TRADEOFFS BETWEEN DENSITY, RELIABILITY & TOTAL COST OF OWNERSHIP IN POWER SYSTEMS

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G. Mulcahy

TDI POWER

GARY MULCAHY

Gary Mulcahy is Executive Vice President of the Commercial Products Division of Transistor Devices, Inc. (TDI). He received his BE-EE from New York University followed by graduate study at the Polytechnic Institute of New York. Mr. Mulcahy is a recognized authority in power conversion technology and the design, development and production of power systems for maximum performance and reliability with minimal life cycle cost of ownership.

EXECUTIVE SUMMARY

Improved components, technology and packaging / cooling concepts have reduced the size (watts / cubic-inch), weight (watts / pound) and initial cost (dollars / watt) of power conversion products. When implemented properly, these support new system goals of smaller, lighter and cheaper, along with improved reliability and reduced maintenance (i.e., lower operating costs).

However, as vendors strive for initial sales advantage, design for smaller/lighter/cheaper is invariably hotter, denser and less reliable, to the detriment of the primary system goals of maximum performance and reliability while minimizing total cost of ownership.

As these attributes are pushed, the designer is often obliged to reduce the number and quality of components and/or operate them at higher/hotter stress levels, cramming them into less and less space. These ultimately result in the prohibitive costs of excessive failure: System Downtime, Increased Maintenance Cost, and Catastrophic Facility Events.

TDI has taken these factors into account to set inviolable guidelines of best practice to assure optimal design in the trade-off between smaller/lighter/cheaper and the essential goals of maximum reliability and minimum cost of ownership.

INTRODUCTION:

Modern electronic systems provide increased value in less space. Power conversion equipment has undergone dramatic volume reductions through the years, with module-level power conversion density (= delivered power / package volume) increasing significantly, as illustrated in Figure 1.

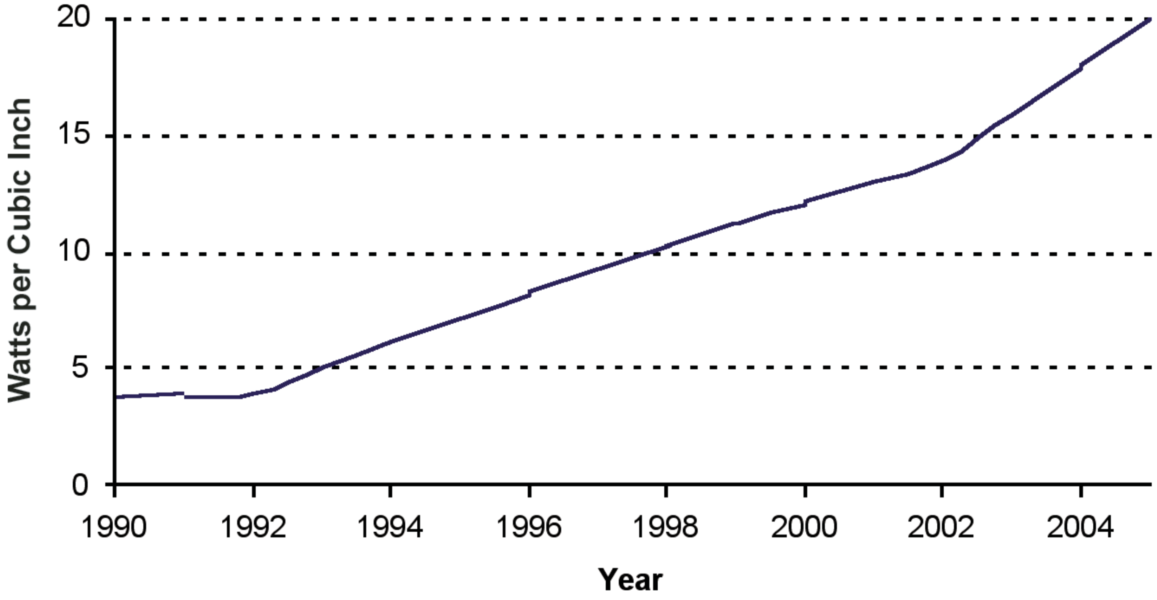

Figure 1: Packaging Density Trends

One has to be careful when examining module-level power density, as these numbers can be misleading. The true power density of a system includes the volume of ancillary equipment required for surge protection, electro-magnetic noise filtering, cooling support, power monitoring and protection circuits, power distribution, etc.

Increased power requirements of data processing, communication and storage applications have placed greater demands on power conversion equipment. These demands have led some to the poorly founded perception of “if it’s smaller, it must be better”, along with “if it’s smaller, it must be more cost effective”.

Contrary to these perceptions, however, increased power conversion packaging density carries with it a number of issues that are counter-productive to system reliability, system and data availability, safety, and overall cost of ownership. All of these issues should be carefully considered prior to deciding just how far to push product size and energy density.

THE NEED FOR POWER CONVERSION RELIABILITY

Electronic equipment is often fundamental to business and commerce, where loss of function, service or data results in large monetary penalties or compromised safety. Quite often, systems are designed with redundancy so that no single failure event shuts the system down. However, even with redundancy, it is crucial that system operation not be compromised through propagation of a single point failure to other equipment via safety, fire, smoke, noise, or other issues. Power conversion equipment reliability is vital to realizing this goal.

Premature failure or wear out of power conversion equipment continues to be a major concern in various industries. Higher packaging density can contribute to the problem, raising overall cost of ownership and negating any initially perceived advantages with being smaller.

UNIQUE CHALLENGES OF DECREASING SIZE OF POWER CONVERSION EQUIPMENT

Power conversion equipment, especially equipment that interfaces directly to utility AC power, presents numerous, unique challenges to the equipment designer. Power conversion equipment is generally broken down into two main categories. Off-line (or AC-DC) Power Supplies interface to AC power, converting it to an electrically isolated and conditioned DC voltage. DC-DC Converters are utilized between the output of Off-line equipment and the final circuitry. They provide local isolation and voltage reduction, as necessary, for the particular circuits being powered.

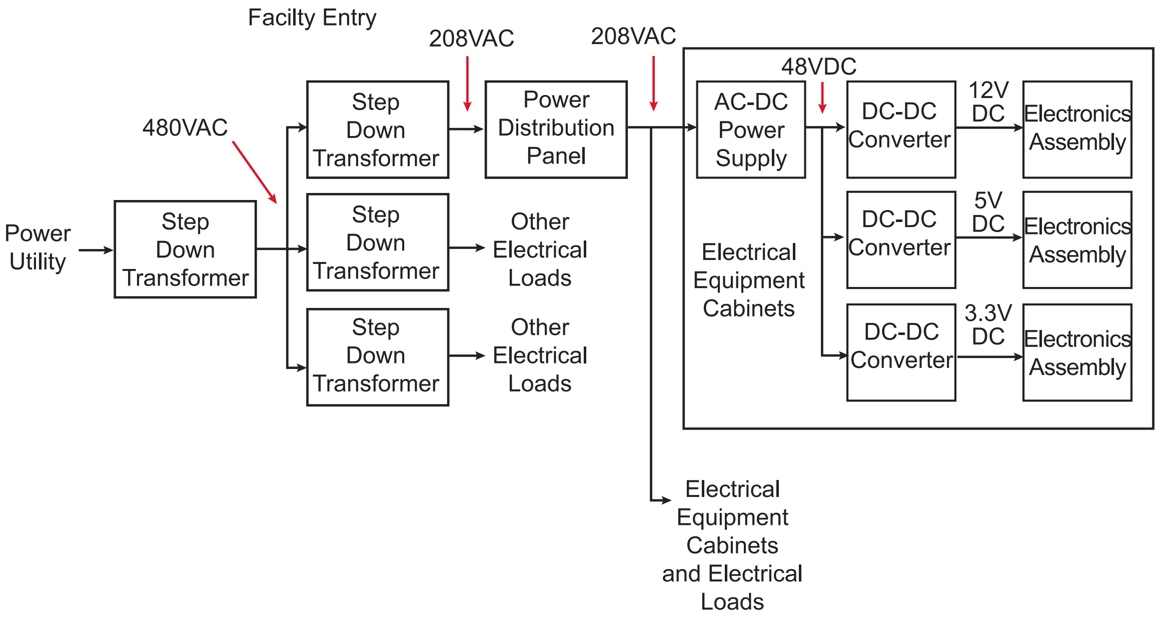

Figure 2: Typical Application of AC-DC and DC-DC Power Converters

Off-line equipment will typically have a major part of its circuitry operating from a 400VDC, or higher, voltage bus. Component operating energy density (= operating voltage x operating current / package volume) rivals that of other components in electronic systems, but, more importantly, potential energy density (= available voltage x available current / package volume) is often an order of magnitude greater than what is seen in other parts of the system. Failure modes present significant risk of system compromising events (flash, smoke, smell, fire) and the potential for these types of events increases as packaging density increases.

High voltage transient events presented by the input power line also challenge power conversion equipment. It is not uncommon for short duration (<100 microseconds) voltage surges in the thousands of volts, or longer duration (>100 milliseconds) voltage swells in the hundreds of volts to be present. As components are stacked closer together, care must be taken so as not to compromise surge immunity.

Off-line power supplies are also often the last line of defense regarding system electro-magnetic interference emissions, or EMI, compliance. Effective management of EMI often requires physical segregation of circuits and noise generators, which can be at odds with strategies for higher packaging density.

COMPONENT AND CONDUCTOR SPACING

Voltage and conductor spacing must be carefully considered to provide long-term reliability. Most products are qualified to various safety agency requirements, which set minimum spacing criteria for protection of personnel. For example, in order to assure no breakdown of insulation over surfaces, UL1950 requires a minimum of 4mm of distance between any conductor connected to the AC power line and any conductive material that personnel may come in contact with.

Experience has shown that these criteria are not necessarily a formula for extended reliability. Data Center and office environments are often prone to airborne contaminants. Since most data processing equipment is forced air cooled, infusion of conductive airborne contaminants is one of the leading causes of premature unit failure.

Beyond conductive particle infusion, gradual infusion of normally non-conductive dust, along with pre-existing sources of ionic contaminants, humidity and the presence of significant electrical fields within power conversion equipment can lead to conductive dendrite growth. As shown in Figure 3, even in “clean” office and data processing environments, dust and other airborne environmental contaminants can build up to problematic levels over time.

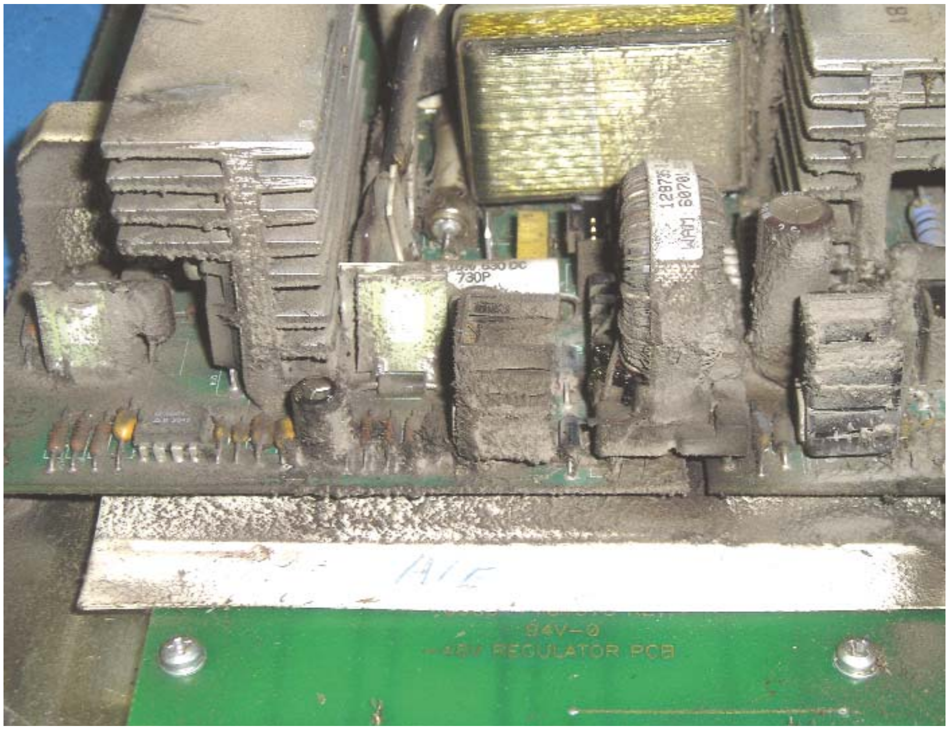

Figure 3: Dust build up in data processing application

Dendrites are microscopic conductive paths that are formed when ionic materials, in the presence of moisture and an electric field, disassociate into negatively and positively charged materials. Figure 4 presents a photograph of a dendrite growing between two PC board traces.

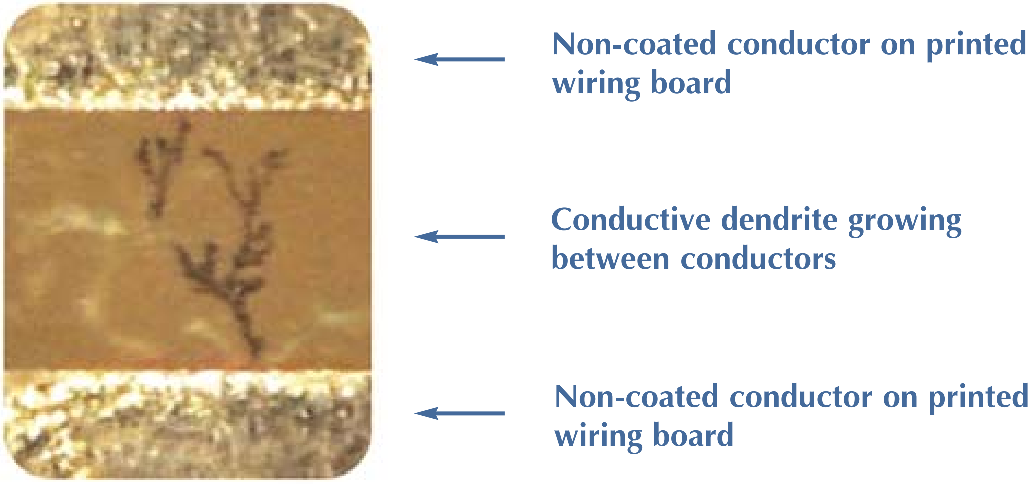

Figure 4: Dendrite (magnified) growing between two traces on PC Board

Non-conductive dust provides a moisture collection medium that enables the dendrite forming process. Pre-existing sources of ionic materials include flux, cleaning fluids, and plating chemistry residue (from the surface finish). All printed wiring boards have a significant amount of their conductors exposed for soldering and connection purposes. Over time, exposure to environmental contaminants can lead to undesired bridging of insulation spacing if adequate counter-measures are not provided.

More generous spacing around critical components and circuit connections can help combat these effects. Along with improved spacing, a pro-active approach that treats critical circuit areas

with a protective coating will significantly improve long-term product performance. (TDI's standard practice is to coat critical areas of printed wiring boards so as to maximize long-term reliability.)

Another often-overlooked aspect of higher density products is the tendency to utilize multi-layer PC boards. With the focus on higher packaging densities, more often than not power products are utilizing six or eight layer boards for power processing and delivery. Design and manufacture of multi-layer boards may be fairly new to many commercial product suppliers. Special considerations are required regarding spacing of internal conductors, especially around via holes, where entrapped moisture and microscopic voids in the board's glass laminate structure can lead to conductive filament growth and premature board failure.

Inner layers of multi-layer boards must also be carefully considered in failure mode scenarios. Power conversion circuits quite often provide an abundance of voltage and/or current during failure events. When combined with under-sized conductors embedded in inner layers of printed wiring boards, lack of oxygen can lead to traces that would normally fuse open to glow white hot, which in turn can cause breakdown of the board's glass laminate structure. Such failure modes can quite easily turn into burning smell, smoke or combustion events.

COMPONENT OPERATING TEMPERATURES

A general rule of thumb in most systems is that as temperature increases, reliability decreases. The Arrhenius Model is generally accepted as an accurate predictor of semiconductor, and other device reliability. This model covers many of the non-mechanical (or non material fatigue) failure modes that cause electronic equipment failure. It is particularly useful in describing failure mechanisms that depend on chemical reactions, diffusion or migration processes. The model suggests the rate a reaction occurs is given by the following equation:

$R(t) = A * e\text{-}(EA /kT)$

Where A is a constant, A x $e^{-(E_{A}/KT)}$ is the activation energy of the reaction, k is Boltzman's Constant and T is temperature in degrees Kelvin. The model predicts that as temperature increases, the rate to failure increases, as depicted in Figure 5.

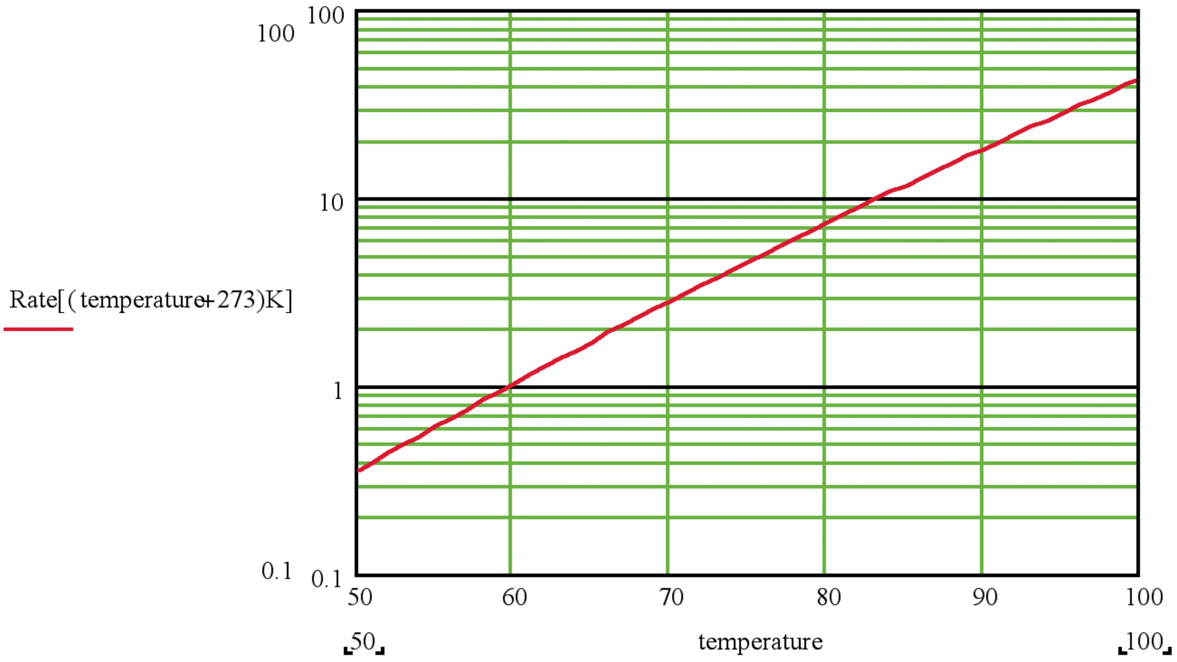

Figure 5: Illustration of Rate to Failure versus Temperature based on the Arrhenius Model

Once the activation energy for a specific failure mechanism is known, the effects of increased temperature on the rate of reaction can be expressed as:

Failure Rate @ Temp T1 / Failure Rate @ Temp T2 = $\exp*(^{E}A /k)\ (1/T2 - 1/T1))$

The typical activation energy for failure mechanisms of components found within electronic power supplies is on the order of 0.5 to 1.5 electron volts. Thus, a 10°C increase in temperature can correlate to a two to eight times increase in various component failure rates.

Component operating temperatures will increase as packaging density increases due to the following reasons:

- Smaller packages will by necessity have smaller fans, which usually cannot push as much air as bigger models.
- As component-packaging density increases, backpressure presented to the cooling fan will also increase, further reducing airflow.
- Electronic components will be physically located closer to each other, causing more effective radiation from hotter components to cooler ones.

Methods to optimize semiconductor heat sink performance are available to the designer and most high-density products utilize these. Finer fin pitch and improved conductivity materials can be leveraged to help manage some temperatures, but, in general, higher density products exhibit increased component temperatures. Increased component packing density generally helps to disrupt airflow, with inconsistent cooling delivered to the design. While some components may be very carefully engineered to receive adequate cooling, other components may be starved of cooling air, with corresponding reliability reductions.

Higher packaging density is quite often particularly challenging to electrolytic capacitors. Reliability of these parts is sensitive to the parts' operating temperature and RMS current. As these increase, the parts' internal vapor pressure will increase, with a correspondingly higher rate of electrolyte loss versus time. As electrolyte is lost, the parts' equivalent series resistance will increase, leading to premature wear out and eventual part failure.

PRODUCT MANUFACTURABILITY CONSIDERATIONS

Fundamental to the success of any design is the ability to characterize, measure, review and improve its performance. Even the most exhaustive program of design review, verification and reliability testing will not uncover every design deficiency. Likewise, the full effect of component and manufacturing process variations will not be known until a product reaches volume production. Total Quality Management theory suggests the best practice for achieving best in class quality and reliability is a program of continuous improvements overseen by a cross-functional product team.

Ultra dense packaging techniques are often at odds with the ability to effectively examine and analyze product performance. This can be especially true when problems occur. As most products delivering higher packaging density use conventional circuits and components, density is achieved through clever packaging, moving components closer together, and stacking components one atop the other. While products may be designed for progressive assembly, they may not be designed for ease of circuit measurement and debug. This can hide subtle circuit problems that may ultimately compromise reliability.

Another factor are the irregular component shapes generally found in power conversion circuits. These do not lend themselves to automated insertion and are usually inserted by hand. As component packaging density increases, the level of skill required assemble the product will increase, leading to unpredictable results if component placement and wiring is not consistent.

GUIDELINES TO ASSURE POWER SYSTEM RELIABILITY AND VALUE

Market forces will continue to create a need for higher packaging density and power conversion product suppliers will continue to push the envelope of how much can be crammed into a given size box. TDI believes that, with the following precautions and practices, packaging density can be increased while the deleterious effects on long-term reliability and total cost of ownership can be minimized.

Figure 6: Multipule Output Power Supply
Note the Cooling Fan on the Front Panel

1. **<u>Take a Total Quality Approach</u> –** Design, characterize and produce the product under the auspices of empowered, cross-functional team, right from the git-go.

2. **<u>Keep it cool</u> –** Heat is the number one enemy of reliability. Fight for every degree of margin you can get. Limit semiconductor junction temperatures to 110°C maximum and de-rate other components using NAVSO P-3641A as a guide.

3. **<u>Don’t overstress components</u> –** Component suppliers are generally overly optimistic regarding performance of their parts at full rating. De-rate component stress levels (voltage, current, temperature) to provide comfortable margins of safety and long life.

4. **<u>Keep it clean</u> –** Dirt, dust, humidity, condensate and pests (bugs, etc.) are one of the primary causes of early product failure. Provide generous spacing on printed circuit board traces and utilize protective (conformal) coatings on sensitive printed circuit boards and similar assemblies.

5. **<u>Don't cheat the product's specification</u> –** Assure that all the features required to serve an application are built into the design.

6. **<u>Make it easy to build, inspect and repair</u> –** The ability to see what's going on and effectively characterize all circuits in their actual operating environment is hugely important to long-term performance.

Figure 7: 500 Watt Inverter
With Cooling Fan on Front Panel

7. **<u>Make it sturdy</u> –** Shipping, handling and operational vibration damage can be a primary cause of failure. Stake or otherwise support components subject to damage by shock or vibration.

8. **<u>Watch out for components with wear out mechanisms</u> –** Assure long life without maintenance. Avoid wear out failures with premium grade electrolytic capacitors and fan bearings.

9. **<u>Fully characterize the design</u> –** Understand everything you can before the product goes into production. Utilize a full program of Design Verification Testing, Highly Accelerated Life Testing (HALT), Highly Abusive Electrical Testing (HAET), Failure Mode Effects Testing (FMEA), and Design Validation Testing.

10. **<u>Shake it, bake it, break it and fix it here, not there</u> –** Utilize in-process Highly Accelerated Stress Screening (HASS) on each and every product manufactured to find and fix design weaknesses, defective components and hidden defects.

TDI
Transistor Devices

For more information,
please contact :

Norman Wolf
VP of Corporate Sales
36 Newburgh Road
Hackettstown, NJ, 07840
Office 908.850.5088
Fax 908.850.5731
Mobile 908.256.6204
norman_wolf@tdipower.com