THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN

Emerging Technology & Products for Mission-Critical Space Power Distribution

- An Invited Talk

April 2, 2015

Don Tan
Fellow / Power Products Development Manager
NGAS, One Space Park
Redondo Beach, CA 90278

Trends in Space Power

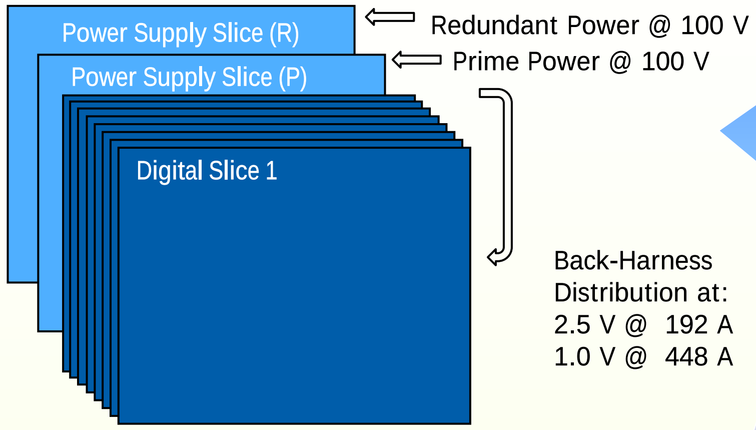
- Trends:
  - Space power demands are ever increasing
  - Payload voltage levels are ever decreasing
  - Relentless pressure on cost and schedule

- We have been working together with our customers to stay at the forefront of these trends with multiple technology and product development programs
  - Adiabatic Point-of-Load Converter (APOL)
  - Advanced Electrical Power Systems (AEPS)

- Today, we will report some of the progress that we have made on power distribution technology and products

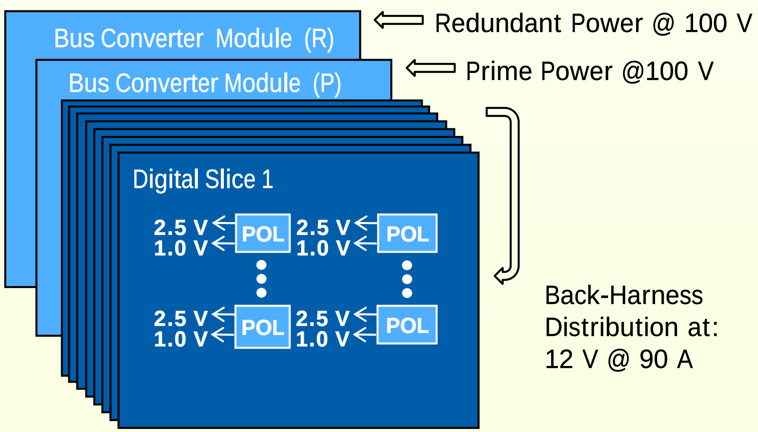
* - Don Tan, "A review of intermediate bus architecture: a system perspective," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Vol. 2, No. 3, Sep., 2014, pp. 363 – 373 *(Invited)*

APOL: The Need



Centralized bus with one-step conversion

- **Problem**: With the increase of prime bus and the decrease of load voltage levels, the centralized architecture can no longer deliver the efficiency required
  - Excessive cable IR drops & weight
  - Significantly degraded power efficiency
- **Solution**: An intermediate power bus and ultra-efficient power converters
  - Reduction of 67% dissipation
  - Increase of 68% through power
  - Reduction of power generation, storage and thermal removal



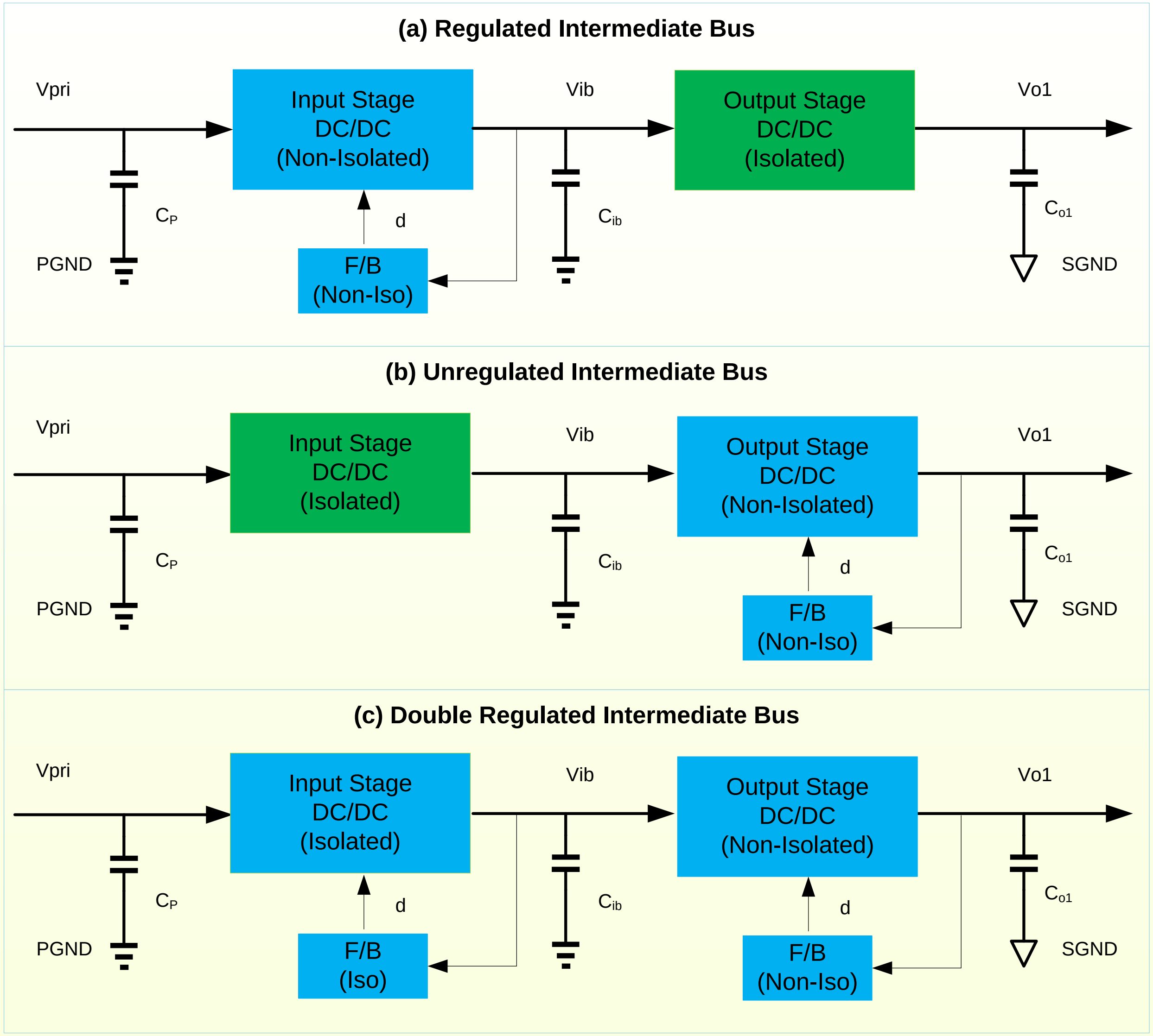
Intermediate bus with two-step conversion

Performance	Centralized	DRIBA
Converter efficiency	75-85%	89-99%
End-to-end power distribution efficiency	65%	>85%
Size reduction	-	>2x
Producibility	Poor	Good
Testability	Poor	Good

DRIBA – Double regulated intermediate bus architecture

Basic Architectures

NORTHROP GRUMMAN

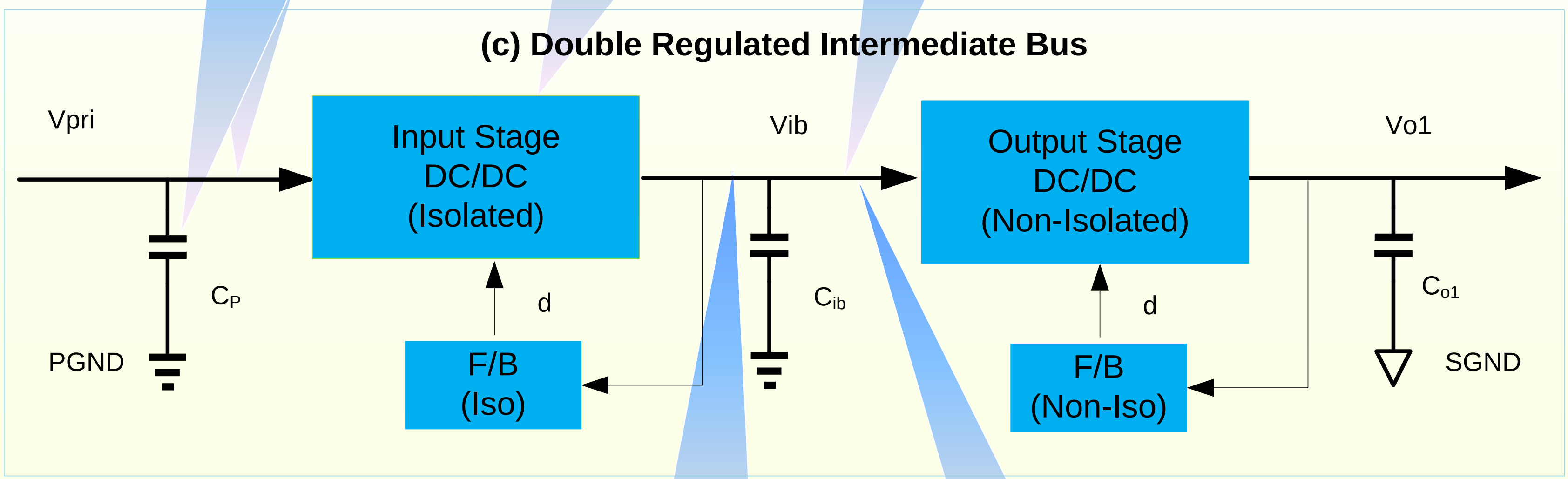


Double Regulated: Input Power Stage

Virtually non-pulsating input current, requiring only small Cp at high voltage level (>24V)

Double forward, isolated, non-fixed duty ratio

Virtually zero voltage ripple for Vib

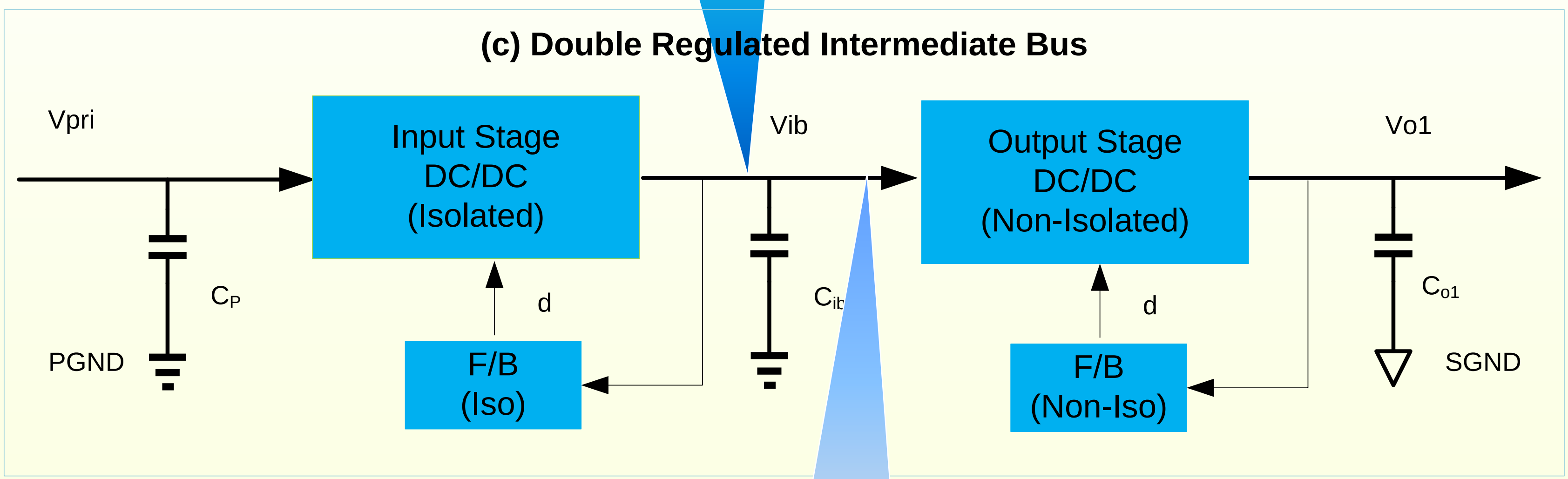


Output current non-pulsating

Vib regulated

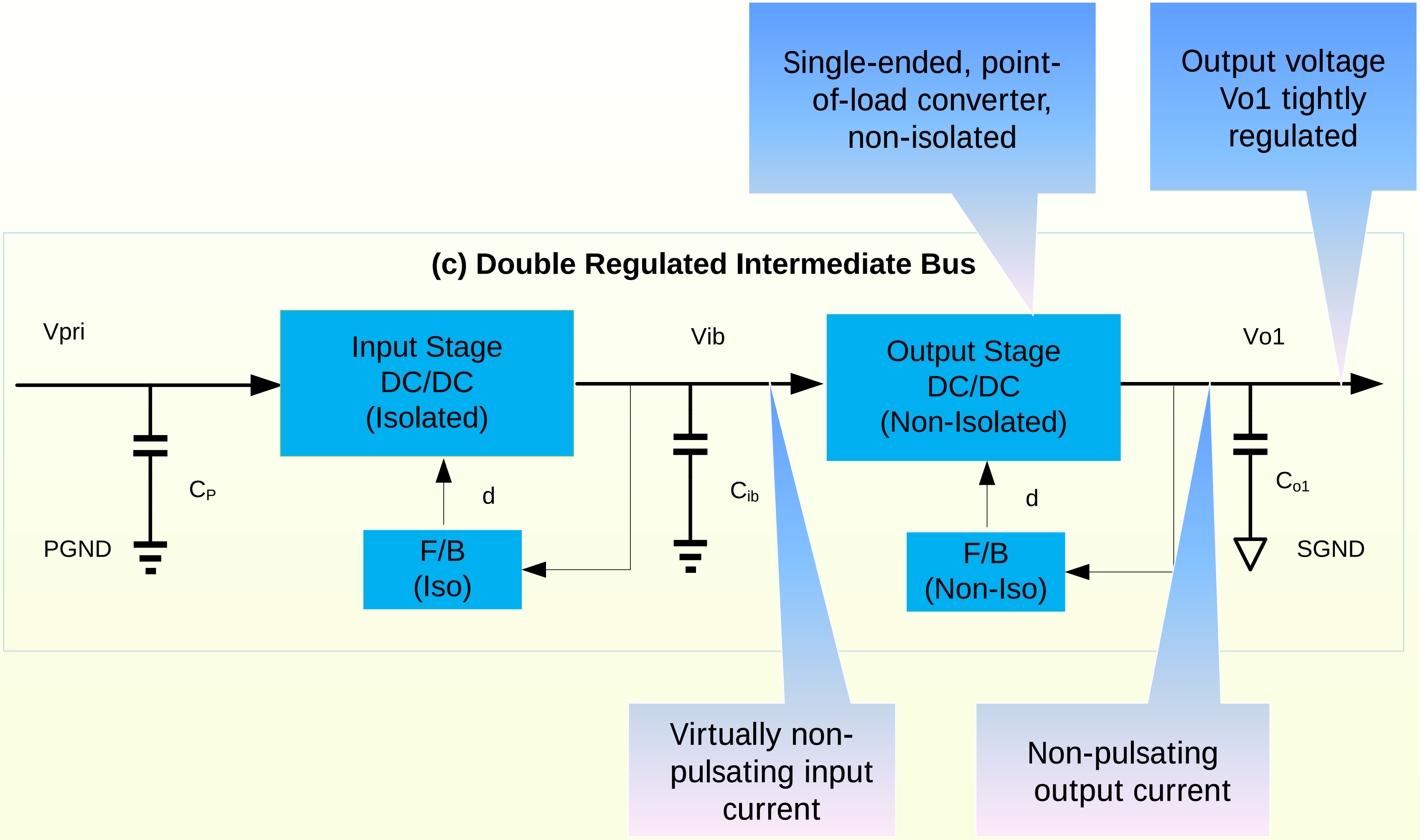
Double Regulated: Bus Voltage Level

Vib as a system design parameter for performance optimization



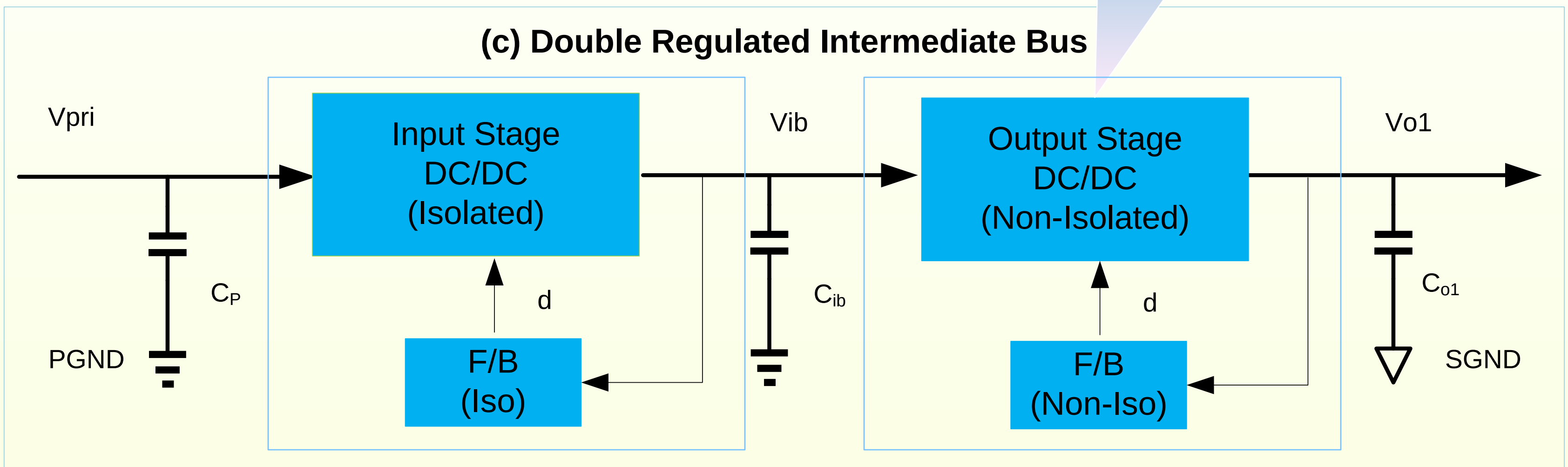
Intermediate bus voltage level is low (< 12V)

Double Regulated: Output Power Stage



Double Regulated: Thermal Property

The output power stage is the most efficient at the point of load

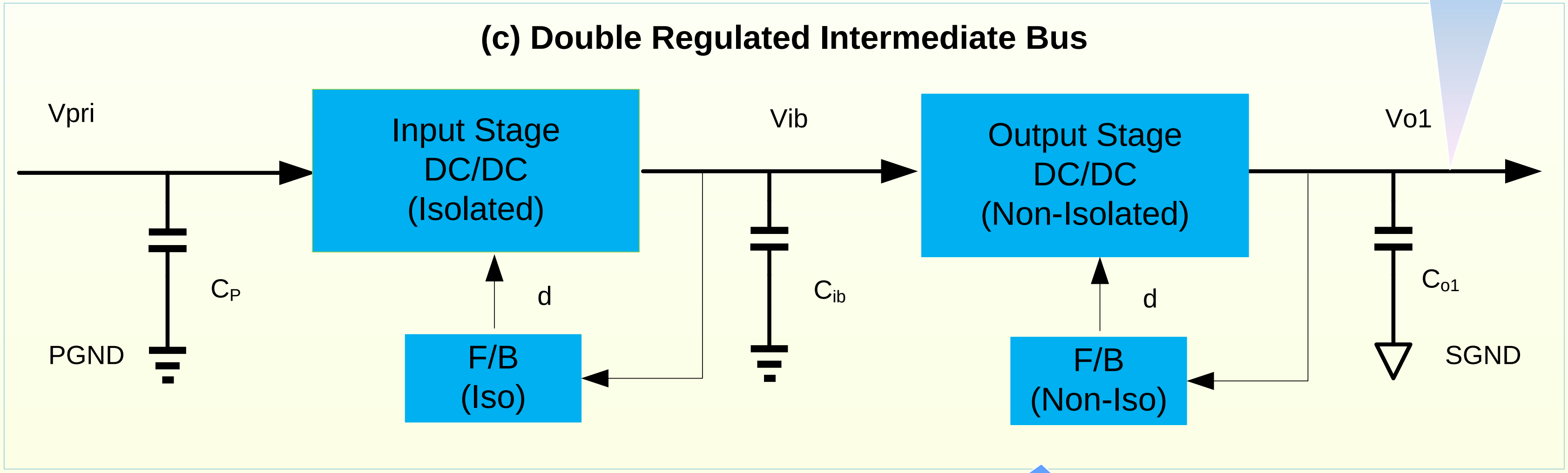


The bus converter can be off the board, but in the vicinity, reducing further the heat flux

Reduced heat flux at the point of load, increasing reliability

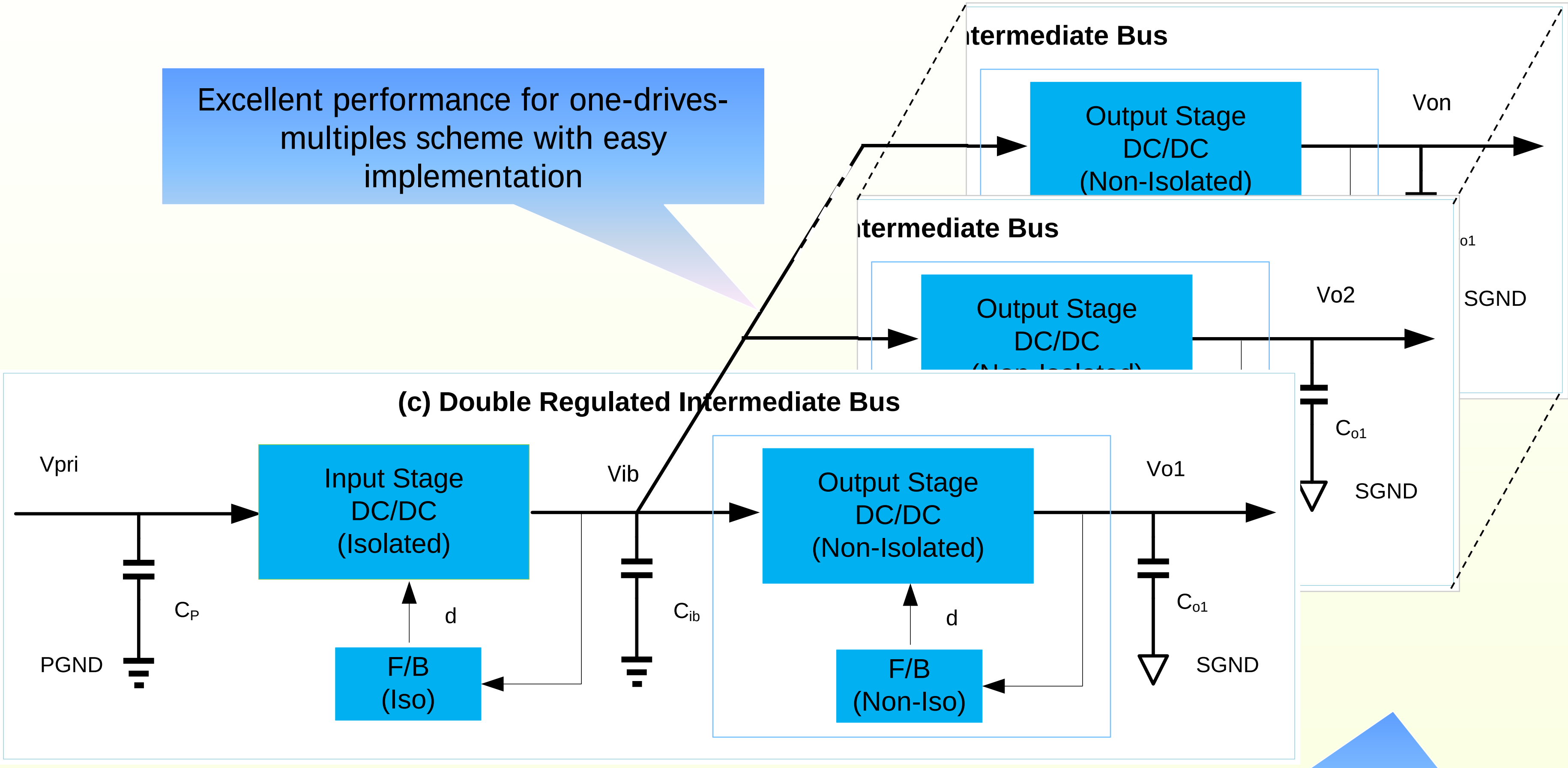
Double Regulated: Regulation

Typical load and line regulation for Vo1 is ±3% by virtue of double regulation



No cross and back regulation since the output is regulated directly

Double Regulated: Multiple Outputs



Excellent performance for one-drives-multiples scheme with easy implementation

Output voltage levels can be set continuously by duty ratio

Regulation Performance

- For a regulation of ±10%, the regulated intermediate bus can be used
- For a regulation of ±5 - 7%, the unregulated intermediate bus is recommended
- For a regulation of <±3% or less, high efficiency and small size, the double regulated intermediate bus is preferred

Summary of Key Performance Parameters

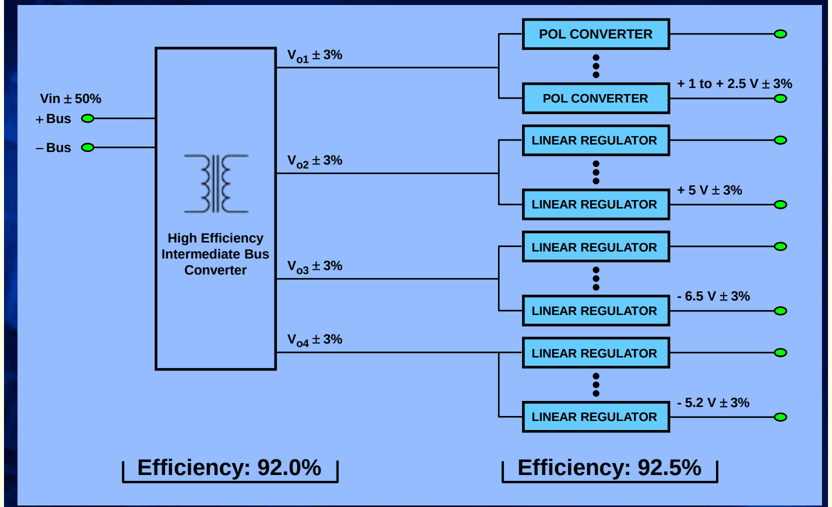
	Input Power Stage	Intermediate Bus Voltage Level	Output Power Stage	Thermal Property	Regulation	Multiple Outputs	System Stability & Output Impedance
Regulated	• Single ended, Buck or Buck-Boost, • Pulsating input current with large cap at bus voltage level (usually >24 V) • Output current can be pulsating • Regulated	High, usually > 12V	• Double ended, push-pull, half or full bridge • Virtually non-pulsating input current • Virtually non-pulsating output current • Unregulated	• Most efficient power stage not at output • Increase of point-of-load heat flux • Reduced reliability	• Typical load/line regulation <±10% • Cross regulation is large • Back regulation is large	• Poor, >±10%, typical	• Favorable in stability • Output impedance high
Unregulated	• Double ended, half or full bridge as bus converter • Virtually non-pulsating input current • Non-pulsating output current • Unregulated with fixed duty ratio	Low, usually < 12V	• Single ended point of load (POL) • Pulsating input current • Non-pulsating output current • Regulated	• Most efficient power stage at the output • Reduced point-of-load heat flux • Increased reliability	• Typical load/line regulation <±7% • No cross regulation • No back regulation	• Good, ±5 -7 %, typical	• Not favorable in stability • Output impedance low
Double Regulated	• Hybrid • Virtually non-pulsating input current • Non-pulsating output current • Virtually zero voltage ripple • Output regulated	• Low, usually < 12V • Value as a design parameter for max system performance	• Hybrid • Virtually non-pulsating input current • Non-pulsating output current • Output regulated	• Most efficient power stage at the output • Reduced point-of-load heat flux • Increased reliability	• Typical load/line regulation <±3% • No cross regulation • No back regulation	• Excellent, <±5%, typical	• Favorable in stability • Output impedance low

APOL Accomplished its Goal

	Measured Best Efficiency at 1/3 Load (%)	Measured Min Efficiency at Full Load (%)
APOL EM	97.1	95.2
APOL BCM EM	92.6	92.1
End-to-End	89.9	87.7

We accomplished all we set out to do on the APOL Program!

Near Adiabatic POL Power Converter



An example of regulated intermediate bus design

Expected Performance and Comparison to the State of the Art

Required thermal removal (kW)	AEHF (centralized power distribution)	TSAT (intermediate bus, unregulated)	NextGen MAWFEA (intermediate bu regulated)
Total payload power (kW)	10	10	10
End-to-end efficiency (%)	65	75	85
End-to-end power dissipation (kW)	5.38	3.33	1.76

- A total of 67% reduction in power dissipation can be achieved
- A 78% increase of payload capability for a given thermal design

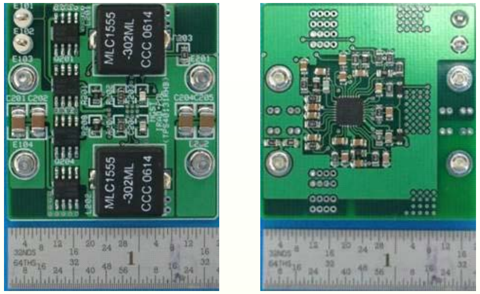
Technical Readiness Levels (TRL)

- At three (3) at the start and greater than six (6) at the end

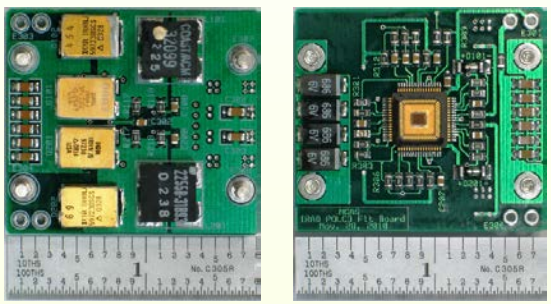
We have accomplished the goal of reducing the power dissipation by a total of 67% through the APOL Program

APOL Hardware Development

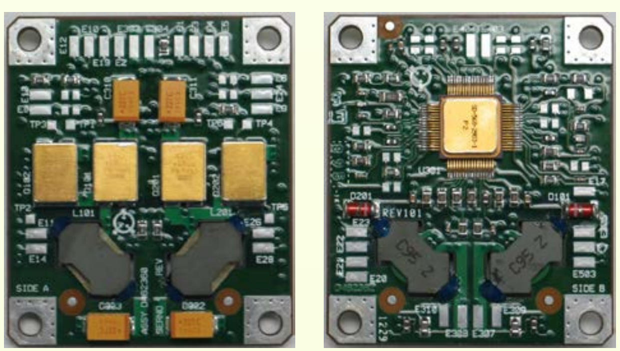
NORTHROP GRUMMAN



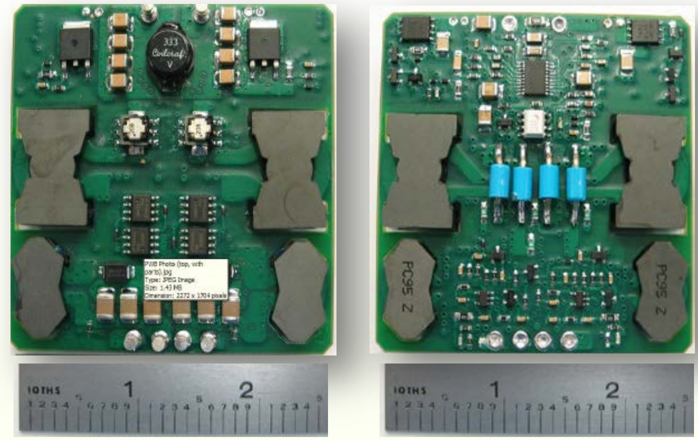
a) APOL Breadboard



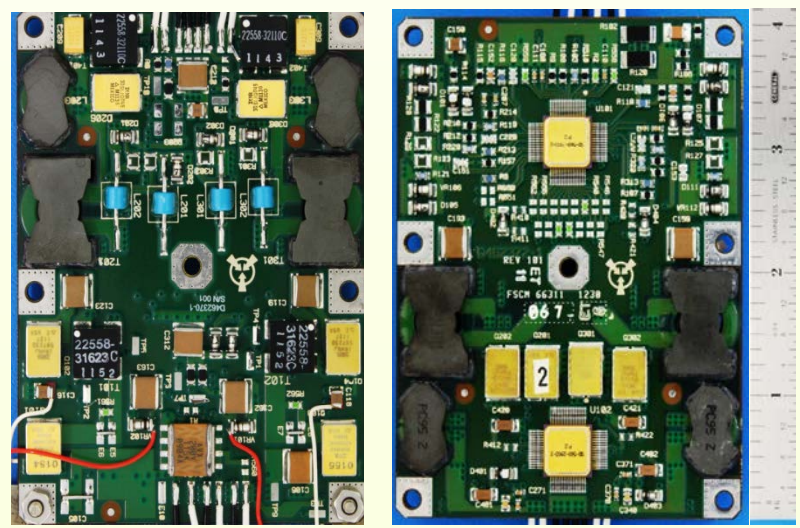
a) APOL Brassboard



c) APOL Engineering Model



a) BCM Brassboard



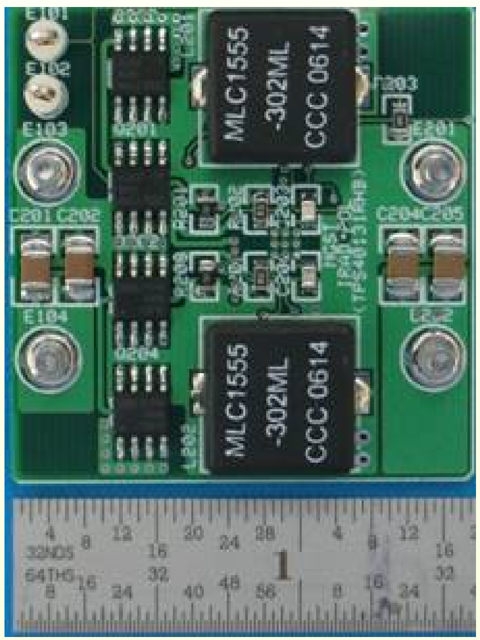
b) BCM Engineering Model

POL Converter Prototype

NORTHROP GRUMMAN

- A Point-of-Load (POL) Converter prototype was then constructed using commercially available open-source PWB software and commercial parts
  - Open space on PWB was reserved for future size growth for radiation hardened designs

Front View



Back View

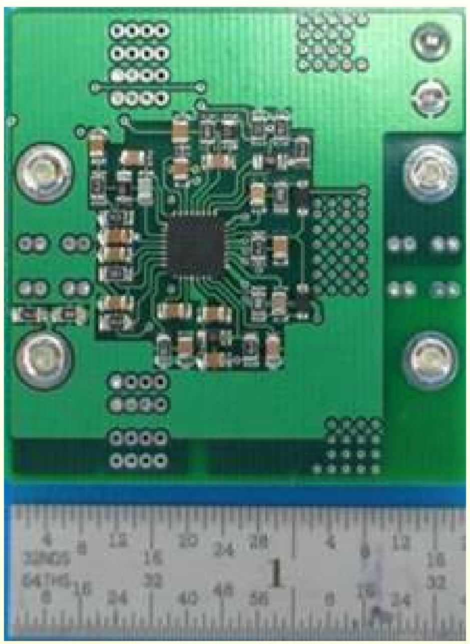


Figure 6 Photos of the prototype point-of-load converter (POLC)

POL Prototype Measured Efficiency

- Efficiency was recorded over wide load, line, and temperature conditions
  - A record power efficiency of 98.99% was obtained during thermal cycling
  - The efficiency was above 97.5% for all lines, loads and temperatures

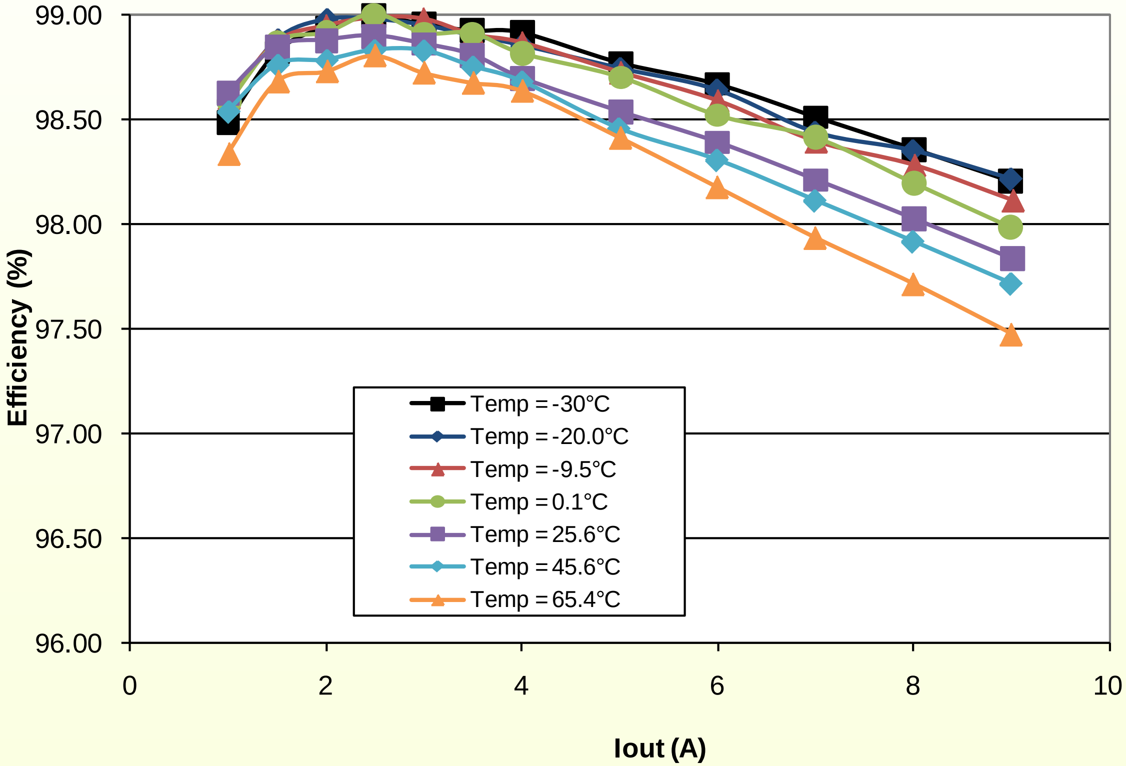


Figure 8 Measured POLC efficiency, demonstrating a record power efficiency of 99% at $4V_{in}$, $3.3V_{out}$ at about 3A

BCM Prototype

- Finally we'd like to share the measured efficiency from our bus converter module (BCM) prototype
  - Our BCM efficiency was measured to be a record high of 95.47%
  - Details can be the subject of a separate presentation

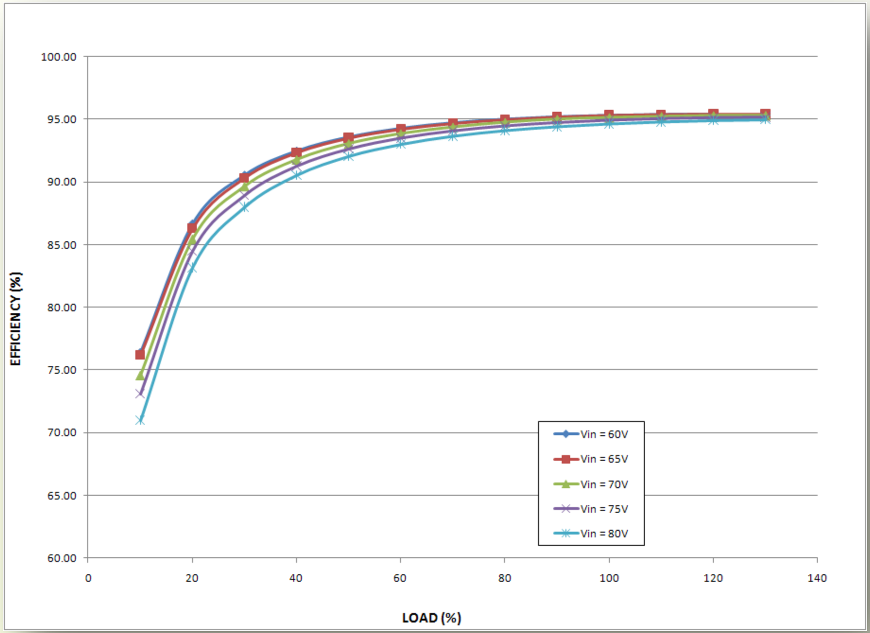


Figure 14 Measured efficiency for the BCM prototype

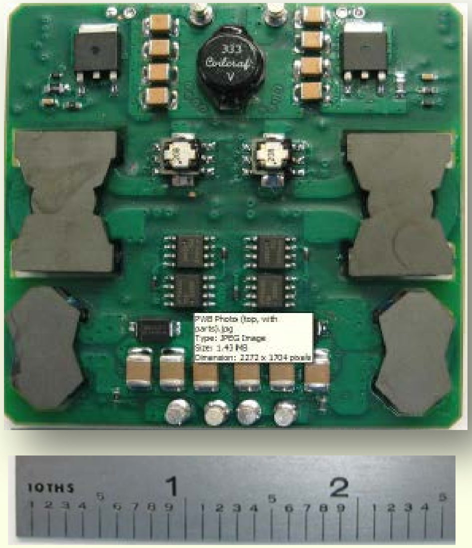
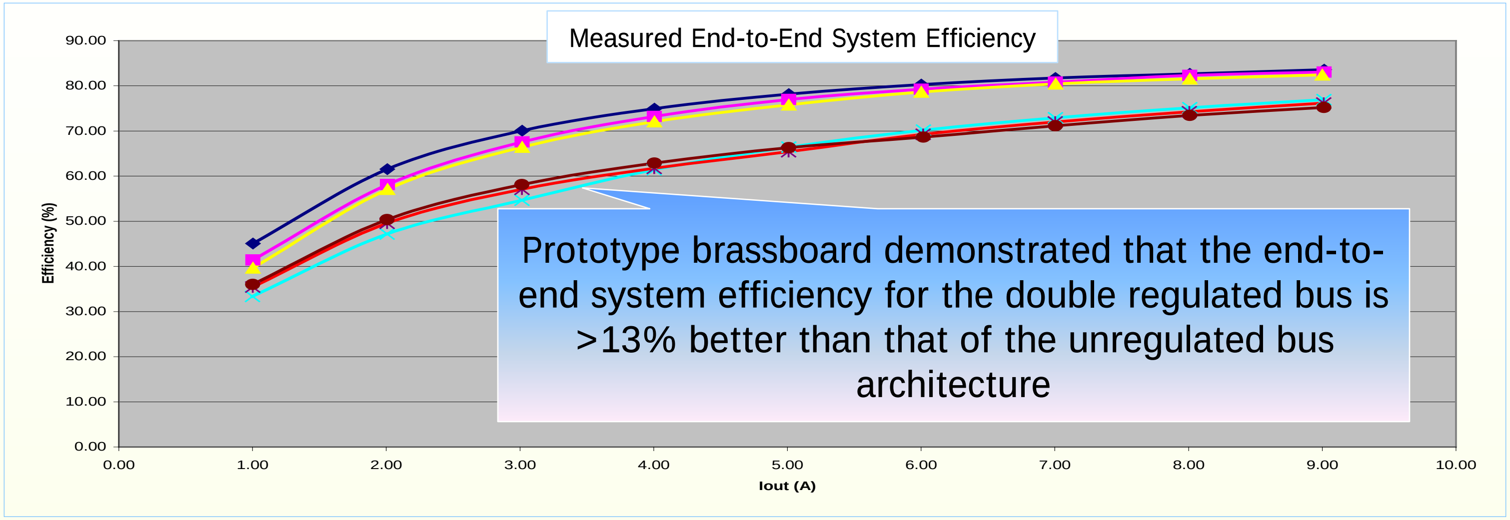
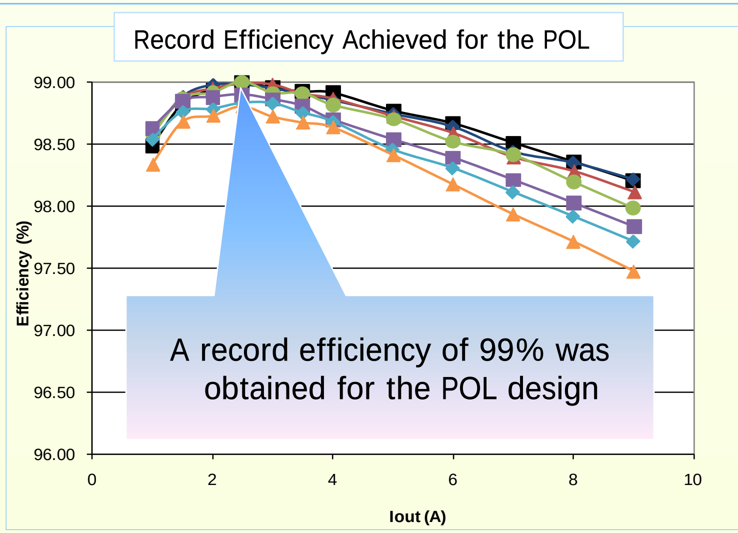
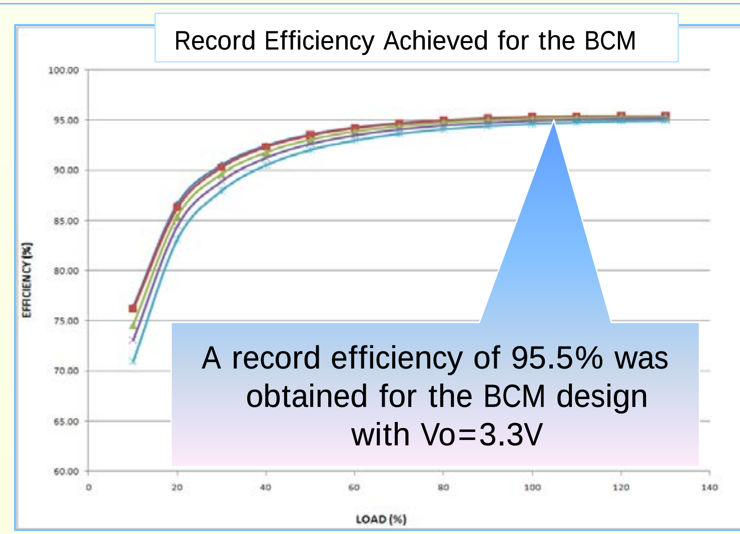


Figure 15 Front view of the BCM prototype

Measured Results on End-to-End Efficiency





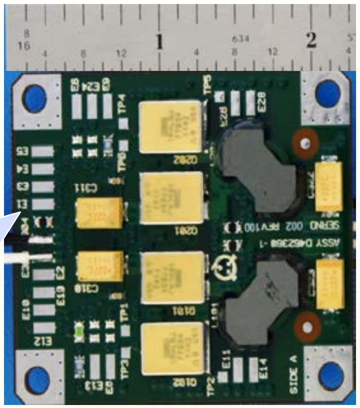


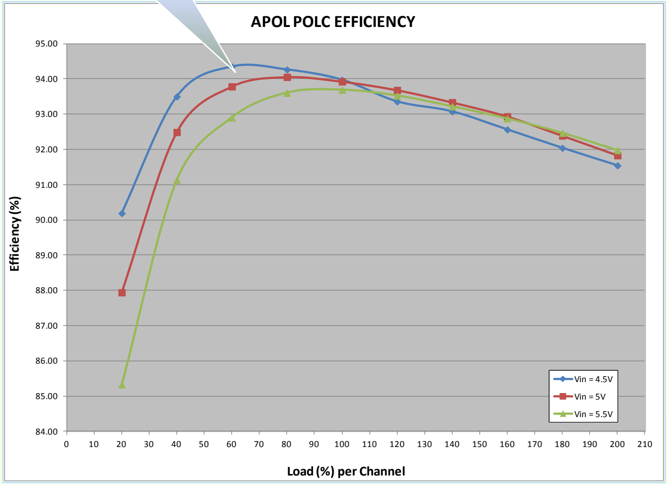
APOL EM Photos

APOL POL EM with R7 MOSFETs

(1.9''x2.2''x.46'' / .14 lbs.)

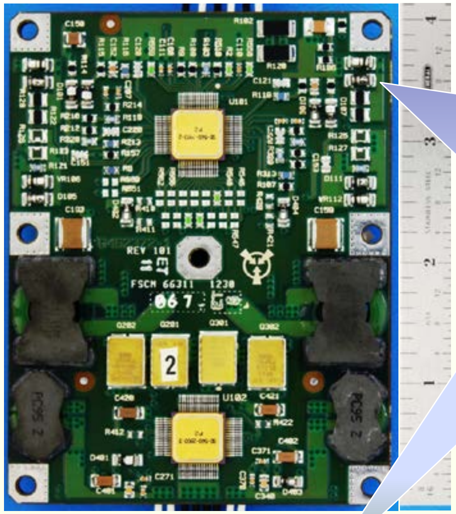
APOL POL EM demonstrated efficiency of 94.35% at 1/3 of the load and 91.54% at full load when tested to 60W, 2x of the designed capability



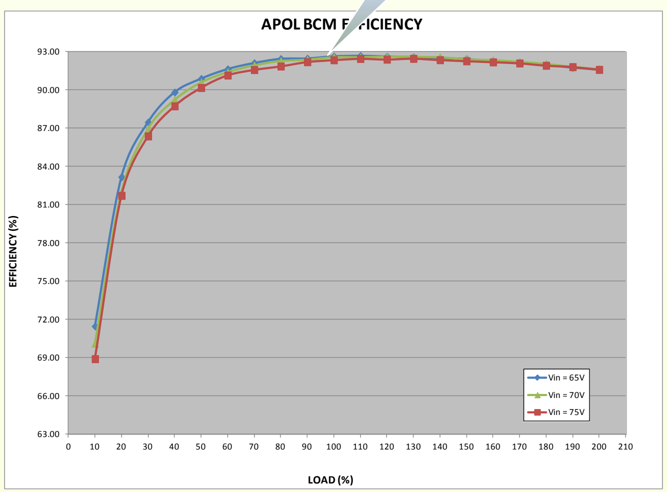


APOL BCM EM with R7 MOSFETs

(3.0''x4.0''x.66'' / .40 lbs.)



APOL BCM EM demonstrated efficiency of 92.64% at 1/2 the load and 91.64% at full load when tested to 120W, 2x of the designed capability



APOL EM demonstrated record efficiency for both the POL and the BCM designs

APOL EM Photos

- POL EM Photos from Production

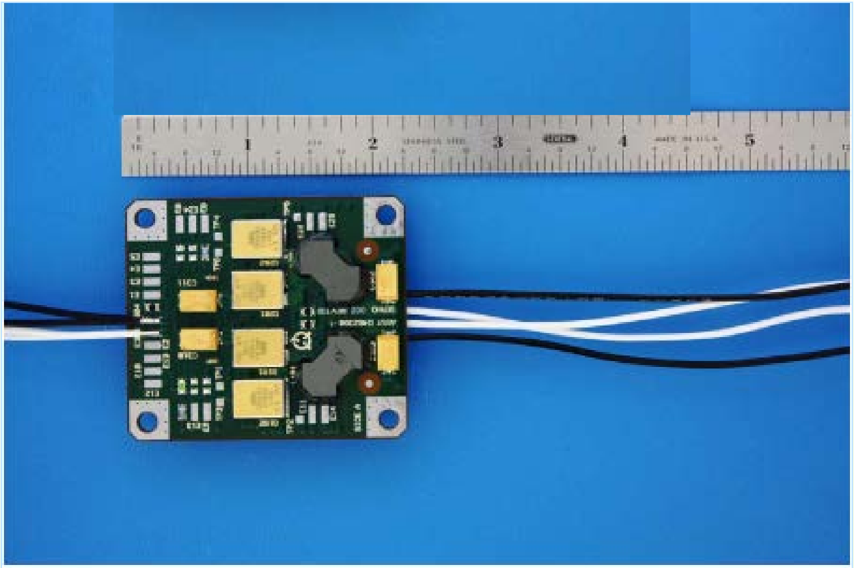


Figure 3-4 Picture of POL (top)

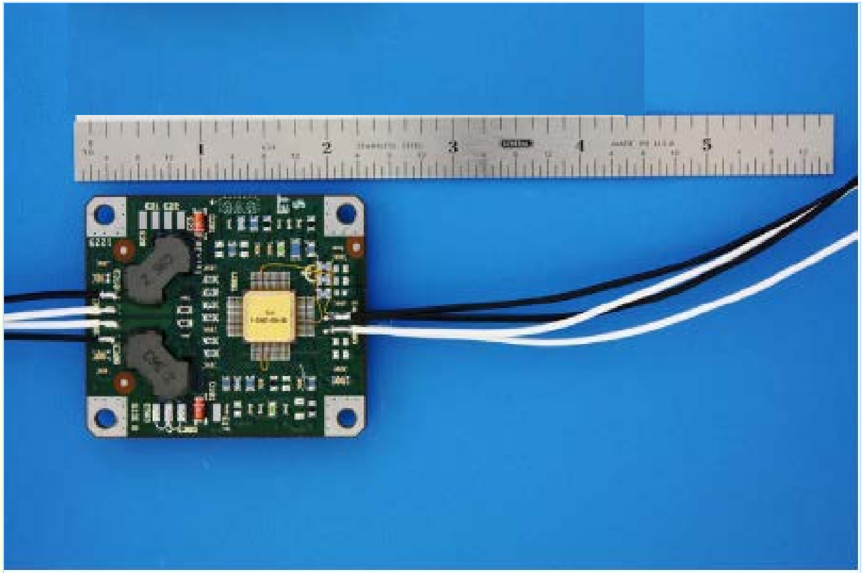


Figure 3-5 Picture of POL (bottom)

POL EM Test Set-Up

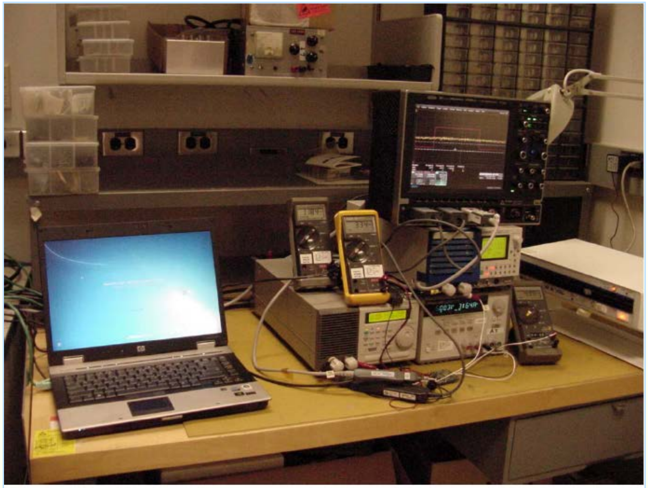


Figure 4-12 General Test Setup

Figure 4-13 Thermal Chamber Setup

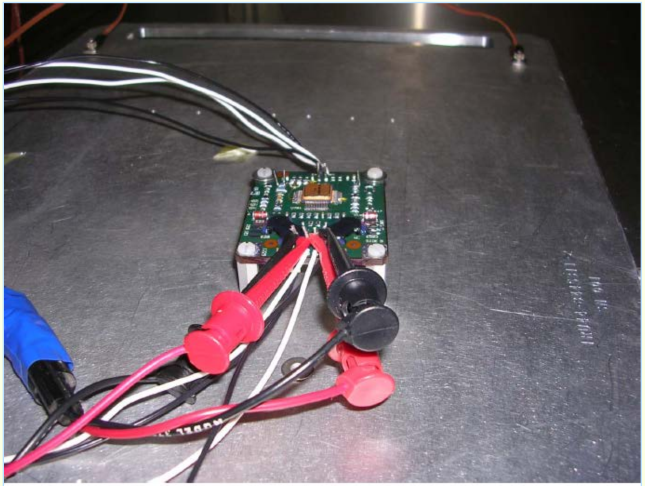


Figure 4-14 Close up of POL in thermal chamber

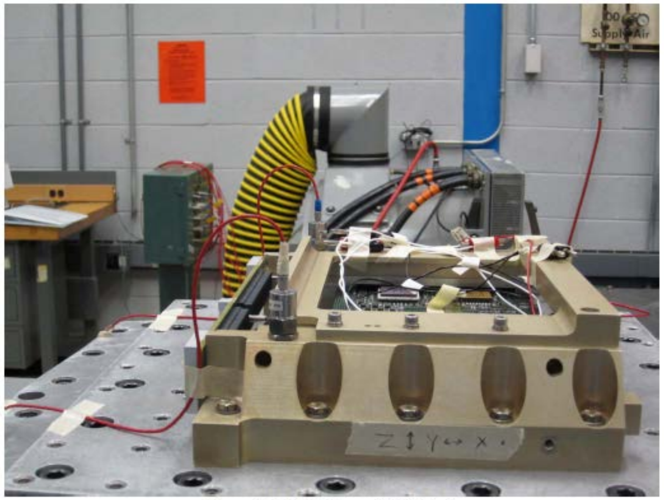


Figure 4-22 Vib Fixture with XYZ axis

POL Measured Efficiency

Before vib and thermal cycling

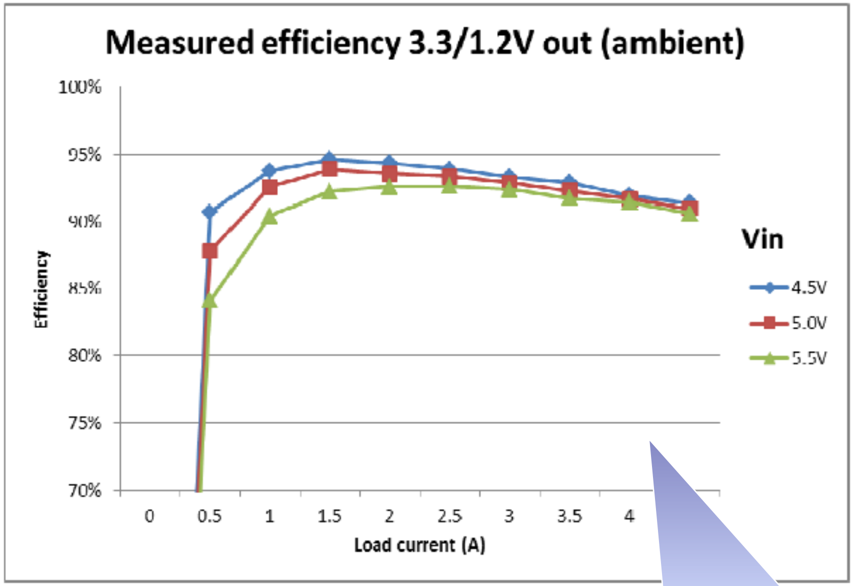
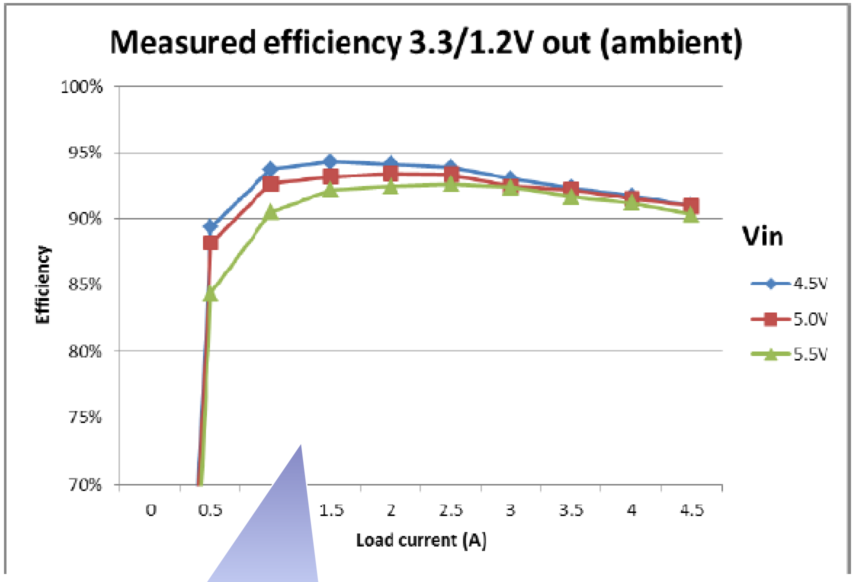


Figure 4-1 Pre-Coat Efficiency Plot

After vib and thermal cycling



4-5 Final Efficiency Curve

The POL measured efficiency virtually unchanged after vibration and thermal cycling tests

APOL EM Photos from Production

- BCM EM Photos from Production

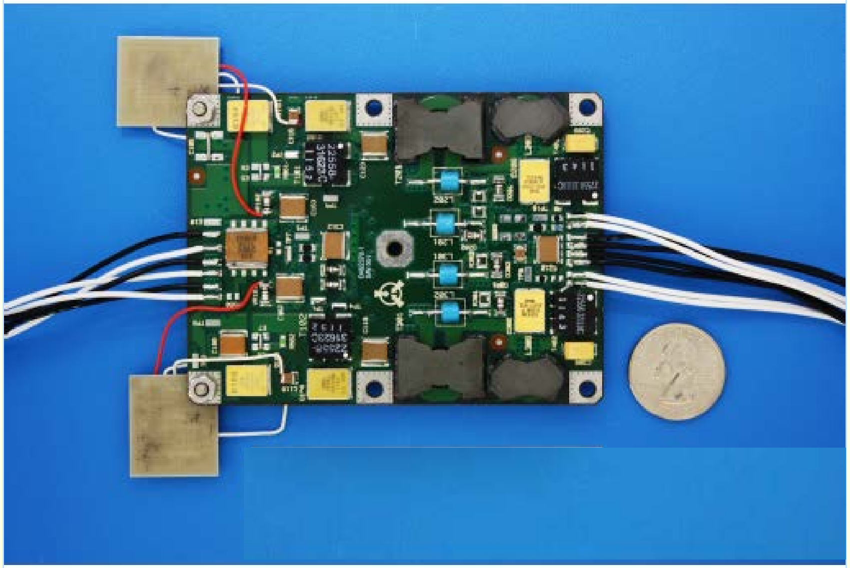


Figure 3-4 BCM Photo Side A

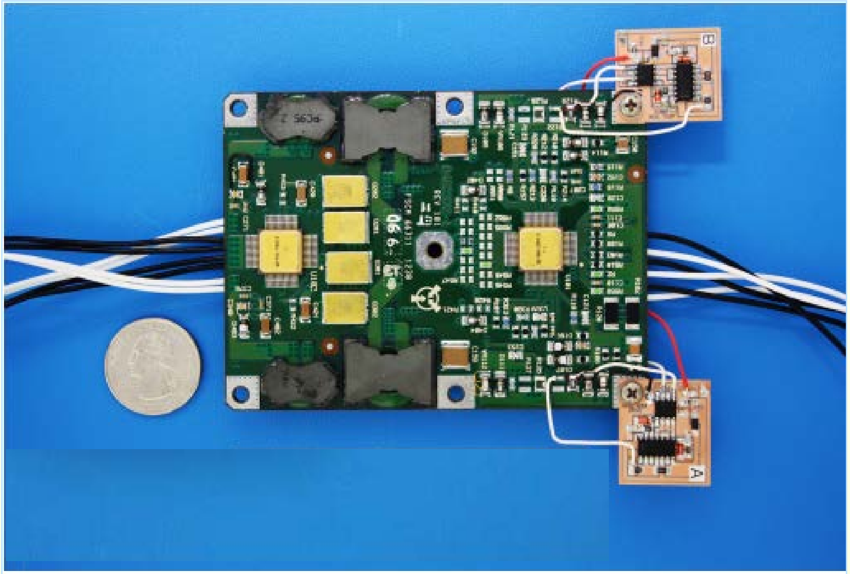


Figure 3-5 BCM Photo Side B

BCM EM Test Set-Up

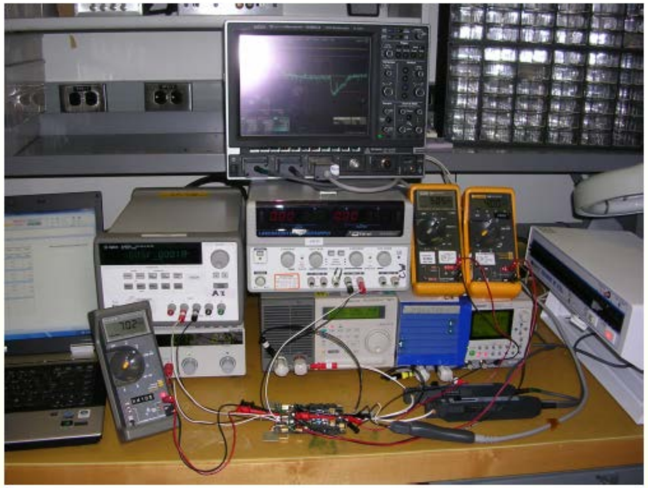


Figure 4-12 General Test Setup

Figure 4-13 Thermal Chamber Setup

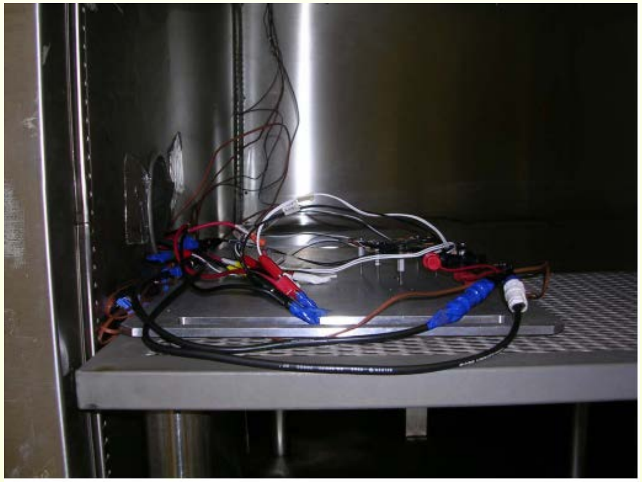


Figure 4-14 Close up of BCM in thermal chamber

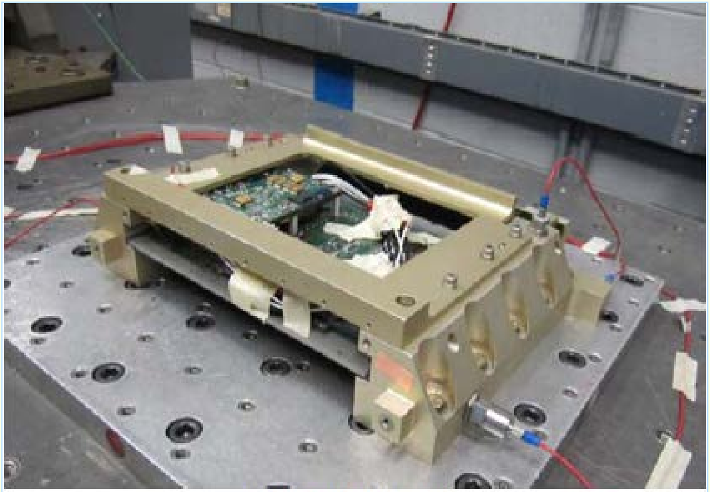


Figure 4-20 Vib Fixture

BCM Measured Efficiency

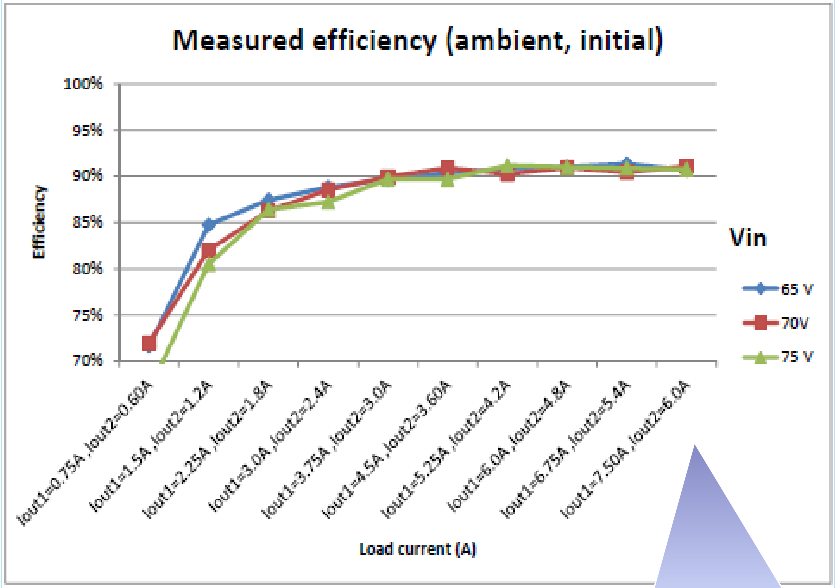
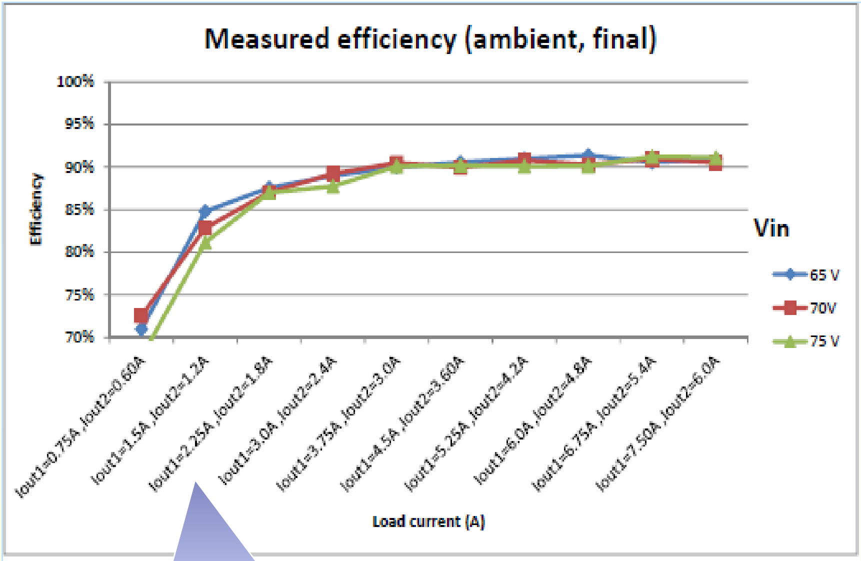


Figure 4-1 Initial Efficiency Plot



igure 4-5 Final Efficiency Curve

The BCM measured efficiency is virtual unchanged after the vibration and thermal cycling tests

THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN