Advanced DC/DC Converters Towards Higher Volumetric Efficiencies for Space Applications

Jeannette Plante, President, Dynamic Range Corporation, Electronic Parts Packaging Engineer

Jack Shue, NASA, Goddard Space Flight Center, Electrical Power Branch

David Liu, MEI Corporation, Manufacturing Processes Engineer

Bright Wang, QSS Group, Electrical Power Systems Designer

Harry Shaw, NASA, Goddard Space Flight Center, Chief Technologist Parts and Packaging Technologies Branch

Saturn's moon Enceladus. Image credit: NASA/JPL/Space Science Institute.

Outline

1. NASA Mission Outlook
2. Issues with DC/DC Converter for Space
3. Statement of Newly Initiated Engineering Activities for DC/DC Converters
4. Overview of Prototyping Work with Novel Materials
5. Results of Cryogenic Testing

Graphic from Arise Mission, JPL

NASA Mission Focus

http://www.nasa.gov

Life on Earth - Humans in Space - Exploration

Science:

WISE: orbiting telescope that will examine galaxies and try to find new stars, MIDEX, U of Utah

TPF: long baseline infrared interferometer, operating in the 7-20um wavelength range, searching for new earths,1800W (s/c), still in solicitation

SIM PlanetQuest: long-baseline optical interferometer in space, determine the positions and distances of stars, precursor to TPF, JPL

NuStar: detecting black holes in the local universe, CalTech

LISA: detect gravitational waves from sources involving massive black holes, GSFC/JPL

Kepler: search for Earth-size planets around stars beyond our solar system, Entered C/D 1/05, Ames

JWST: large, infrared-optimized space telescope, phase C, GSFC

NASA Mission Focus

Return to Flight:

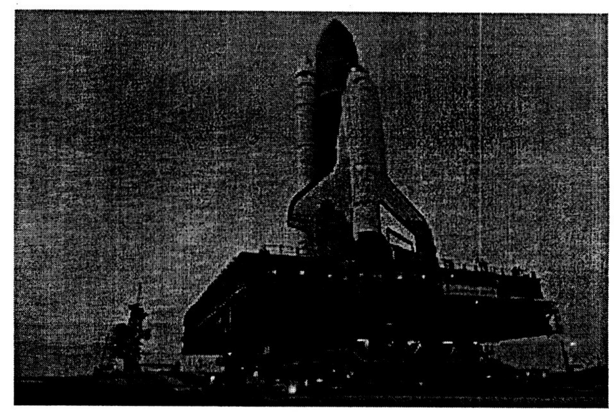
STS-114
Task Group on Next Gen Orbiter

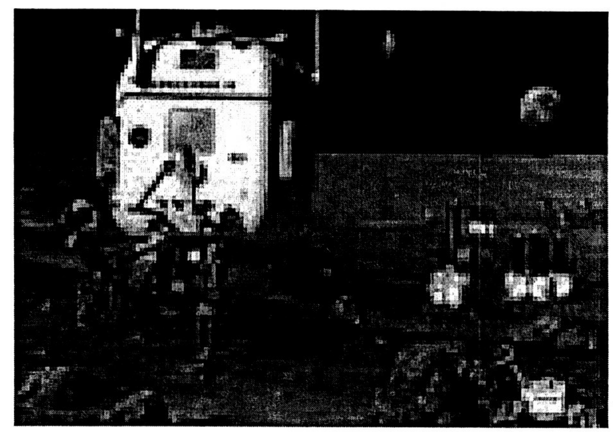
Moon/Mars:

Mars Reconnaissance Orbiter
Lunar Surveyor

Exploration Technologies (H&RT):

Materials & Structures
Communications and Computing
Software and Intelligent Systems
Power, Propulsion, Chemical Systems
Advanced Space Platforms and Systems
Lunar and Planetary Opportunities
In-Space Technology Experiments

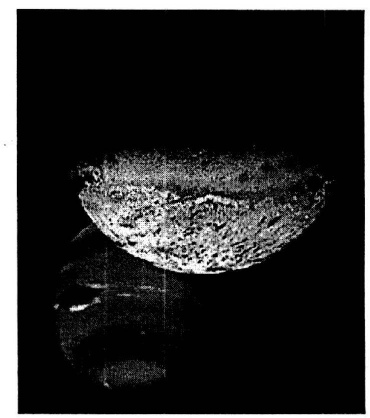




Recent Survey of NASA DC/DC Converter Needs

Center	JPL	JSC	MSFC	GSFC
Output Power	1.5 – 15W, 30 – 60W	Shuttle/ISS: 2 – 3A Others: ≤70 W	40 – 50W	≤5W, 10W, 20 – 40W, 65W
Output Voltage	2.3 – 7.0V	Shuttle/ISS: 120V Others: ≤15 V	±12V, ±15V, +5V	+2.6V, +3.3V, +5.0V, ±5V, ±15V, ±12V
Input Voltage	18 – 36V	Shuttle/ISS: 28 V Others: 120 V	120 V	28V, 42 V
Radiation Tolerance	10K and up	SEE immune	SEE immune	20k – 50k, 100k LET ≥80 will stay for Lunar/Mars

Courtesy of JAXA, April 2004



The blue clouds of Neptune and Neptune's moon Triton. Image credit: NASA/JPL

Current Approach to Selection

Primary: Input Voltage, Output Voltage, Power, Efficiency, Footprint

Secondary: Environment Ratings (Temp, Radiation), /883 testing, other Databook values

Tertiary: Existing specification, QML status

Neptune's outermost ring, credit: NASA

Current Approach to Acquisition

Primary: QML K part number (for GSFC last 3 years, 6/298 were Class K, 22/298 were Class H)

Secondary: PO stating /883 testing and MIL-PRF-38534 rules

Tertiary: Source Control Document (specification)

Schedule Prohibitive: seek new DSCC SMD

Problems Encountered

See http://nepp.nasa.gov/dcdc

- Efficiency Specifications
- Filtering
- Front End Oscillations – Changes in Vin and Zin
- Synchronization and Beat Frequency
- Thermal and Mechanical Packaging Design
- Optocouplers
- Mass/Volume Estimating
- Testing to the Application Conditions
- Establishing the Reliability for a Production Lot of DC-DC Converters
- Government vs. Manufacturer Certification
- Preventing Internal Packaging Defects
- Rectifier Diode Testing In Situ
- Application Scenarios Can Affect Radiation Tolerance of Internal Elements
- Manufacturing Process Changes During Lot Production
- Supply Chain Issues
- Use of Single Lot Date Codes
- Limits to the use of “Heritage” Qualification Data
- Avoiding Damaging Feedback Signals
- Floating Case

Efficiency Specifications and Filtering

- The value given by a datasheet for Efficiency may be for conditions which do not apply to the user's application (Vin, Vout, Load).
- Use of a converter outside of their nominal or design range (Vin, Vout, Load) can result in unpredictable or unstable performance.

- EMI filters are important for protecting the power bus from radiated noise generated by high frequency MOSFET switching inside of the converter.
- EMI filters must be designed (or selected) to match the applicable converter.
- The manufacturer should be consulted to be sure that external filters are selected and applied properly with their converter.
- When an EMI filter uses a common-mode choke, the input and output current windings should be separated from each other to prevent a short circuit between the two if the wire insulation is compromised.

Front End Oscillations and Synchronization

- System conditions can cause damaging front end oscillation in DC-DC converters both due to extremes in input voltage (high and low) and due to changes in input impedance.
- Input impedance can change significantly due to system conditions. Ranges of input impedance should be considered when bench testing to establish acceptable worst case conditions.

- DC-DC converters used in parallel can generate a "beat frequency" if they are not correctly synchronized and power sequenced.
- The proper configuration for synchronizing parallel converters is to assign one as a "teacher" and the others as "students", the "students" having their synch pins connected to the oscillator output pin of the "teacher". The "teacher" unit must be then turned on before the "students".

Electrical Testing and Supply Chain

- Testing by the manufacturer may not be comprehensive because the manufacturer will probably not attend to application worst-case conditions (if a source control drawing is not used), including radiation and thermal-vacuum conditions.
- Users must characterize candidate units to be sure that they perform adequately and are stable under worst case and nominal application conditions.
- If application conditions (nominal and worst case) change over the life cycle of the mission, characterization and acceptance test data should be reviewed to confirm that the part is still considered qualified given the new conditions.

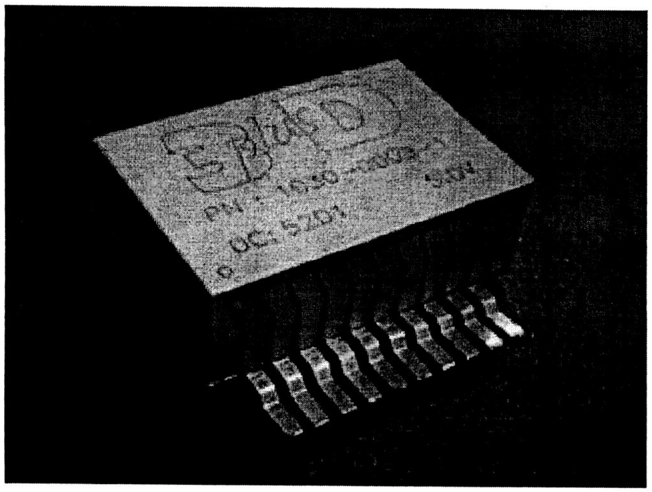
- Use of single lot date codes is important in assuring homogeneous performance (and reliability) throughout the flight lot. The single lot date code standard applies to internal elements and materials as well as the completed units.
- It is critical to be aware of supply chain conditions such as plant transfers and internal element obsolescence, in order to assess risk to on-time delivery

Failures 1997 - 2001

- 28 failures recorded
- Examples of the Problems Found:
  - Electrical test failure (device non-functional) and PIND failure during incoming screening
  - Catastrophic failure during endurance test
  - Thermal cycled device failed leak test after 200 cycles and failed electrical test after 500 cycles
  - DPA showed various wires below pull test limits and capacitors below die shear limit
  - Electrical test failure (isolation) after vibration
  - Detached and cracked capacitor stacks, cracked solder joints to pin after thermal and mechanical shock testing
  - the design of the new MHP hybrids had not been sufficiently investigated and verified. Insufficient margin had been included in the design to cope with variation of the characteristics of add-on elements
  - Non-established reliability capacitors were used
  - Burn-in results showed electrical efficiency not to spec over all temp ranges
  - Lid stuck to internal devices causing solder joint failure when the lid deflected in a vacuum
  - Tin plated passives

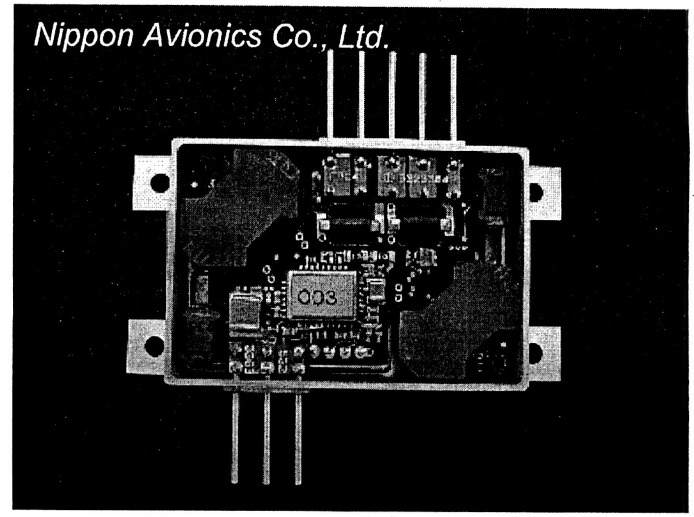
Motivation to Develop Alternatives

ESA/CNES

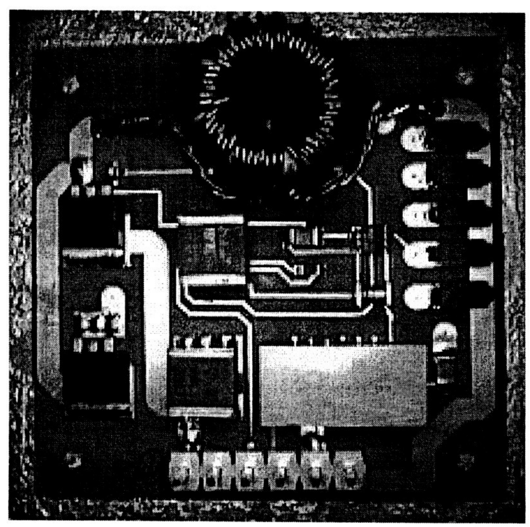


In Production

JAXA



GSFC



Experimenting with New Approaches

Technology Investigation and Bench Testing

2003 Director's Discretionary Fund Award:

- Fabricate and test a useful circuit such as a DC/DC converter or a charge amplifier using embedded components and novel materials with in-house MCM processes.

- Demonstrate how such designs can be accomplished with existing PCB layout tools and commercially available components and thermal materials.

- Provide a limited environmental test to demonstrate that the technology could be adapted for spaceflight usage.

Motivation to Develop New Selection and Procurement Methods

April '05 Start:

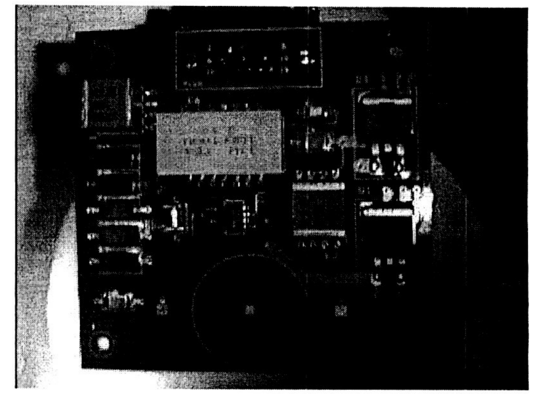
- Development of a User Applications Manual for DC/DC Converters
- Development of a Characterization and Evaluation Protocol for DC/DC converters
- Continue to update the DC/DC converter website with new information
- Continue to update known DC/DC converter problems database
- Evaluation of DC/DC converter hardware and technologies at the bench top level

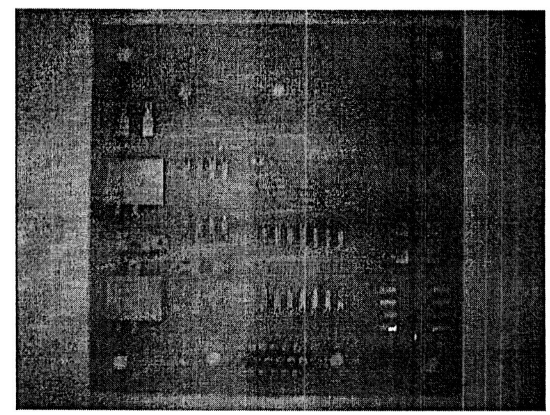
Prototyping Results

- Circuit 1
- Circuit 1 on FR4
- Circuit 1 on AlN + FR4
- Circuit 1 on AlN
- Circuit 1 on AlN + Al-Diamond HS
- Circuit 1 on AlN + Al Plate HS
- Circuit 2 simplification and embedded passives
- Circuit 1 on AlN in LNi

In-house Design: Circuit 1

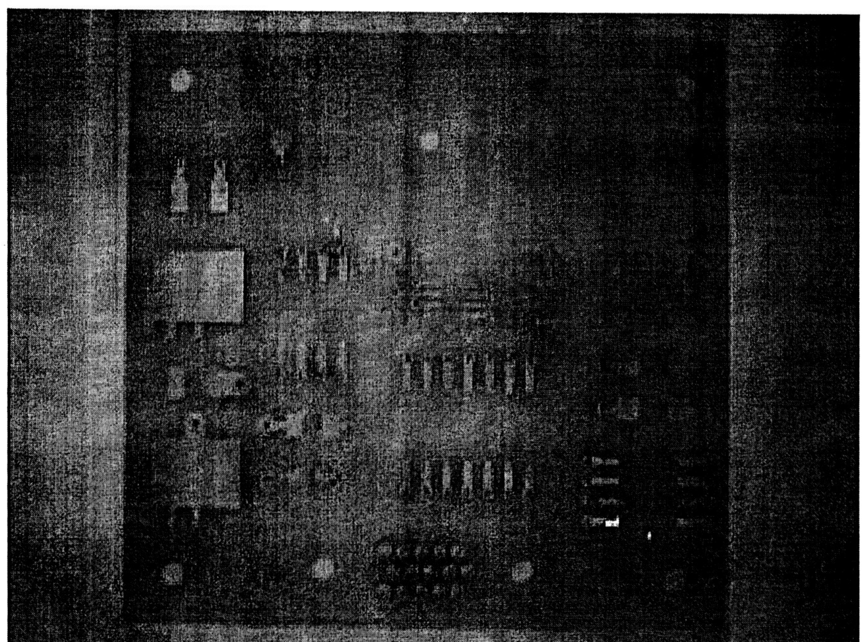
- 28Vin, 3.5Vout, 5A, switching speed of 100 kHz, ripple suppressed
- Signal generation circuit off-board
- effective volume: 2.75” x 2.75” x 0.25” = 1.891 $inch^3$ (69.85 x 69.85 x 6.35 mm^3)
- FR4 Substrate
- w/ and w/o AlN Heat Spreader

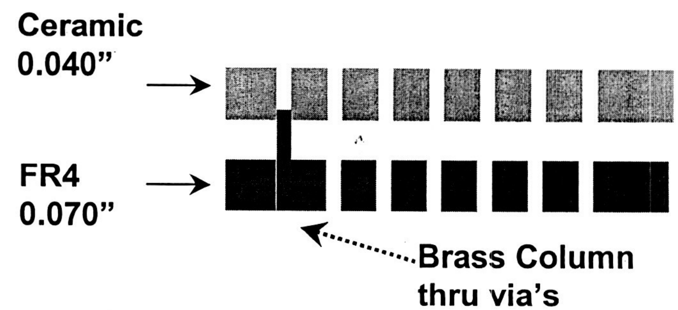




AlN Heat Spreader Attach

Brass columns act as filled vias connecting FR4 via to AlN via





Solder joint from pin to via annular ring

Measurement Results of Testing Circuit on FR4 and FR4+AlN Laminates

	FR4	AlN	FR4	AlN	FR4	AlN
Sw F (kHz)	50	50	100	100	50	100
Vin (V)	28	28	28	28	28	28
Iin (A)	0.83	0.81	0.85	0.84	1.37	1.38
Vo (V)	3.5	3.45	3.49	3.46	3.39	3.36
Io (A)	5.09	5.04	5.08	5.02	8.03	8
Pi (W)	23.24	22.68	23.8	23.52	38.36	38.64
Po (W)	17.82	17.39	17.72	17.73	27.22	26.88
Eff (%)	76.66	76.67	74.49	74.1	70.11	69.56
Meas'd Temp (°C) Q1/D1/L1	43.5/ 60.7/ 33.9	31.2/ 31.6/ 35.4	48.1/ 70.4/ 32.2	31.3/ 32.3/ 32.4	48.1/ 48.2/ 40.1	52.6/ 53.6/ 41.0
Vol. Eff. (W/inch3)	**9.43**	**9.20**	**9.37**	**9.37**	**14.40**	**14.22**

Aluminum Diamond Composite Properties Compared to Those of Typical Heat Sink Materials

Description	Thermal Conductivity (W/m ·k)	CTE (ppm/K)	Density (g/cm^3)
85W/15Cu wt%	180	7.2	16.2
Diamond/Al 50%	**550-650**	**7.5**	**3.10**
Al 100%	190	24	2.78
Cu 100%	395	19	8.96

Volumetric Efficiency on AlN and AlN + Al-Diamond

	SW. Frequ (kHz)	Output Power (W)	Elec. EFF. (%)	Vol. Eff. ($W/inch^3$)
AlN alone	100	27.38	76.67	**14.48**
AlN alone	100	34.20	74.10	**18.09**
AlN alone	100	40.97	70.11	**21.67**
AlN + Al-Diamond HS	100	51.30	69.56	**27.13**

Electrical Performance Circuit 1 on AlN and Al-Diamond Heat Spreader

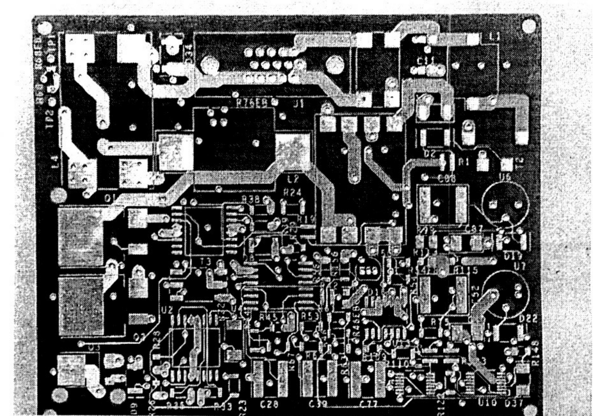
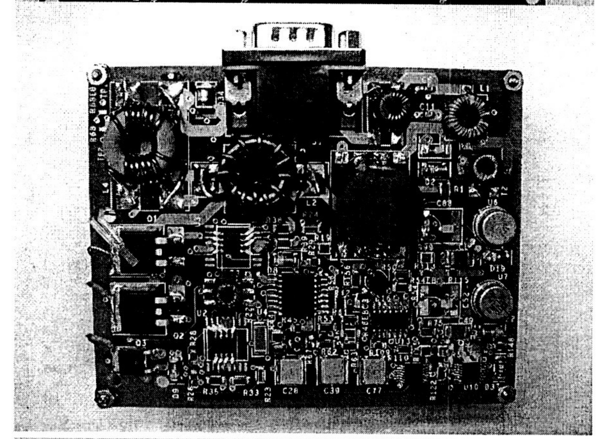
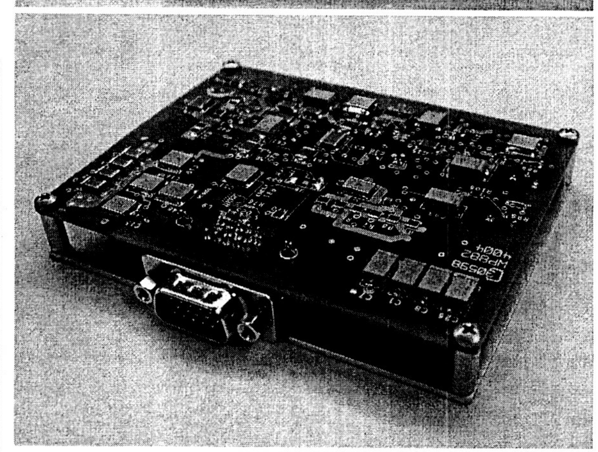
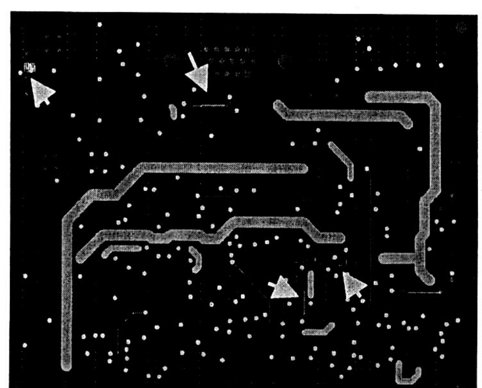
		AlN Substrate w/Al+Diamond Heat Spreader	
Vin (V)		28.02	35.02
Iin (A)		2.35	2.68
Vo (V)		3.4	3.41
Io (A)		15.04	20.54
Pi (W)		65.85	93.85
Po (W)		51.14	70.04
Vol. Eff. (W/Inch^3)		27.05	37.06
Elec. Eff. (%)		77.66	74.63
Meas'd Temp (°C)	Board Center	60.5	69.6
	Q1 Case	50.8	63.4
	D1 Case	51.3	60.3
	L1 Core	61.3	75.6

Electrical & Thermal Performance of Circuit 1 on AlN w/Al Plate HS or Al-Diamond HS

Sub-strate	Vin (V)	Iin (A)	Vo (V)	Io (A)	Pi (W)	Po (W)	Vol Eff. (W/In^3)	Elec Eff (%)	Measured Temp Rise (°C) Board/Q1/D1/L1			
AlN & Al Plate	28.04	2.43	3.40	15.04	68.04	**51.32**	**27.15**	75.56	60.8	50.2	51.5	63.5
AlN & Al-Diamond	28.02	2.35	3.40	15.04	65.85	**51.14**	**27.05**	77.66	60.5	50.8	51.3	61.3
AlN & Al Plate	35.01	2.89	3.41	20.55	101.18	**70.08**	**37.07**	**69.26**	80.8	72.5	71.2	90.4
AlN & Al-Diamond	35.02	2.68	3.41	20.54	93.85	**70.04**	**37.06**	**74.63**	69.6	63.4	60.3	75.6

Circuit 2

- Current Source, 5A, 40W
- Simplified circuit from a flight heritage design (removed several sections and simplified remaining, was 10” x 12” board, became 3” x 4”)
- Experimented with embedded passives to discover miniaturization advantages and performance over temperature

Electrical Performance of Circuit 1 and Circuit 2

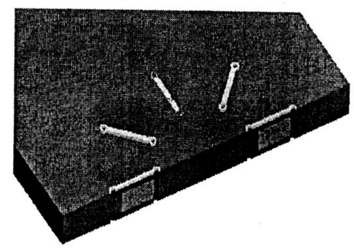
Title and Description	Vin (V)	Iin (A)	Vo (V)	Io (A)	Pi (W)	Po (W)	Elec Eff (%)	Vo Ripple (mV pp)	Measured Temp (°C)			
									Main MOSFET	Fly-wheel MOSFET	Forward MOSFET	Main XFMR
Circuit 1 [1]	**28.02**	**3.75**	**3.30**	**22.8**	**105.01**	**75.31**	**71.67**	**52.2**	**47.6**	**50.1**	**N/A**	**57.4**
Circuit 2 [2]	**28.14**	**0.68**	**2.50**	**5.04**	**19.14**	**12.60**	**65.80**	**100**	**56.8**	**77.4**	**74.5**	**45.6**

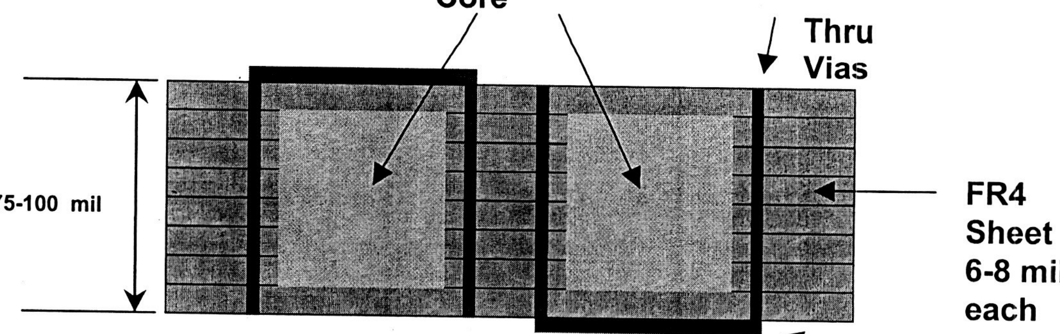
Note 1: 1.88 inch³ volume, Power processing circuit only, Aluminum Nitride board, and 4" x 4"x 0.75" Al-Diamond Heatsink, no embedded passives

Note 2: 6.50 inch³ volume, Input/output EMI filters, Current mode control, Synchronized rectification, Output short circuit protection, Input under voltage protection, ON/OFF command, On-board temperature monitor, and 0.056" Aluminum Heatsink, used embedded resistors *[R46EB, 1kΩ(764 ohms actual); R54EB, 100Ω (79.0 actual); R68EB, 100Ω (79.0 actual); and R76EB, 1kΩ (824 actual)]*

Embedded Components

- Embedded resistors used in Circuit 2
- Embedded traces and clamshell transformer and inductor used however not high power enough for demo circuits
- Plans to design embedded core construction

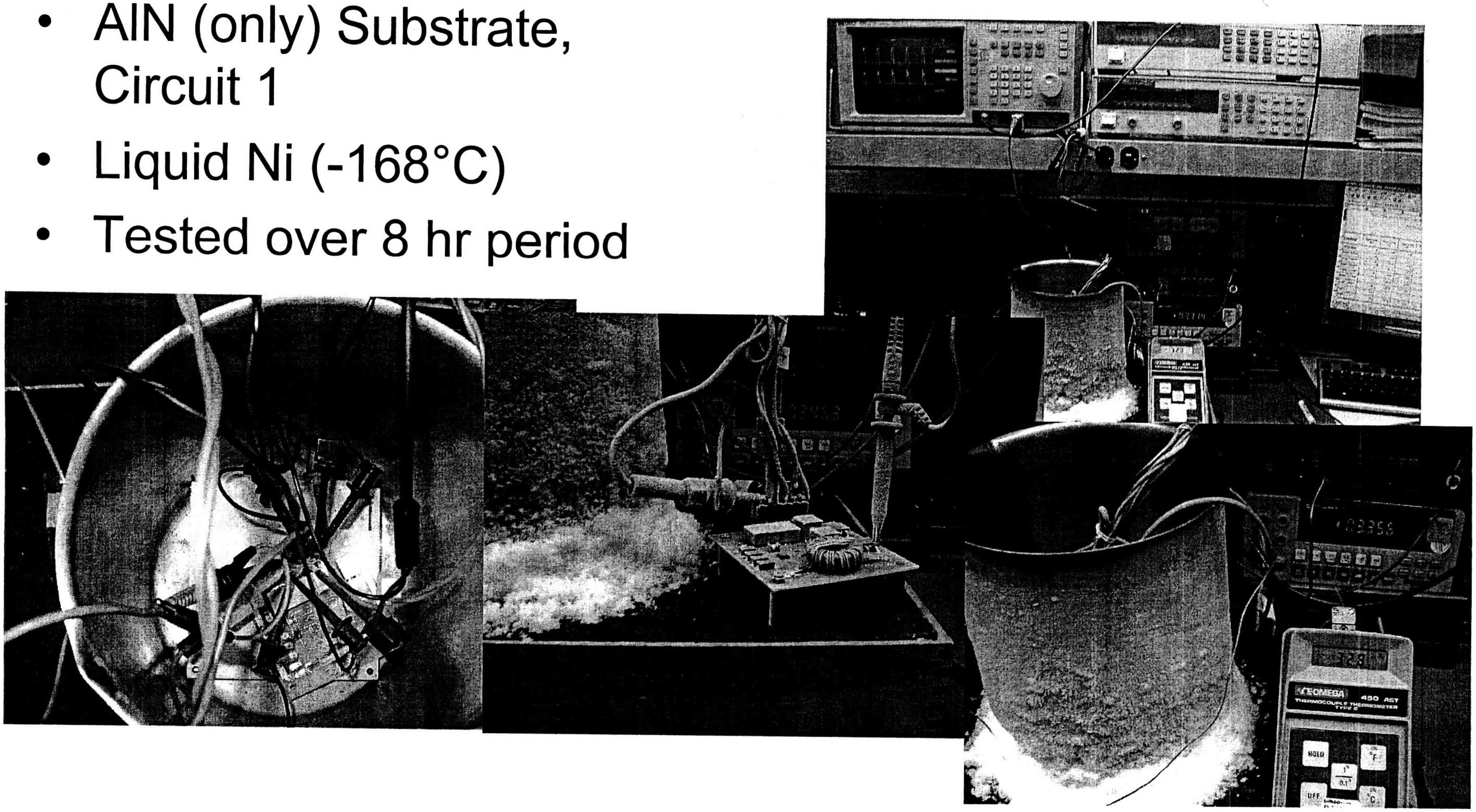




Magnetic core will be laminated into the PCB, the coils will be built with plated through via holes and plating traces.

Cryogenic Testing

- AlN (only) Substrate, Circuit 1
- Liquid Ni (-168°C)
- Tested over 8 hr period



Electrical Performance of Circuit 1 on AlN Substrate No Heatsink, in LN_2

TEST CONDITION	Duty Cycle (%)	Vi (V)	Iin (A)	Vo (V)	Io (A) (I limited)	Pi (W)	Po (W)	Power Effici. (%)	Vout Ripple (mVp-p)
At ambient temperature	16	28.02	1.562	**3.31**	**10.0**	43.74	33.10	75.86	450
LNi, 7:45 am	16	28.03	1.511	**3.32**	**10.0**	42.33	33.20	78.44	225
LNi,8:45 am	16	28.06	1.509	**3.30**	**10.0**	42.34	33.00	77.94	220
LNi, 9:50am	16	28.07	1.511	**3.32**	**10.0**	42.41	33.30	78.52	220
LNi, 10:48am	16	28.07	1.513	**3.34**	**10.0**	42.47	33.40	78.61	150
LNi, 11:50am	16	28.07	1.508	**3.33**	**10.0**	42.33	33.30	78.67	140
LNi, 12:55pm	16	28.07	1.514	**3.33**	**10.0**	42.49	33.40	78.14	140
LNi, 1:50 pm	16	28.07	1.513	**3.31**	**10.0**	42.47	33.10	78.00	130
LNi, 2:50 pm	16	28.07	1.515	**3.32**	**10.0**	42.53	33.20	78.07	130
LNi, 3:37 pm	**16**	**28.07**	**1.624**	3.23	10.0	**45.59**	**32.30**	**70.85**	**230**

After approximately eight hours the input power began to rise, the efficiency followed with a similar decrease and the output ripple when out of specification. This is believed to be due to the current flow being over the specified value of the low ESR tantalum capacitors.

Summary (1 of 2)

- NASA continues to develop science driven satellites and will add new systems via the Exploration Initiative however these new systems are not yet defined with respect to power needs and architectures
- DC/DC Converters have been failing in space hardware (during development and sometimes in operation) for many years and NASA continues to have problems with them.
- The need for application and procurement guidelines for DC/DC converters and has prompted a new initiative to generate engineering information and tools that will help designers and parts engineers avoid future failures
- In an attempt to have more input into DC/DC converter designs, space organizations have begun to participate in new product designs.

Summary (2 of 2)

- New converter designs can be enabled using commercially available parts and materials which enhance thermal performance thereby increasing volumetric efficiency.
- Embedded resistor and capacitor technology did not provide significant size reduction. Embedded transformer/inductor traces with clamshell ferrites were also not significantly effective for increasing volumetric efficiency of our design. However, embedded core configurations are promising for enabling further volumetric efficiency gains.
- The commercially available parts and construction methods, including embedded resistors can be used in an aggressive approach for achieving volumetric efficiency for an extreme environment (thermal shock and cryogenic temperature)

Special Thanks To:

Jack Shue, Bright Wang, David Liu, Brandon Lee, Darryl Lakins, Shawn MacMurphy, Art Ruitberg, JPL Power Systems Group