Guidelines for Reliable DC/DC Converters for Space Use

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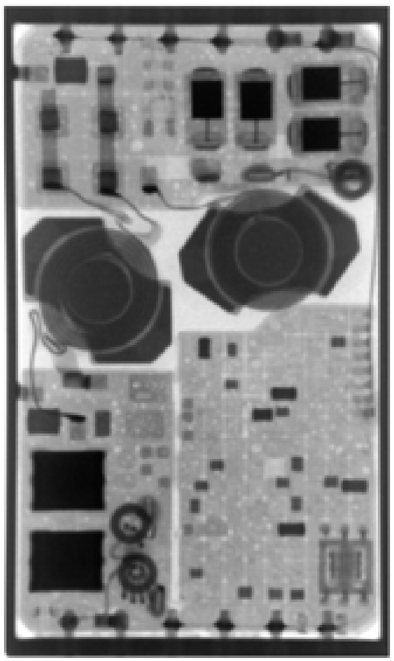
Project Background

- NESC saw the need to study the persistent failure of DC/DC Converters during ground testing and in flight, motivated investigation of causes and mitigation options. Research indicated <u>misapplication</u> and device <u>quality</u> to be root causes. The study took 20 months.

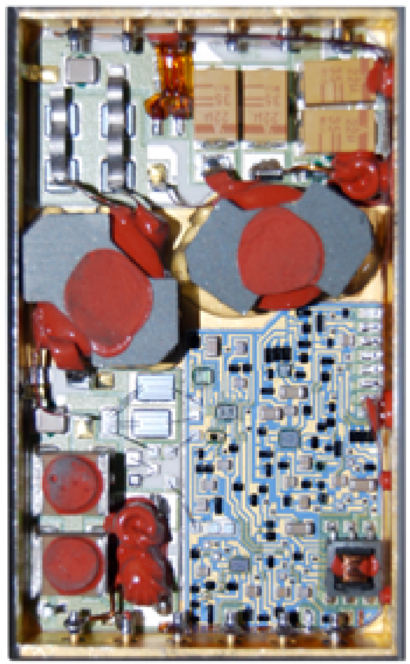
- Team included multiple NASA Centers : JPL, JSC, MSFC, GSFC

Hybrid Converter

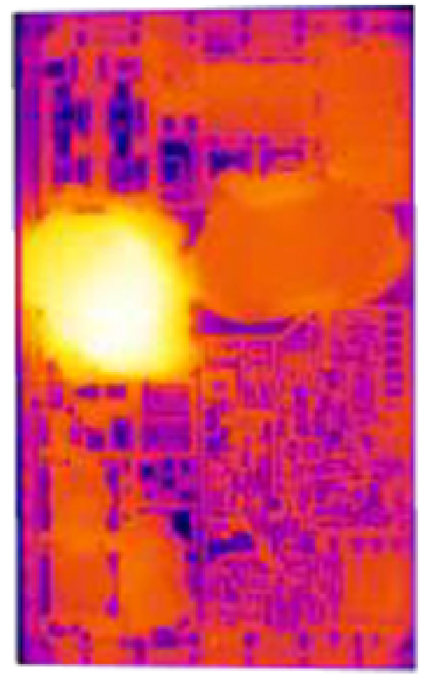
X-Ray



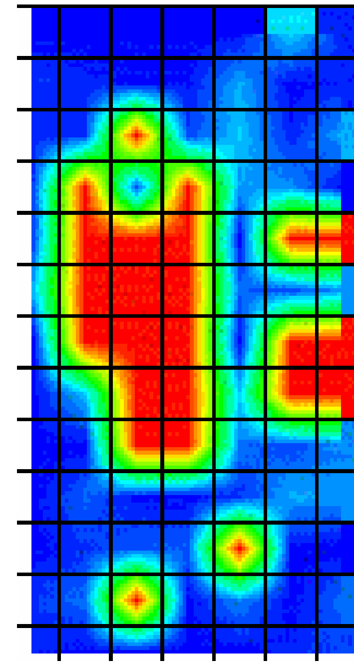
Visible



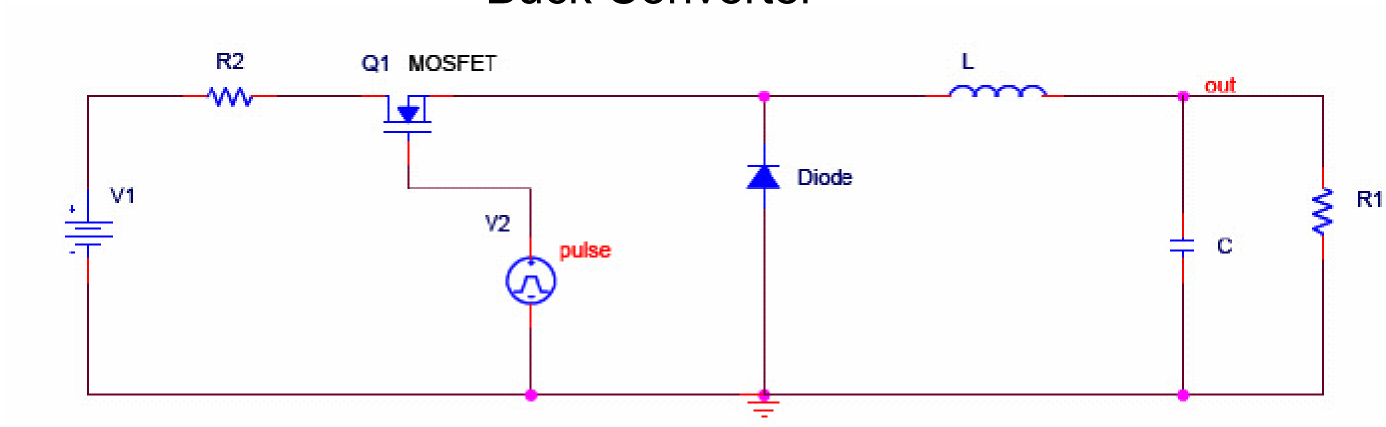
Thermal Under Load



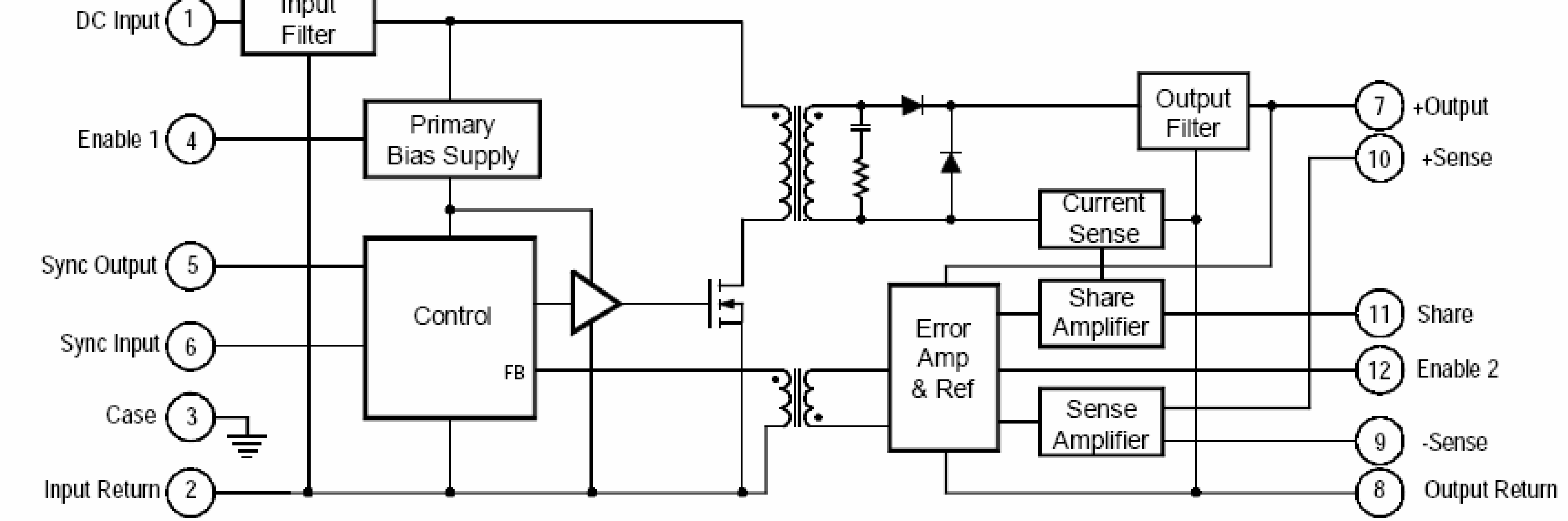
EM 24MHz



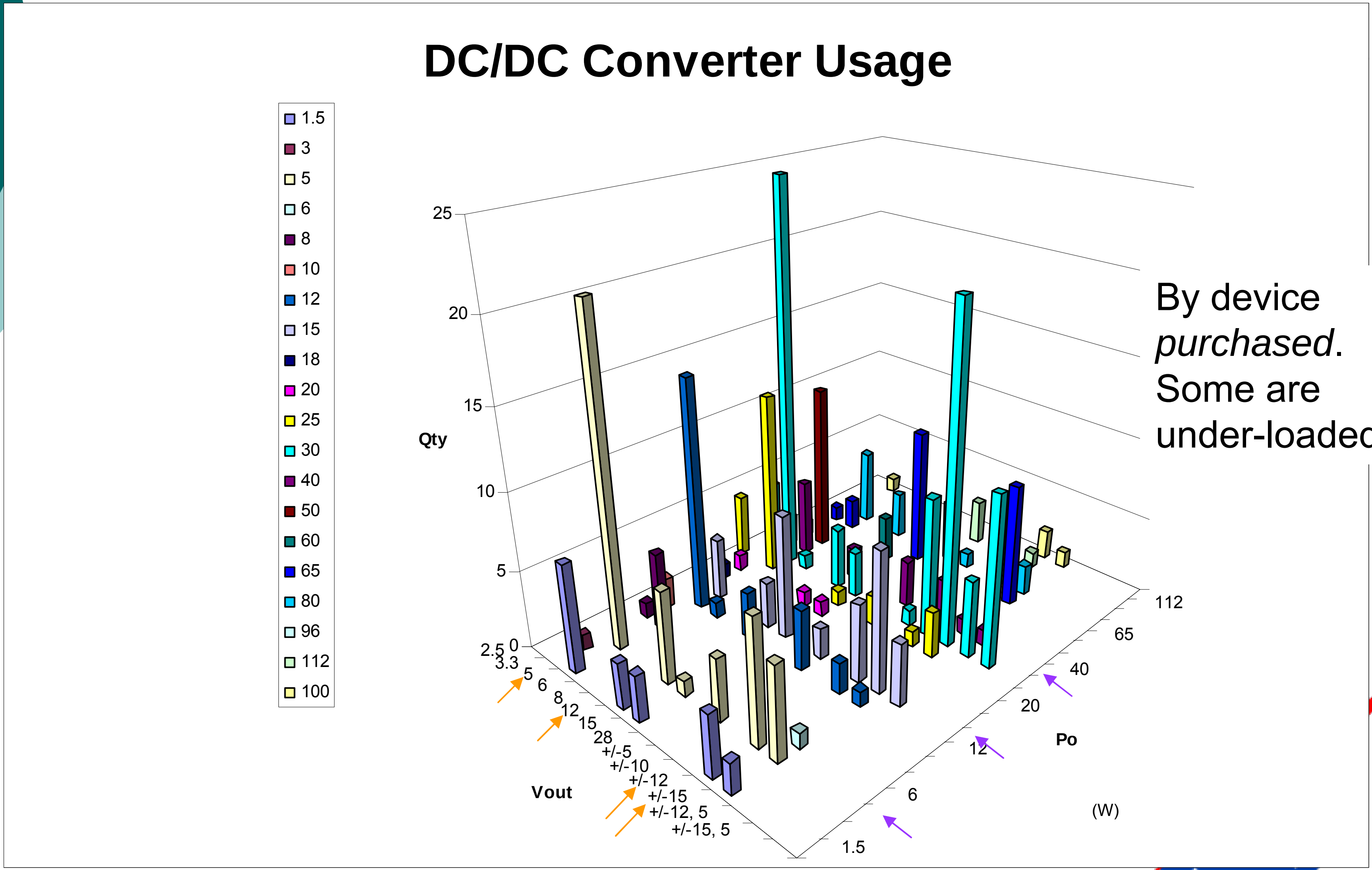
Buck Converter



Isolated Buck Derivative

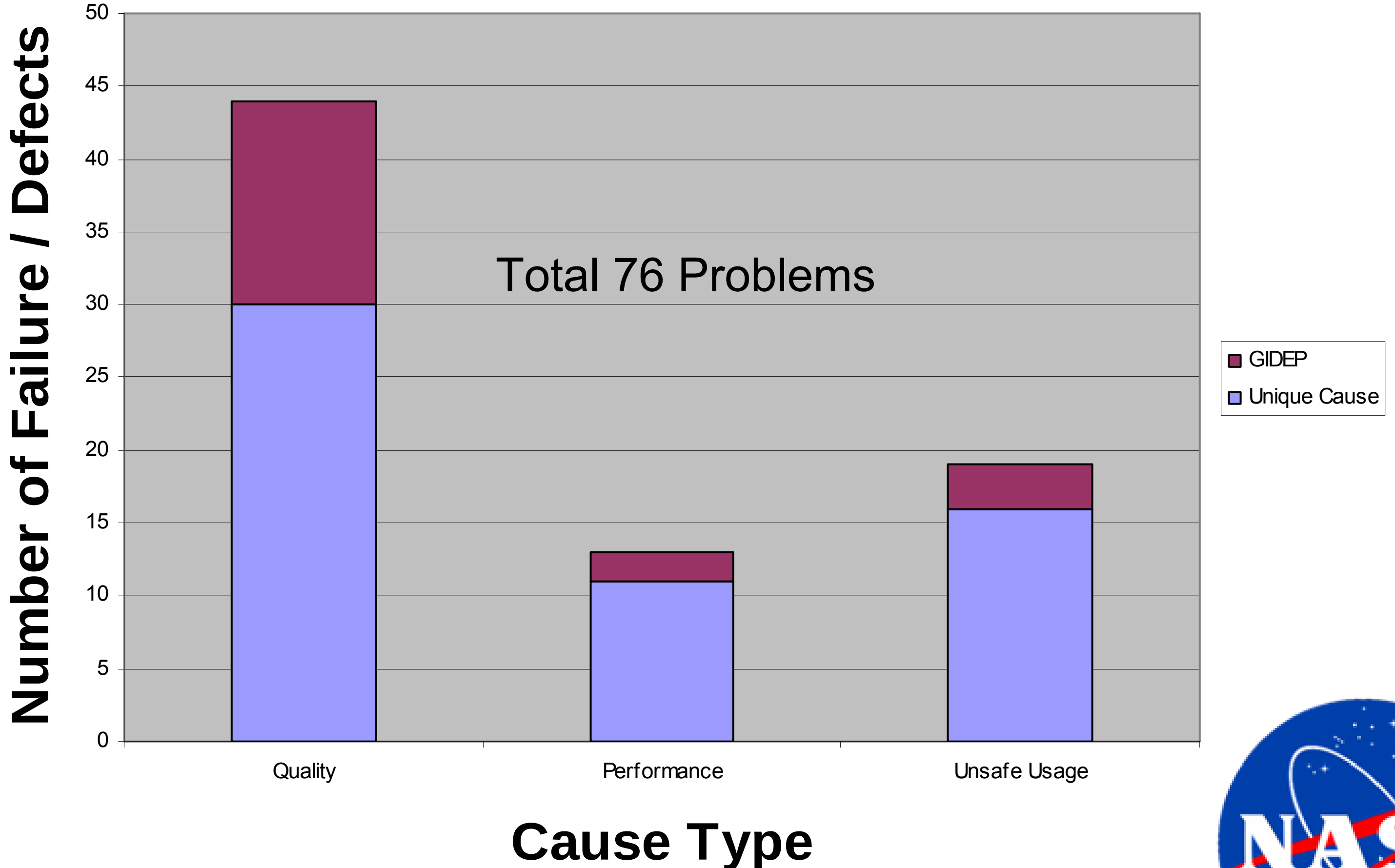


Tracked Usage (~ 5yrs)

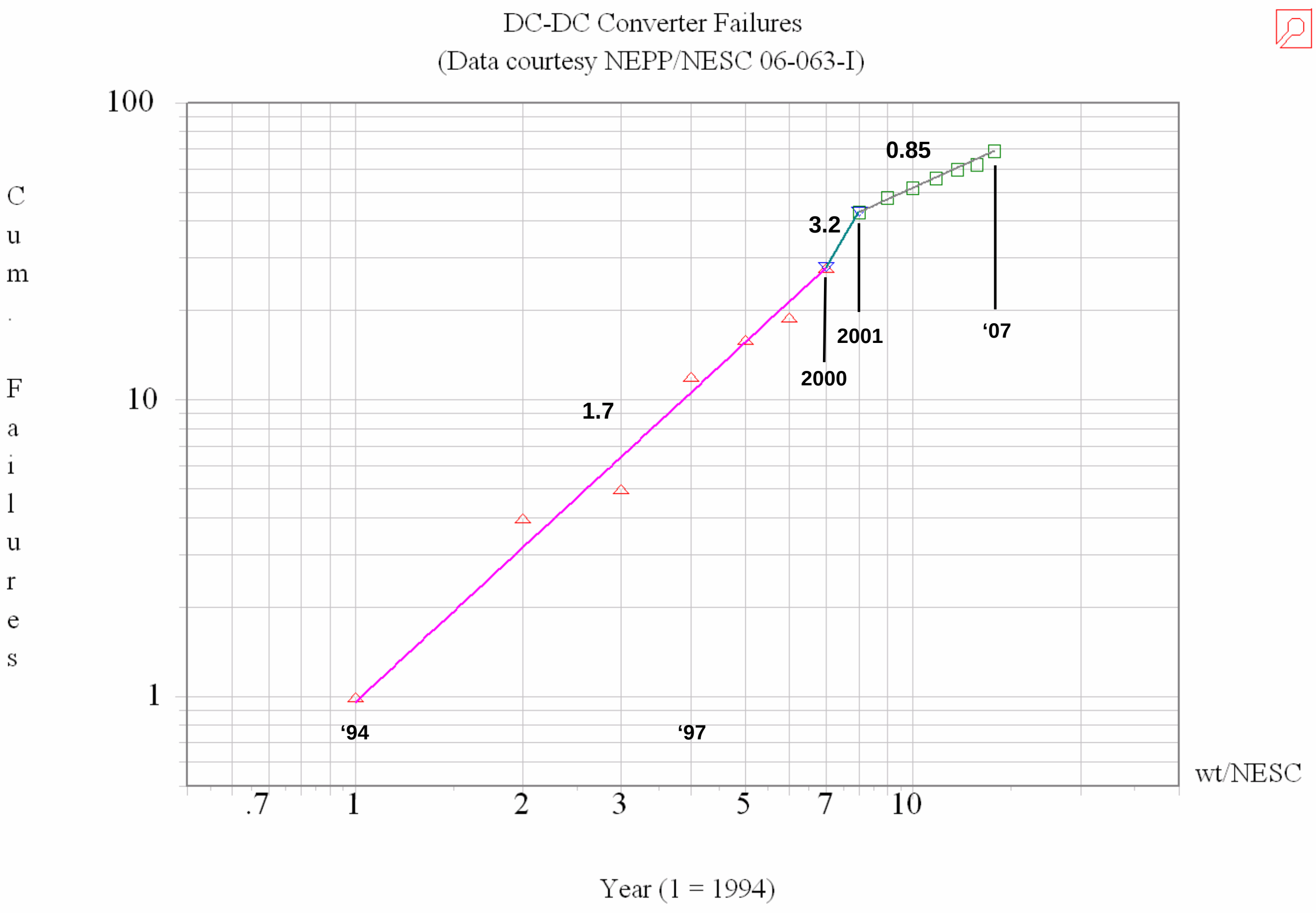


By device *purchased*. Some are under-loaded.

Tracked Failures / Defects (~14 years)



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



Reliability trend plot of DC-DC Converter failures by year from NEPP/NESC Database.
Data are from recorded NASA and other aerospace failures by year; they are not sorted by style or supplier.
The slopes are the numbers above the line segments: 1.7 and 3.2 indicate degradation
(negative reliability growth) and 0.85 indicates a return away from degradation.

Scope of Guideline Document

Practices for local processes:

Some intro-level information to enable broad readership:

Scope of "DC/DC Converter":

- SM-PWM type (100 kHz to 1MHz)
- hybrid microcircuit construction – primarily MIL-PRF-38534 product

Special Warnings Highlighted

Examples of Lessons Learned on Actual Projects

Not included in Scope of Guideline Document

<u>Scope of "DC/DC Converter"</u>:

- Potted modules in the contents of COTS
- Primary and POL
- Critical EMI filter issues

Lack of time, not interest.

Examples and Cautions

Excerpt from Chapter 4.0 Performance Requirements…..

EXAMPLE: Sense lines were used to eliminate voltage drops across a filter. The filter included a common mode choke. The choke added a pole, and the converter became unstable under heavy loading. [ref. 2]

CAUTION 4.1-2: If the remote sense feature is not used, …..

EXAMPLE: During converter testing by NASA, …….

Datasheet Parameters Needed

normally provided   💻= scope shot or plot also required

Voltage: **8 Items** 7 items normally provided

Turn-on Behavior: **3 Items** 0 items normally provided

Power and Load: **13 Items** 💻 5 items normally provided

Stability Management / Transients : **4 Items** 💻

1/2 item normally provided

Datasheet Information Needed

Similarity of parameter list
for 28Vin, 3.3Vout design

datasheet completeness score

mfr1 datasheet	mfr1 datasheet	Mil Spec SMD	Mil Spec SMD	Mil Spec SMD	mfr2 datasheet	mfr3 datasheet
82%	82%	52%	49%	53%	57%	31%

-55ºC, 25ºC and 125ºC   Over line and load   Emphasis on load between 0% and 50%

Example of Data Left Out

|Zin| > |Zout|

Middlebrook's criteria for input filter stability. Both impedances can be measured experimentally, or can be modeled, and then plotted on the same Bode plot. The resultant system is stable if at no frequency the magnitude plots intersect.

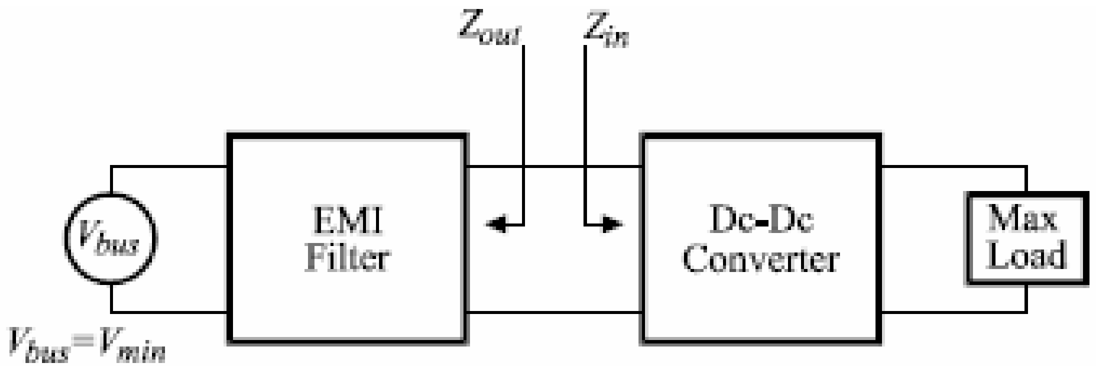


Figure 4.6-1. Block Diagram

Many EMI Filters do not completely follow this!

Example of Statements of Best Practice & Lessons Learned

Special features (including remote sense, current sharing, inhibit, and synchronization) need to be used with caution.

Improper implementation of special features can lead to load damage, converter damage, or erratic system behavior.

Example of Statements of Best Practice & Lessons Learned

A key parameter of converter selection is load performance. Not all converters operate well at light **(less than 20%)** load or with heavy capacitive loads. Vendors do not design for very low loads and typically do not characterize the converters behavior at low loads.

Derating criteria of ≥ 20% load is recommended.

Example of Statements of Best Practice & Lessons Learned

Uncontrolled inrush current can lead to erratic system behavior, blown protection fuses, and damage to the converter.

This will also apply during characterization and Qualification testing.

Example of Statements of Best Practice & Lessons Learned

Motor-boating or oscillation may occur at the input and output of the converter during its turn-on period, if input voltage ramp is slow and the Inhibit function is not used.

On a NASA project, a soft-start circuit was based on **the vendor's application note**, without the Inhibit function. An oscillation caused overstress and failure of the converter's internal elements.

Often Heard Statement

"Space Grade", "Space Qualified", "Radiation Hardened", and **"Class K Equivalent"**

These are marketing terms which may or may not meet mission quality and reliability requirements. Manufacturer may change what is inside!

Recent Example of "Class K Equivalent"

- Project bought "Class K Equivalent" due to time and money constraints.
- Process changes not allowed in Class K caused units to fail bond pull test.

Bottom line, units failed bond pull test at GSFC with no spare time or money for recovery

Recent Example of "Class K Equivalent"

- Project bought "Class K Equivalent" and changed requirements on unit.
- Requirements change, changed internal layout.
- Units failed due to layout, and new parts driven by requirements change.

Bottom line, units failed. It was and still is "Class K Equivalent", but **never** Class K.

Buying to the Data Sheet

- Manufacturer states in data sheets, that they can and will change parameters without notice to customers.

This is true, sometimes changing from unit to unit built on same day

Test Method Coverage

- 23 Tests, over temp, over load, over line, to address required parameters
- Precaution regarding thermal control
- Precaution regarding minimum output Load
- Ground connections
- Oscilloscope settings
- Test-specific instructions and precautions
- Set-up diagrams
- Examples of results/data required

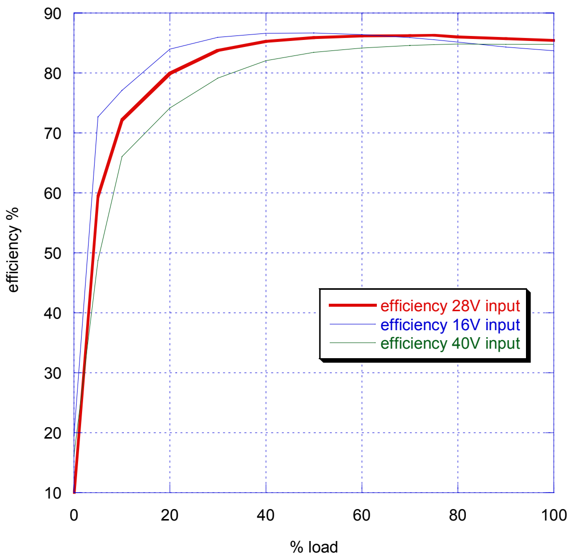
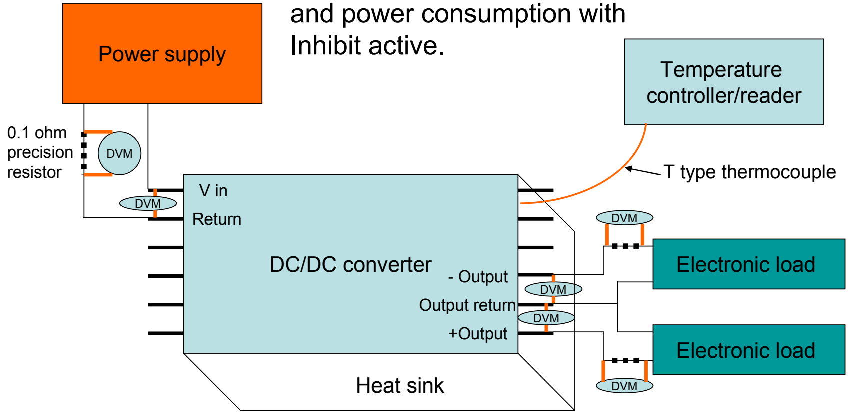


Figure 6.2-3 Efficiency vs. output load percent of maximum load, at three input voltages, at 25C.

Figure 6.2-1 Test set-up for load regulation, efficiency, and power consumption with Inhibit active.



Some Procurement Lessons Learned

- Class K provides lowest lot jeopardy and customer controlled electrical parameters list (+ over temp)
- Equivalent oversight of non-QML vendor is large effort. Factor this into the procurement process/cost
- Element selection and control affects Radiation Hardness

- Class K delivery times: 26 – 52 wks
- Class H delivery times: 16 – 24 wks
- “Class K Equivalent” delivery times: 16-24 wks

- Early negotiation of an NDA will provide ready-access to schematics and failure information when it is needed.
- Review lot data from converter screening and QCI is completed before the flight lot is shipped from the vendor.

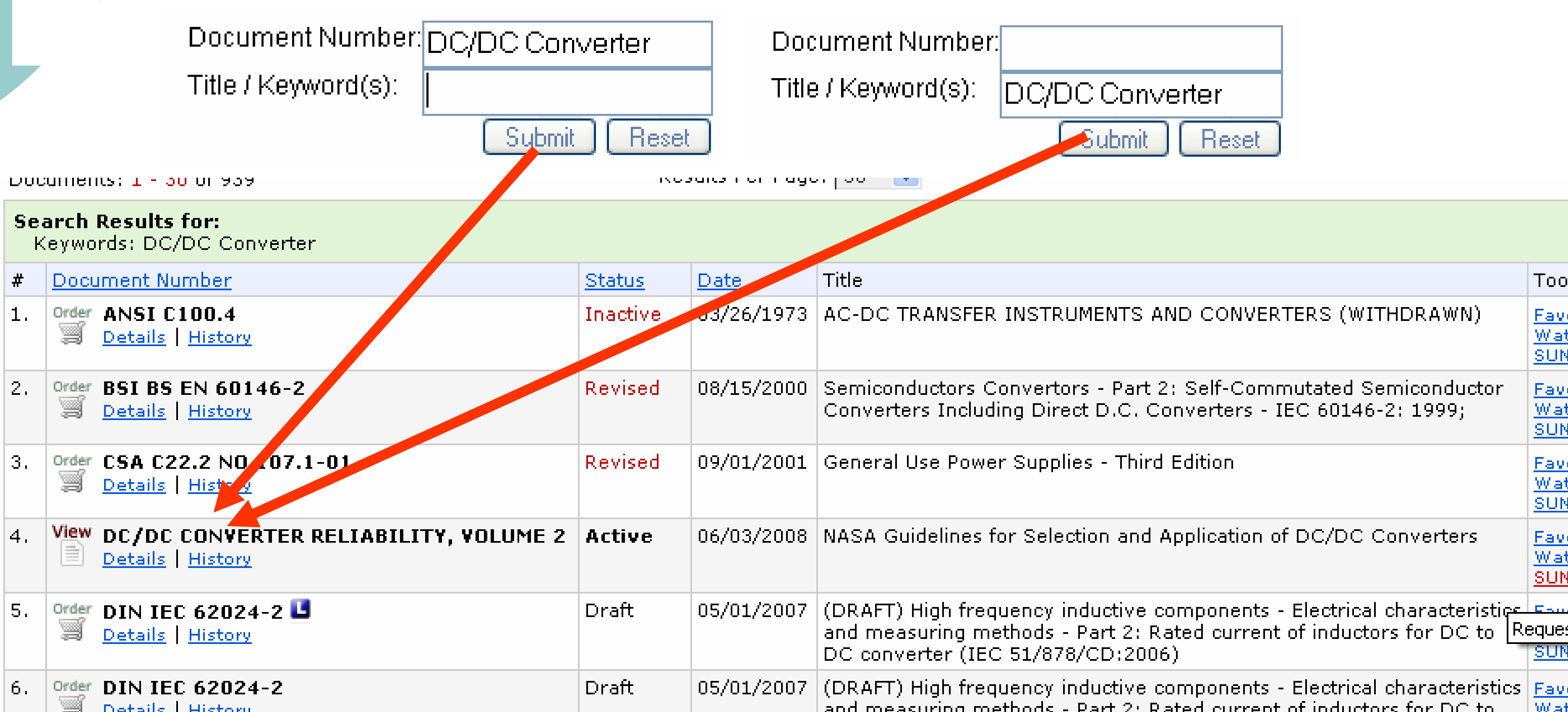
Publication Status

Document approved by NESC: April 2008

ITAR Review/Release: Limited to Govt and Govt Contractors

Document available now through http://standards.nasa.gov/

Keyword -or- Document Number search on "**DC/DC Converter**"



#	Document Number	Status	Date	Title
1.	Order ANSI C100.4 Details | History	Inactive	03/26/1973	AC-DC TRANSFER INSTRUMENTS AND CONVERTERS (WITHDRAWN)
2.	Order BSI BS EN 60146-2 Details | History	Revised	08/15/2000	Semiconductors Convertors - Part 2: Self-Commutated Semiconductor Converters Including Direct D.C. Converters - IEC 60146-2: 1999;
3.	Order CSA C22.2 NO 107.1-01 Details | History	Revised	09/01/2001	General Use Power Supplies - Third Edition
4.	View DC/DC CONVERTER RELIABILITY, VOLUME 2 Details | History	Active	06/03/2008	NASA Guidelines for Selection and Application of DC/DC Converters
5.	Order DIN IEC 62024-2 Details | History	Draft	05/01/2007	(DRAFT) High frequency inductive components - Electrical characteristics and measuring methods - Part 2: Rated current of inductors for DC to DC converter (IEC 51/878/CD:2006)
6.	Order DIN IEC 62024-2 Details | History	Draft	05/01/2007	(DRAFT) High frequency inductive components - Electrical characteristics [illegible]

Backup Slides

Project Background

• Persistent failure of DC/DC Converters during ground testing and in flight, motivated investigation of causes and mitigation options. Research indicated <u>misapplication</u> and device <u>quality</u> to be root causes.

• NASA Engineering Safety Center awarded study to:

- Document and share lessons learned
- Demonstrate safe operating conditions and failure modes that occur outside of safe operating region
- Guide users about how to select and procure "good" devices
- Set up a system to track usage and failures

•Team included multiple NASA Centers : JPL, JSC, MSFC, GSFC

•Deliverables: Guideline document, website, usage database, test reports, test methods

• Project started in fall of 2006. Final report accepted by NESC April 2008.

Tracked Failures/Defects (~14 yrs)

- Workmanship & Quality Defects - Device Does Not Meet Performance Needs - Unsafe Operation Conditions - Uncharacterized Behaviors -

Total # of failures/defects recorded since 1994 : 77
GIDEP Alerts written since 1984: 19

Unique Root Causes All:	Unique Root Causes according to GIDEP:
Quality: 30	Quality: 14
Performance: 11	Performance: 2
Unsafe Usage: 16	Unsafe Usage: 3

- The perception that the problems are quality related is not entirely true. Misapplication and under-characterization also significant problems.
- GIDEP system is not capturing Space Industry DCDC converter failures and not capturing misapplication and functionality problems.

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

Scope of Guideline Document

<u>practices for local processes</u>:
- managing conditions for stability
- using special features: sync, trim, undervoltage lockout, sequencing, etc.
- device characterization and evaluation
- vendor risk factors
- procurement activities and methods
- post-delivery activities
- SoCD template, failure & usage data

<u>Some intro-level information to enable broad readership</u>:
- managers
- systems engineers
- electrical designers
- parts engineers
- quality engineers

Special Warnings Highlighted

<u>Scope of "DC/DC Converter"</u>:
- SM-PWM type (100 kHz to 1MHz)
- hybrid microcircuit construction – primarily MIL-PRF-38534 product
- potted modules in the context of COTS
- primary and POL devices
- critical EMI filter issues

Examples of Lessons Learned on Actual Projects

Examples and Cautions

Excerpt from Chapter 4.0 Performance Requirements…..

EXAMPLE: Sense lines were used to eliminate voltage drops across a filter. The filter included a common mode choke. The choke added a pole, and the converter became unstable under heavy loading. [ref. 2]

CAUTION 4.1-2: If the remote sense feature is not used, the sense lines must be connected directly to the appropriate output terminal (same polarity). If the remote sense lines are left unconnected, the converter may regulate at higher voltage levels (up to 1V, in some cases). Although the converter will typically not be damaged by such operation, downstream circuitry may be vulnerable to overstress from higher than expected converter output voltage. If the vendor datasheet does not specify the proper connection for unused sense pins, contact the vendor for application guidance.

EXAMPLE: During converter testing by NASA, incorrect results were obtained on one converter model due to a test set-up issue involving the sense lines. The converter datasheet lacked instruction for proper connection of unused sense pins, and the vendor was not contacted for guidance. During the test, the sense lines were left open, and the advertised 12.0V nominal output measured 12.9V. Testing was repeated with the sense lines connected directly to the converter output and return pins, and output measured closer to the 12.0V nominal. [ref. 3]

Datasheet Parameters Needed

normally provided   💻= scope shot or plot also required

Voltage: Vin Max, Vin Min, ΔVout Max with Line, ΔVout Max with Temp, ΔVout Max with Load, Output Voltage Ripple (~ 500 kHz to 1MHz), Output Voltage Rise Time vs. Load for Multiple Output Styles, Input Undervoltage Shutdown

Turn-on Behavior: Turn-on Time with Line, Turn-on Time with Temp, Turn-on Time with Load

Transient Response: Line Transient Response 💻, Load Transient Response including Low Load 💻

Power and Load: Output Power Max, Output Power Min including Stability Precautions, Output Current Max, Output Current Min, Load Imbalance Max for Multiple Output Styles, Efficiency with Load including Low Load 💻, Power at No Load, Power with Inhibit, Number of Converters that can be used in Parallel, Capacitive Load Max, Output Overvoltage Shutdown, Output Short Circuit Protection

Stability Management: Input Impedance, Gain and Phase Margin 💻

Datasheet Information Needed

Similarity of parameter list for 28Vin, 3.3Vout design

datasheet completeness score

mfr1 datasheet	mfr1 datasheet	Mil Spec SMD	Mil Spec SMD	Mil Spec SMD	mfr2 datasheet	mfr3 datasheet
82%	82%	52%	49%	53%	57%	31%

normally provided (examples)

Vin Max Vin Min

ΔVout Max with Line

ΔVout Max with Temp

ΔVout Max with Load

Output Voltage Ripple (~ 500 kHz to 1MHz)

Input Undervoltage Shutdown

Line Transient Response 💻

Output Power Max

Case Temperature with Load Max for Safe Operation

Synchronization Frequency Range

Isolation

TID Tolerance

Physical Dimensions

not normally provided *(examples)*

Output Voltage Rise Time vs. Load for Multiple Output Styles

Input Ripple Current Max 💻

Input Common Mode Current Max 💻

Input Differential Mode Current Max 💻

Roll-off Value and Q for Input Filter

Turn-on Time with Line

Approved Radiation Assurance Program Information (approver, date, document reference number)

SEE Tolerance

Mass

Mounting Instructions

Required Sequence for Using Sync and Inhibit

DSCC Part Approval Status or SMD Cross-reference

Derating Criteria Applied to Elements

💻 = scope shot or plot also required

-55ºC, 25ºC and 125ºC   Over line and load   Emphasis on load between 0% and 50%

The vendor datasheet may guarantee a Sync input signal range but not test it on every lot. In one incident, a vendor’s design change was not communicated to NASA and caused a converter to fail synchronization.

Several reliability analyses are needed to assess the converter’s internal circuit design. Do not treat the converter as a black box. For worst case analysis, an accurate parts parametric database is needed for mission life, temperature, and radiation effects.

Improper oscilloscope settings or connections can lead to erroneous data, damage to the converter, or damage to test equipment. Always record voltage and current of both input and output of converter. Characterize the converter over full mission range of input voltage, load, transient, and temperature conditions.

Many converters have been destroyed due to undamped injection transformers or turn-on of the amplifier after the converter input power is applied.

When performing input impedance testing do not over-drive the excitation signal. Excitation signals should not be larger than what is required to allow the signal to be picked out from the noise floor. Excessive signal drive can cause erroneous data.

The same advanced packaging techniques that enable miniaturization of hybrid converters can make them a technology risk to projects.

Hybridized converters are "hand-assembled" which leads to longer lead times and higher variability of device quality. Slightly more than half of recorded converter failures have been due to poor quality.

Hybrid converters contain large numbers of wire bonds and a variety of die and surface bonding surfaces. Bond pull tests and process controls can be reduce the risk of weak bonds in flight units.

Thermal management is critical because hybrid converters generate significant internal heat. Thermal and electrical conduction requirements may compete in the Box/Board packaging design.

MIL-PRF-38534, the military specification for the hybrid converter part type, focuses on packaging quality and reliability.

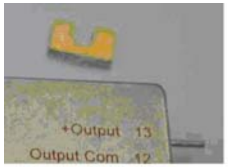
Pre-cap visual inspection should *always* be performed for flight units. Pre-cap inspection requires specially-trained and experienced inspectors. NASA Workmanship training does not cover pre-cap visual instruction.

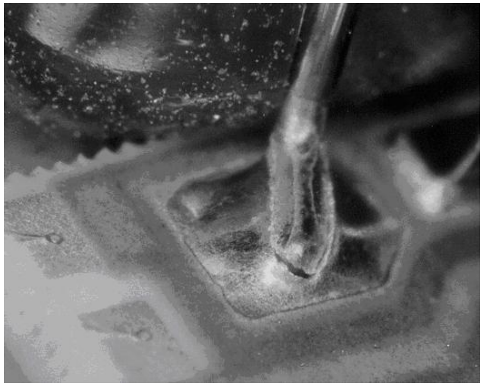
Table 5.1-1. Reliability Analyses for Hybrid DC/DC Converters

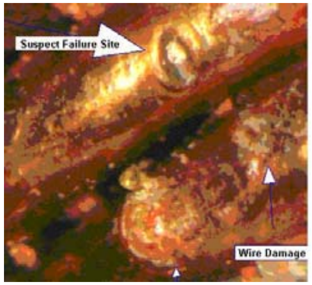
Typical Priority	Analysis Name	Applicable to
1	Parts Stress	All Projects, since parts can be overstressed even during ground test or short missions
2	Worst Case	All Projects, to avoid ground test oscillation related failures. Also for missions with longer duration (> 1 year) or higher total dose (> 3Krad)
3	Single Event Effects (SEE)	All Projects, but lack of formal analysis can be mitigated by careful converter parts list review
4	Interface Failure Modes & Effects	Only where needed to support box level Interface Failure Modes and Effects Criticality Analysis (FMECA)
5	Mean Time Between Failures (MTBF)	Manned missions or other missions with in-flight reparability
6	Thermal	Where needed to support Parts Stress Analysis (PSA), but lack of formal analysis can be mitigated by conservative assumptions for PSA
7	Mechanical Stress	Missions with thermal cycle requirements not enveloped by converter qualification test

Overview and Lessons Learned Packaging and Elements

- Outer package material and plating
- Internal Substrates
- Element Placement
- Interconnect Technologies
- Use of Polymeric Materials in the Package Cavity
- General Quality and Workmanship
- Internal Visual Inspection and DPA







- Commodity-specific concerns
- Application notes from MIL-STD-975
- Lessons learned from defects found in DPA’s
- Lessons learned about swap-in of elements with same generic part number, different vendor
- Emerging information about BME capacitors
- Explanation of MIL-PRF-38534 Element Evaluation requirements

Managing Risk Through Quality Options

Environment	Mission Duration	Service Interval	Function Redundancy	System Redundancy	Mass	Volume
Radiation	>10 yrs	None	Single String	None	Large	Large
Operating Temperature	5 – 10 yrs	>10 yrs	Dual	Like	Moderate	Moderate
Non-Operating Temperature	3 – 5 yrs	5 – 10 yrs	Triple	Unlike	Low	Small
Thermal Cycling Rate	1 – 2 yrs	3 – 5 yrs				
Thermal Cycling Range	3 mos – 1 yr	1 – 2 yrs				
Atmosphere (Vac/Explo/High)	<3 mos	3 mos – 1 yr				
Atmosphere (Pressure Change Rate)	DTO (# of flights)	<3 mos				
Mechanical (Shock/Vibe)		DTO (# of flights)				

Financial Budget	Time Budget	Criticality/ Visibility
Large	Long	High
Moderate	Moderate	Moderate-High
Small	Short	Moderate
		Low
		Very Low
		DTO*

Quality System	Major Manufacturer	Years in Industry	Quality Buy-In (do they really do what they say)	Sole Source
QML	Yes	>10 yrs	Excellent	No
ISO/Equivalent	Some Product	3 - 10 yrs	Good	Some Parts
In-House	No	< 3 yrs	Fair	Yes
None	Garage Shop		Poor	
			Unknown	

1

GIDEP ALERTS	Percent of site volume	Line in Service	Process Control	CONUS (Continental US)
Rare	Major portion of plant output	>10 yrs	Excellent	Yes
Occasional	Medium level of plant output	3 - 10 yrs	Good	Some Parts
Frequent	Small portion of plant output	< 3 yrs	Fair	No
Unknown (non-participant)	Infrequent output		Poor	
			Unknown	

Vendor Risk Factors Identified

•Field history of “off-the-shelf” circuits

•Status of resolution of prior failures and defects. Add SOW requirements to address lessons learned?

•Discovery of unpublished application notes/usage limitations. Subsystem Peer Review to learn “Tribal Knowledge”. *Get the vendor’s input on subsystem design*.

•New to the Space market? Quality system in place to monitor processes?

•Experience with design reviews: worst case analysis, radiation control plans, thermal analysis, etc. Is there information that can be shared Project-to-Project?

•Test laboratory infrastructure/knowledge: Burn-in at full power? Turn-on conditions?

•Delivery history. Avoiding delays due to buyer actions. Impact of new designs.

•QML certified? Test Optimizations?

•Off-shore assembly facilities?

Pre-Award Survey & Procurement

- Carefully managing the procurement document: SoCD, PO, Contract, how to translate NASA Project requirements (technical and quality) into Parts Buy terms.
- Deliverables: Reports, EM Units, DPA Units, Flight Units. Delivery Schedule
- Roles and responsibilities of the oversight team.
- Oversight of scheduled use of subcontractors (package house, test house)
- What to watch for during the build: lot control, travelers, rework, wirebond strength distribution
- Incoming inspections and additional 100% screening
- Installation considerations: grounding, thermal circuit, mounting tabs
- SoCD boilerplate