JPL Advanced Thermal Technology Team

- Dave Bame — MER & MSL Heat Rejection System
- Pradeep Bhandari — Pumped Fluid Loops, Long-Life Pumps
- Gaj Birur — Advanced Thermal Control Technologies
- Gani Ganapathi — MER Heat Rejection System
- Ram Manvi — Venus Thermal Control Technologies
- Keith Novak — MER Loop Heat Pipe and Heat Switch
- Mike Pauken — LHP; Venus/Titan Thermal Technologies
- Mauro Prina — High Temperature Pumped loops
- Jose Rodriguez — TES Loop Heat Pipe
- Eric Sunada — MER Heat Switch; Thermal Stability Techs.
- Glenn Tsuyuki — MER Pumped Loop; Mars Lightweight Insulation
OUTLINE

• Future NASA/JPL Missions
• JPL Thermal Control Technology Roadmap
• Specific Technologies Under Development
• Conclusions
Future Space Science Missions at JPL

- Thermal control requirements of many of the future NASA space science missions are expected to be very demanding

- Mars missions -
  - MRO(2005), Phoenix (2007)
  - Mars Science Laboratory (2009), Mars Sample Return (2013)

- Deep Space Science Missions (Missions to other Planets)
  - Jupiter Icy Moon Orbiter, Europa Orbiter/Lander,
  - Venus Surface Sample Mission, Jupiter Multiprobe,
  - Titan In-Situ Mission, Saturn Ring Observer, Neptune Orbiter

- Other Space Missions -
  - Earth orbiting spacecraft/science payload, space telescopes, space interferometer missions, and science instruments
  - Microspacecraft missions, Inflatable/deployable spacecraft
Mars Exploration Program (2001)

Launch Year

<table>
<thead>
<tr>
<th>2001</th>
<th>2003</th>
<th>2005</th>
<th>2007</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Mars Odyssey</td>
<td>ESA Mars Express</td>
<td>NASA Mars Reconnaissance Orbiter</td>
<td>Italian G. Marconi Telecom Orbiter</td>
<td>Italian / NASA Science Orbiter</td>
</tr>
<tr>
<td>Japanese Nozomi Orbiter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Science pathways responsive to discovery

...Next Decade

SAR recon orbiter
More Recon
More MSR?
Get samples
First MSR
Explore local diversity
Multi-scout Orbiter & Landers
Life inference
Smart lander with life inference
Get to subsurface
Deep drilling lab
Sample return
Mars Exploration Program (2004)

Launch Year

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars Telesat Orbiter</td>
<td>Scout</td>
<td>Mars Sample Return</td>
<td>Scout</td>
<td>MTO 2 Telesat</td>
<td>Scout</td>
</tr>
<tr>
<td>Mars Science Laboratory</td>
<td>Astrobiology Field Laboratory</td>
<td>OR</td>
<td>Deep Drill Lander</td>
<td>OR</td>
<td>Network Landers</td>
</tr>
</tbody>
</table>
Mars Exploration Rovers (2003)

- 90-sol science missions
- Equatorial landing sites
- Deep temp. swings (-90 to 10°C)

Lander after the Egress of Spirit Rover at Gusev Crater (sol 19)

MER Rover (2003)

Opportunity Rover self portrait (Sol 322)
Mars Rovers – Past, Present, and Future

MSL (2009), ~ 500 kg
Pumped Fluid Loops

Issues:
• Large Thermal Loads
• Long Life

Sojourner (1996), 12 kg
Aerogel, Passive TC

MER (2003), 180 kg
Aerogel, Heat Switch

Pre-decisional DRAFT - for Planning & Discussion Purposes Only
Planetary Extreme Environment

Temperature (°C)

Pressure (bars)

-250
0
250
500

0
10
100
1000

0.01
0.1
1
10
100
1000

Titan In-Situ
Earth
Jupiter Probes
Europa Surface and Subsurface
Venus Surface Exploration

Pressure, bars

Depth wrt 1 bar, km

Temperature, K

Papers/##Aerowks/2005-wkshp/jpl techno--.ppt
March 9, 2005; Gaj Birur
Venusian Environment

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Altitude (km)</th>
<th>Pressure (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
<td>MONS MAXWELL</td>
</tr>
<tr>
<td>365</td>
<td>365</td>
<td>90 Bars</td>
</tr>
<tr>
<td>220</td>
<td>20</td>
<td>LOW ALTITUDE BALLOON 15 Bars</td>
</tr>
<tr>
<td>130</td>
<td>40</td>
<td>MEDIUM ALTITUDE BALLOON 2 Bars</td>
</tr>
<tr>
<td>70</td>
<td>50</td>
<td>HIGH ALTITUDE BALLOON 0.5 Bar</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>SULFURIC CLOUD LAYER</td>
</tr>
<tr>
<td>30</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>460</td>
<td></td>
</tr>
</tbody>
</table>

High Altitude Balloon: 0.5 Bar

Medium Altitude Balloon: 2 Bars

Low Altitude Balloon: 15 Bars

Lander: 11 km, 365°C

Mons Maxwell: 90 Bars
Titan In-Situ and Comet Environment

Thermal technologies needed to protect the science and engineering equipment to survive and operate in Titan/Comets low temperature (-180 to -140 C) environment:
Space Interferometer Missions

- Space Interferometer Missions, Terrestrial Planet Finder, and future space telescope missions need picometer accuracy and 100 micro-Kelvin temperature stability.
Jupiter Icy Moon Orbiter (JIMO)

THERMAL CONTROL CHALLENGES

• Large thermal and electric power management (~100 kWe, 0.5 to 2 MWt)
• High heat flux thermal control
• High temperature heat transfer and rejection issues

Pre-decisional DRAFT- for Planning and Discussion Purpose Only
• **HRS for Lunar Mission**  
(David Westheimer, PI, NASA/JSC)  
- Vapor Compression Heat pump  
- Lightweight Radiator (JPL)  
- Multi-environment Evaporative Heat Sink  

• **Microspacecraft Inspector**  
(Dr. Juergen Mueller, PI, JPL)  
- Variable emittance radiator (JPL)
### JPL Thermal Control Technology Roadmap

#### PASSIVE TECHNOLOGIES

<table>
<thead>
<tr>
<th>Technology</th>
<th>Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop Heat Pipe</td>
<td>Mars rovers, Microspacecraft, Deep Space Missions, ST-8</td>
</tr>
<tr>
<td>PCM Thermal Storage</td>
<td>Mars, Extreme Env. Missions (Venus)</td>
</tr>
<tr>
<td>Heat Switches</td>
<td>Deep Space, Mars rovers, Earth Orbiting Missions</td>
</tr>
<tr>
<td>Variable Emitt. Devices</td>
<td>Deep Space, Earth Orbiting, Microspacecraft Missions (ESR&amp;T)</td>
</tr>
<tr>
<td>Passive Loop Arch.</td>
<td>Mars, Deep Space, Earth Orbiting Missions, SIM</td>
</tr>
</tbody>
</table>

#### ACTIVE TECHNOLOGIES

<table>
<thead>
<tr>
<th>Technology</th>
<th>Missions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-temp.loops</td>
<td>Mars Missions, JIMO, Deep Space Missions</td>
</tr>
<tr>
<td>Active High heat flux and Micro-cooling Sys</td>
<td>Deep Space Missions, Microspacecraft, Earth Orbiting</td>
</tr>
<tr>
<td>Active Loop Architecture</td>
<td>Mars Missions, JIMO, Microspacecraft Missions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>05</th>
<th>06</th>
<th>07</th>
<th>08</th>
<th>09</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Mechanically Pumped Cooling Loops

Description

- Mechanically pumped single-phase cooling loop used on Mars Pathfinder (1996) and MER (2003) for thermal control
- A pump assembly of 7 kg uses CFC-11 to remove ~160 W from spacecraft electronics to an external radiator
- A high temperature (~100 °C) pump test loop is used for life testing pumps for high heat rejection capacity (>3 KW)

Participants & Facilities

- JPL is investigating this technology for future Mars and deep space missions
- Engineering pump units (Pacific Design Technology, Goleta, CA) are under life test at JPL
High Temperature Pump Testbed

- Designed to maintain pump and fluid at 120°C with a system pressure ~ 150 psia (1 MPa)
- Successfully operated for 2900 hrs at 120°C with water
- Currently being tested with CFC-11 at 100°C
Material Compatibility Tests (Water & CFC-11)

WATER

- Stainless steel and Aluminum tubing samples are filled with Nanopure water and baked 150°C

- Material compatibility testing at 150°C showed that the nano-pure water reacts with aluminum and is incompatible

- Corrosion inhibitors and additives are needed for long-term use of water at 150°C in Al

CFC-11

- Stainless steel, Aluminum, and SS/Al welded tubing samples are filled with CFC-11 and baked in a 100°C oven

- The high temperature loop (with ss and aluminum tubing) will be run with an engineering pump and CFC-11 at 100°C
MSL Long-Life Testbed

Testbed for life testing MSL mechanically pumped loop technologies
**Description:**
- A versatile thermal control device: transfers heat, controls temps., and act as a heat switch (all in one)
- Light weight (< 250 gms to transfer 100 W) device compared to other the hardware of same function
- Enormous flexibility in locating heat sources and sinks on the spacecraft

**Participants & Facilities:**
- JPL is investigating this technology for ST-8, Mars rover & μS/C applications
- Tests performed at JPL and Goddard during FY00-02 for evaluating miniature multiple evaporator LHP
- Currently a small multiple evaporator LHP technology being investigated for ST-8 with NASA GSFC (Jentung Ku, PI)
EOS-TES Loop Heat Pipes
(Full Size/Capacity LHPs)

- EOS-TES is using five LHPs in its thermal design (Jose Rodriguez)
- Propylene LHPs in the 75 to 150 W range
- TES is currently operating on EOS spacecraft with all the LHP functioning satisfactorily
Heat Switch for Space & Mars Surface Applications

Description

• Wax actuated heat switch for Mars with target performance of 0.4 W/C, switch ratio of 30 in 8 torr CO₂, weighing less than 120 gms. Currently functioning well on the two MER rovers.

Participants & Facilities

• Wax actuated heat switch for MER was developed by Starsys, in Boulder, CO.

• The heat switches have been operating satisfactorily for over 300 sols on Mars on two rovers.
Advanced pumps & cold plates for two-phase cooling loops (NASA SBIR Phase I Project)

DESCRIPTION:
- Compact, lightweight reliable two-phase pumped loop
- Compact hermetic pump design using direct electromagnetic drive of the impeller
- Positive displacement pump tolerates 2-phase flow at inlet
- Advanced offset strip fin design for cold plate
- Suitable for high heat fluxes or long distances between heat source and radiator
- Useful for distributed sources and sinks on a single loop
- Suitable for loads from <10 W to > 2kW

Participants & Facilities
PI: Dr. Jerry Martin
Mesoscopic Devices, LLC, Broomfield, CO
- Joe Marsala, Thermal Form & Function, LLC, MA

Project Duration: Jan. 2005 to July 2005

NASA Technical Monitor: Eric Sunada, JPL

SCHEDULE and MILESTONES
- Phase I goal: Demonstrate ~500 W pumped cooling loop (July 2005)

Applications:
- High density micro/nano-spacecraft electronics. High power electronics - JIMO. Laser Diode Arrays for Earth Science Missions
- Rack-mount server computers, power electronics, microwave systems, phased array radar

Hermetic pump prototype
Ø 30 mm
DESCRIPTION:

- Variable Emittance panels based on Conducting Polymers, Ionic Els.. Phase II development of a Phase I SBIR project.

- Flexible, very thin, very durable, very lightweight (20 mg/cm²), very low power (about 50 µW/cm²), unsealed unit in vacuum (> 6 months demonstrated).

- Emittance variation > 0.4, range 0.15 to 0.89. Low $\alpha_s$

- Modular electronic controller for automated “dialing” of desired Emittance; Antioxidants or vacuum package for long shelf life in air

SCHEDULE and MILESTONES

- Year 1 - Completion of major space durability testing, refinement of Solar-Absorptance-lowering coating and refinement of air stability.

- Year 2 - Completion of all remaining space durability testing. Fabricate optimized prototype devices and non-rad-hard Intelligent Controller.

APPLICATIONS

- Substitute for Mechanical louvers, variable conductance heat pipes, heat switches for LEO, GEO, inter-planetary, intra-planetary missions.

- Dual use: Military (battlefield) IR camouflage.

Participants & Facilities

PI: Dr. P. Chandrasekhar
Ashwin-Ushas Corp, Inc., Lakewood, NJ
www.ashwin-ushas.com

- Georgia Tech Research Institute (Controller - Andre Lovas)
- AFRL (independent thermal vac testing - Charlotte Gerhart)

NASA COTR: Dr Gaj Birur, JPL
HYBRID COOLING LOOP TECHNOLOGY
(NASA SBIR Phase II Project)

DESCRIPTION:
• Combining robust liquid supply of mechanically pumps with passive flow control of capillary structures
• High heat flux removal: 350 W/cm² demonstrated in Phase I
• Cooling of large area: 4cm² demonstrated in Phase I
• Low thermal resistance: 0.008 to 0.065°C/W/cm² demonstrated in Phase I
• Passive flow control: No active control is needed even at transient and asymmetric heating conditions
• Phase II to test prototypes for space applications

SCHEDULE and MILESTONES
• Year 1 – Develop integral evaporator/reservoir assembly.
• Year 2 – Design, fabricate and test engineering units for spacecraft thermal control applications.

APPLICATIONS
• Substitute for capillary- and mechanically pumped loops for better performance, greater reliability and more robust operation for satellites and exploration systems thermal control.
• Dual use: Military and commercial high power electronics and opto-electronics.

Participants & Facilities
PI: Dr. Jon Zuo
Advanced Cooling Technologies, Inc., Lancaster, PA www.1-ACT.com
• Johns Hopkins University Applied Physics Laboratory (miniature adaptive liquid nozzle development)

NASA COTR: Dr. Anthony Paris, JPL
Self-Contained Distributed Cooling Module for High Heat Sources (NASA SBIR Phase II Project)

DESCRIPTION:
• Autonomous thermal management system with self-pumped cooling module.
• Outperforms heatpipes; Heat fluxes >100 W/cm²
• Inherently scalable design
• Compact module with low mass & power (<1 W)
• Stackable fixed-valve micropump integrated in module
• Ceramic stereolithography manufacturing process

APPLICATIONS:
• Microspacecraft missions, Lasers, Radar, Lidar, Fuel cells, Avionics
• Microprocessors, Inverters, X-ray, Wide-band gap semiconductors, Hybrid electric vehicles, Power conversion

SCHEDULE and MILESTONES:
• Year 1 (Completed): Optimized heatsink and pump operation.
• Year 2: Brassboard prototype—Fully integrated system with microprocessor chip as heat source
• Project completion: December 2005

Heatsink + Pump = Chip-sized cooling module 1.0 °C/W single phase, < 0.5 °C/W 2-phase

PARTICIPANTS:
PI: Dr. Reza Shekarriz, MicroEnergy Technologies, Vancouver, WA
Co-I: Dr. Fred Forster, University of Washington
Co-I: Walter Zimbeck, Technology Assessment & Transfer

NASA COTR: Dr. Anthony Paris, JPL
DESCRIPTION:

• Ceramic substrate with embedded Microchannel Heat Exchanger for high heat flux electronics
• High thermal conductivity Al nitride (AlN, 200 W/mK) with single phase, mechanically pumped systems
• Ceramic Stereolithography fabrication - enables monolithic microchannel substrates, automation
• CFD modeling to optimize channel geometry
• Two Application Targets: include Low heat flux (25 W/cm²): chip cooling, compact package; High heat flux (100 W/cm²): laser diode arrays

Participants & Facilities

PI: Walter Zimbeck, Technology Assessment & Transfer, Inc. Annapolis, MD www.techassess.com
• MicroEnergy Technologies - CFD modeling (Reza Shekarriz)
• Swales Aerospace - Laser cooling system (Dave Bugby)
Project Duration: 12/03 – 12/05

NASA COTR: Dr. Tony Paris, JPL

SCHEDULE and MILESTONES
• Year 1 - Design Optimization, Req. Definition
  • Modeling, prototype fab., benchscale testing
• Year 2 – Prototype System Fabrication/Test
  • Deliver 25 W/cm² chip cooling system to JPL
  • Demonstrate Laser Diode Array cooling system

Applications
• High density micro/nano-spacecraft electronics. High power electronics – JIMO. Laser Diode Arrays for Earth Science Missions
• Desktop & Laptop PCs, Network servers, Power Electronics for Elec. Vehicles, Ind. Lasers
Conclusions

• Advanced thermal control technologies are needed to enable many of the future NASA science missions

• JPL has been developing several technologies working with industry and NASA centers

• Several advanced technologies have been infused into flights in the last 10 years; more are expected in the next 10 years
Phase Change Material (PCM) Thermal Storage Technology

Description

• Phase change material (PCM) utilizes latent heat to protect equipment against temperature extremes by increasing thermal capacity

• It stores excess heat when available and releases when needed. Simple and reliable technology

• Applications in Mars and extreme environment missions

Current Status

• A dodecane (MP -10.5 C) PCM capsule (ESLI, San Diego) was integrated with miniature LHP and tested for Mars rover battery thermal control

• A Hexadecane (MP, 18 C) PCM from ESLI is being evaluated for Mars rover battery thermal control at JPL