Low Temperature Thermal Cycle Survivability and Reliability Study for Brushless Motor Drive Electronics(#1360)

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Outline

- **Introduction**
  - **Current capabilities**
  - **Needed technologies**
- **Electronic Packaging:**
  - **Selection of materials and assembly processes**
  - **Failure analysis**
- **Electronics components:**
  - **Low temperature testing**
  - **Reliability at low temperatures**
  - **Development of new components**
- **Electronics motor drive assembly**
- **Conclusions**
- **Acknowledgements**

Current Technology Capabilities

- **Currently used drive electronics for motors and actuators requires thermal control for entire mission life**
  - **Space rated electronics functional temperature range -55ºC to +125ºC vs Mars environment -120ºC to +20ºC**
- **Motor drive electronics is typically located in a central location of the spacecraft/rover and a large quantities of wires (up to 20 per actuator) must be cabled from the central location to each actuator**
  - **MER has about 40 actuators, MSL will need about the same number**
- **Actuators rotary life capabilities that are inadequate for planned future rover missions**
  - **Brush motors have limited life on Mars and very little life in vacuum**
  - **Brushless motors have no life issues in vacuum or on Mars**

Objectives

- **Develop the technologies to build a flight actuator that will:**
  - **Survive and function in the Martian environment without the need for thermal control:**
    - **Operating range: -120°C to +85 °C**
    - **Total Life Test Cycles: 2010 (3X) from -120°C to +85 °C**
    - **Functionally tested to -135°C to establish reliability margin**
- **Extend the mechanical life of a mission more than a factor of 20 beyond current actuator capabilities:**
  - **A roving range beyond 100 km**

Needed Technologies

- **Electronic packaging - selection of materials and assembly techniques for thermal cycling survivability**
- **Electronics - parts design, fabrication, and characterization for operation down to -120 C**
- **Electro-mechanical - motor and gearbox for reliable, long life operation**

Technologies

- **Electronics:**
  - **Understand how existing electronic parts behave, operate, and change over temperature**
  - **Extend mission assurance and reliability requirements for electronics down to temperatures of -120°C and lower**
  - **Understand failure mechanisms of electronic parts at these temperatures**
  - **Design, fabricate and qualify electronic parts (to replace parts that do not function as required at low temperatures)**

Technologies

- **Electronic packaging:**
  - **Find acceptable material combinations that will survive the required number of thermal cycles in the -120C to +85C temperature range**
  - **Understand failure mechanisms of electronic packaging over the required number and range of thermal cycles and their mitigation**
  - **Understand manufacturing issues associated with the selected packaging technology**

Technologies

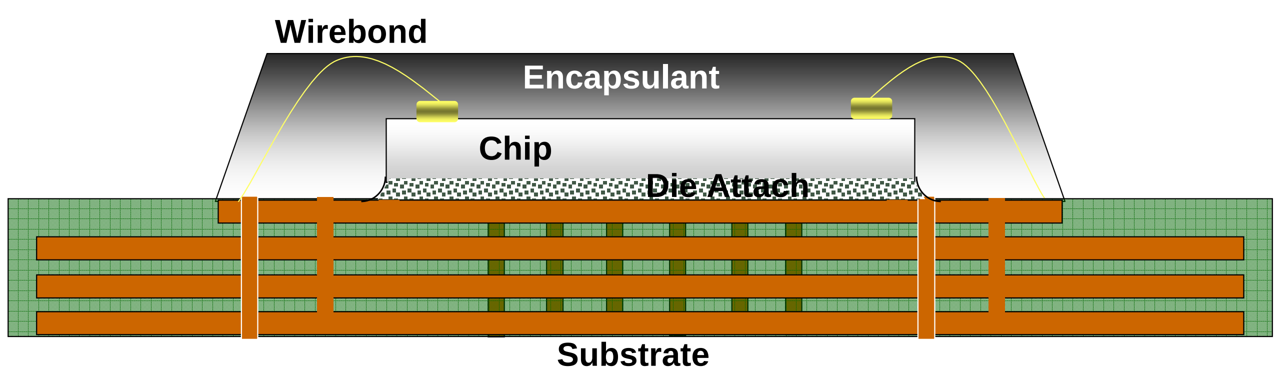
- **Electro-mechanical:**
  - **Determine what standard motor fabrication methods will survive the environmental thermal cycling**
  - **Determine the material combinations for gears, bearings, and lubrication that will provide the required rotary life and strength**
  - **Reduce the mass of a standard actuator assembly by 30%**

Electronic Packaging

Selection of packaging technology

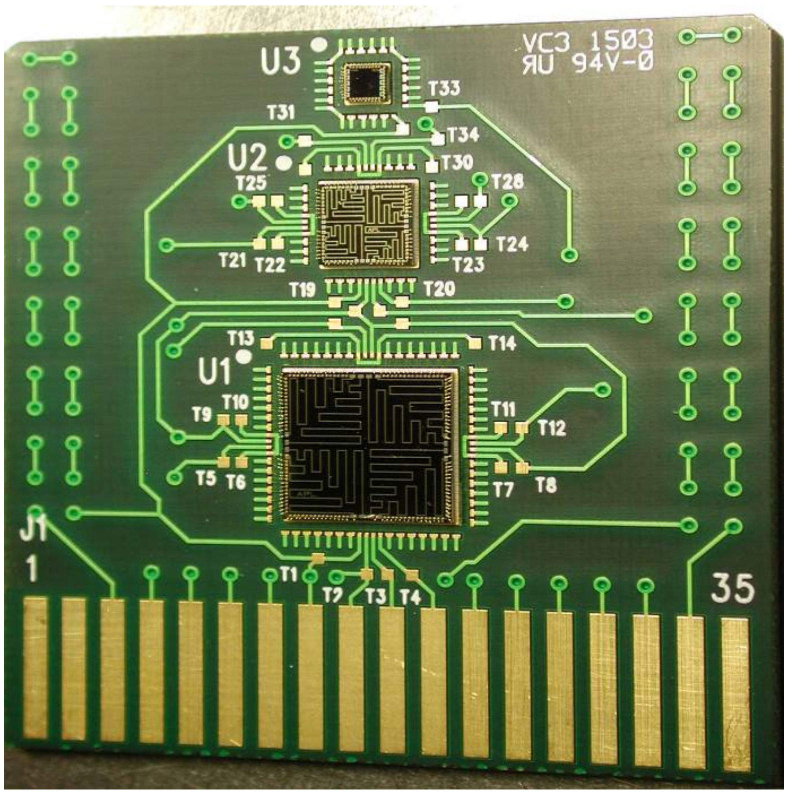
Selected Chip-on-Board :

- Minimal number of interfaces and interconnects
- Stress relief in wire bonds
- Good density



Chip-on-Board

Selection of packaging materials combinations - Test Vehicle 1 (TV1)



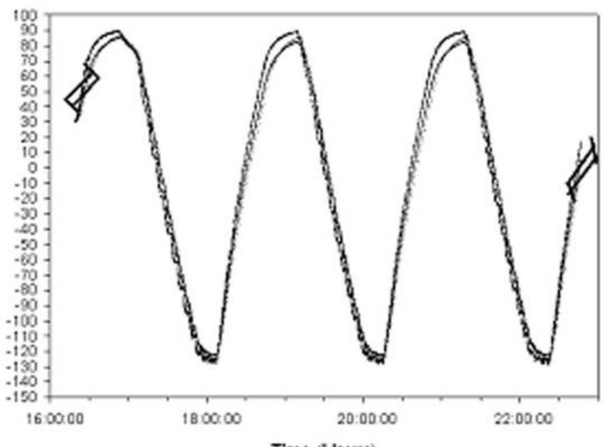
TV-1 Test Coupons shown without encapsulation

	Materials
Substrate	Polyimide , LTCC, Alumina
Encapsulant	Epoxy(Hysol 4402), Silicone based, Parylene
Die Attach	Epoxy, Solder (In), UV Curable Silicone
Wire	Au standard

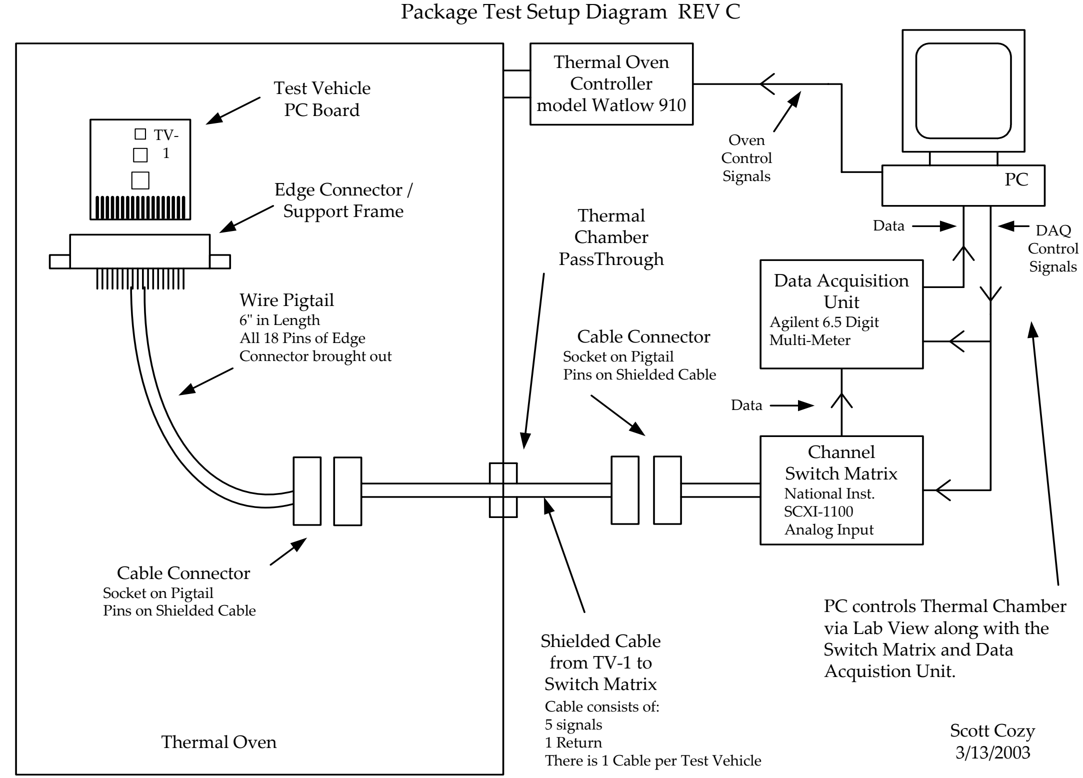
- Test vehicle one (TV1) represented different die sizes, wire bonds, via chains, and board/die attach/conformal coat material combinations
    - 270 test vehicles covering 27 material combinations
- TV1 testing completed with thermal cycles up to and beyond 2000

Environmental Testing

Tenney Model T6C-LN2
Environmental test chamber

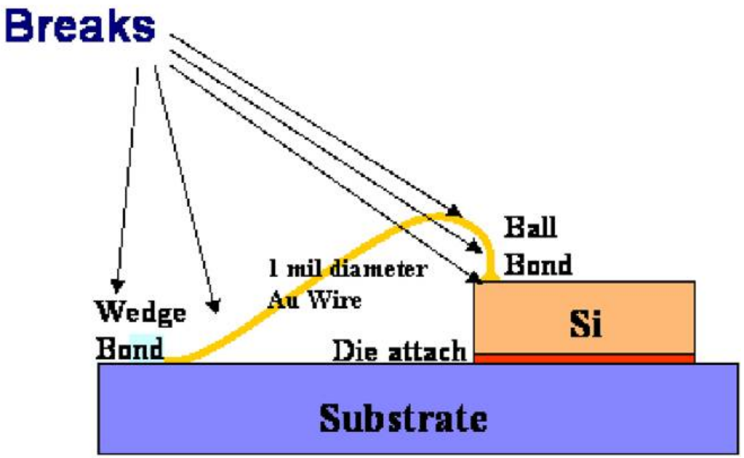


Thermocouple Cycling Data

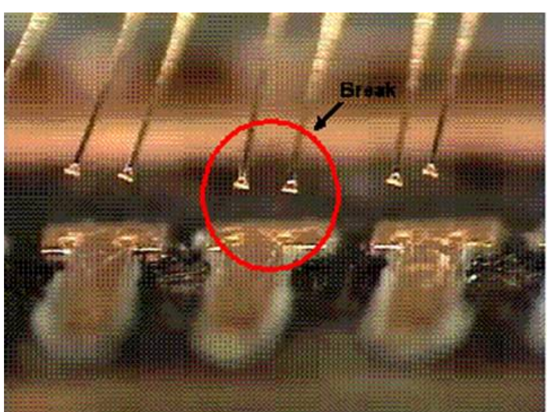


Continuous Monitoring Set-up

TV1 Test Results



TV1: 5 Failure Types

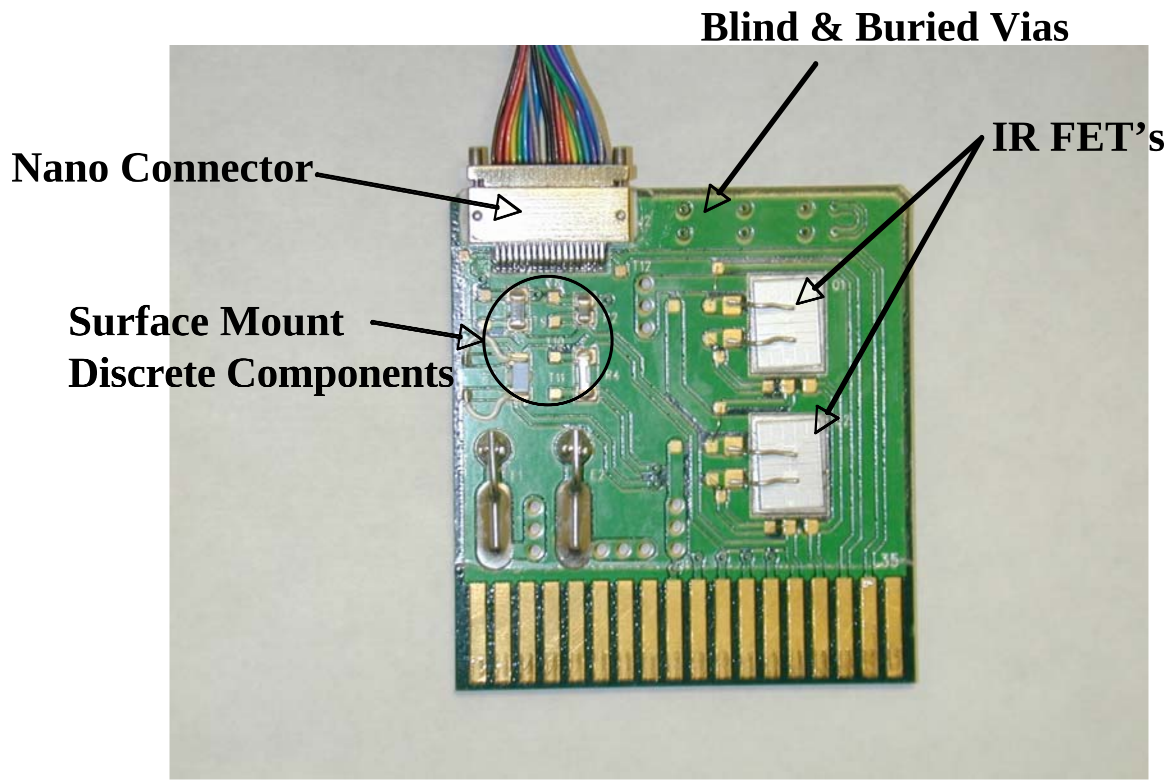


Break at the wedge bond on the substrate

SUBSTRATE TYPE	CYCLES		S/N	TOTAL CYCLES
POLYIMIDE	**10231332**			
	ABLEBOND 967-1	FP4402	-1	150
		DOW	-2	250
		PARYLENE	-3	2865
	ZYMET TC-611	FP4402	-4	150
		DOW	-5	1000
		PARYLENE	-6	3247
	INDIUM 100%	FP4402	-7	150
		DOW	-8	1000
		PARYLENE	-9	2295-2665

Selection of materials and assembly processes - TV2

- TV2 incorporated lessons learned from TV1- used surviving material combination from TV1
- Three types of substrate, three different die attach, and two encapsulating coating
  - 180 different test vehicles assembled, 10 of each configuration
- Each TV2 assembly included two International Rectifier FET die, 4 surface mount discrete components, one 37 pin nano-connector, blind and buried vias, and high current bifurcated terminals.



Assembled TV2 test vehicle

TV2 test results

SUB.	SERIAL NO	VIA (Ohms)	MOSFET DIE ATTACH	MOSFET DIE Al wb Dia.	RESISTORS ATTACH R1 (#)	R2 (#)	R3	R4 (# / *)	CONN. ATTACH (*)	CONN. STAKING	COAT.	TOTAL CYCLES
Polyimide	P001-010*	0.3	Ab 967-1	20 mil-638-863	Ab 967-1 638-863	Ab 967-1 638-863	Zymet TC/Sn63	Ab 967-1*	In80	2216 B/A	Dow	738-1531
	P011-020	0.3	Ab 967-1	20 mil-863-1182	Ab 967-1	Ab 967-1	Zymet TC/Sn63	Ab 967-1*	In80	2216 B/A	Pary C	1431-1918
	P021-030	0.3	In80	20 mil-638-863	In80	In80	Zymet TC/Sn63	In80* - 638-863	Sn 63	Zy TC	Dow	1182-2778
	P031-040*	0.3	In80	20 mil-638-863	In80	In80	Zymet TC/Sn63	In80#	Sn 63	Zy TC	Pary C	638-2778
	P041-050	0.3	Zy 6000.2,	5 mil	In80	In80	Zymet TC/Sn63	In80*-0-638	In80-638-863		Dow	638-2678
	P051-060	0.3	Zy 6000.2,	5 mil	In80	In80	Zymet TC/Sn63	In80*	Sn 63		Pary C	2778

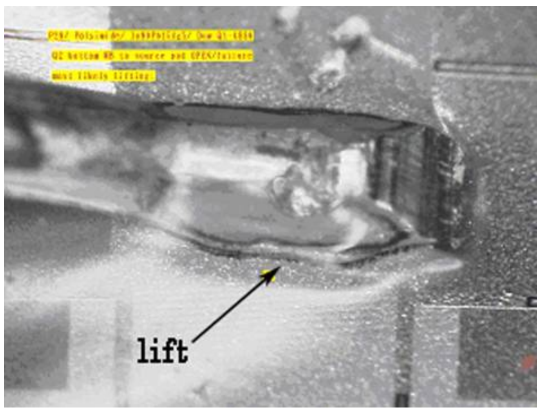
* SnPb finish
\# Au finish
Failure Investigation
Failure
Material/process consideration
Survived

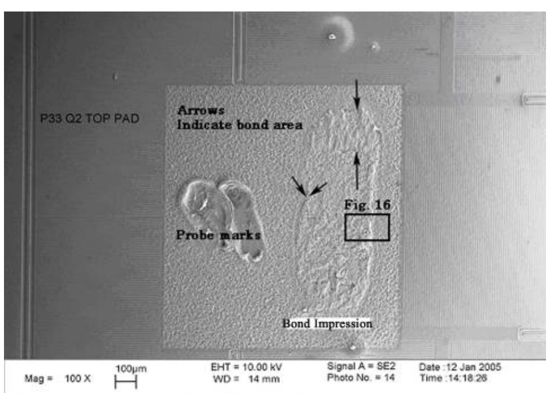
Four failure types were observed:

- 20 mil heavy Al wire bond lifting from the die
- Nano-connector lead lifting from the Au pad on the substrate
- Resistors with SnPbAg endcap finish: solder cracking
- Resistors with SnPb endcap finish: epoxy die attach failure

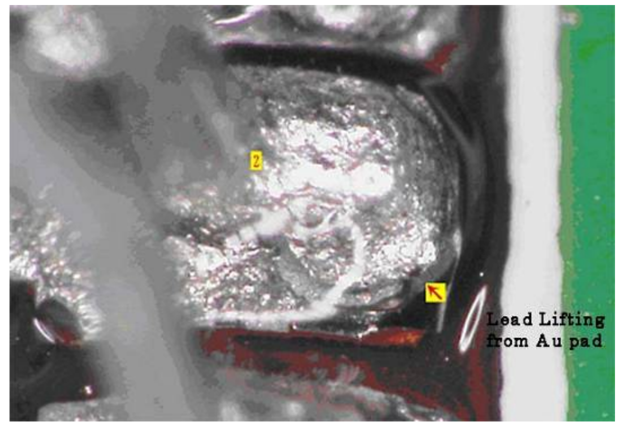
TV2 test results - failure analysis

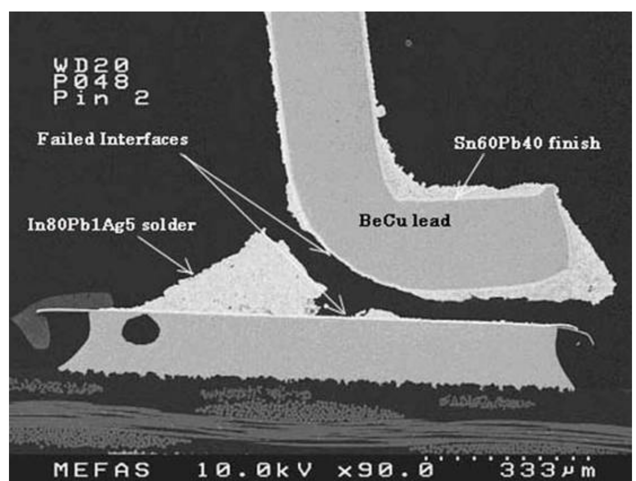
20 mil heavy Al wire bond lifting



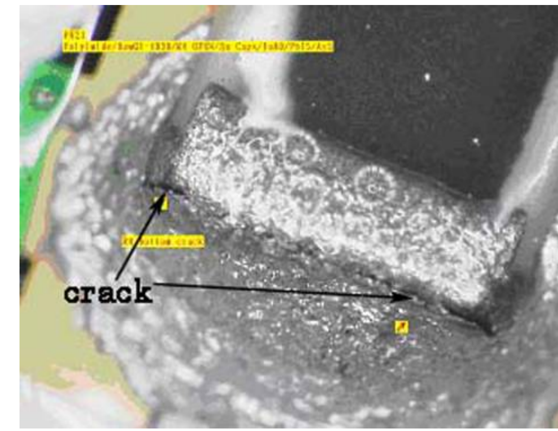


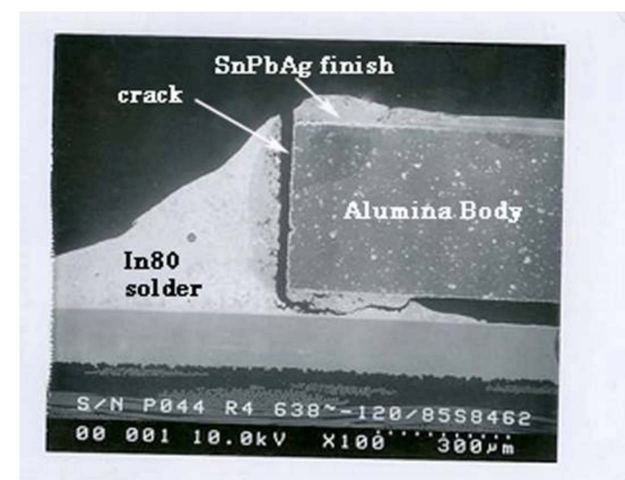
Nano-connector lead lifting





Resistor Cracking





General packaging recommendations

In order to survive 2000 cycles in -120 C to +85 C following materials and assembly methods are

Recommended:

- **Indium solder for die attach of silicon die with Au metallization**
- **In80Pb15Ag5 die attach on MOSFET with Ag backside metallization**
- **Epoxy: 84-1**
- **Conformal Coating: Parylene C**
- **Finish: Ni/Au finish for passive components**
- **Vias: 20 mil dia. through-hole and blind vias**
- **Heavy Al wire: ≤15 mil heavy Al wire bonds on die**
- **≤20 mil heavy Al wire on substrate**
- **Bus Wire: Silver plated**

Not recommended:

- **Encapsulant: Uralanes, Solithanes, Epoxies (FP4402),Silicones**
- **Attach materials: Sn-Pb solder, Ablebond 967-1, Zymet TC-611, Zymet 6000.2, attach materials**
- **Finish: Sn-Pb component finish**
- **Greater than 15 mil dia. Al wire on die**

Electronic Packaging - Conclusions

- Chip on board selected as the most promising packaging method for surviving a large number of wide temperature (-120 C to +85 C) thermal cycles

- Combinations of materials (substrate, die attach, encapsulant) had to be selected experimentally due to the lack of material properties data at low temperatures

- Selected packaging methodology, materials, and assembly techniques can be used in future for all electronic components that require survivability in Mars environment

Electronics

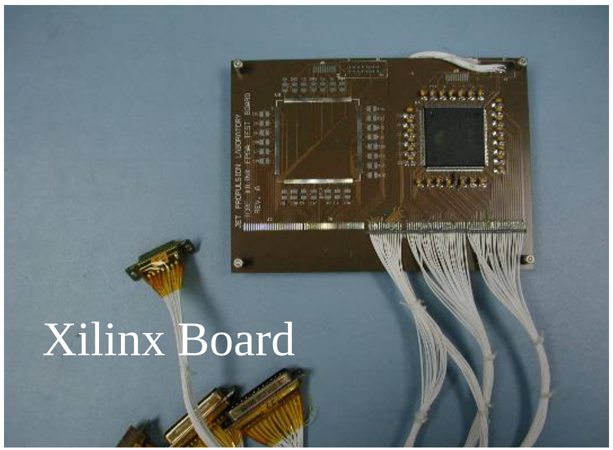
Electronics - Challenge

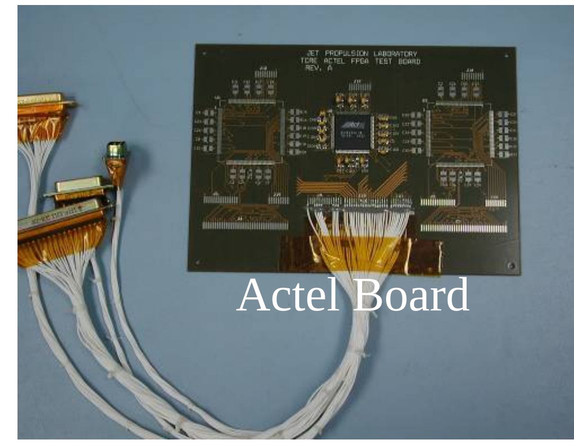
- **Need electronic components that can reliably operate in the -120 C to + 85 C temperature range**
- **Commercial Off The Shelf analog electronic components (power transistors, diodes, amplifiers, ADC's…) are designed and tested down to –55 C. These parts have unknown electrical characteristics at temperatures lower than –55C**
- **Complex programmable digital circuits like Field Programmable Gate Arrays (FPGAs) or microprocessors may have issues at low temperature related to clock tree, on board RAM, setup and hold times etc.**
- **The reliability of both analog and digital commercial CMOS components at lower than –55C is generally unknown**

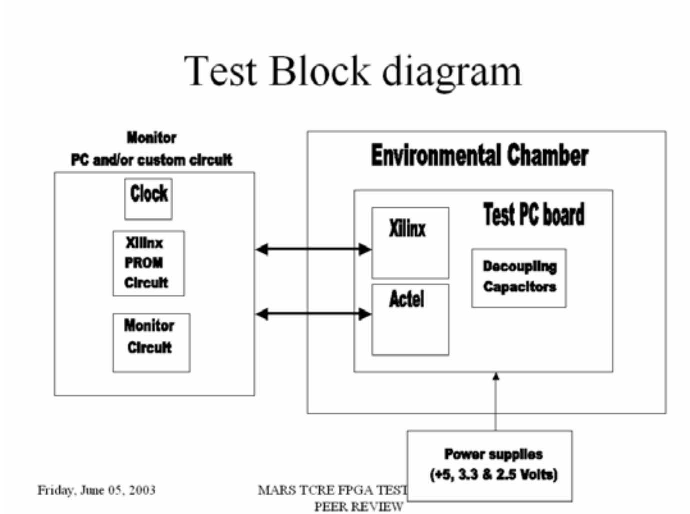
Electronics - Solution

- **Test and develop electronic components that can reliably operate between –120C and 85C:**
  - **Conduct electronic performance characterization at low temperatures (-120C) of all electronics components (transistors, amplifiers, ADC's, operational amplifiers etc., passive components) needed for motor drive electronics**
    - **Parametric testing down to -150 C**
  - **For parts that perform adequately, evaluate long term reliability test (hot carrier injection)**
    - **1000 hrs soak test at -150 C**
  - **In case needed parts are not available and are not performing as required at low temperatures, develop technology files that enables design and fabrication of IC's that can operate between –120C and 85C**
    - **Design, fabrication and qualification of operational amplifier**

Electronics - parametric testing at low temperatures (example)







Commercial Actel FPGA (A54SX32A) results:

1. **Digital logic functioned down to –165C**
2. **Power cycling functioned to -165 C**

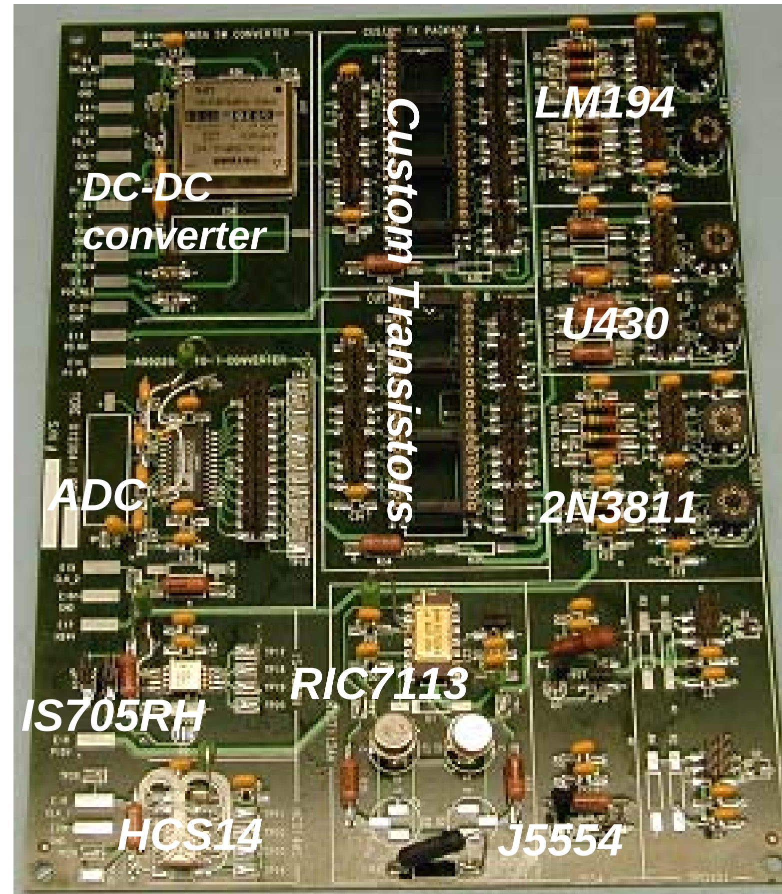
Commercial Xilinx FPGA (XCVR600) results:

1. **Digital logic (program load at 0C) functioned down to –165 C**
2. **Power cycling, initialization current increased from 10 mA at 0C to 800 mA at –40C.**

Electronics - 1000 hrs soak test at low temperatures (example)

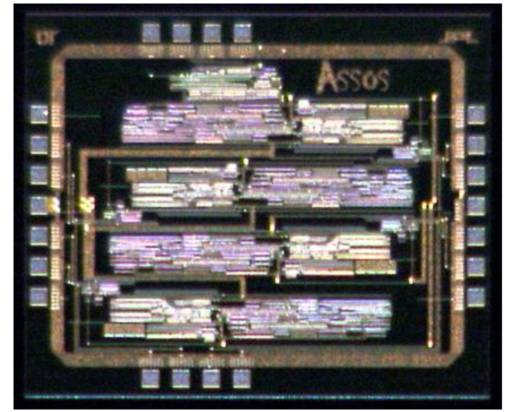
- **1000 hrs cold soak test of the COTS:**
  - **Soak test temperature –150C**
  - **COTS mounted on test boards**
  - **Continuous power and signals applied to COTS**
  - **Electrical characterization performed every 200 hrs**

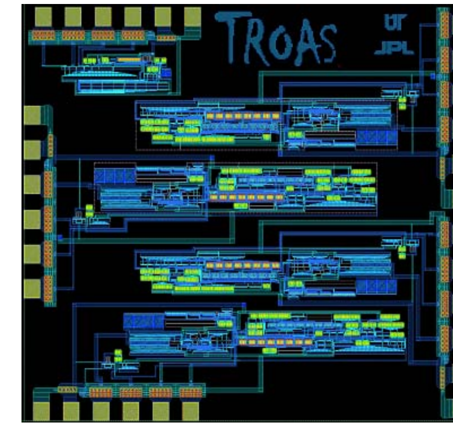
1000 Hrs Test Oven & Setup

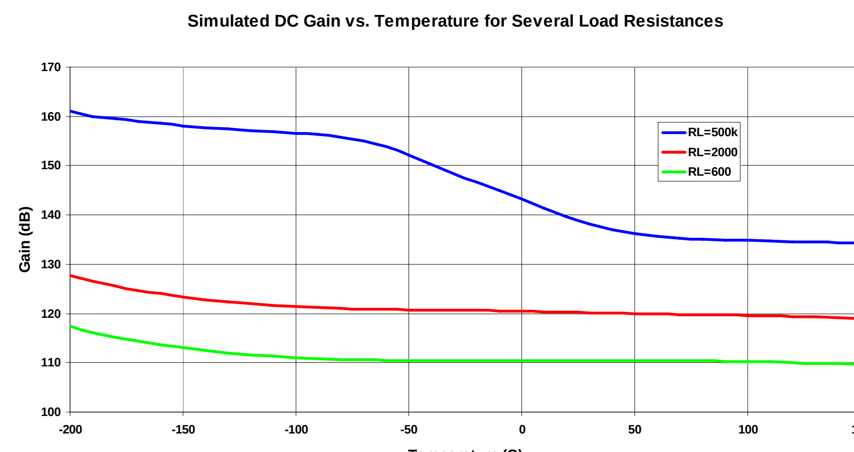


Electronics - development of operational amplifier

- **Essential part in motor drive electronics**
- **Designed to be LMC6484 footprint compatible**
- **Simulated to operate –180C to 80C**
- **Fabricated at Honeywell, space rated process**
- **Established qualification process**





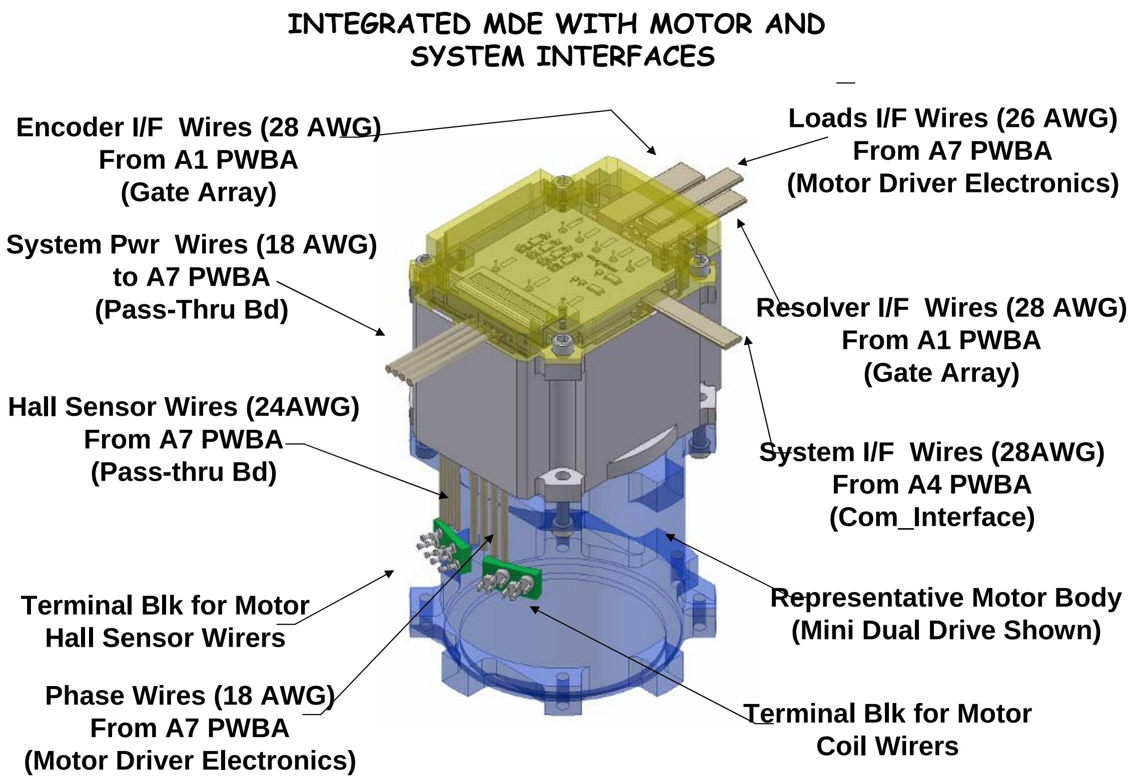


Electronics - Conclusions

- Digital electronics components perform adequately at low temperatures (-120 C)
- Testing of analog components gave mixed results -components based on bipolar transistors are not suitable for use at low temperatures due to the loss of gain
- Design methodology for low temperature components was developed
- Some components, operational amplifiers and voltage reference, were developed and optimized for low temperature performance
- Solution for all electronics components is now available for motor drive electronics operating in Mars environment

Integrated Motor Drive Electronics

Motor drive assembly



Benefits of Technology Development and Conclusions

- **Current motor design enebles rover missions to travel over much greater expanse of Martian surface (large rotary life of brushless dc motor)**

- **Results in significantly reduced system cabling, saving system mass, design cost, and ATLO integration time and cost (only with electronics at the motor)**

- **Reduced system cabling to actuators on extremities reduces a significant risk associated with flexing cabling to reach those actuators**

Benefits of Technology Development and Conclusions

- **No system power is required to thermally control actuators or their drive electronics located on rover extremities such as mobility or robotic arm eliminating special thermal hardware for actuators on rover extremities**
- **Modular design allows the use of a single electronic design at all locations significantly reducing the quantities required for spare hardware**
- **Modular design can be used for all future Mars surface and orbital missions**

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