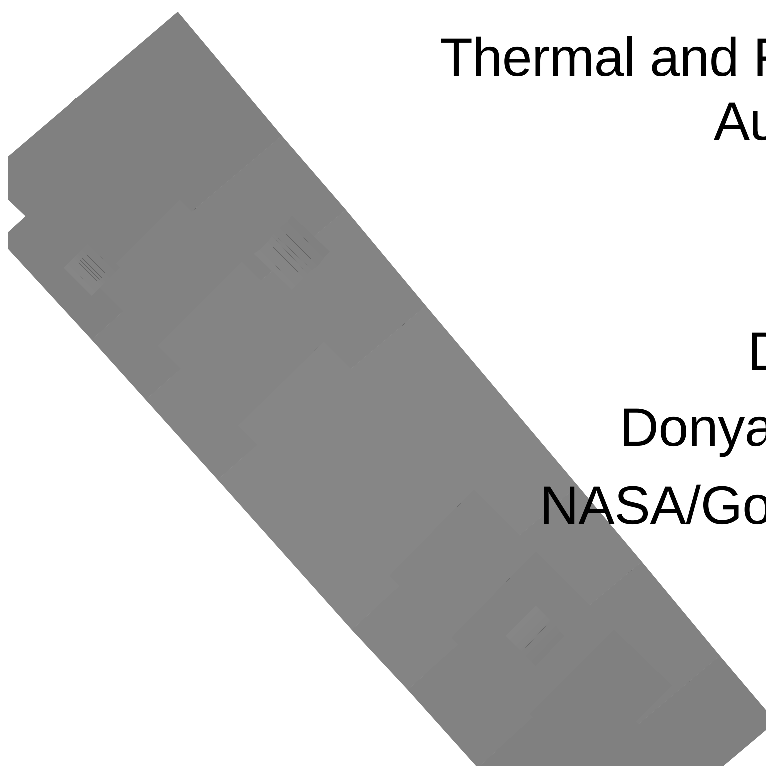
VARIABLE EMITTANCE COATINGS FOR THERMAL CONTROL



Thermal and Fluids Analysis Workshop 2003
August 18 – 22, 2003
Hampton, VA

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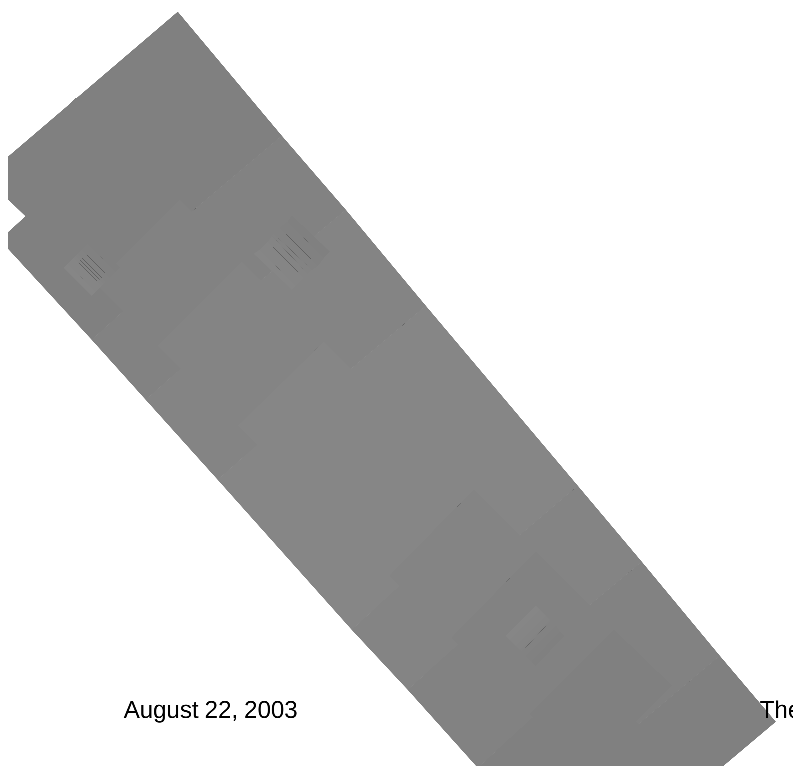
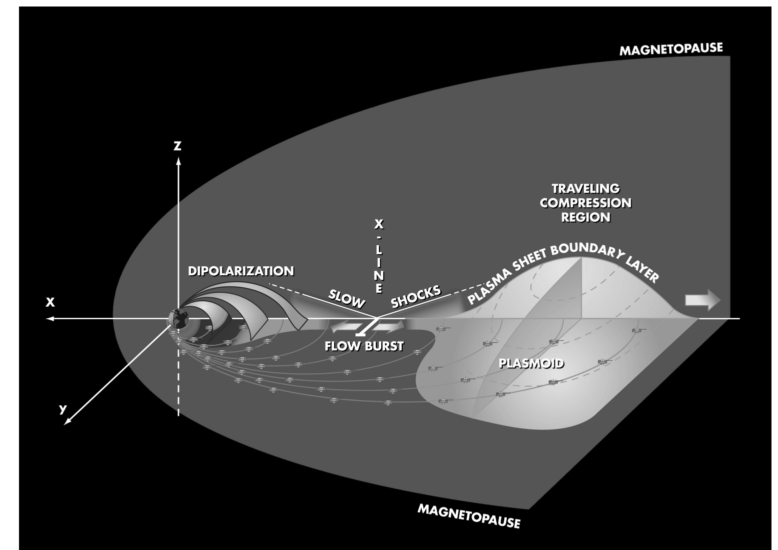
Agenda

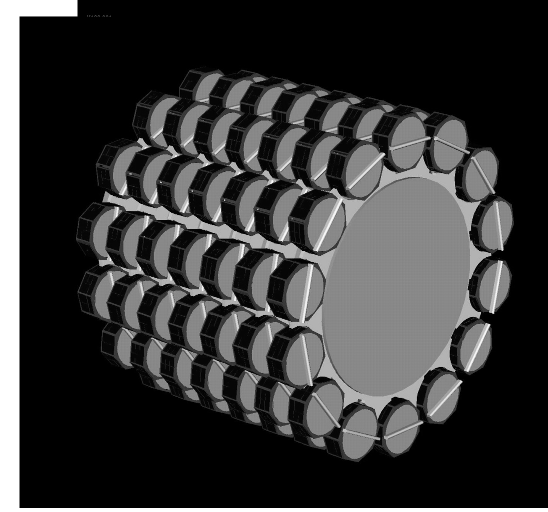
- Background
- ST-5 Flight Opportunity
- Overview of Variable Emittance Coatings
- Development of VEC Technologies for ST-5
- Major Issues/Concerns

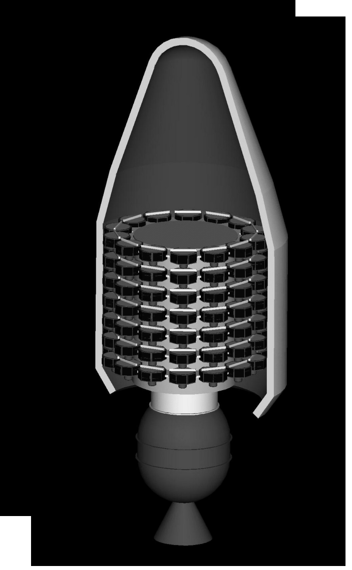


Background

- Future missions such as DRACO want to determine how the magnetotail stores, transports, and releases matter and energy:
  - Include fleets of 50 to 100 satellites
  - Elliptical orbits with dense sampling from 7 - 40 RE
- Unique thermal control problems:
  - Low mass result in large temperature variations
  - Power limited
  - Extreme environments – up to 8 hour eclipses
- *Need means of modulating heat rejection rate*





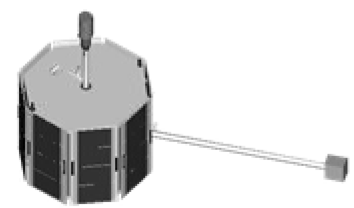


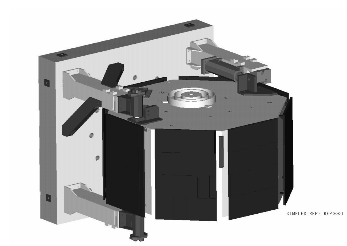
Space Technology 5:
Technology Validation Mission

- ST5 is a constellation of three spacecraft whose level one requirements are to:
  - Design, develop, integrate, test and operate three full service spacecraft, each with a mass less than 25kg, through the use of breakthrough technologies
  - Demonstrate the ability to achieve accurate, research-quality scientific measurements utilizing a nanosatellite with a mass less than 25 kg
  - Execute the design, development, test and operation of multiple spacecraft to act as a single constellation rather than as individual elements
- Primary Technology Thrusts:
  - High performance, low mass
  - Low power, low voltage, rad-tolerant electronics
  - Low cost manufacturing & testing techniques
  - Autonomy for both onboard & ground operations
  - Scaleable

Space Technology 5
Mission Summary

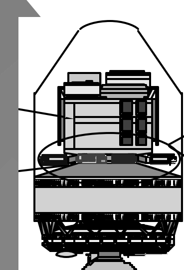
SPACECRAFT





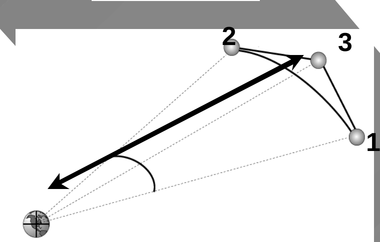
- Full Functional Autonomous Spacecraft with Integrated Technology Development
- Science Grade Magnetic Sensitivity (~0.2nT)
- Mass: £ 25Kg
- Size: Diameter ~ 50.8 cm (Flat-to-Flat)
  Height ~27.6 cm (Deck-to-Deck)
- Power: ~21.5W (Usable for Load)
  ~7.5 Ah Battery
- Uplink: @ 1Kbps / Downlink: @1Kbps or 100Kbps (X-Band)
- Data Storage: 20 Mbyte
- Spin Stabilized at Separation (~25 RPM After Deployments)
- Deployments: Magnetometer
- Radiation Tolerant: 100Krad-Si/3 Months

LAUNCH



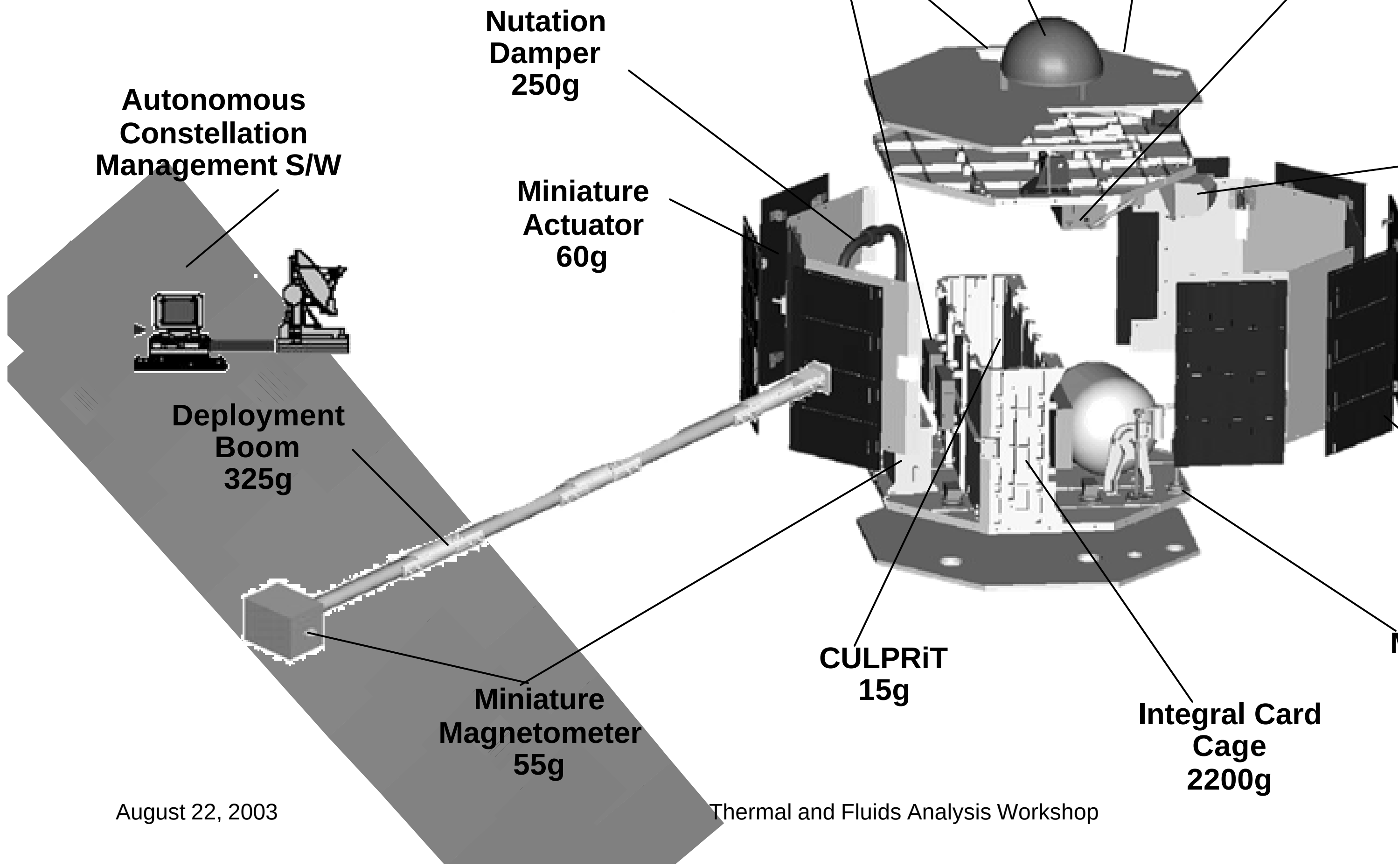
- Ride: Boeing Delta IV or Lockheed Atlas V
- Orbital Injection: Geosynchronous Transfer Orbit (240 x 37,000Km)
- Secondary Payload

MISSION



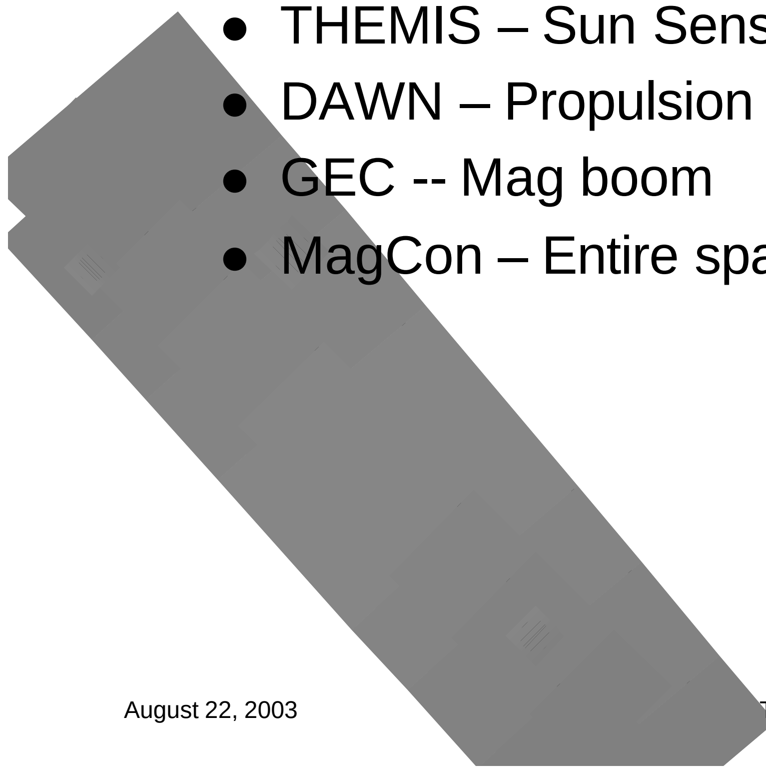
- 3-Spacecraft Constellation
- 3-Month Design Life
- ~11 Hr Orbit Period
- 20-30 Minute Ground Contact Per Orbit
- Autonomous Constellation Management / "Lights Out" Operations

Space Technology 5 Spacecraft



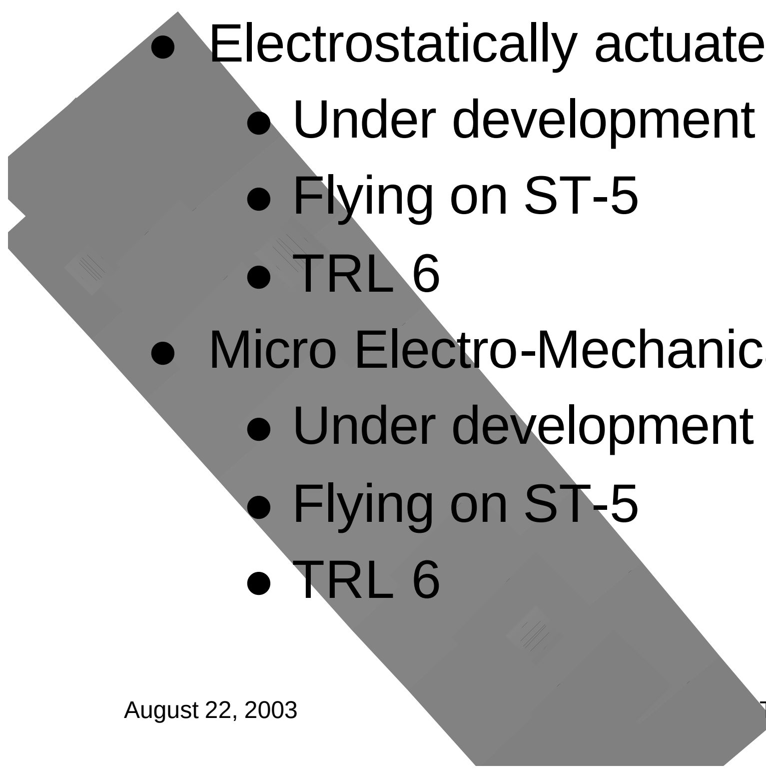
Space Technology 5
Development Status

- Schedule
  - Component level qualification testing underway.
  - November 2003 – Spacecraft 1 I&T
  - December 2004 – Launch Readiness Date
- ST-5 technologies already being infused into future missions
  - THEMIS – Sun Sensor
  - DAWN – Propulsion tank
  - GEC -- Mag boom
  - MagCon – Entire spacecraft bus



Variable Emittance Coatings
Overview (1 of 3)

- Variable Emittance Coatings (VEC) have been under development at GSFC since the mid-1990's:
  - Electrochromically actuated polymers
    - Under development by Ashwin Ushas Co., Inc.
    - TRL 3
    - Had difficulty surviving vacuum
  - Electrostatically actuated flaps
    - Under development by Sensortex, Inc.
    - Flying on ST-5
    - TRL 6
  - Micro Electro-Mechanical Systems (MEMS) “Mini Shutters”
    - Under development by JHU APL and Sandia National Laboratory
    - Flying on ST-5
    - TRL 6



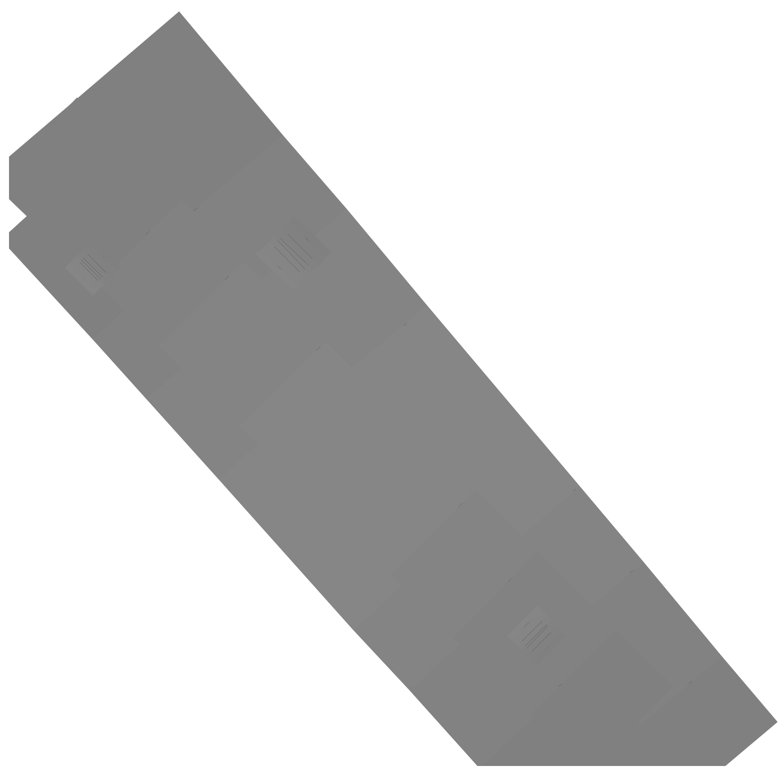
Variable Emittance Coatings
Overview (2 of 3)

- Benefits
  - By changing the effective infrared emittance of the surface, they allow the radiative heat transfer rate to be modulated upon command
  - Significant benefits identified by systems level studies on representative spacecraft. For a 6:1 variation in e* :
    - 50 – 90% heater power savings
    - Similar mass/cost savings over VCHP/louver applications
  - Major reductions in component temperature variations will lead to improved reliability
  - VEC coatings generically useful for all S/C, but especially suitable for small S/C and fleets of small S/C
    - VEC coatings very lightweight and negligible power consumption
    - VEC coatings provide a flexible design solution; do not need customized thermal design for all S/C in a fleet

Variable Emittance Coatings
Overview (3 of 3)

- Development Participants
  - NASA/GSFC
  - JPL
  - Johns Hopkins University Applied Physics Lab
  - Sandia National Laboratories
  - Sensortex Corp.
  - Air Force Research Laboratory
  - Ashwin-Ushas Corp.
- Co-Funding Sources
  - JPL
  - APL/Johns Hopkins University
  - DoE/Sandia National Laboratories
  - DoD/Air Force RL
  - NASA SBIR Program

Development of VEC Technologies for ST-5



Objectives

- Develop highly innovative thermal control coatings which can repeatedly change their properties in response to an external signal
  - To validate the technologies as part of the spacecraft thermal control system
  - Demonstrate variable emittance range of 0.2 to 0.8
- Program currently includes two alternative concepts (MEMS and Electrostatic) with both ground testing and flight experiment verification
- Each spacecraft will carry two different VEC radiators-one on the top deck and the other on the bottom
- Goal is to mature technologies to TRL 9 - Perception is that each concept has different advantages and applications
- Demonstrate survival in harsh space environment (UV, solar wind micrometeroid, hard vacuum, temperature cycling, etc.)
- Determine lifecycle cost: device itself, design effort, I&T issues, etc.

General Requirements

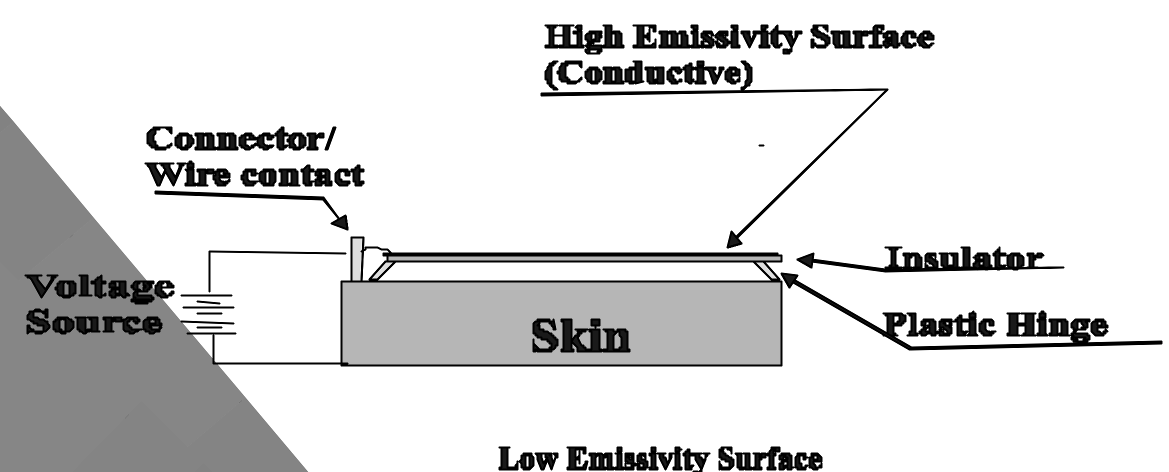
- Package Requirements
  - Total weight shall not exceed 350g
    - This mass limit includes radiator, electronics, mounting and support hardware, cables, and instrumentation.
  - Radiator assembly constrained to a 10 cm (L) x 9 cm (W) x 3 cm (H) footprint.
  - ECU will be housed in a 8.77cm x 8.77cm x 3.91 cm package
- Power Requirements
  - The controller (ECU) is powered by 5.23V ± 0.1V supply from Electrical Power System
  - Allocated Power
    - 217 mW nominal and 365 mW maximum - to drive controller and to actuate the ESR radiator

Electrostacially Acutated Flaps
Project Organization

- Technology being developed by Sensortex, Inc located in Pennsylvania with a subcontract to JHU APL for the control electronics.
- Funding Source: Phase I and II SBIRs
- Project Manager – William Biter
  - Project management interface with NASA GSFC and JHU APL
  - Overall project management & schedule / budget compliance
  - E-mail: wbiter@sensortex.com
  - (610)444-2383
- Stephen Hess
  - Operational interface with NASA GSFC and JHU APL
  - E-mail: smhess@sensortex.com

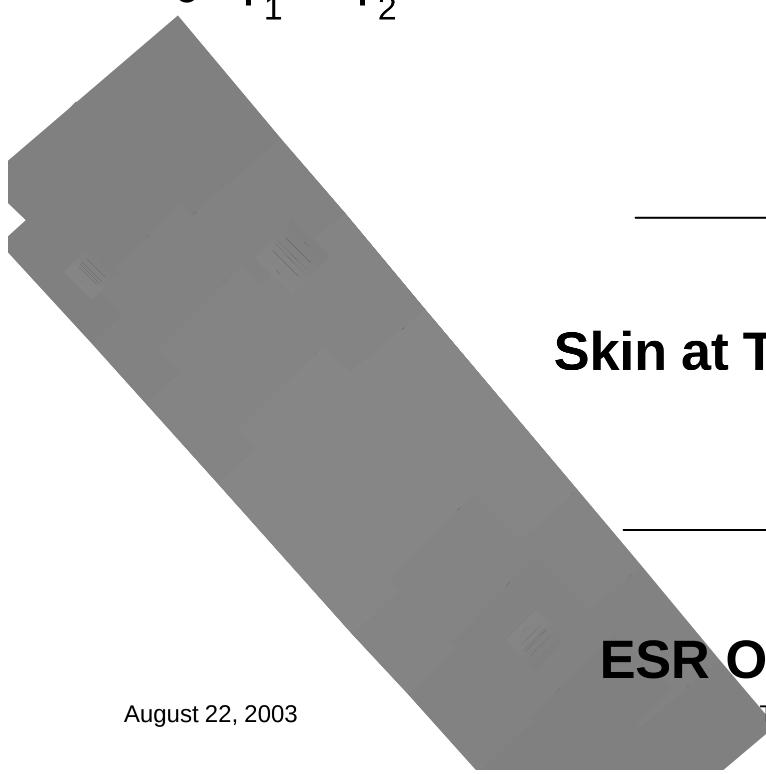
Electrostacially Acutated Flaps
Technology Overview

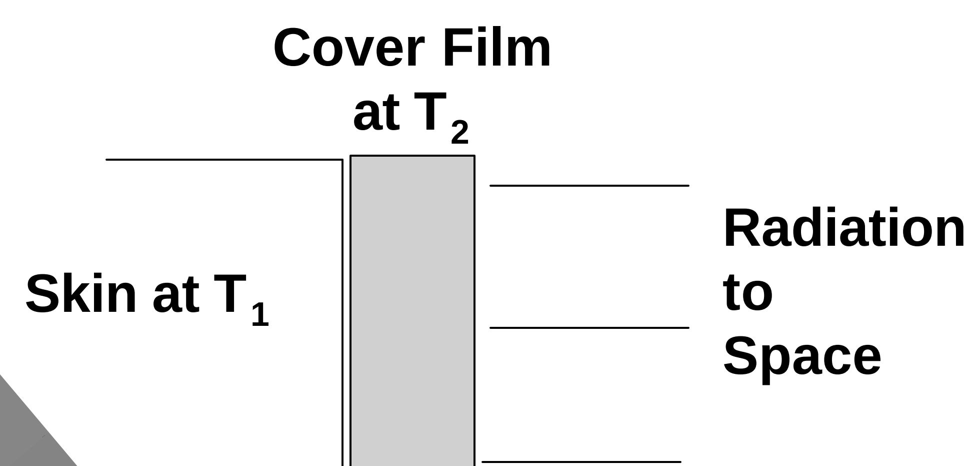
- Simple approach to control radiation.
- Thin conformal membrane (cover) is attracted to skin using electrostatic forces produces intimate contact.
- Thermal transfer from spacecraft skin to emissive film switches from conduction to radiation.
- Effect is change in effective emissivity of device.



Electrostacially Acutated Flaps
Operational Approach

- ESR On State - High Effective Emittance
  - Film in good thermal contact with spacecraft skin.
  - Heat transfer from spacecraft skin to ESR via conduction.
  - High emissivity cover radiates energy to space.
  - $T_1 = T_2$

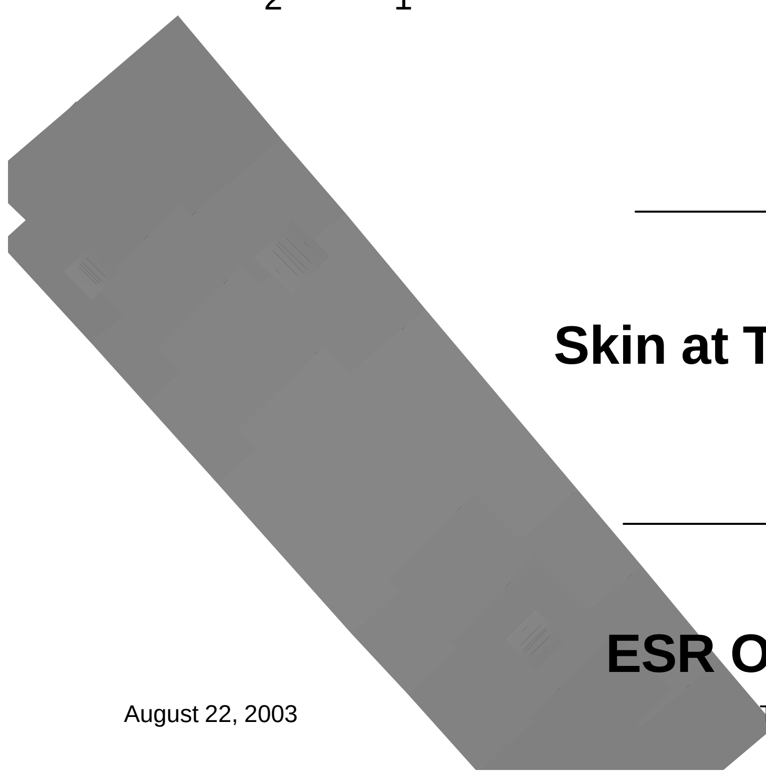


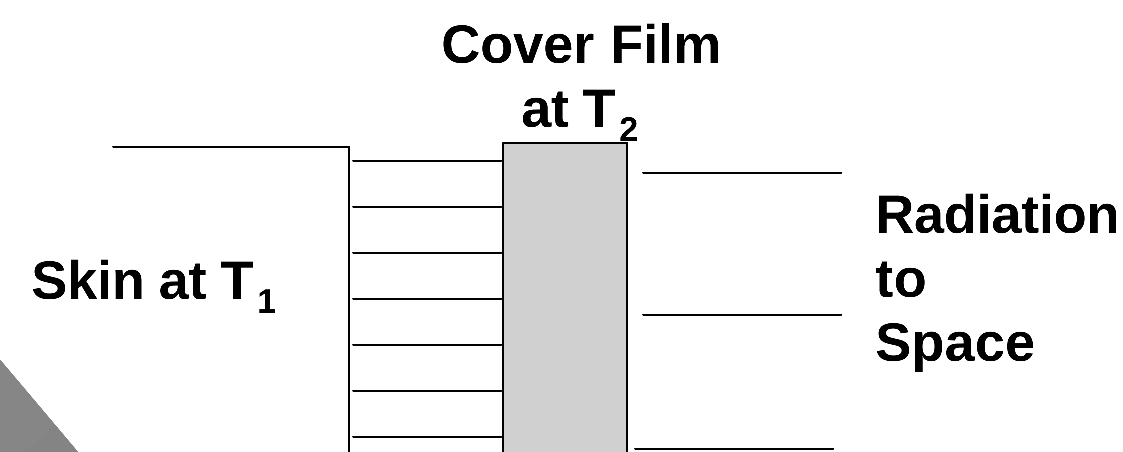


ESR On - High Effective Emittance

Electrostacially Acutated Flaps
Operational Approach

- ESR Off State - Low Effective Emittance
  - Film not in thermal contact with spacecraft skin.
  - Radiation heat exchange between skin and film cover
  - Spacecraft and underside of film have low emittance properties
  - $T_2 << T_1$

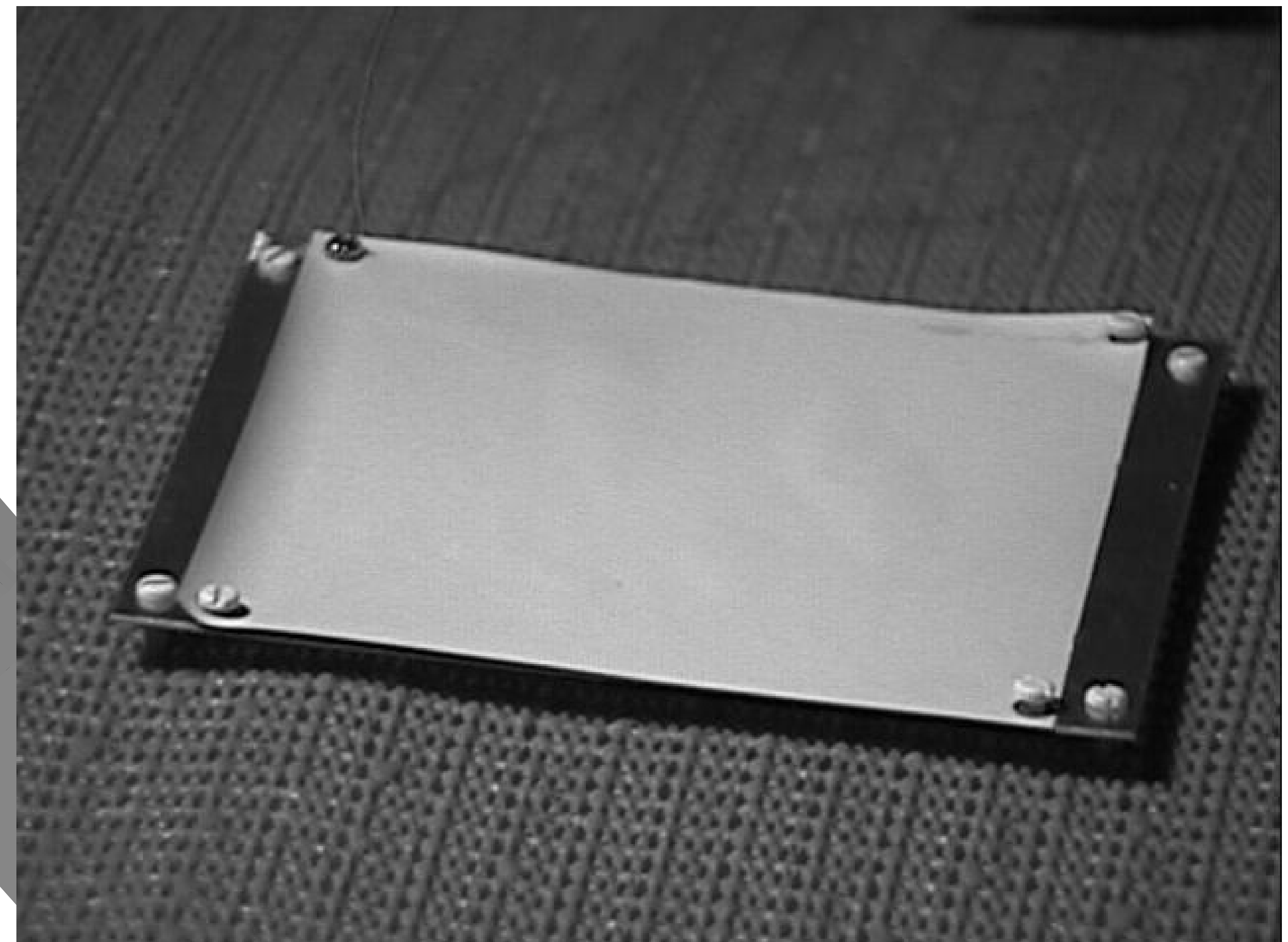




ESR Off - Low Effective Emittance

Electrostacially Acutated Flaps
ESR “Off” - No Applied Voltage

Electrostacially Acutated Flaps
ESR "On" – 400 Volts Applied



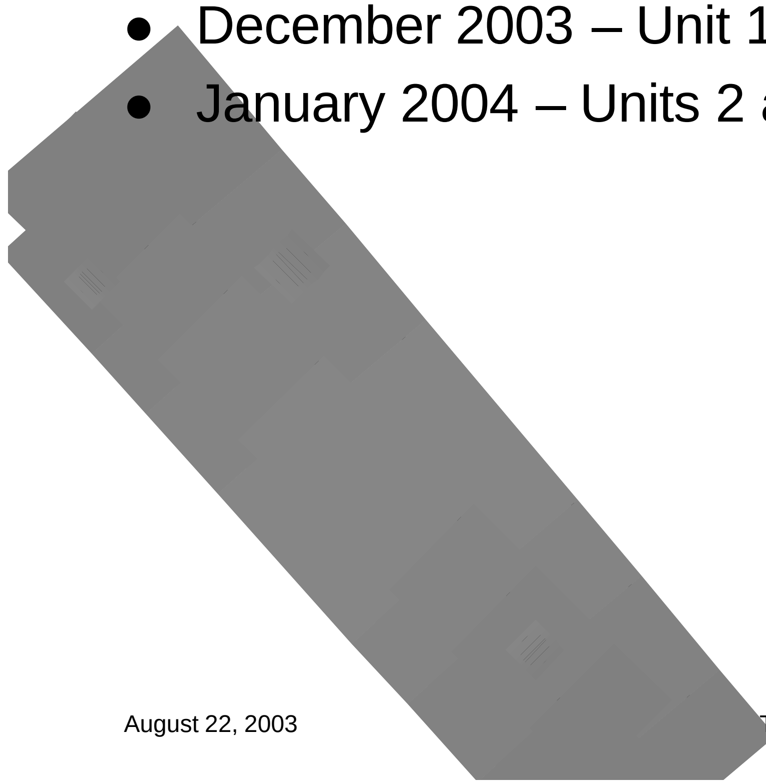
Electrostacially Acutated Flaps

Current Status

- Operating cells fabricated and tested.
  - Large observed changes in emissivity during cold (LN2 temperature) thermal vacuum testing.
  - Consistently obtain active area emissivity changes > .6 at 99% confidence level.
  - Cells tested with more than 10,000 operating cycles (limited test conditions).
  - Demonstrated ability to control the four active areas
- Flight substrates fabricated and assembly underway.
- Electronic control unit under fabrication

Electrostacially Acutated Flaps
Milestone/Schedule

- All milestones consistent with and support ST-5 project schedule.
- Electronics breadboard to NASA for FLATSAT testing – 28 February 2003.
- October - November 2003 - Qualification Testing of Unit 1
- November - December 2003 - Acceptance Testing of Units 2 and 3
- December 2003 – Unit 1 shipped to GSFC
- January 2004 – Units 2 and 3 shipped to GSFC

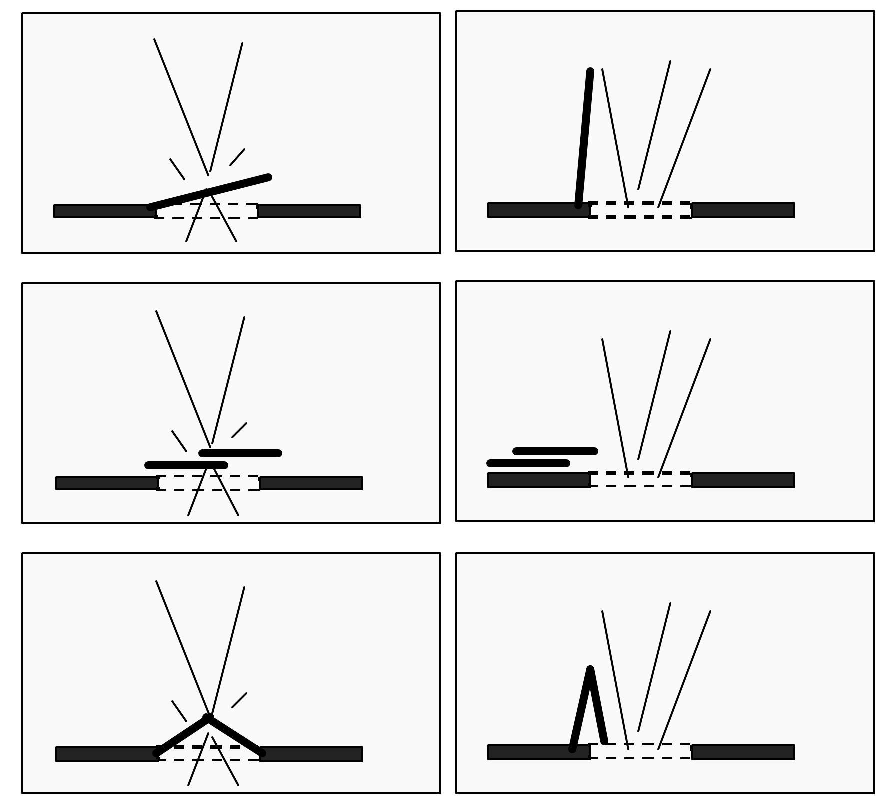


MEMS Shutters
Project Organization

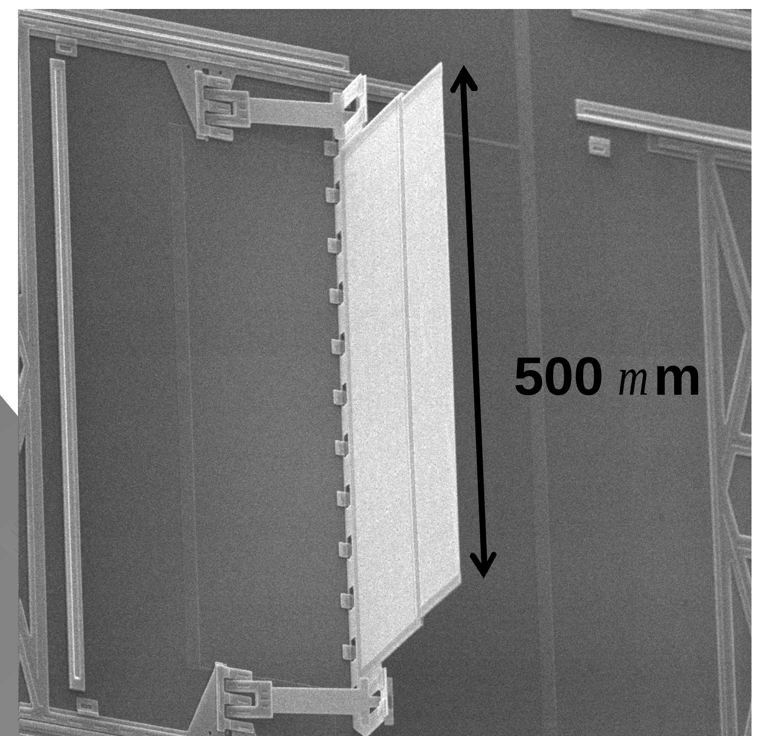
- Technology being developed by JHU APL
- Funding Source: Internal Funding and subsequent contract
- Project Manager – Ann Darrin
  - Project management interface with NASA GSFC
  - Overall project management & schedule/budget compliance
  - E-mail: Ann.Darrin@jhuapl.edu
  - (240) 228 – 4952
- Robert Osiander
  - Responsible for radiator development
  - E-mail: Robert.Osiander@jhuapl.edu
- Dawnielle Farrar
  - Responsible for control electronics
  - E-mail: Dawnielle.Farrar@jhuapl.edu

MEMS
Technology Overview

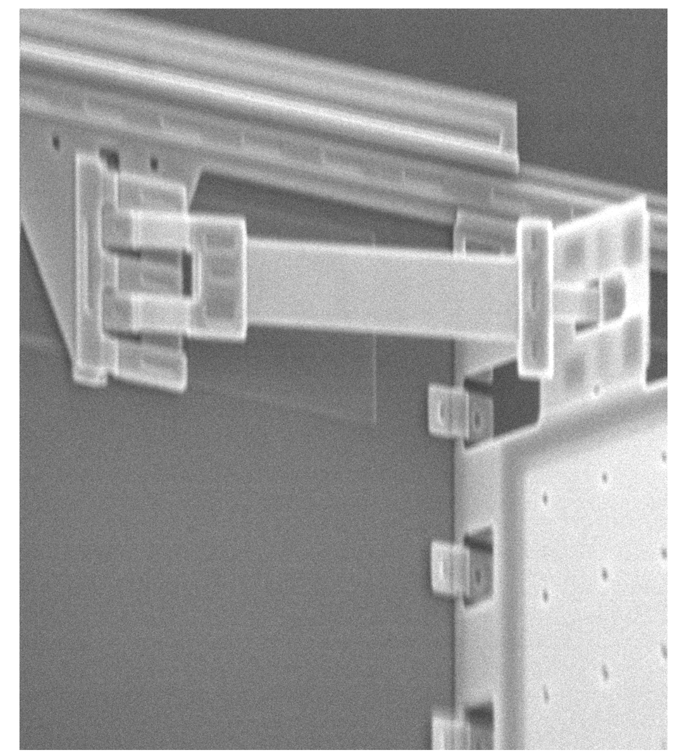
- Micromachined devices which are similar in function and design to conventional mechanical louvers where a mechanical vane or window is opened and closed to vary the radiative view to space
- Expected emittance changes of $\Delta e = 0.8$
- Emittance will be remotely controlled with low power electrostatic drive.
- Three concepts
  - Louvers
  - Sliders
  - Folders
- Each design has its limitation



MEMS Louvers
SEMs of First Design

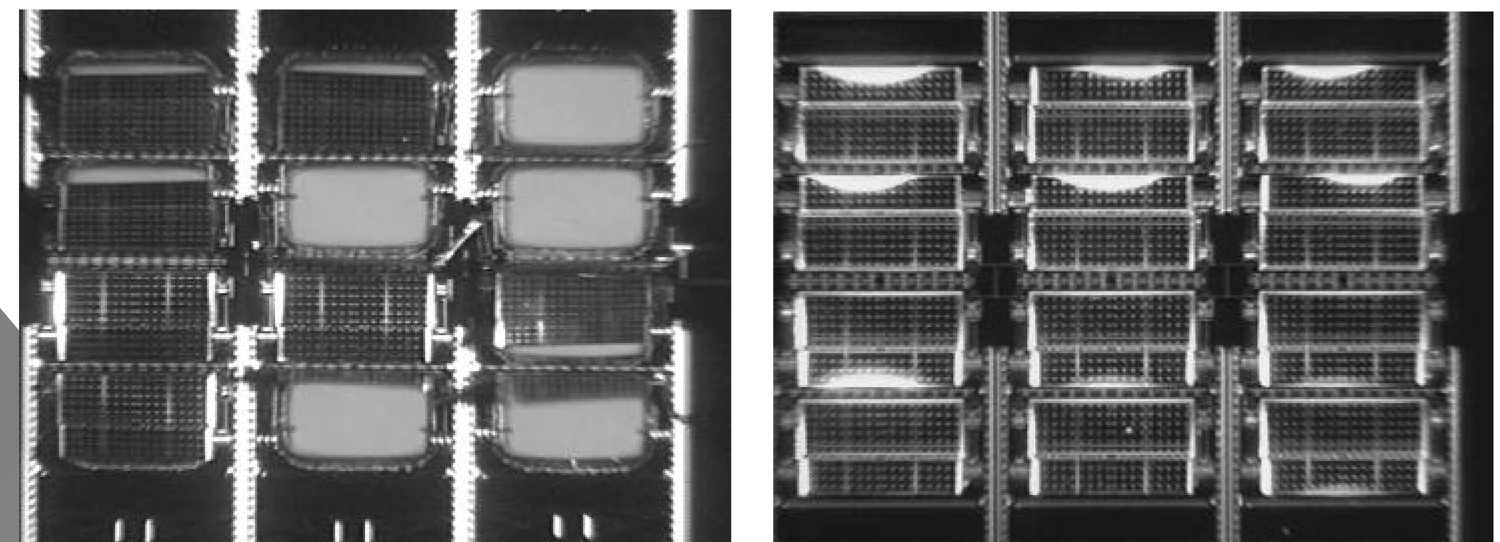


Open Louver



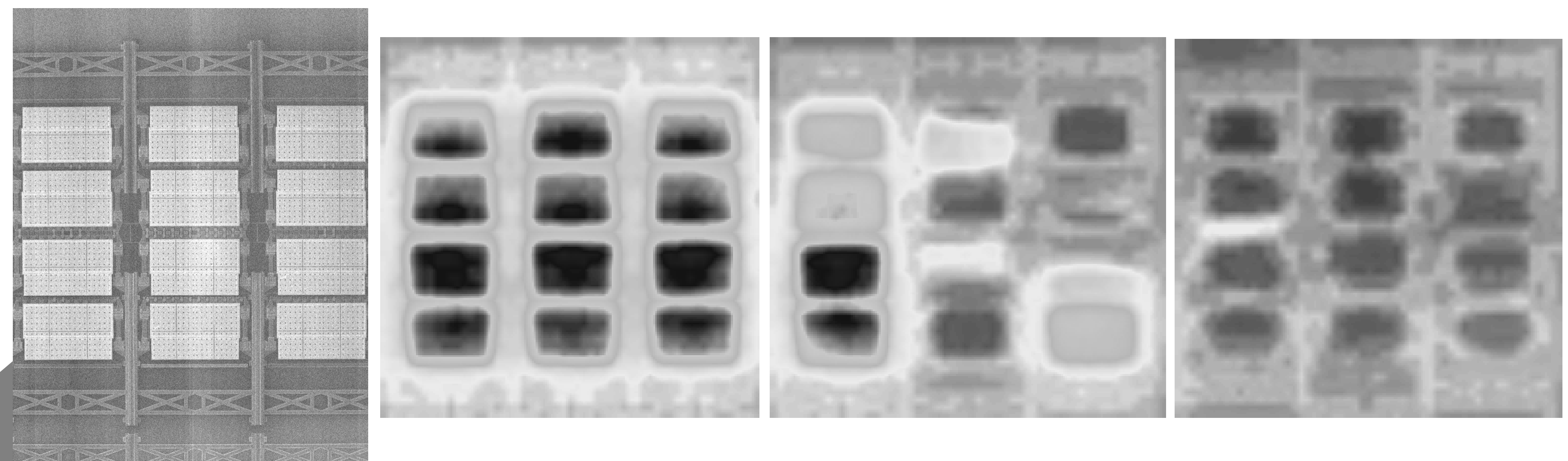
Hinge Detail

MEMS Louvers
Optical Image of First Design

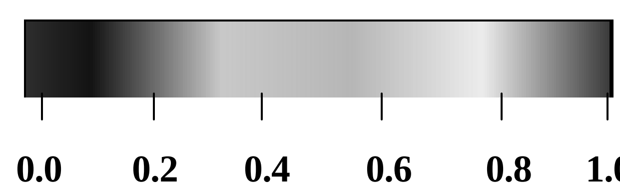


Optical Image of a Louver Array, With Open Louvers (Left) and All Louvers Closed (Right). The Open Louvers Expose the Radiator (Gray Background) Through the Etched Openings.

MEMS Louvers
IR Measurements of First Design



Closed------------Partially Open--------------Open



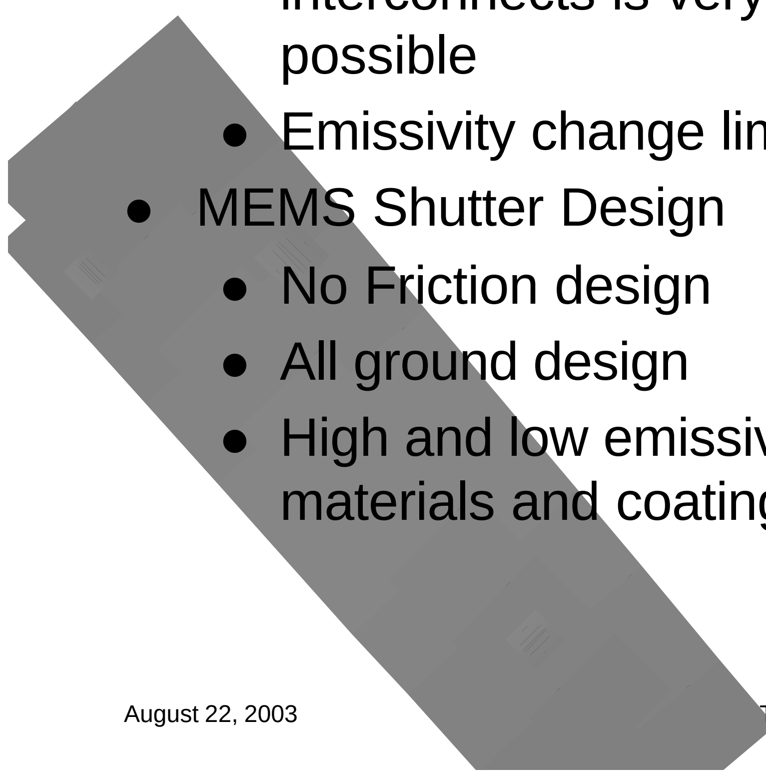
Emissivity (3-5 μm)

<u>Louver Array Emissivity:</u>

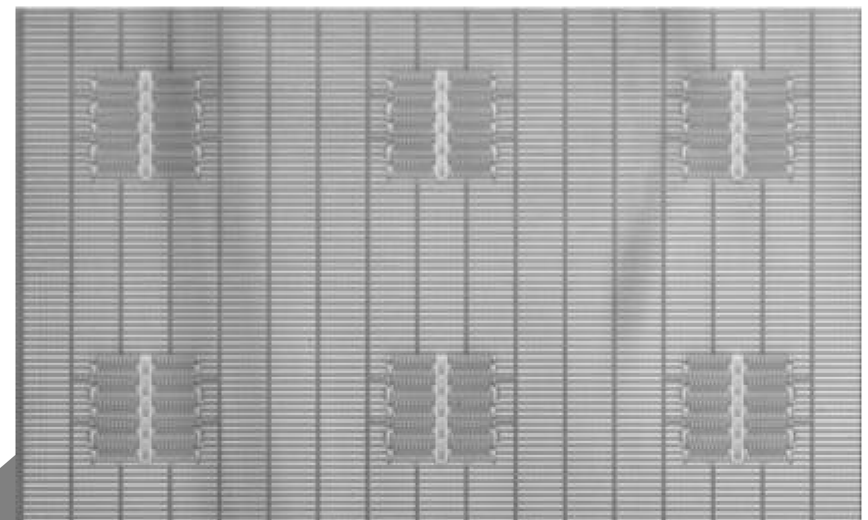
Closed	**0.5**
Partially Open	**0.75**
Open	**0.88**

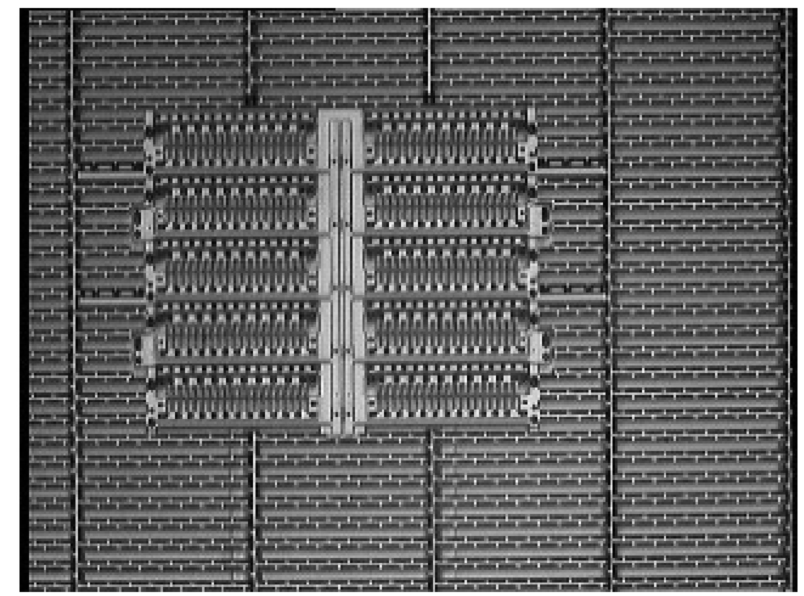
MEMS Shutters
Final Design Selection

- Development issues resulted in shutter design
  - Low Power Electrostatic comb drive required Sandia's 5-Layer Special SUMMiT V MEMS Process (comb drive footprint only 10 % of Area)
  - Turnaround time for the special SUMMiT V with buried interconnects is very long (9-12 months) - only one prototype run possible
  - Emissivity change limited by design to 40 % (eHigh - eLow)
- MEMS Shutter Design
  - No Friction design
  - All ground design
  - High and low emissivity limited to the properties of MEMS materials and coatings (Gold, Silicon)



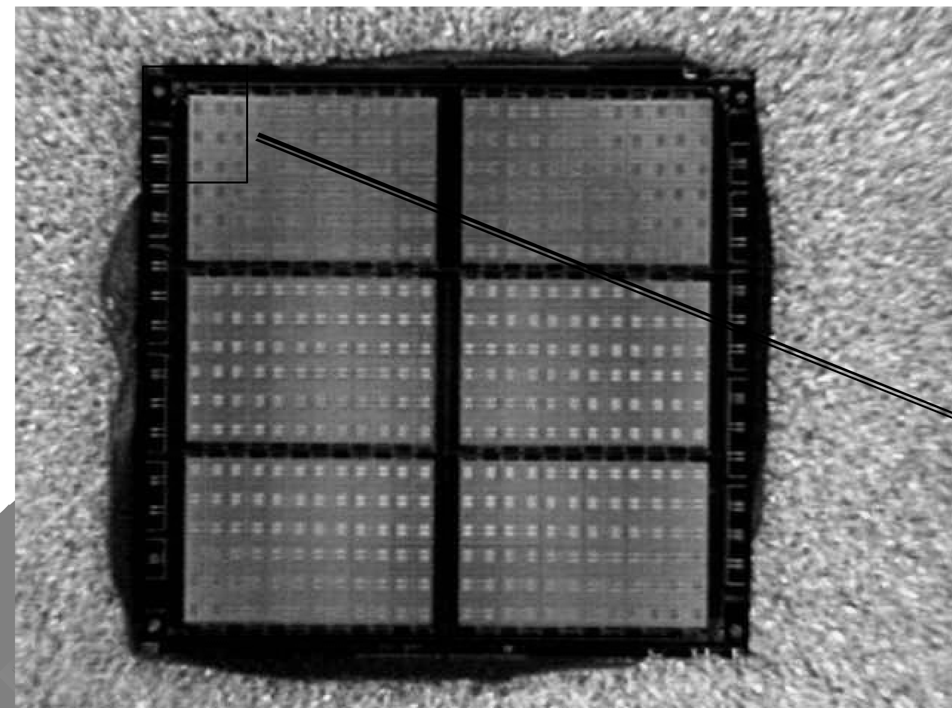
MEMS Shutters
Basic Design



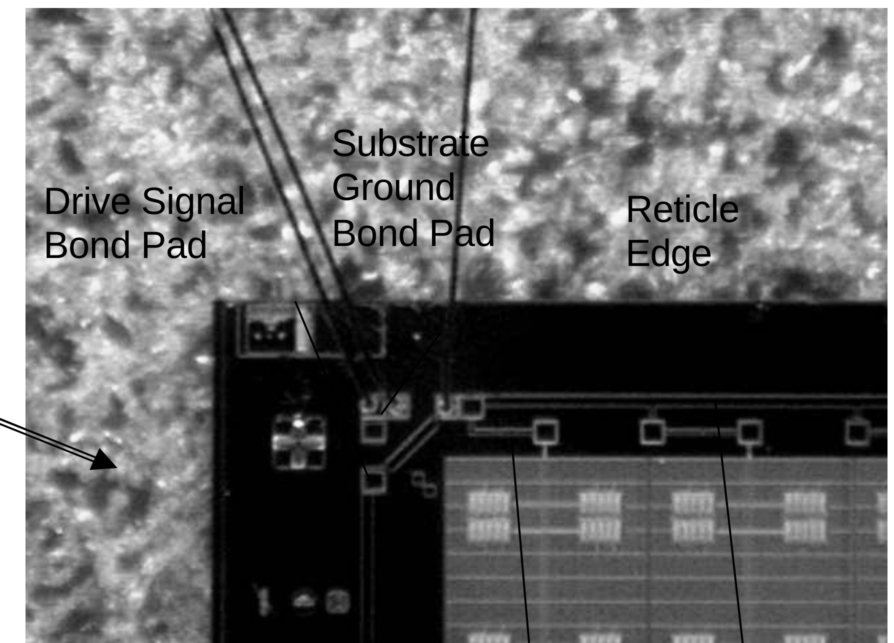


- Shutters and Slits: 6 mm x 150 mm
- Die Design Area: 11.8 x 11.8 mm
- Active Area: 1.12 cm^2
- Diced Die: (12.65 x 13.03 mm) 1.65 cm^2
- 9 Building Block: 1.77 mm x 0.88 mm, driven simultaneously by 6 comb drive units
- Design repeatable over 6 in wafer

MEMS Shutters
Flight Design



11.8 mm

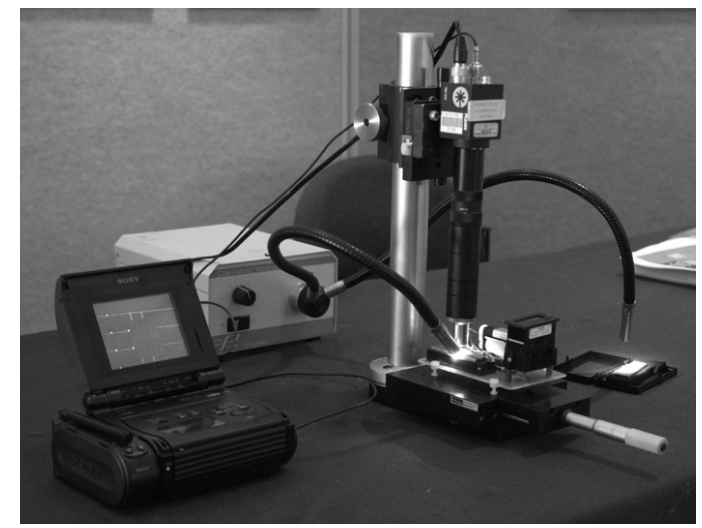


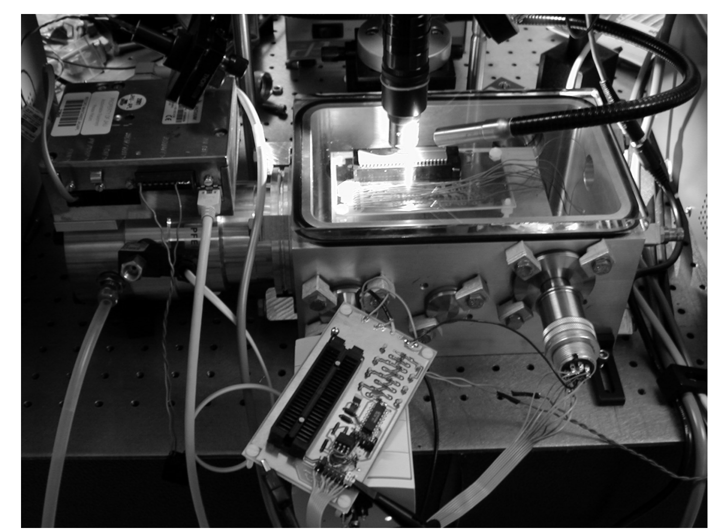
- All Building Blocks connected to a single Bus with 20 mA Fuse connect to buried Interconnects
- Dual Bond Pads for Bus and Ground at corners

MEMS Shutters
Current Status

- Final generation shutter die delivered, 12 wafers (+ 1 test wafer), 69 die/wafer
  - All process-steps performed and verified on test wafer
  - Test wafer dies mounted and tested
- Performance-Testing on Prototype
  - Endurance testing in Air (> 1 year)
  - Vacuum testing (> 3 Million cycles)
  - Temperature Testing in Vacuum
  - High: +80°C
  - Low: - 130°C
  - 6 Temperature Cycling: - 40 °C to +80 °C
  - IR Emissivity

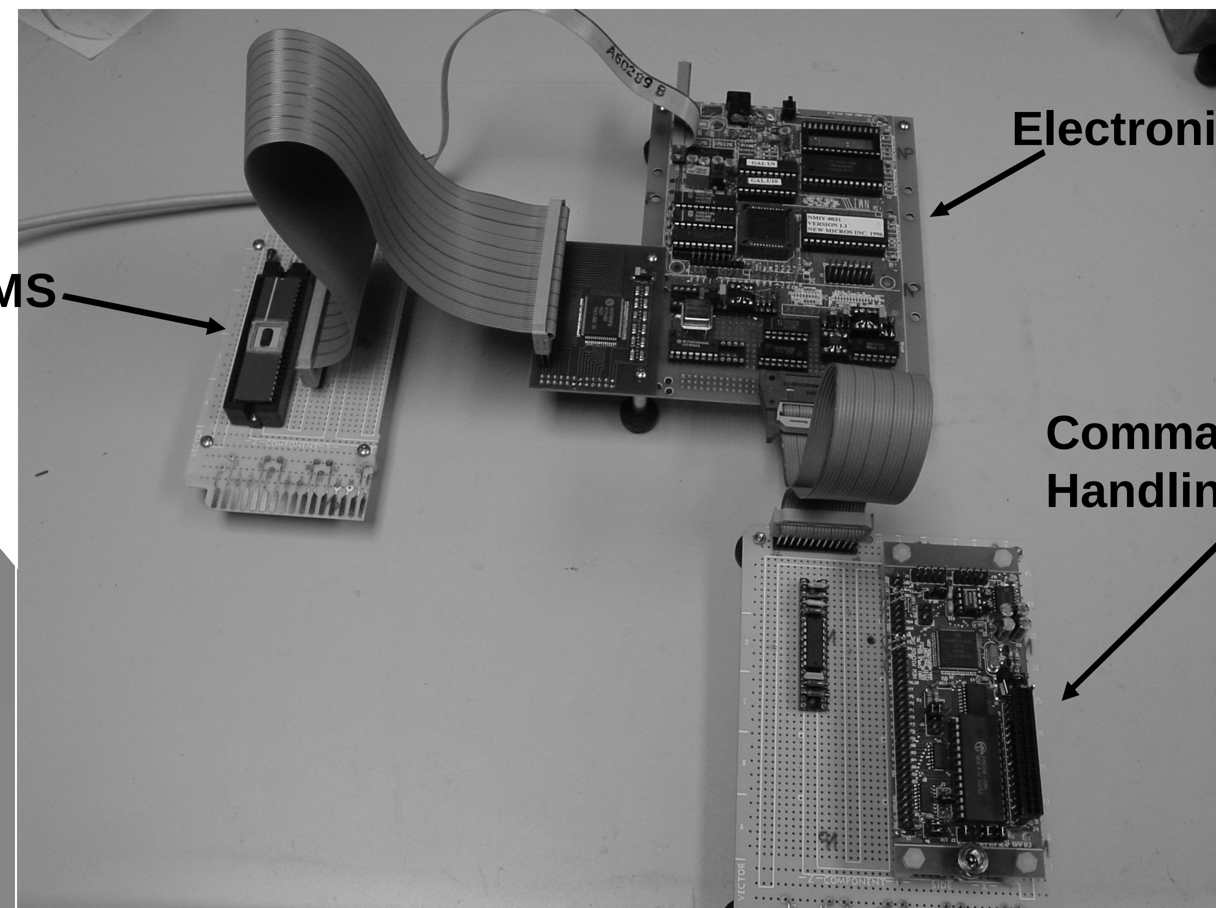
Ambient





Vacuum

MEMS Shutters
Current Status



MEMS Shutters

Milestone/Schedule

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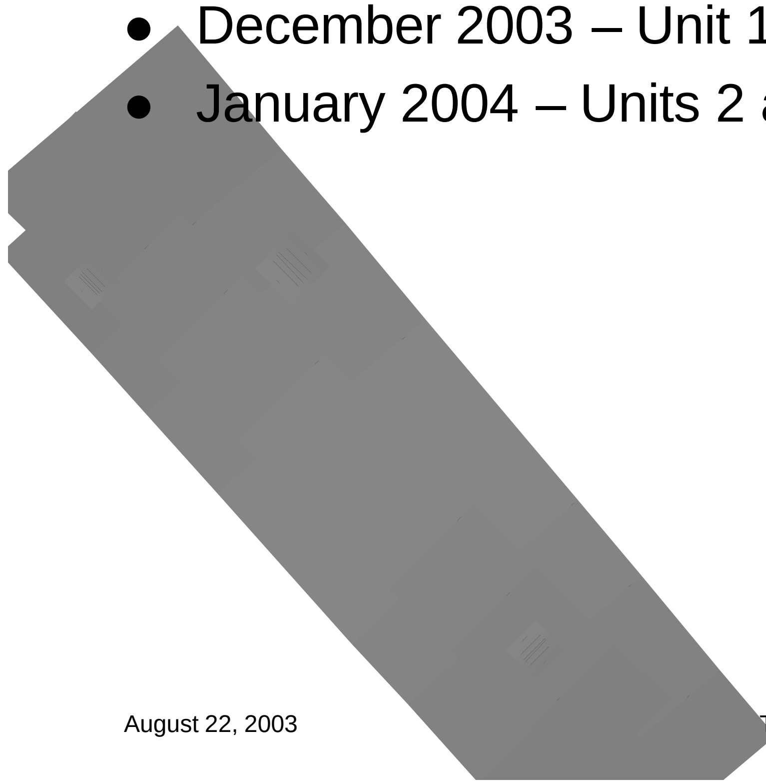

Major Issues/Concerns

- Initially started out with two other VEC technologies that had sealing problems and could not survive vacuum
  - Electrochromic
  - Electrophoretic
- Difficulty finding Rad-hard 5 Volt parts
  - Expensive
  - Long lead times
- Change in MEMS design due to hinge failures resulted in reduced performance
- Funding has been the major issue
  - Project wouldn't pick up funding until technology was at TRL 5
  - Technologies started out as concepts with very little funding
- Companies not experienced in producing hardware requiring lots of assistance/support.

Literature

- M.S. Rodgers, J. J. Sniegowski, Designing Microelectromechanical Systems-on-a-Chip in a 5-Level Surface Micromachine Technology, Presented at the 2nd International Conference on Engineering Design and Automation, Maui, Hawaii, August 9-12, 1998.
- J. Champion, R. Osiander, A. M. Garrison Darrin, and T. Swanson, "MEMS Louvers for Thermal Control", MNT99 Proceedings, pp 233-241, 1999
- A. M. Garrison Darrin, R. Osiander, J. Champion, T. Swanson, and D. Douglas, "Variable Emissivity Through MEMS Technology", STAIF AIP Conference Proceedings 504, Mohamed S. El-Genk, ed., pp 803-809, New York, 2000
- L.M.Grob., T.D.Swanson, "Parametric Study of Variable Emissivity Radiator Surfaces," in proceedings of Space Technology and Applications International Forum (STAIF-2000), edited by M. El-Genk, AIP Conference Proceedings, New York, 2000, pp. 809-814.
- J. Champion, R. Osiander, A. M. Garrison Darrin, T. Swanson, D. Douglas, and L. Grob, "Variable Emissivity Through MEMS", ITHERM Proceedings, p 215, 2000

Literature

- J. Champion, R. Osiander, A. M. Darrin, J. Sniegowski, S. Rogers, D. Douglas, and T. Swanson, "Micromachined Louver Arrays for Spacecraft Thermal Control Radiators", AIAA2001-0215, January 8-11, 2001
- Douglas, D., Michalek, T. and Swanson, T. D., "Design of the Thermal Control System for the Space Technology 5 Microsatellite," 31st International Conference on Environmental Systems 2000-01-2214, 2001.
- D.Douglas, T. Swanson, R. Osiander, J. Champion, A. Garrison Darrin, W. Biter, and P. Chandrasekhar, "Development of the Variable Emittance Thermal Suite for the Space Technology 5 Microsatellite", Space Technology & Applications International Forum, 2002
- R. Osiander, J. L. Champion, M. A. Darrin, J. J. Allen, D. Douglas, T. D. Swanson, "Micro-machined Shutter Arrays for Thermal Control Radiators on ST-5", AIAA-2002-0359, 2002

Literature

- D. Farrar, W. Schneider, R. Osiander, J.L. Champion, A.G. Darrin, D. Douglas, T.D. Swanson, "Controlling Variable Emittance (MEMS) Coatings for Space Applications", ITHERM Proceedings, 2002
- R. Osiander, J.L. Champion, A.G. Darrin, D. Farrar, W. Schneider, J. J. Allen, D. Douglas, T.D. Swanson, “MEMS Louvers for ST-5", Spacecraft Thermal Control Workshop, 2002
- R. Osiander, J.L. Champion, A.G. Darrin, D. Farrar, W. Schneider, J. J. Allen, D. Douglas, T.D. Swanson , J.Allen,E.Wyckoff, “MEMS Shutters for Spacecraft Thermal Control", Nanospace, 2002
- D.Farrar, W.Sneider, R.Osiander, J.Champion, M.A. Darrin, D.Douglas, T.Swanson, “Controlling Variable Emittance Coatings (MEMS) for Space Applications", Space Technology & Applications International Forum, 2003