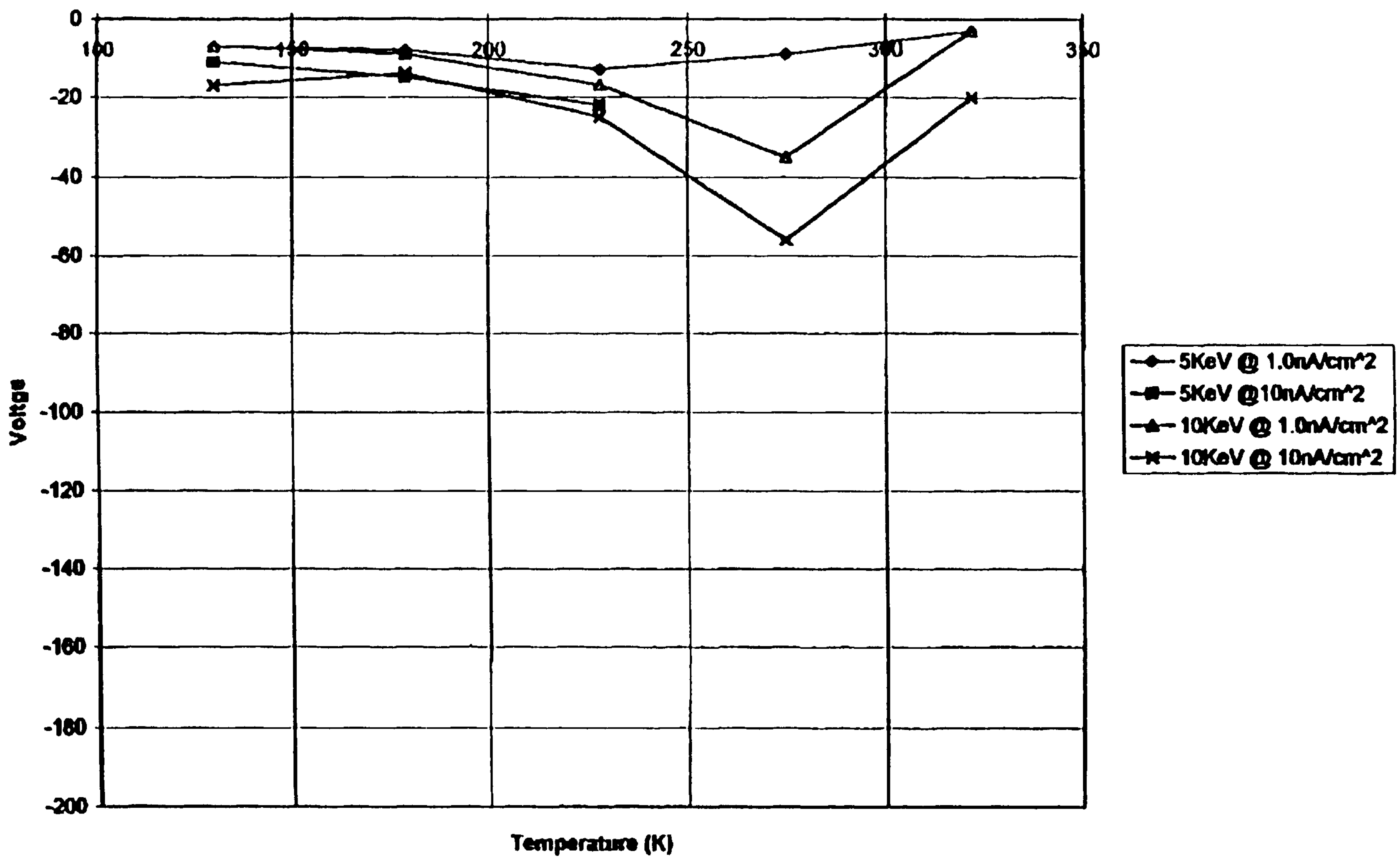
Page 1

Typical Performance of Promising Conductive White Thermal Control Coatings in Low Earth Orbit (LEO)				
Material	**Pre-exposure α_S**	**Post-exposure α_S**	**$\Delta\alpha$**	**Tested By**
Concept: Flexible conductive white TCC with DS13N in stripped silicone.				
DS13N/LO-41	0.161	0.278	0.117	Aerospace Corp.
DS13N/LO-41	0.163	0.239	0.076	Aerospace Corp.
DS13N/LO-41	0.210	0.430	0.22	GSFC*
Conductive Concepts with Other Pigments:				
ZOT/Phos. Sol.	0.131	0.149	0.018	Aerospace Corp.
ZOT/Phos. Sol.	0.128	0.151	0.023	Aerospace Corp.
ZOT/SS-55	0.117	0.156	0.039	Aerospace Corp.
ZOT/SS-55	0.112	0.156	0.044	Aerospace Corp.
ZOT/SS-55	0.129	0.180	0.051	GSFC
Eu_2O_3/SS-55	0.087	0.138	0.051	Aerospace Corp.
Eu_2O_3/SS-55	0.100	0.126	0.028	Aerospace Corp.
Eu_2O_3/DHS-2	0.093	0.158	0.065	Aerospace Corp.
Eu_2O_3/DHS-2	0.076	0.108	0.032	Aerospace Corp.
Eu_2O_3/SS-55	0.096	0.129	0.033	GSFC*

* GSFC test involves exposure to 1000 ESH of UV.
** This GSFC test involves exposure to 4000 ESH of UV.

All tests carried out at Aerospace Corporation involves exposure to (2000 ESH of UV + 8.26 x 10^{13} e^-/cm^2 [100 KeV] + 5.18 x 10^{13} e^-/cm^2 [35 KeV]) typical DMSP orbit.

ZnO(CF)DHS-2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-180
-200
Voltage
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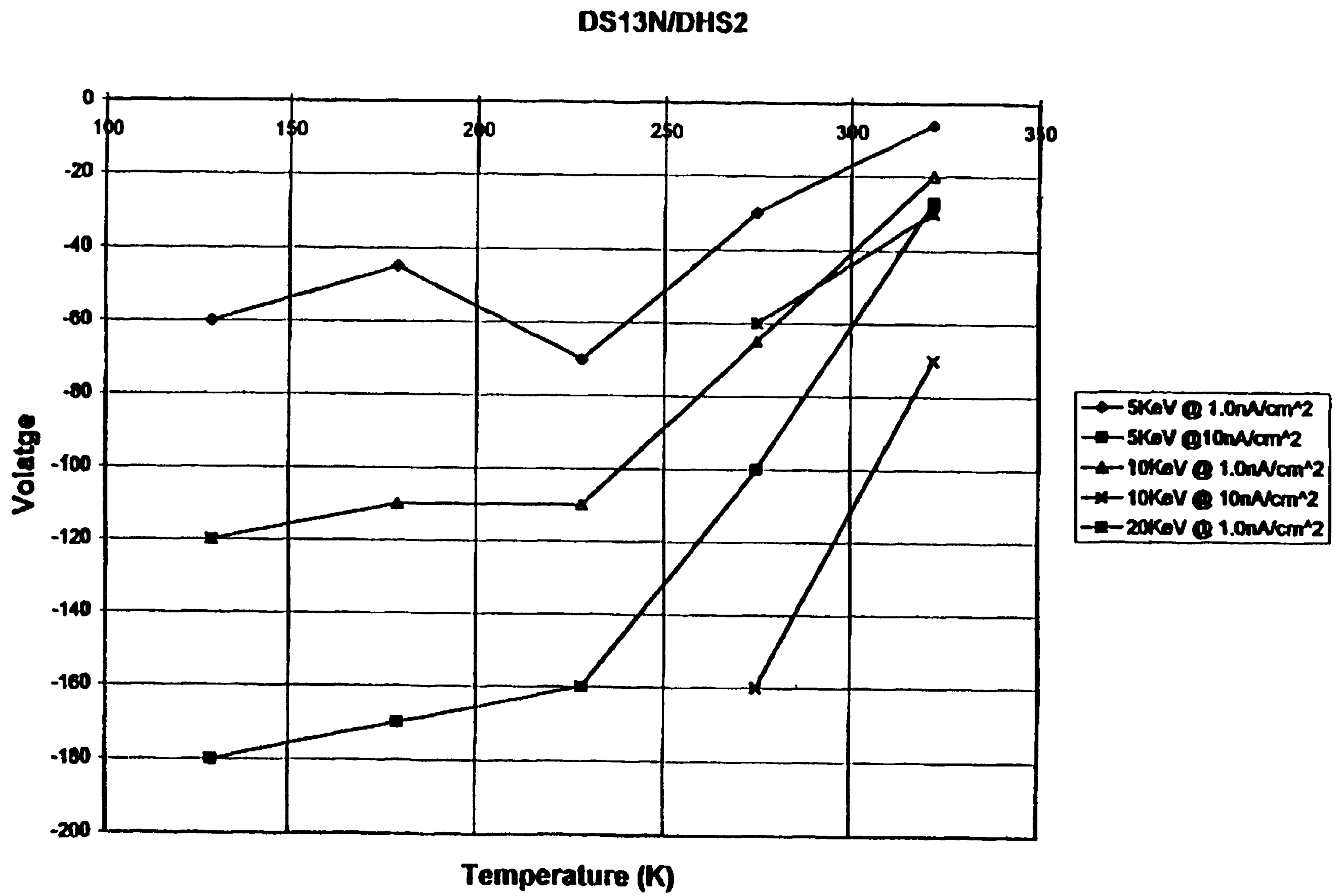
250
300
350
Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2


DS13N/DHS2
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-200
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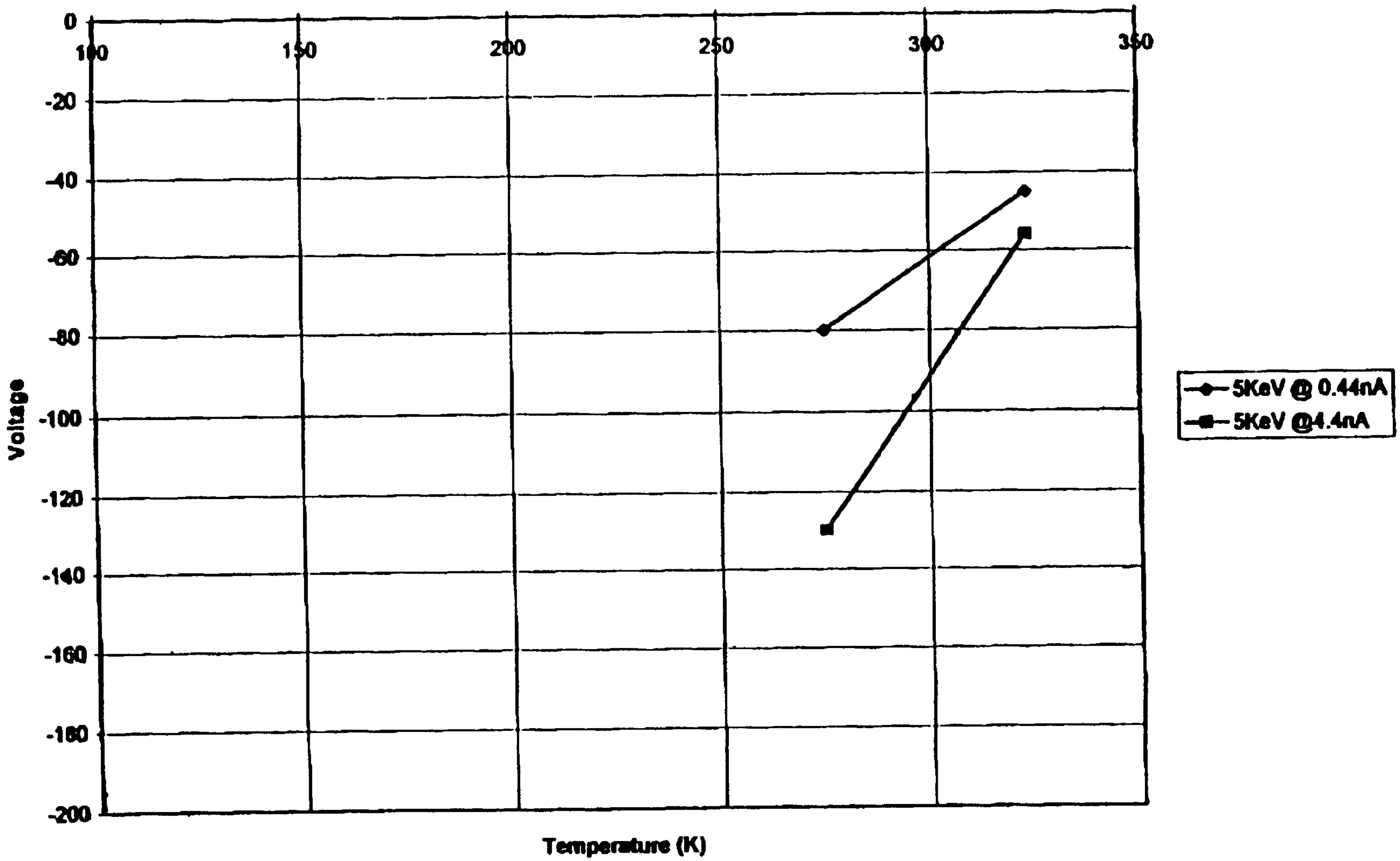
Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2
20KeV @ 1.0nA/cm^2

S13N/DHS-2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Voltage
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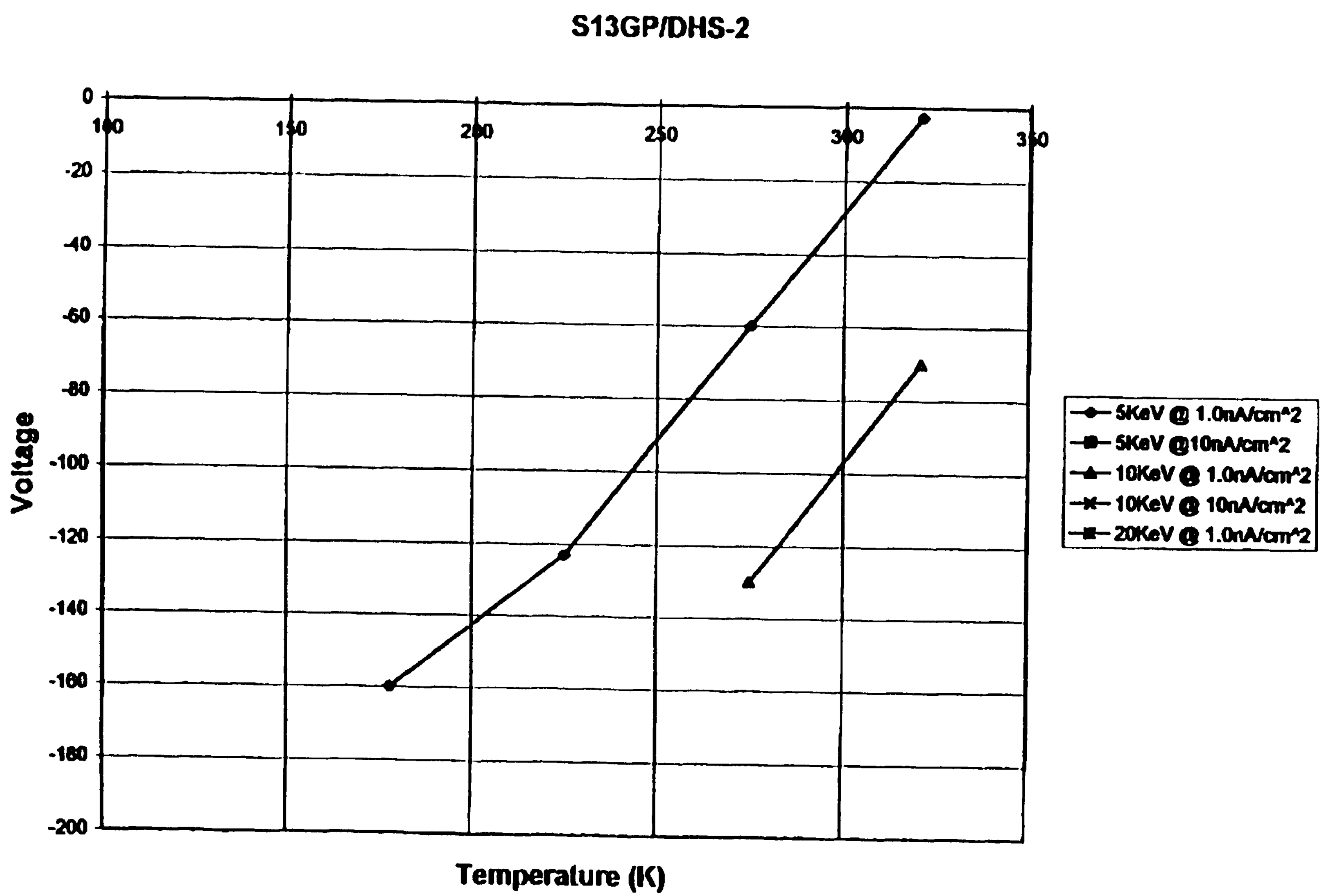
350
Temperature (K)
5KeV @ 0.44nA
5KeV @4.4nA


S13GP/DHS-2
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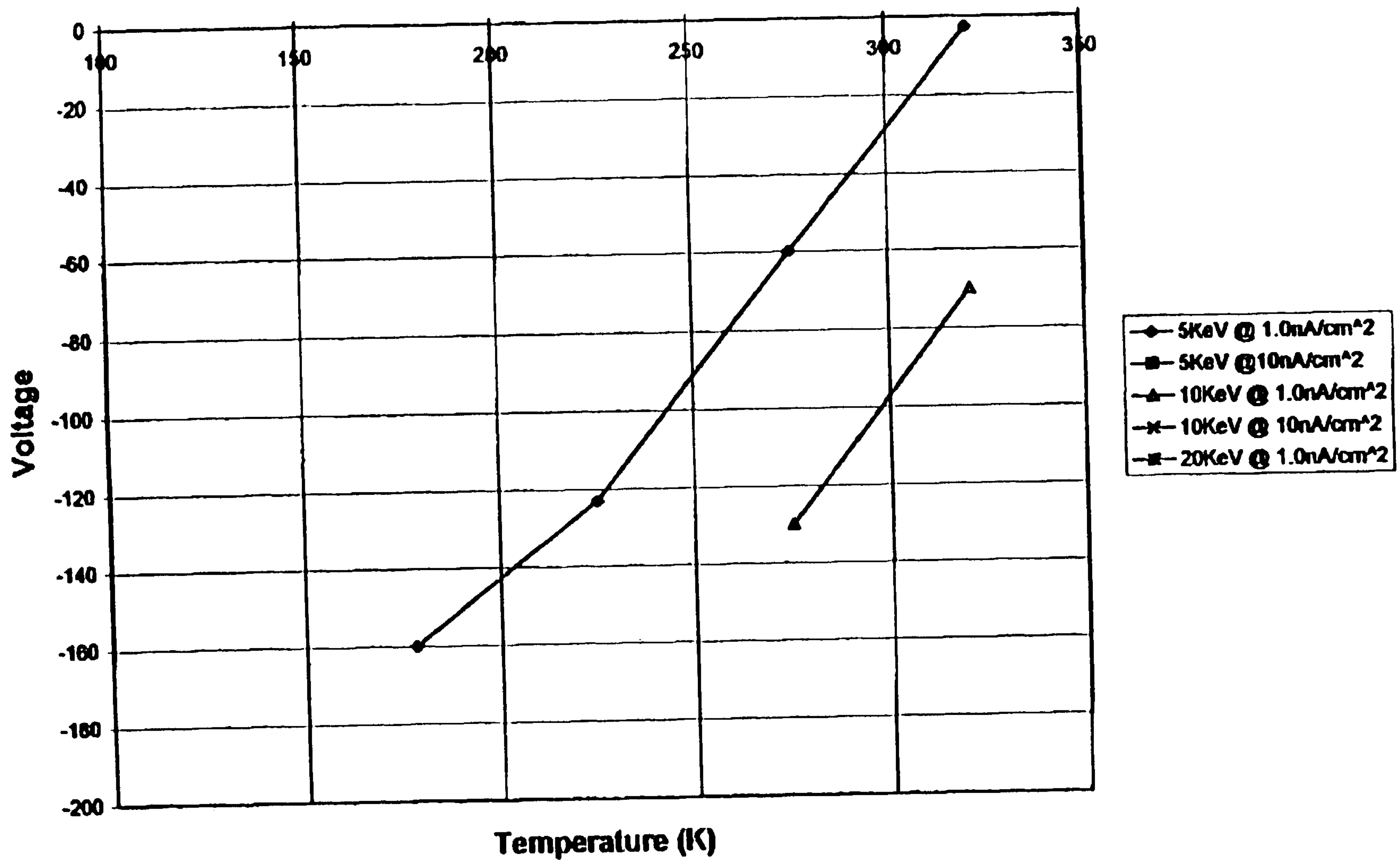
-100
-120
-140
-160
-180
-200
Voltage
100
150
200
250
300
350
Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2
20KeV @ 1.0nA/cm^2

S13GP/DHS-2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100
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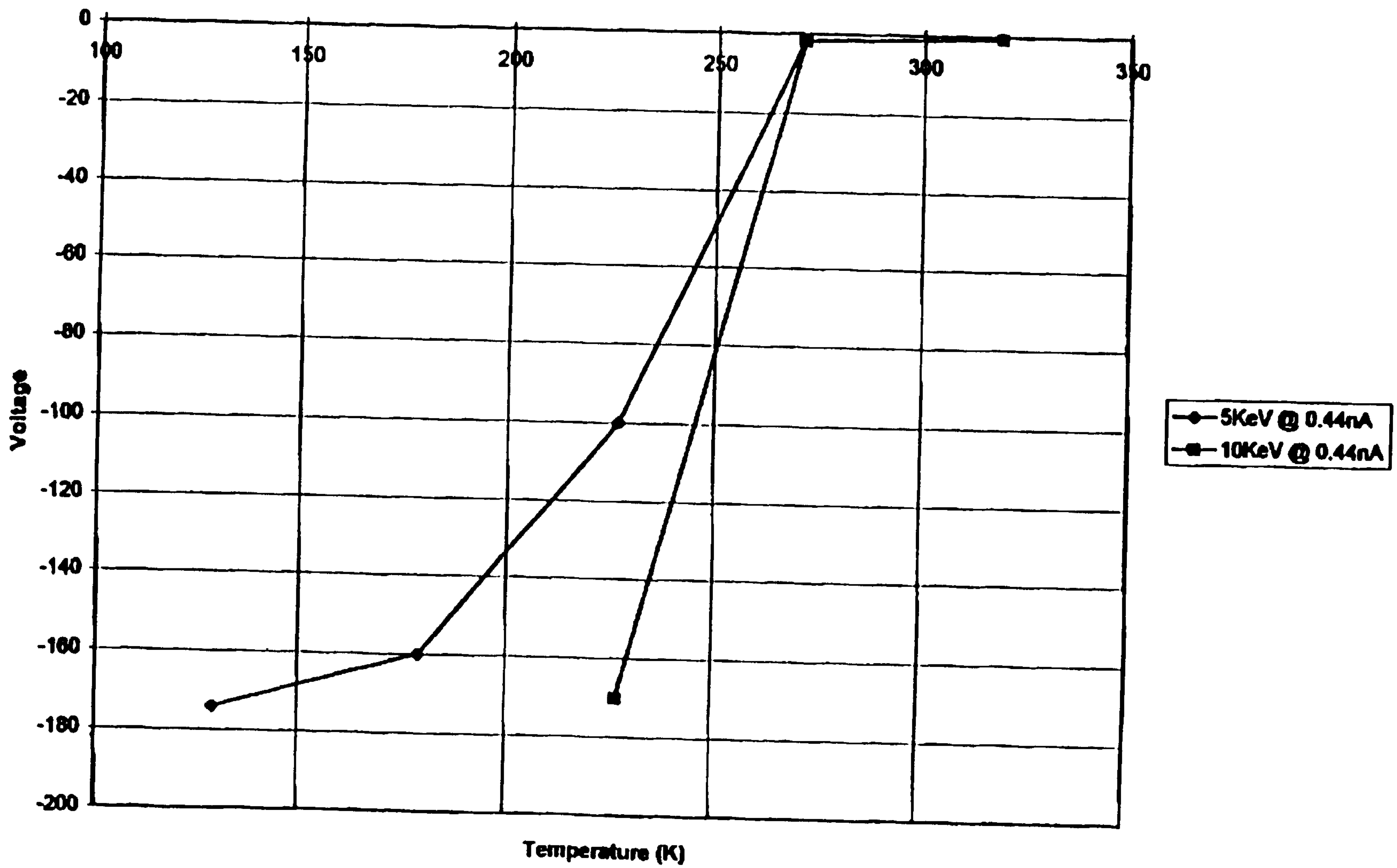
250
300
350
Temperature (K)
5KeV @ 1.0nA/cm^2
5KeV @10nA/cm^2
10KeV @ 1.0nA/cm^2
10KeV @ 10nA/cm^2
20KeV @ 1.0nA/cm^2

ZOT/SS-55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-140
-160
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Voltage
100
150
200
250
300
350
Temperature (K)
5KeV @ 0.44nA
10KeV @ 0.44nA

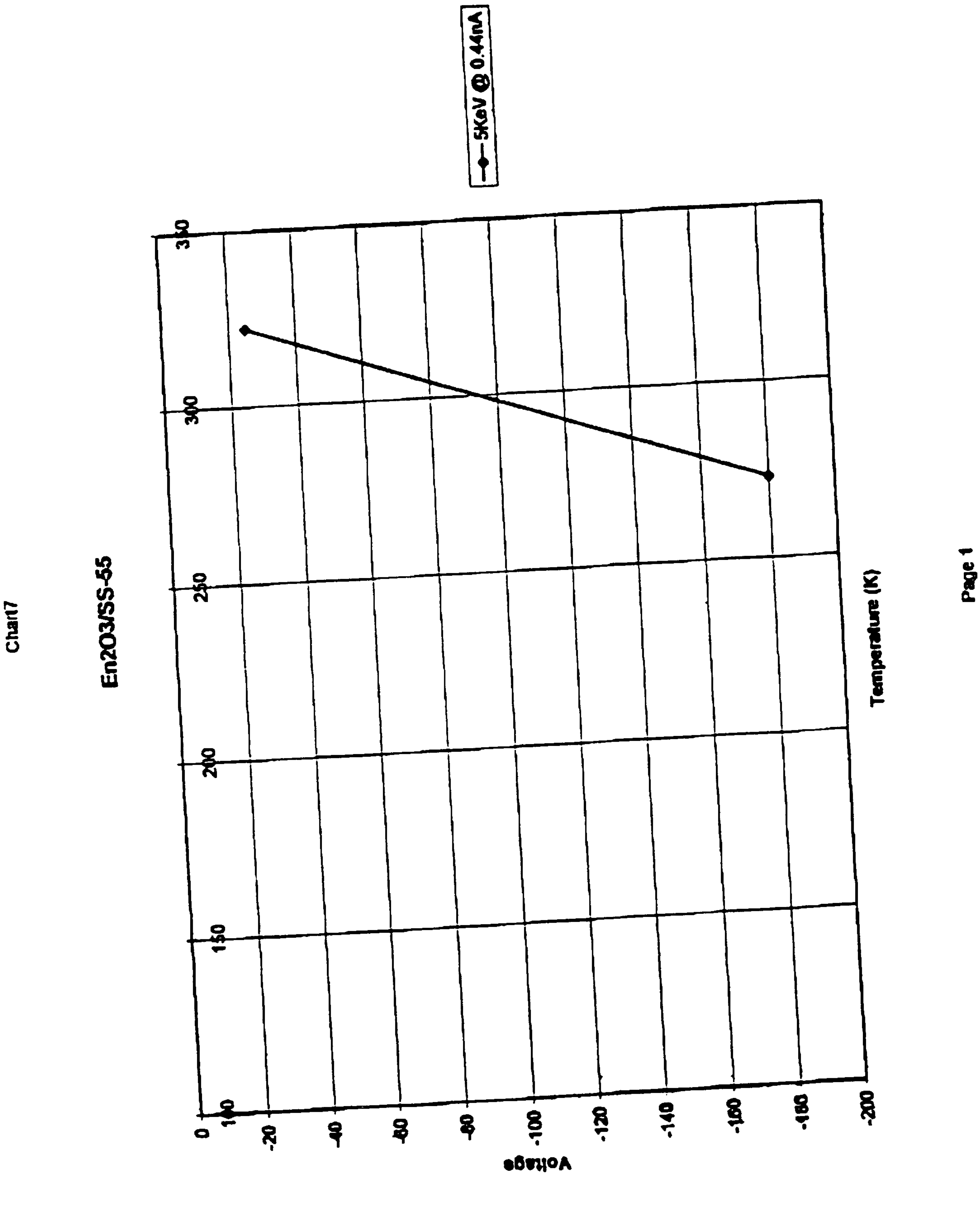


Chart7
En2O3/SS-55
5KeV @ 0.44nA
Voltage
Temperature (K)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
100
150
200
250
300
350
Page 1

FUTURE

- Screening studies have pointed out 18 best candidate coatings for further scale-up, optimization.
- Conductivity needs of each component are different. We urge designers to contact IITRI to integrate these coatings on hardware.
- Further efforts should address scale-up, batch-to-batch variation with testing and characterization.
- Characterizing coating response to all SCATHA energies is not part of the program.

CLOSURE

- Program goals to formulate conductive thermal control for Task A and Task B have been accomplished

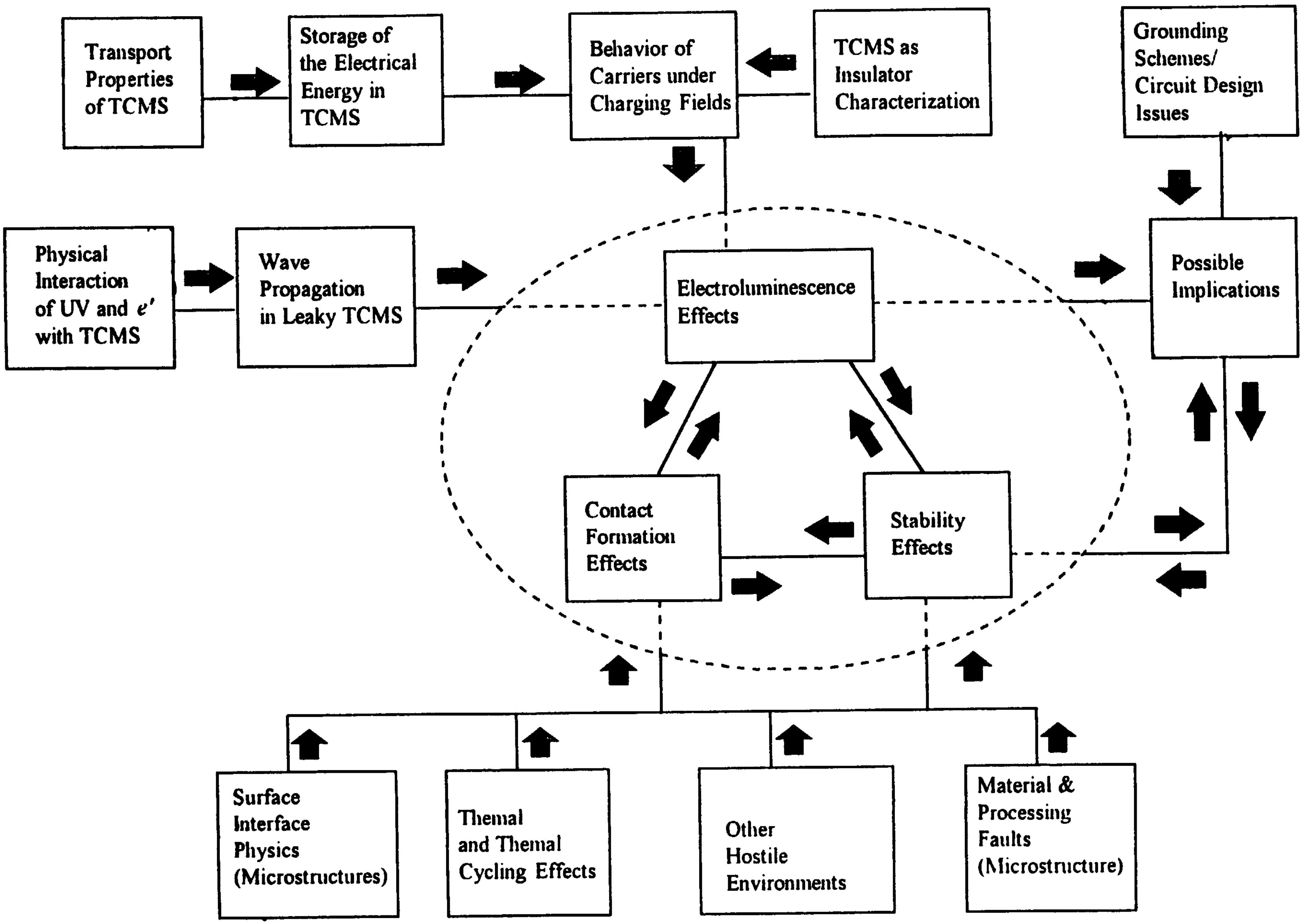
- Space environment simulation/screening studies have been completed and identifies required formulation for scale-up and future studies to integrate them on hardware.

- Results to date indicate Z93CXY (ZnO(FC)/DHS-2) and Z-93SCXY (S13GP/DHS-2), (DS13N/DHS-2) as stable white conductive coating that meet program goals.

- High temperature doping does not contribute to space environment stability.

FUTURE (continued)

- Further flight experiments devoted to the selected concept is a must.
- Hardware designers/users may need to balance RF losses and charging based on selected concept.



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"AO -VUV Resistant TOR and COR Polymers For Space Applications"

"1997 Spacecraft Contamination and Coatings Workshop"

Annapolis, Maryland

Sponsored by GSFC and SEE Program, MSFC

July 10, 1997

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Chelmsford, MA 01824

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James Zweiner, Jason Vaughn, MSFC

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TRITON SYSTEMS, INC.

Develops and Commercializes Materials & Process Technologies in:

- Advanced Polymers and Polymer Composites
- Metal Matrix Composites,
- Ceramic Matrix Composites
- Scratch Resistant/Antireflective Coatings

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TOR and COR Polymers
AO-UV Resistant For Space and Ground Applications

- Basic TOR - COR Properties
- Kapton & FEP in AO - VUV Space Testing
- TOR - Kapton and COR - FEP in AO-VUV Ground Testing
- TOR and COR α and ε for SSMs in MLIs
- Conductive C-COR
- TOR for Inflatables, FSAs, MLIs, Thread, Wire insulation, Tethers
- TOR Composites for LOX Storage
- Scale-up and Device Testing

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TOR and COR

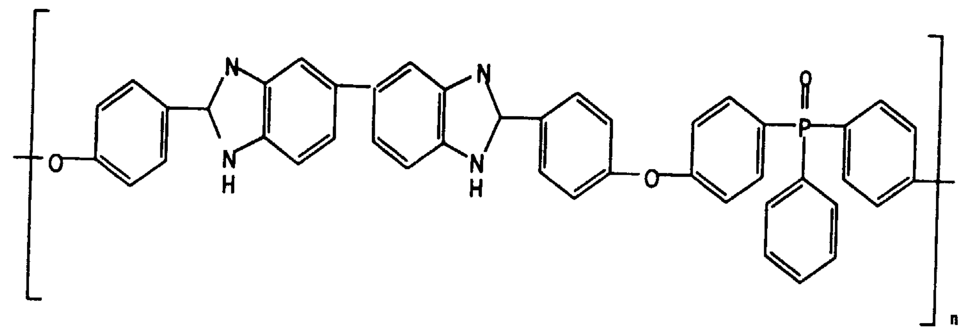
Poly-Arylene Ether (PAE) - Phosphene Oxides

- **TOR - Kapton - like in color, α, ε, Tg**
  - A polybenzimidazole (PAEBI)
  - 10-fold more AO-VUV-resistant than Kapton in Ground Testing
  - Comparable in strength, α, ε, Tg, compared to Kapton
  - NASA Patents are Licensed to Triton Systems
  - Scale-up, Cost Reduction, improved TOR-LM in progress

- **COR - Teflon - like in Color, α, ε,**
  - A Colorless transparent PAE
  - 2-10 - fold more AO-VUV-resistant than FEP in Ground Testing
  - Higher strength , modulus, Tg, compared to FEP
  - lighter than FEP ($\rho = 1.4$ compared to 2.15)
  - New Conductive C-COR in Development
  - Scale-up and Cost Reduction in progress

Triton TOR and COR Polymers

- TOR = PAEBI



- COR - A colorles polyarylene ether (PAE) - phosphene oxide

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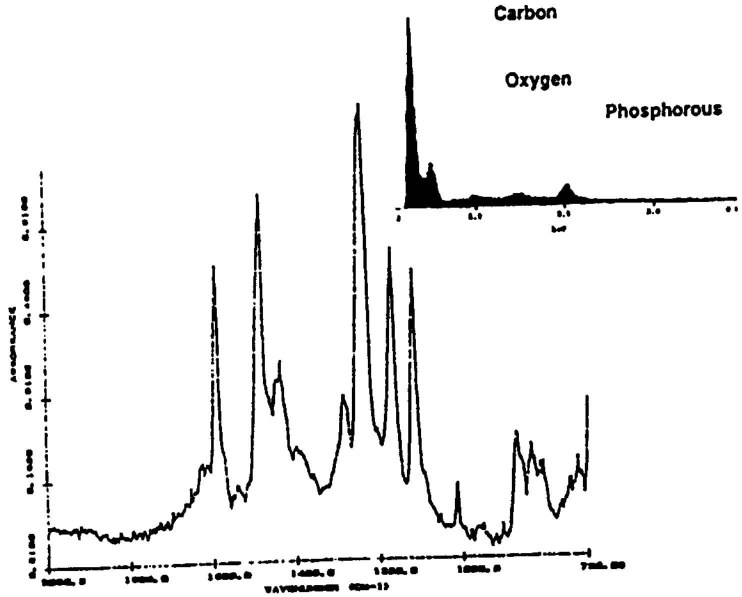
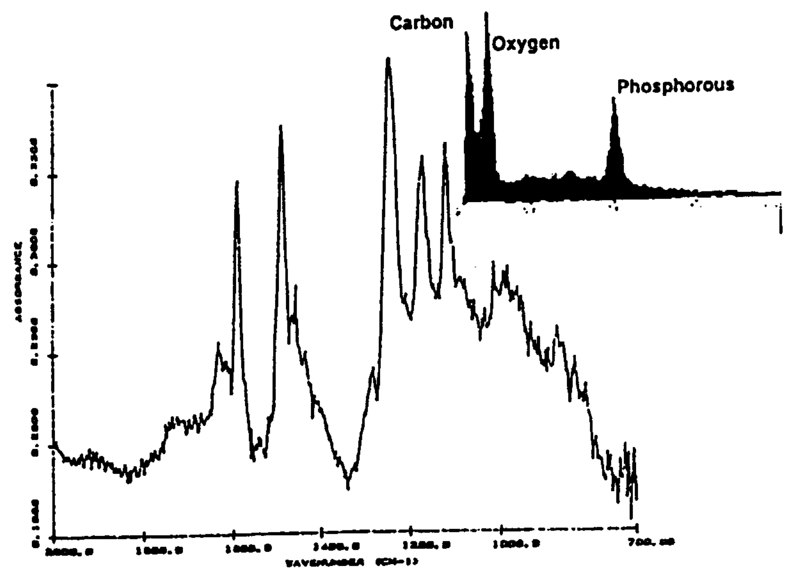
TOR and COR Polymers
AO - UV Resistance based in Phosphene Oxide

FTIR and EDS Spectra of TOR





Before AO

After AO

FTIR and EDS Spectra of TOR

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Comparative Properties of TOR and COR with Kapton™ and FEP Teflon™

	TOR	TOR-LM	Kapton™	COR	Teflon(FEP)™
Tg °(C)	370	320	340	280	260
Density (g/cc)	1.4	1.4	1.4	1.4	2.2
Tensile Strength (Ksi)	20	17	34	9	3.5
Modulus (Ksi)	500	280	370	300	80
Elongation (%)	8 %	10 %	70 %	10 %	200-300 %

Background on Triton AO-VUV Ground Testing
Definitions for AO and VUV Testing

AO Flux (AO/cm2-sec)	= AO atoms per area - time
AO Fluence (AO/cm2)	= Flux x t (sec)
	= AO atoms per area - time integrated
VUV Flux (ES)	= Eqivalent Suns
VUV Fluence (ESH)	= ES x t(hours)
	= Equivalent Sun Hours
Re (cc/AO)= Reactivity	= ccof sample eroded per AO
	= cm of sample eroded per Fluence (AO/cm2)
	= Δg / [d(g/cc) A(cm2) Fluence (AO/cm2)
EY(g/AO)= Erosion yield	= g of sample eroded per AO
EY(g/AO)	= R(cc/AO) x d(g/cc)

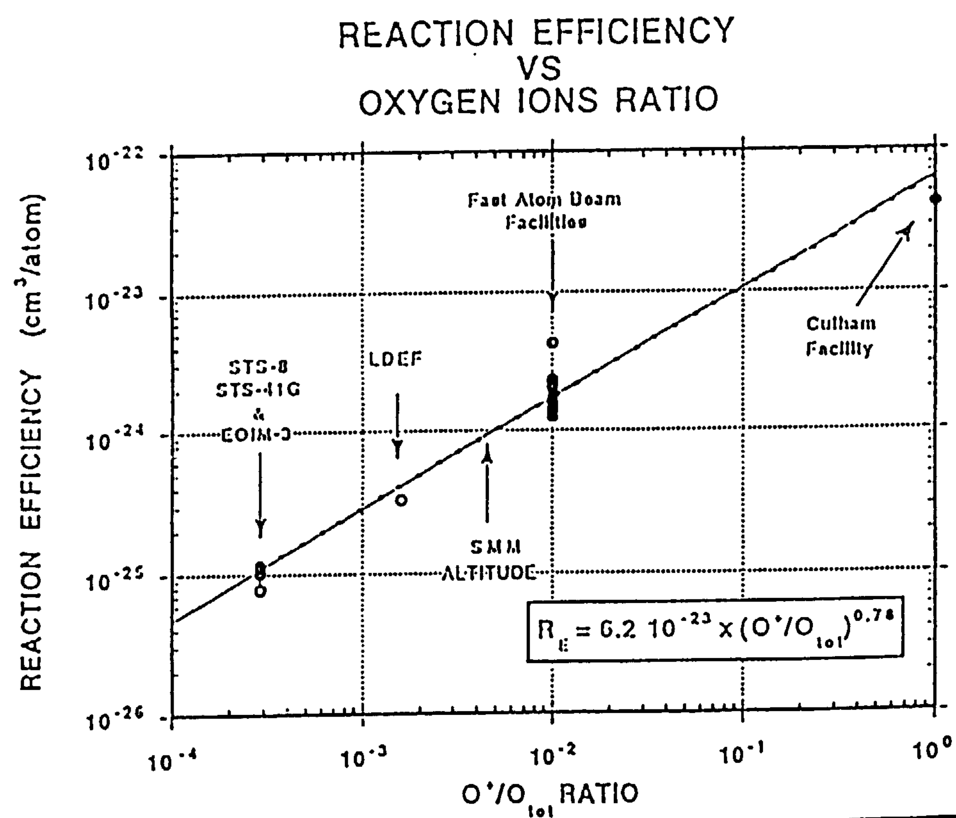
Space Flights - Altitude, AO, VUV, Re

- Kapton Re = 3.0 x 10-24 cc/AO - a calibration constant
- FEP Re = .05 x 10-24 cc/AO for STS
  Re = .30 x 10-24 cc/AO for LDEF - Why > than for STS ?
- [O+/AO] is one explaination; VUV - AO is another explaination

Vehicle	Alt(km)	t(hr)	VUV (ESH)	Fluence 1021AO/cm2	VUV/ AO	O+/O	Re(10-24 cc/AO) Kap	Re(10-24 cc/AO) FEP
STS-5	300	40	20	0.10	200	10-4	3.0	<..05
STS-8	225	41	20	0.35	57	10-4	3.0	<..05
STS-41G	272	34	15	0.27	55	10-4	3.0	<..05
EOIM-3	230	42	23	0.22	104	10-4	3.0	.09
STS	**LOW**	**SHORT**	**LOW**	**LOW**	**LOW**	**LOW**	**Std**	**LOW**
LDEF	482	69 mo.	11,200	9.0	1224	10-3	3.0	0.30
LDEF	334 final	18 mo	2,922	8.0	360	10-3	3.0	0.30
LDEF	**HIGH**	**LONG**	**HIGH**	**HIGH**	**HIGH**	**HIGH**	**Std**	**HIGH**

O+ as a Potential Explaination of Re(FEP)

- F. Levadou and M. van Eesbeek, Huntsville p. 73 (1993)
  D. Zimcik Can Aero & Space J Vol 33 pp 4-10 (1987)Testing



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LDEF

- **Erosion of Kapton and FEP seen on RAM - High AO - High VUV**
- **Erosion Kapton & FEP not seen on TE - Zero AO - Same VUV**

LDEF Location	VUV (ESH)	Fluence 1021AO/cm2	VUV/ AO	Damage to Kapton / FEP
RAM Row 9	11,200	9.0	1,240	High Erosion
TE Row 3	11,100	< .0001	> exp. 8	No Erosion in High VUV - no AO
Top Row 12	6,800	1.3	5,230	Lower Erosion (less AO)
Space End	14,500	0.46	31,521	Lower Erosion (low AO)
Earth End	4,500	0.33	13,636	Low Erosion (low AO)

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Space and Ground AO-VUV Testers

- Fast AO Testers Simulate AO in Space - but not VUV in Space
- Slow testers simulate Fast Testers

Tester	eV	VUV (ESH)	Max Fluence 1021AO/cm2	VUV / AO	Re Kapton	Re FEP
LDEF Control	5.0	11,200	9.0	1,240	3.0	0.3
LANL - fast	1.5	6.6	0.80	8.0	3.0	0.56
UTIAS - fast	2.0	0.0	1.87	0	3.0	0.13
UTIAS - Triton Test	2.0	+ 4,500	1.87	2,442	3.0	0.17
MSFC - fast	6.0	300	0.70	400	3.0	1.6
PSI - fast	5.0	1.8	0.38	4.6	3.0	1.6
LeRC - slow	0.04	104	0.55	188	3.0	4.7

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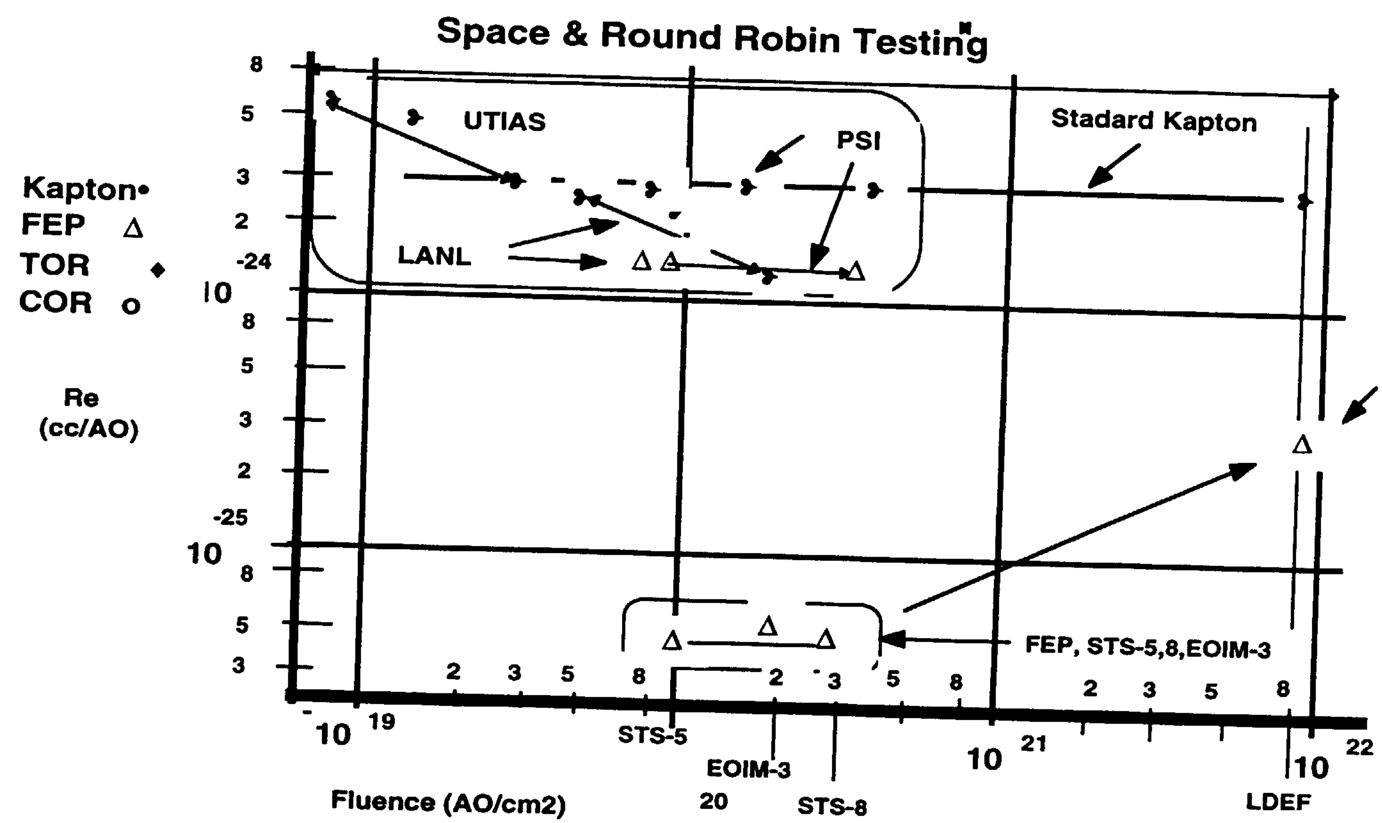
Triton Analysis of Round Robin Data of 1993



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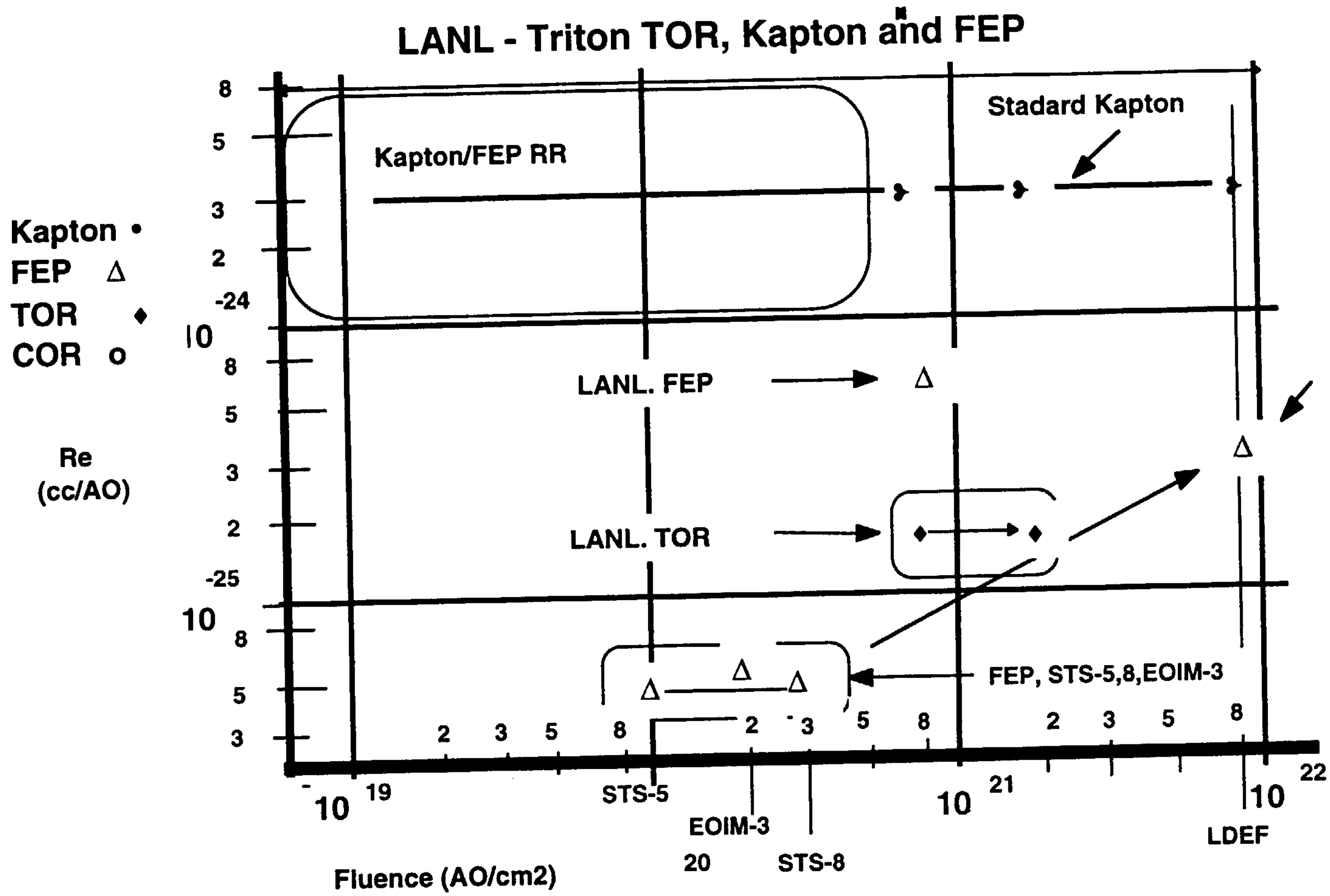
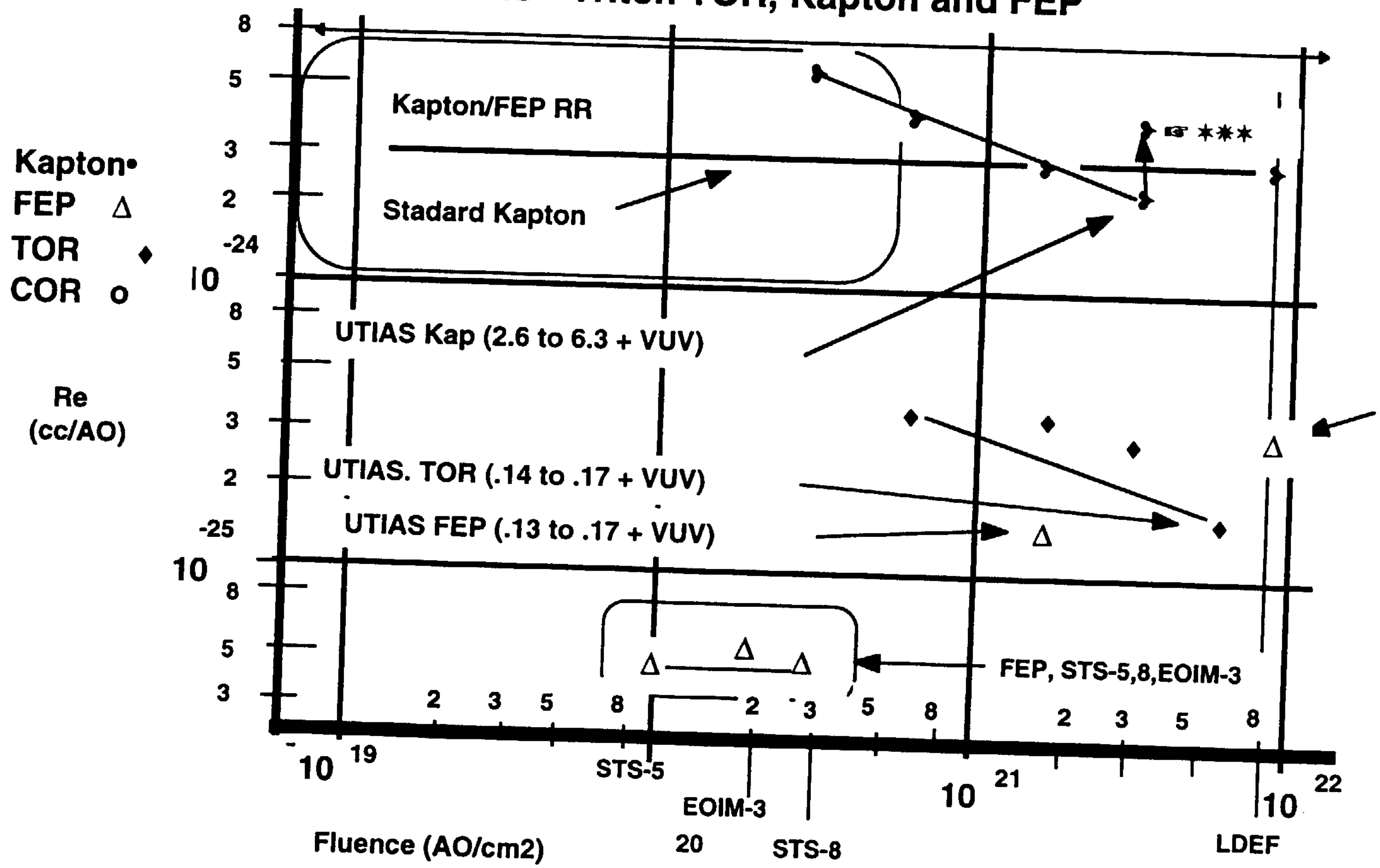
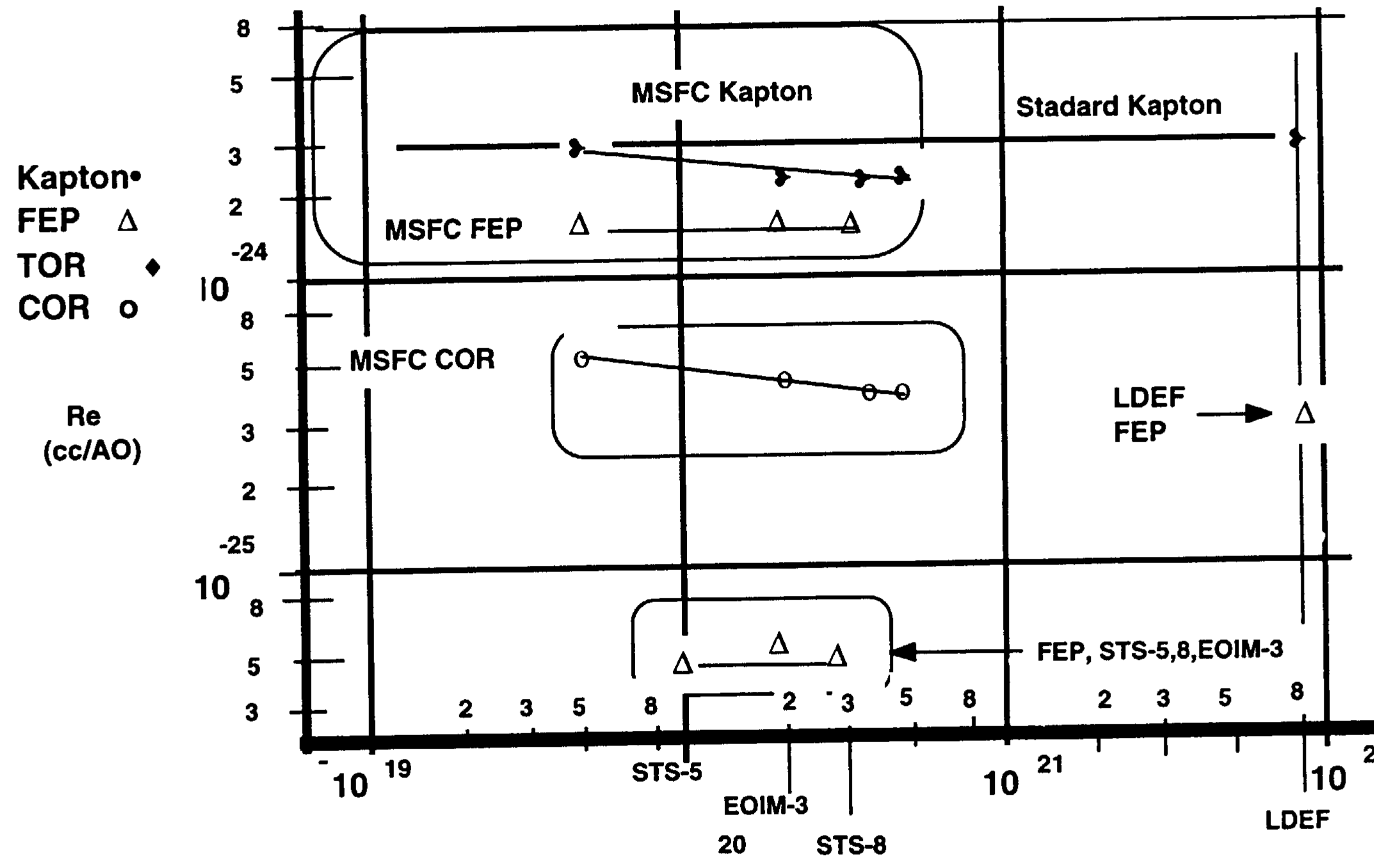
Fast AO Exposures for Triton at LANL, 1993



UTIAS - Triton TOR, Kapton and FEP

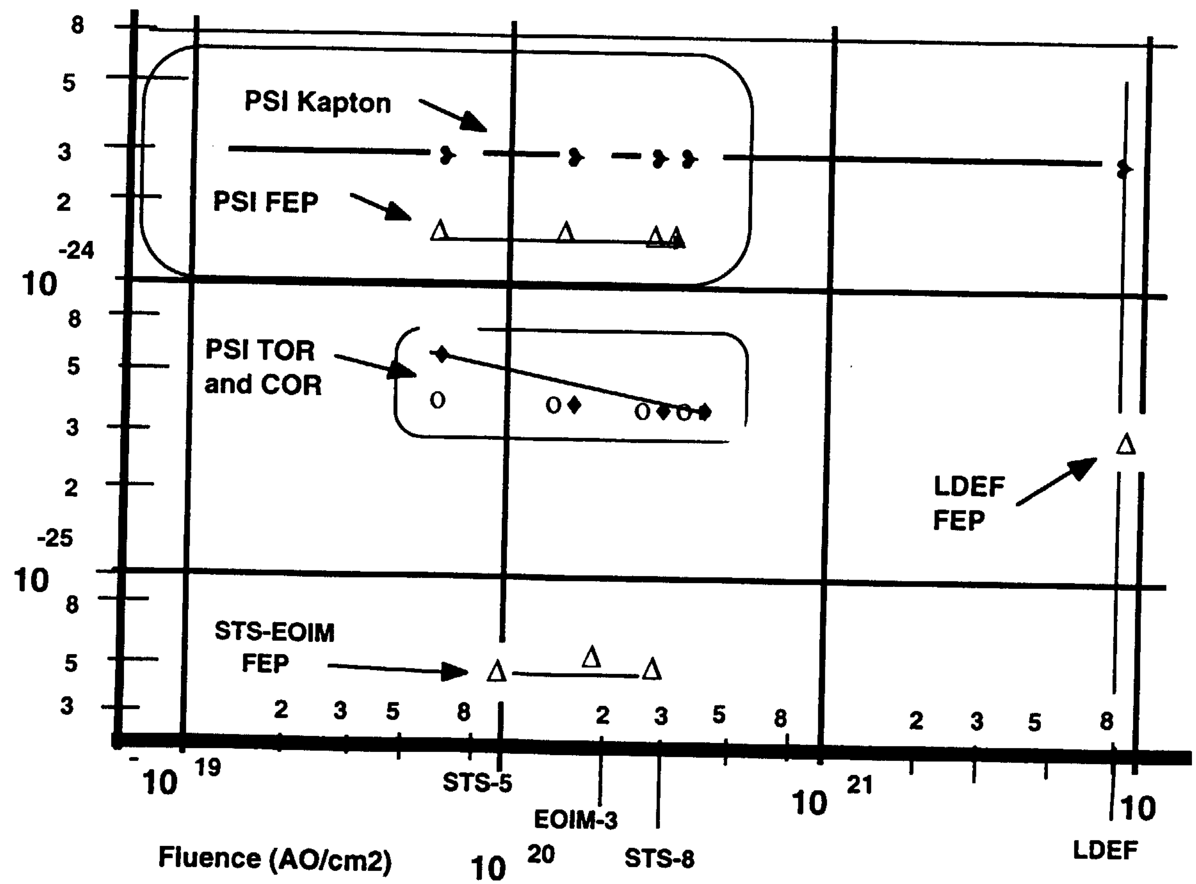


MSFC - Triton COR, Kapton and FEP

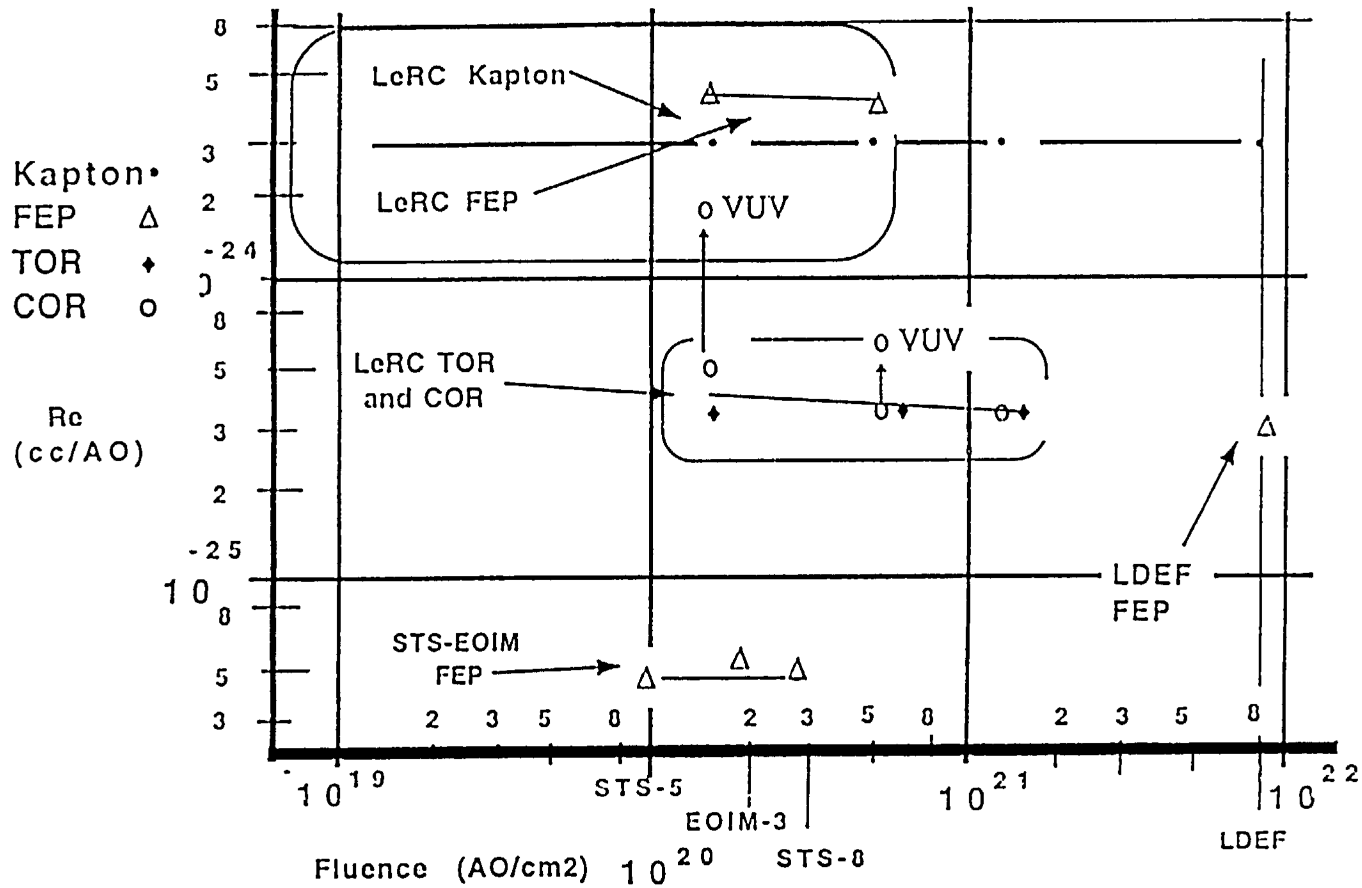


Triton Testing at PSI - AO with O+, no VUV

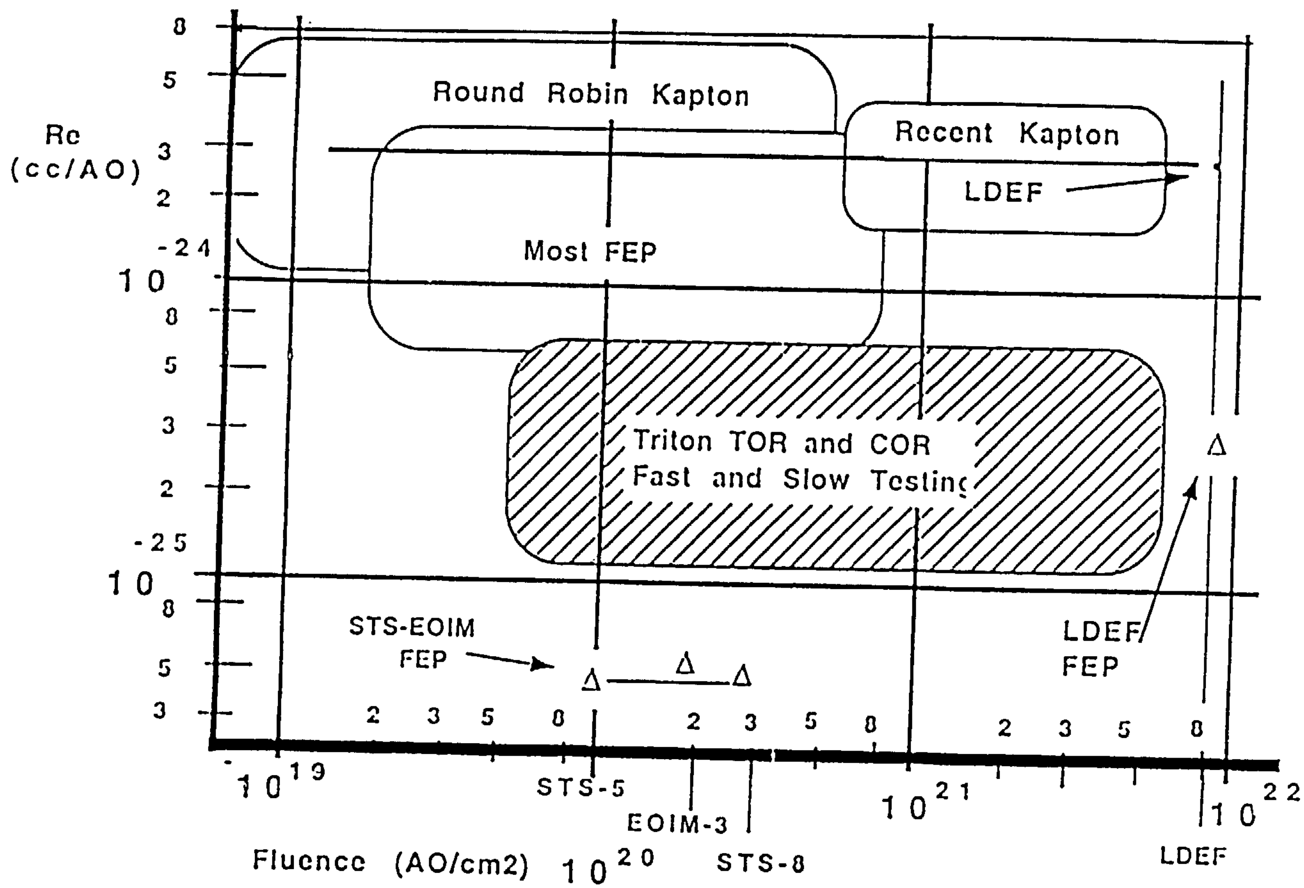
PSI - Triton TOR, COR, Kapton and FEP



Triton Testing at LeRC - Slow AOs with O+, + VUV



Summary of Triton AO-VUV Ground Testing



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Summary of Triton AO - VUV Ground Testing

1. LANL	TOR more AO-VUV Resistant than Kapton
2. UTIAS	TOR more AO-VUV Resistant than Kapton
3. MSFC	COR more AO-VUV Resistant than FEP
4. PSI	TOR more AO-VUV Resistant than Kapton COR more AO-VUV Resistant than FEP
5. LeRC (slow)	TOR more AO-VUV Resistant than Kapton COR more AO-VUV Resistant than FEP

Stability of TOR Against AO Erosion with added VUV UTIAS and LeRC Testing

Tester	Sample	ESH	Erosion
UTIAS	TOR	0 to 4,500 ESH	Re from .13 to .17
	Kapton	0 to 4,500 ESH	Re from 2.6 to 6.3
LeRC	TOR	50 to 180 ESH	Re from ..33 to .35
	Kapton	13 to 45	Re calibrated at 3.0

UTIAS - TOR is constant in Re up to 4,500 ESH; Kapton Erodes > 2x
LeRC - TOR is constant in Re up to 180 ESH
Re of Kapton is taken to be 3.0 with added VUV

TOR Stability in Absorptance (α) up to 1,000 ESH of UV - GSFC Testing

Sample	ESH	α Value	% α change	
1 mil TOR	1,081	.375	.375	(+ 00 %)
Other VUV Stable Materials				
Alumina Composite	"	.134	.135	(+ 00 %)
IISTRE on Kevlar	"	.188	.195	(+07 %)
NTA on Kapton	"	.560	.565	(+ 01%)
Other VUV Unstable Materials				
Gortex on VDA	"	.052	.093	(+ 79 %)
A276 /Epoxy	"	.303	.526	(+ 77 %)

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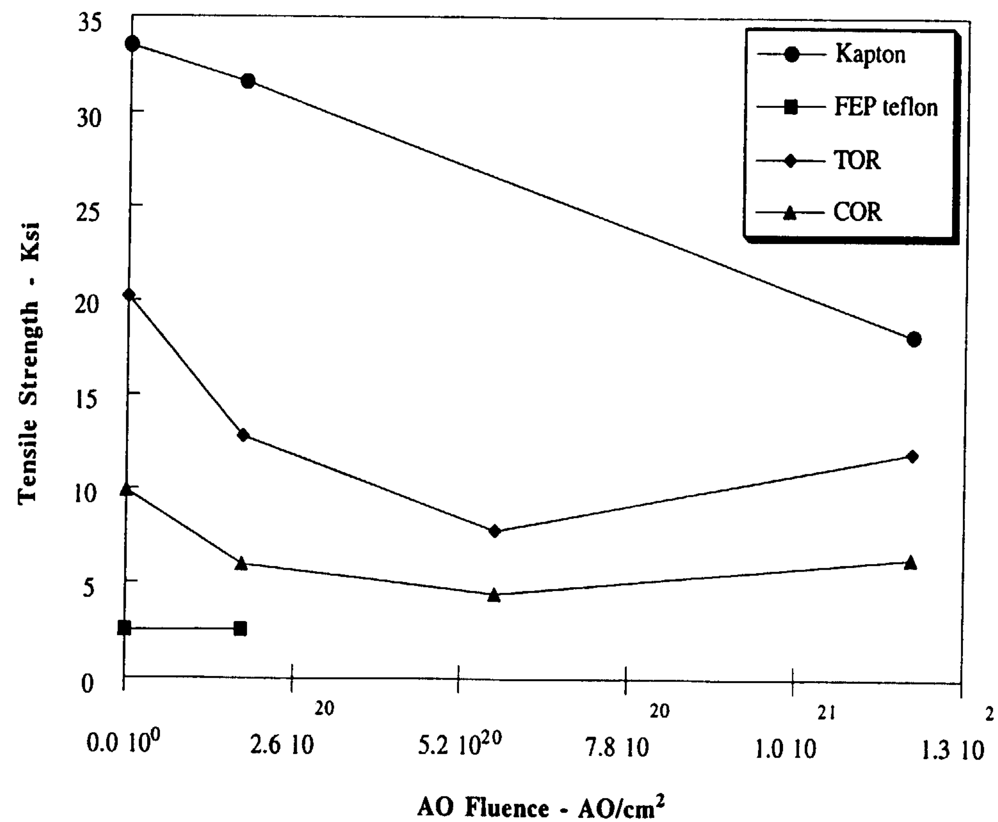
COR and TOR with Kapton and Teflon Tensile Strength as a Function of AO-VUV Fluence

LeRC Testing

Tensile Strength vs. AO Fluence



Space Applications Under Development for TOR & COR

- TOR-Al SSMs for MLIs
- COR-Ag SSMs for MLIs
- C-COR - Ag for Conductive SSMs and RF Antennas
- TOR-Cu for FSAs (Flexible Solar Arrays)
- TOR for Inflatables
- TOR Threads for MLIs
- TOR Resin for Wire Insulation & Tethers
- TOR Composites for LOX Tanks

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• TOR-Al SSMs for MLIs

α and ε for TOR vs Kapton MSFC Testing

Thickness mils	Kapton-Al α/ε	TOR-Al α/ε	TOR-Silver α/ε
0.5	.33/.55 = .60	.29/.60 = .48	.20/.60 = .33
1.0	.35/.66 = .53	.31/.72 = .43	.23/.72 = .32
2.0	.39/.72 = .54	.35/.82 = .43	.27/.82 = .33
5.0	.45/.88 = .51	.41/.95 = .43	.34/.95 = .38

- **COR-Ag SSMs for MLIs α and ε forCOR vs. FEP MSFC Testing**

Thickness mils	FEP Teflon-Silver α	ε	α/ε	COR-Silver α	ε	α/ε
0.5	.09	.40	0.17	.078	.47	0.166
1.0	.09	.48	0.14	.084	.56	0.150
2.0	.09	.60	0.11	.088	.72	0.122
5.0	.09	.40	0.17	.109	.85	0.128

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TOR and COR Stable in α and ε to Fast AO Radiation (MSFC Testing)

Sample	No AO Exposure			1.7 x 1021 AO/cm2		
	α	ε	α/ε	α	ε	α/ε
TOR	0.41	0.71	0.58	0.50	0.72	0.69
Kapton	0.35	0.66	0.53	-	-	0.62
TOR-LM	0.19	0.64	0.30	0.27	0.68	0.40
COR	0.10	0.63	0.16	0.16	0.69	0.23
FEP Teflon	-	-	0.17	-	-	0.24
C-COR	0.31	0.74	0.42	0.39	0.75	0.52

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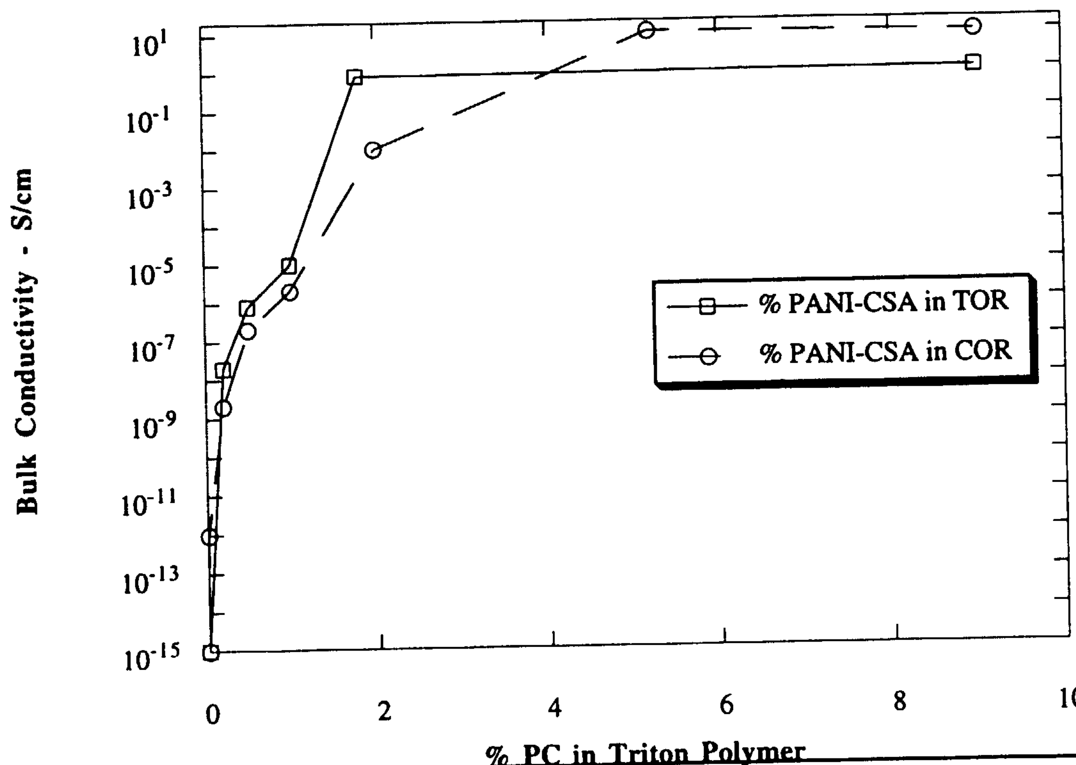
Conductive C-COR For Conductive Films Inflatable RF Antennas

PC-11 Doped Triton COR & TOR Polymer Films



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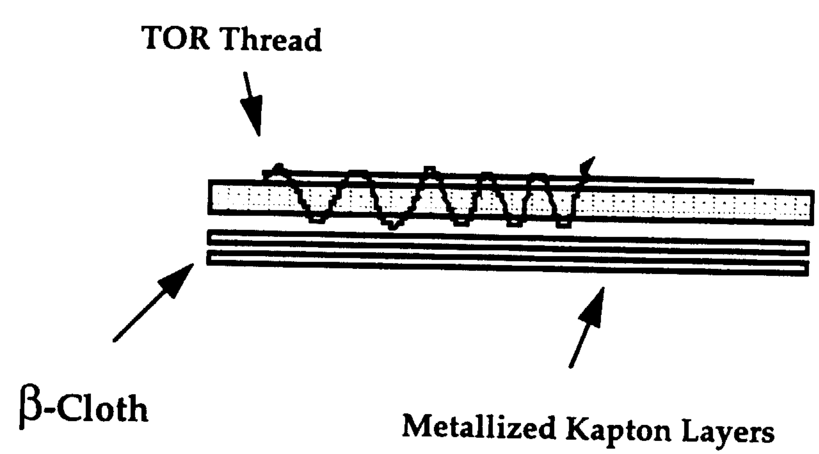
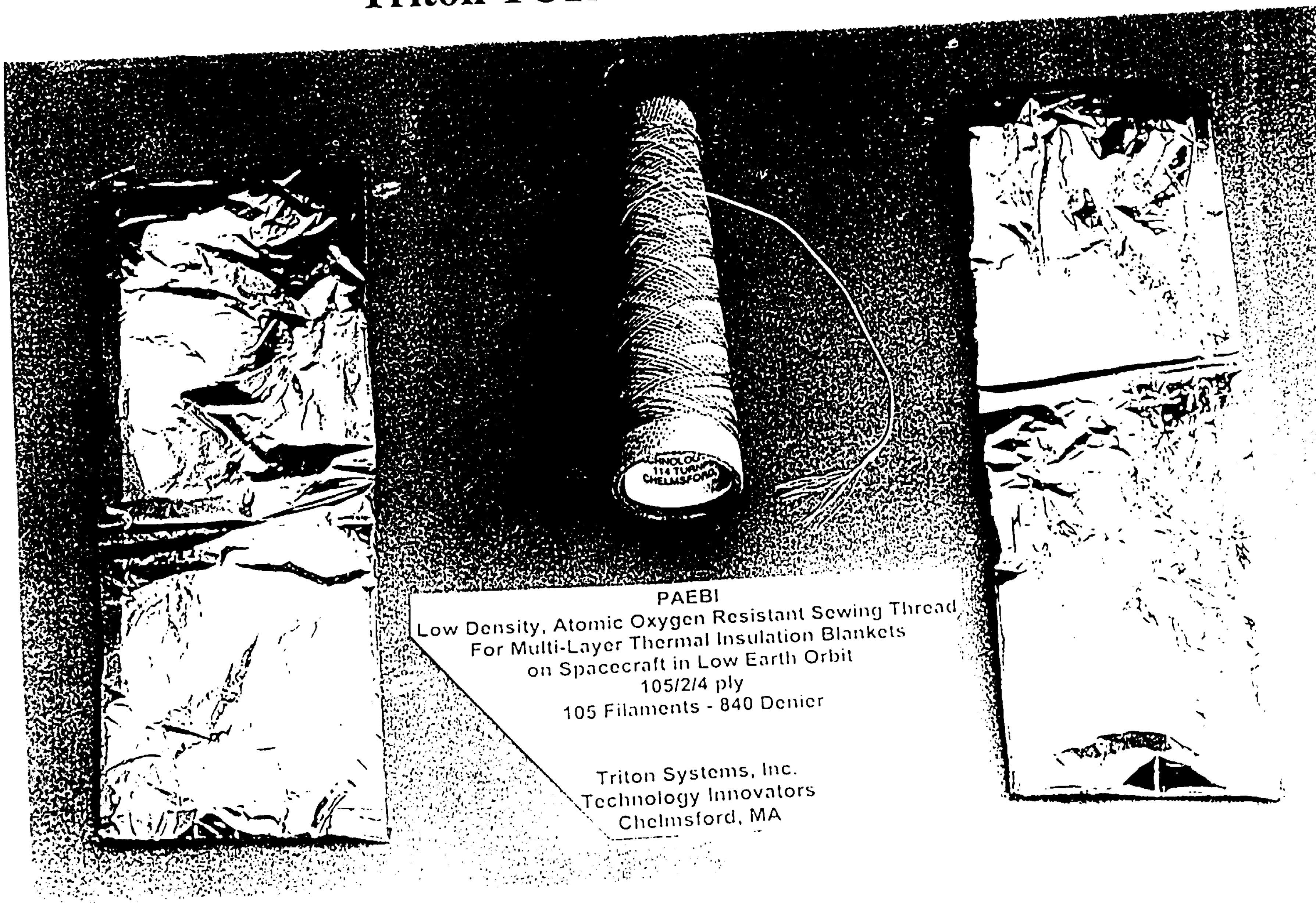
TOR Threads for Multilayer Insulation Blanket (MLI)



Triton TOR - AO Resistant Threads



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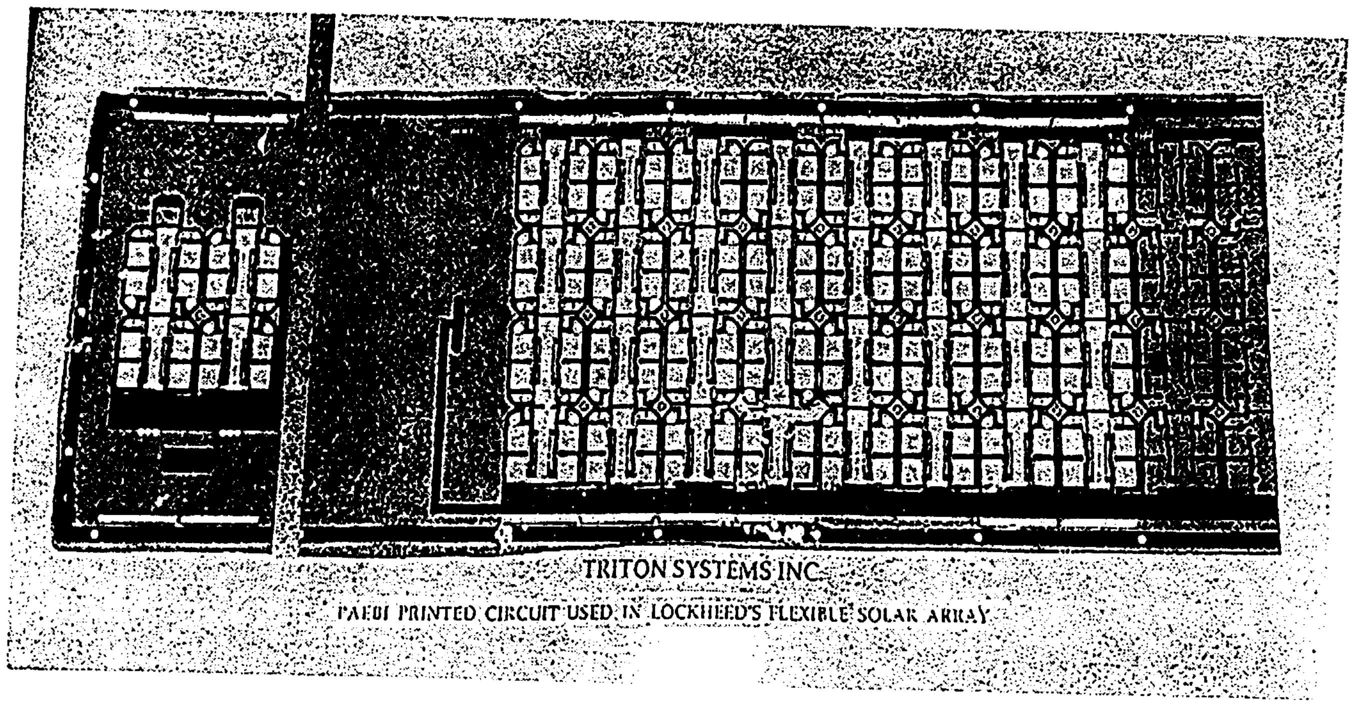
Triton TOR - AO Resistant Full Sized FSA



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TOR and COR Films For Inflatable Structures

- JPL Space Inflatable Workshop, October, '96,
  Triton Paper "New Inflatable Polymer Materials"

- Low Modulus TOR-LM and COR
- C-COR for an RF Reflective Antenna
- AO - VUV Resistant
- Radiation Testing in Progress

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TOR Composite for LOX Tanks and Leads

TOR / COR Pass the LOX Impact Test

	LOX Test		
Polymer Film	Polymer Type	0 Failures in 20 Tries to Pass	
COR and TOR	PAE-POs	0/20	= Pass
Kapton, Vespel	Polyimides	0/20	= Pass
Teflons	Polyfluoros	0/20	= Pass
Vectra, Xydar	Liquid Crystals	0/20	= Pass
Mylar, Viton, Nylon	Various	2 to 9 / 20	= Failure

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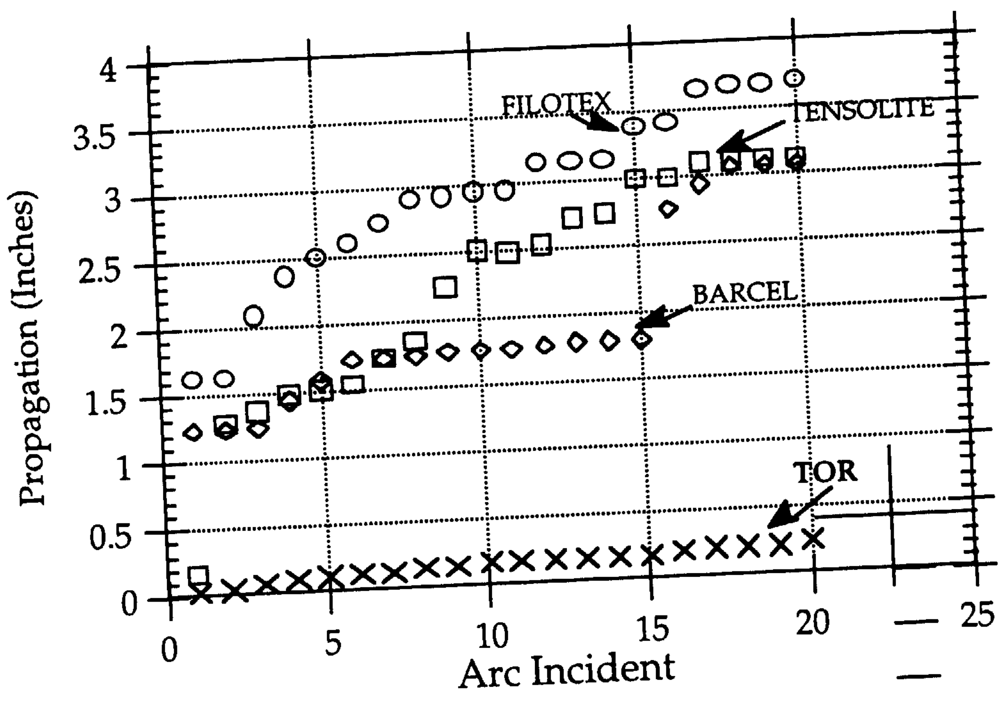
Triton TOR Resin is Arc Track Resistant for Wire Insulation and Tethers



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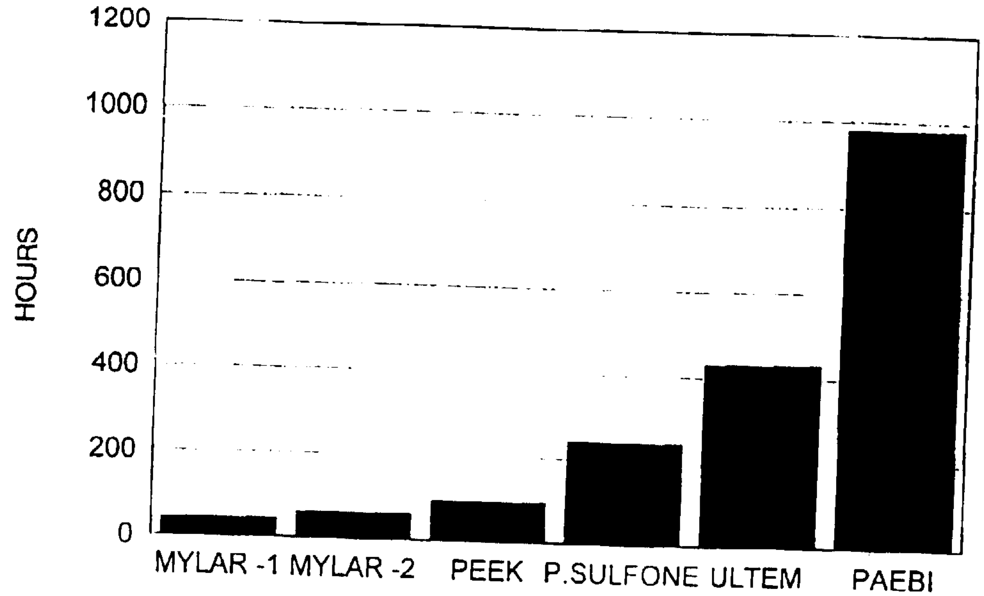
VOLTAGE ENDURANCE

412 HZ, 3 KV, 1/4" ELCTRS, 10 MIL FILMS



TIME FOR 5TH FAILURE OF 9 POINTS

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TOR and COR Polymers
for Space Applications

- TOR Films for Inflatables, SSMs, MLIs, FSAs,
- TOR Resins for Insulation and Tethers
- TOR Composites for LOX Tanks
- COR Films for SSMs, MLIs,
- C-COR for COnductive SSMs, MLI, Inflatbles
- TOR Threads for Spac, Wires, Tethers

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1997 NASA/GSFC Spacecraft Contamination And Coatings Workshop

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