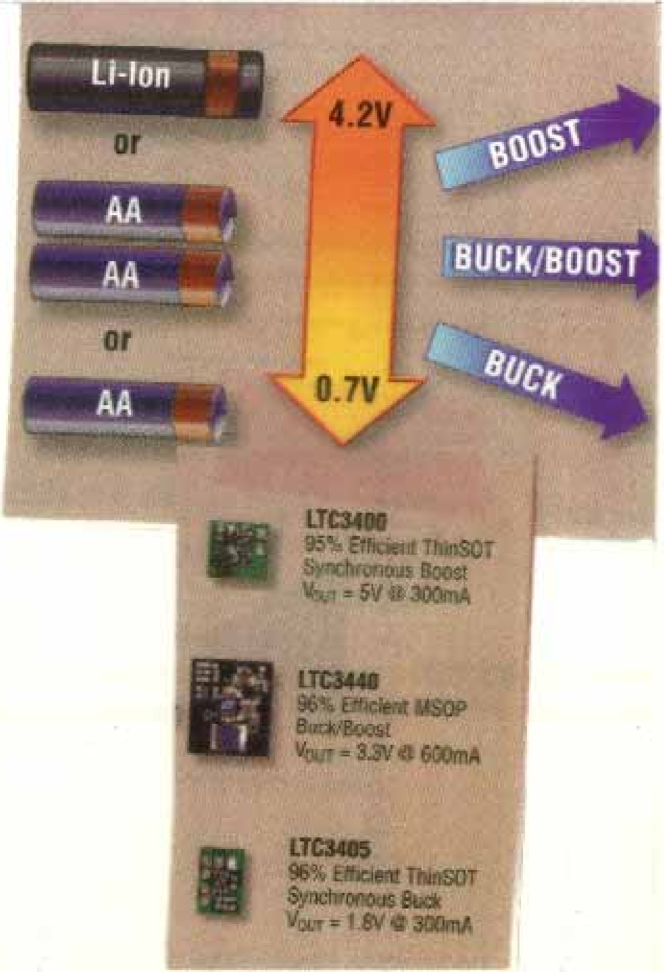
ECE 562

Week 4 Lecture 1

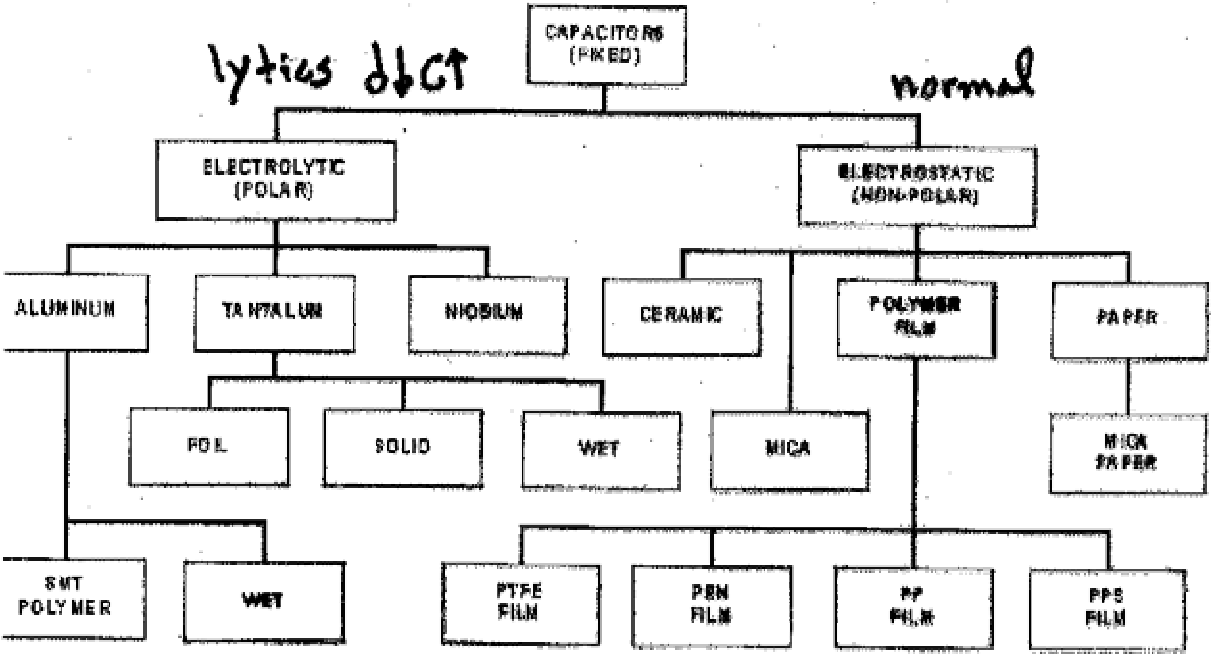
Fall 2008

Week 4 Lecture 1 Summary

- Section notes
  - Slides 3-9 – Types of capacitore
  - Slides 10-16- Capacitor ESR's and construction
  - Slides 17-23 - Electrolytic capacitors
  - Slides 24-33 - Comparison of capacitor types
  - Slides 34-48 - Non-ideal capacitor behaviors
  - Slides 49-55 – Super-capacitors
  - Slides 56-65 – Super-capacitor applications

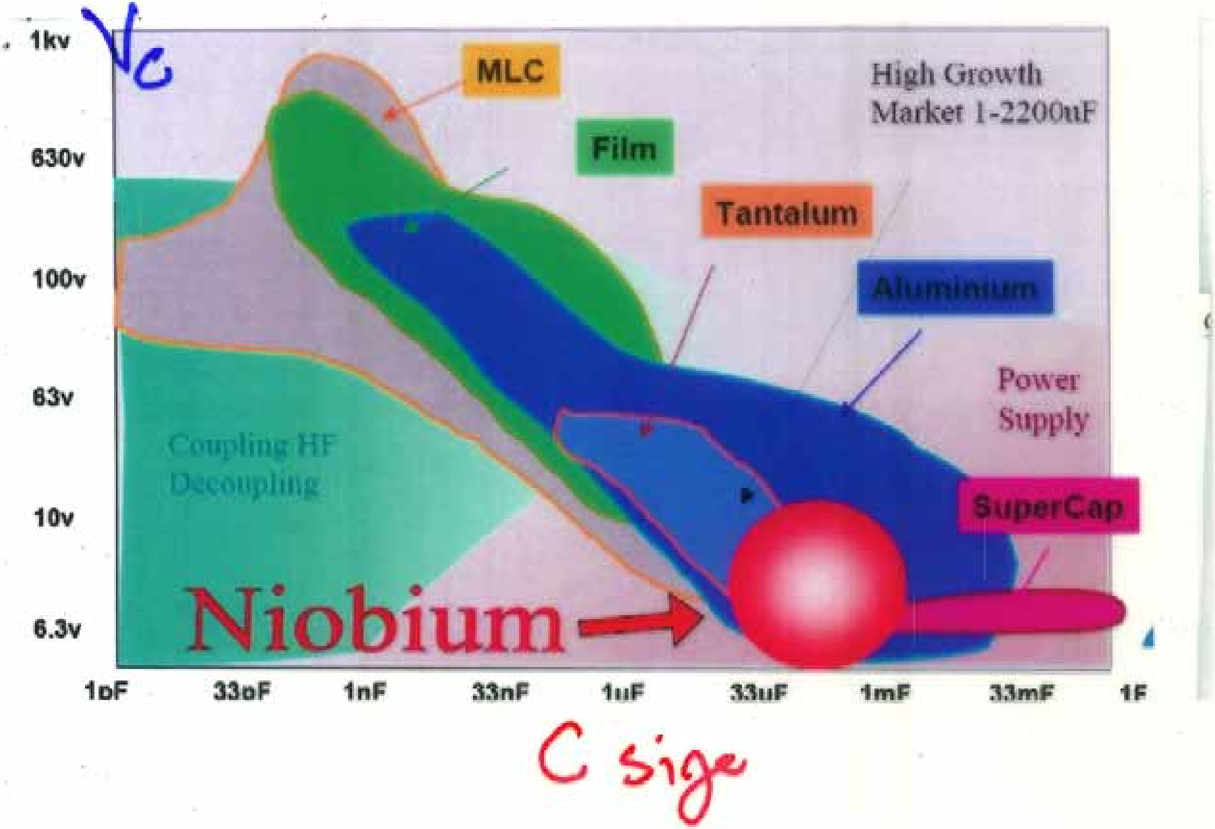

Li-Ion
or
AA
AA
or
AA
4.2V
0.7V
BOOST
BUCK/BOOST
BUCK
LTC3400
95% Efficient ThinSOT
Synchronous Boost
V_{OUT} = 5V @ 300mA
LTC3440
96% Efficient MSOP
Buck/Boost
V_{OUT} = 3.3V @ 600mA
LTC3405
96% Efficient ThinSOT
Synchronous Buck
V_{OUT} = 1.8V @ 300mA

Capacitor Technologies



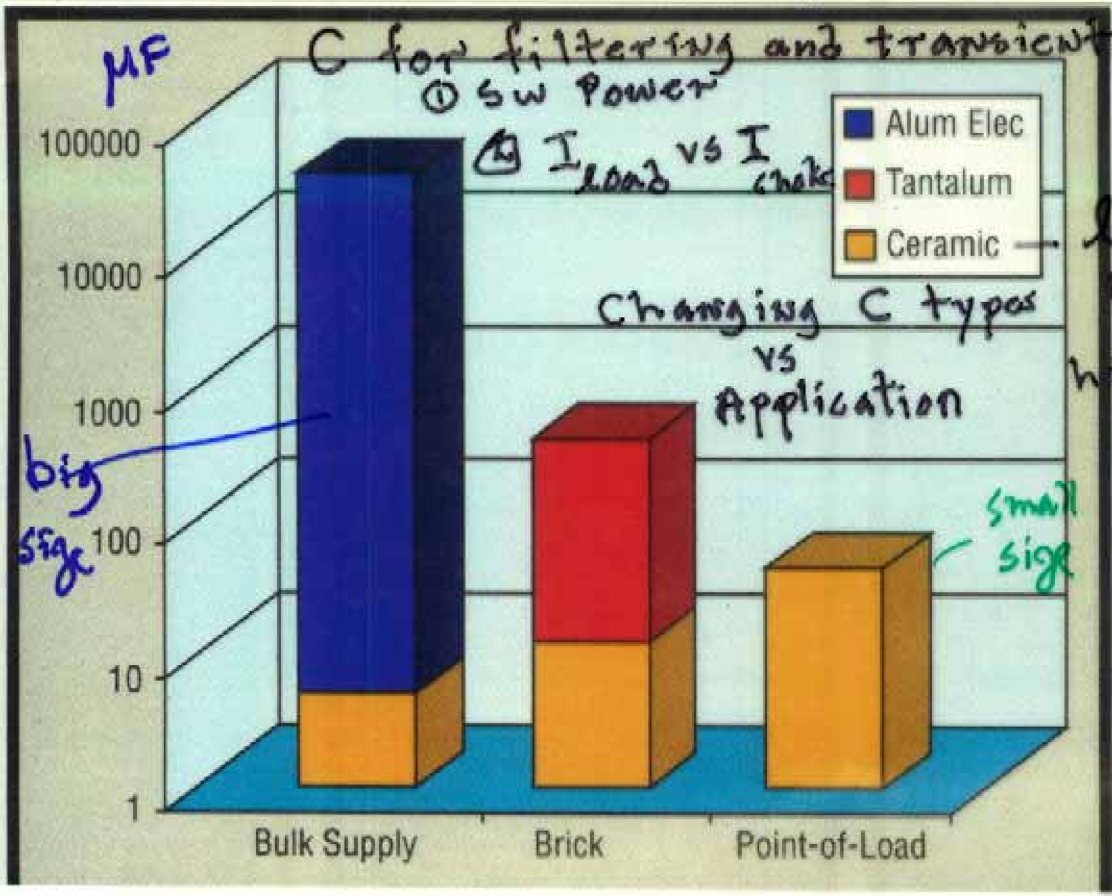
Rule #1

The application is specific. So is the capacitor.



Vc
1kv
630v
100v
63v
10v
6.3v
MLC
Film
Tantalum
Aluminium
SuperCap
High Growth
Market 1-2200uF
Power
Supply
Coupling HF
Decoupling
Niobium
1pF
33pF
1nF
33nF
1uF
33uF
1mF
33mF
1F
C size

More V rails | Lower |V|, Faster f



SMD : xy lm

1206 ⇒ 120 mil * 60 mil

metric 1220 1.2 mm * 2 mm

Capacitor size codes

The capacitor sizes are specified either in the EIA surface mount device (SMD) specifications, such as 0201, 3216 or the EIA capacitor size specifications such as Size A, B, C etc (typically used for Tantalum capacitors). The SMD specifications is a set of 2 numbers, each 2 digits and each specifying size in mils (one thousandths of an inch). So, a 1206 component would be 120 mils by 60 mils. Note that there is a metric version (EIAJ or JIS) of this spec where 1220 would mean 1.2 mm by 2.0 mm. Beware!

- The EIA capacitor codes (e.g A,B,C etc) are outlined in the below table.(source: Kemet). The numeric dimensions are in mm and the number after the "-" signifies the maximum height.

Case Code	
KEMET	EIA
R	2012-12
S	3216-12
T	3528-12
U	6032-15
V	7343-20
A	3216-18
B	3528-21
C	6032-28
D	7343-31
X	7343-43
E	7260-38

Tall

Low ESR Chip Capacitors

The S-Series line of low ESR, high Q, high frequency multilayer ceramic capacitors is made with a proprietary combination of low loss dielectric and a highly conductive electrode system. This process lowers their equivalent series resistance. They are offered in 0201, 0402, 0603, and 0805 sizes, and in capacitance values from 0.2 pF to 220 pF.

Johanson Technology Inc., Camarillo, Calif.

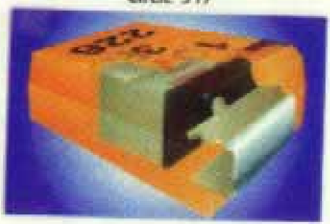
Circle 315

Tantalum Chip Capacitor

The organic polymer KO-CAP (T520B) offers high capacitance in a smaller footprint. Used as a drop-in replacement for a 1210 high-capacitance ceramic, it can save board space as a replacement for C- and D-sized tantalum chips. With reduced ESR (70mΩ), there is enhanced capacitance retention in higher frequencies as compared to a standard MnO_2. It is offered in the "B" case size in 47μF rated at 6.3V, 68μF at 4V, and 100μF at 3V.

KEMET Electronics, Greenville, S.C.

Circle 317



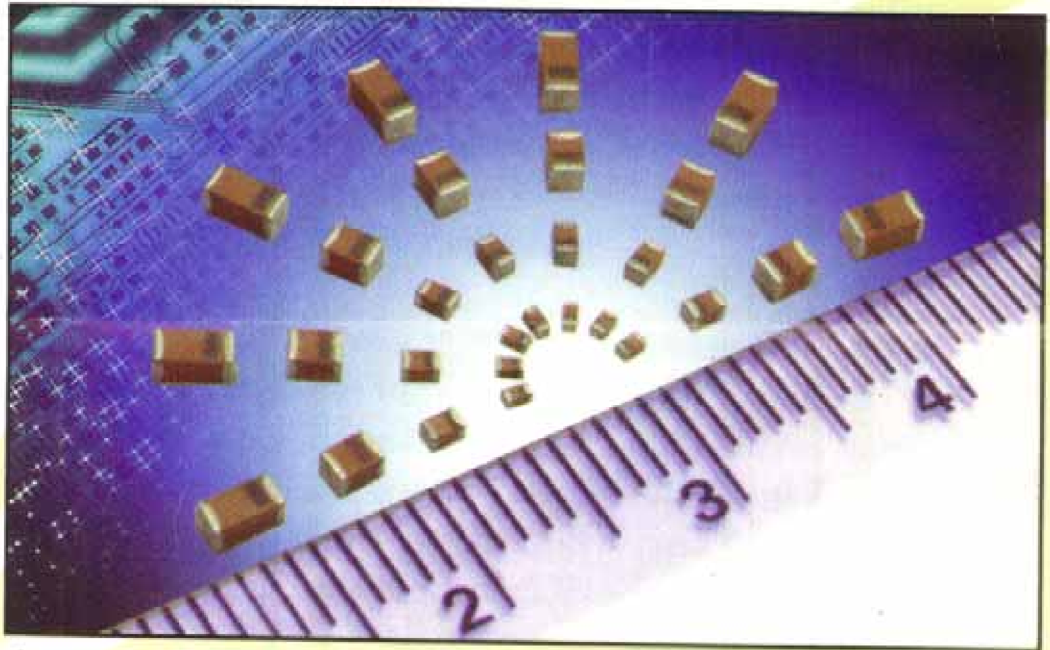
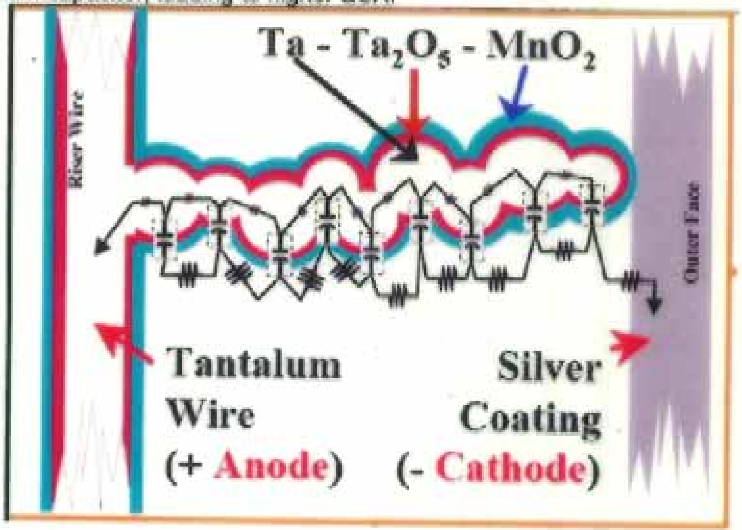


Fig. 3. *A growing trend with passive components is the migration to small case sizes. AVX's TACmicrochip series of tantalum chip capacitors deliver up to 10 μF in an 0402 case.*

- Tantalum
  - Small size vs C
  - High capacitance
  - Low ESR (30-150mohm)
  - Use caution on input
  - Being replaced by niobium

Electrolytic: C big ESR low (f) low

- Following picture illustrates the distributed resistance in the construction of a Tantalum capacitor, leading to higher ESR.



- Although the ESL is negligible in most capacitors, some of the same factors that affect ESR, also affect ESL:

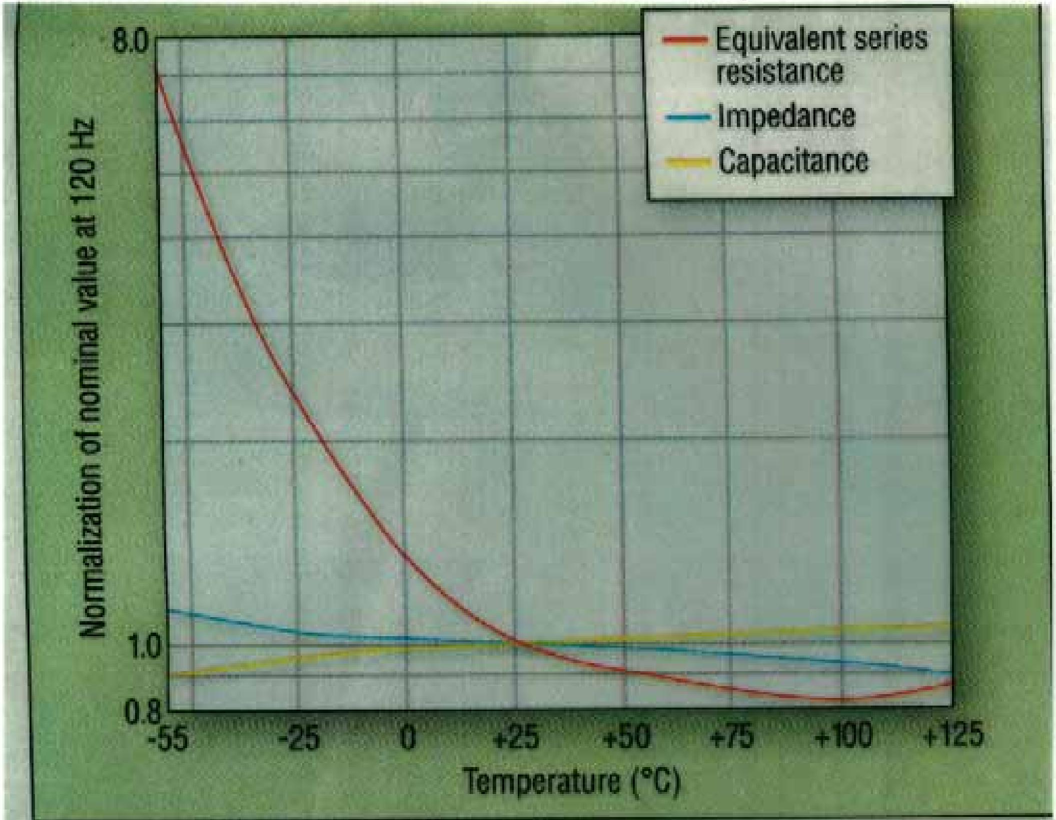


Fig. 6. *The wet-tantalum curves show a dramatic rise in ESR at low temperature. (Data courtesy of NASA.)*

Decoupling and the Pitfalls of Tantalum Capacitors

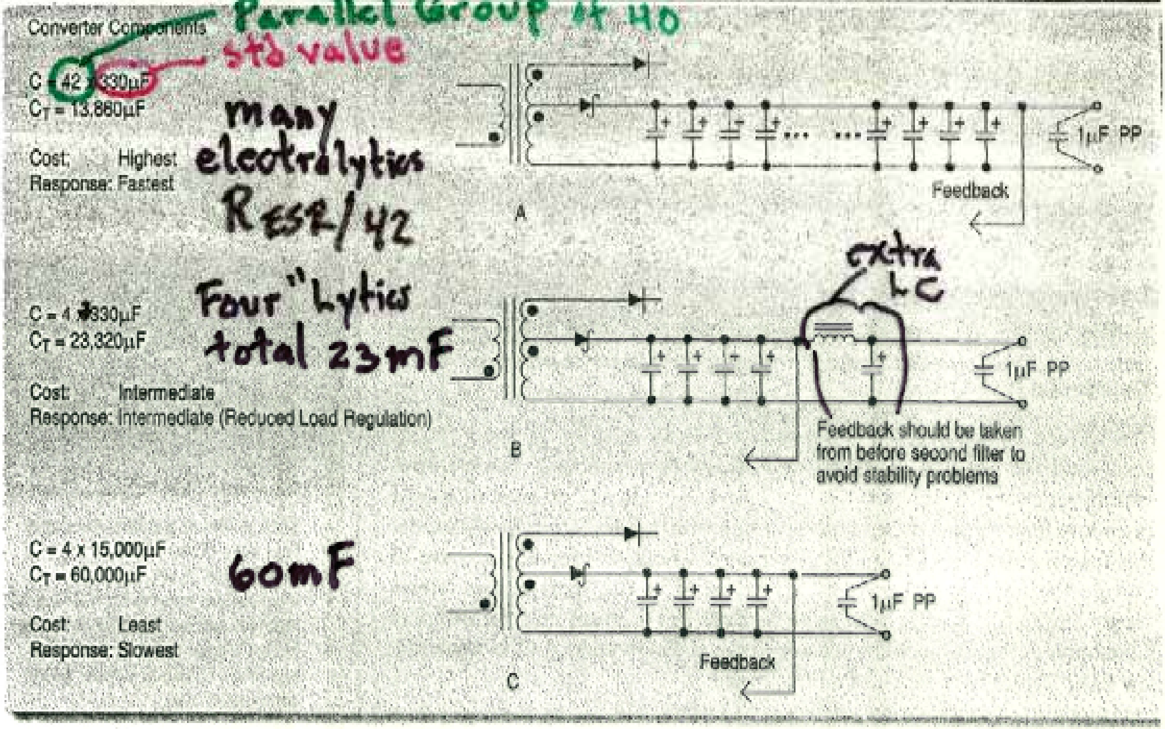
Tantalum capacitors have a capacitance per unit volume almost 3 times better than Aluminum Electrolytics. However:

- Their max rating is typically less than 50V.
- Even that rating is "nebulous", since 50% derating of the max voltage rating ma need to be applied.
- Voltage derating is specifically recommended when the capacitor may see a larg inrush current --- like the input cap of all topologies, and also the output cap of th boost topology. So for example, a 35V Tantalum cap may then be usable only u to about 18V. (That is roughly a "derating" of 50%).

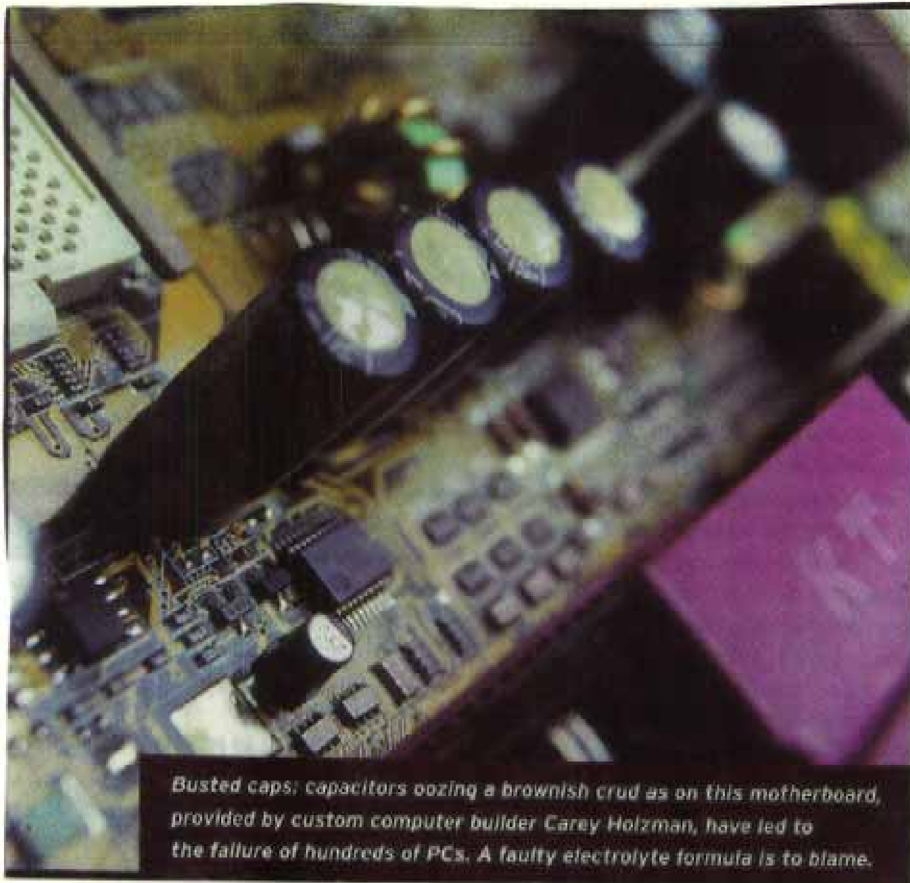
Surface-mount aluminum electrolytic capacitors are emerging as an alternative for tanalum chip capacitors. NIC Components' caps (left) aim at PC, telecom, consumer and industrial applications.

Film vs. Electrolytic Caps

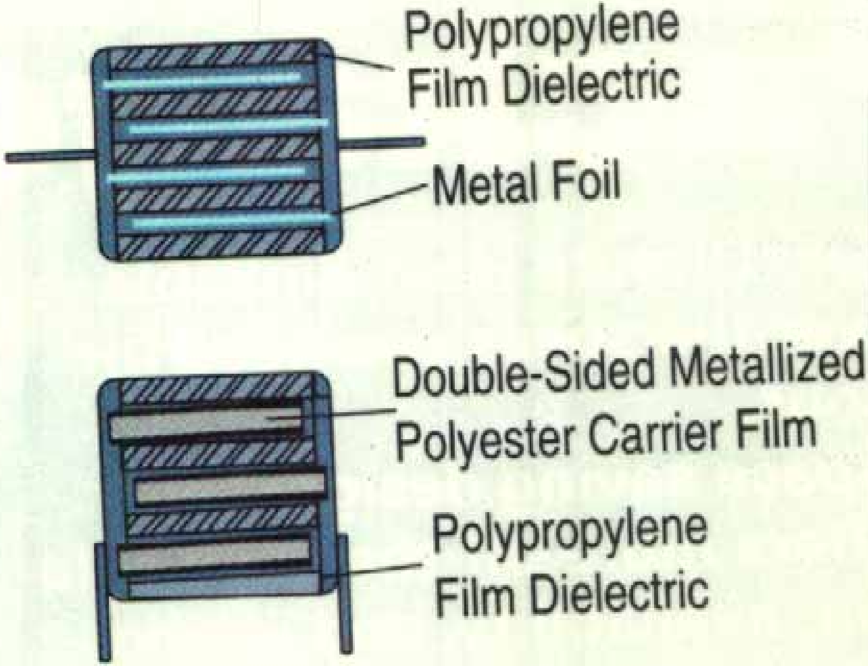
Same ripple current



Output filters for equivalent ripple.



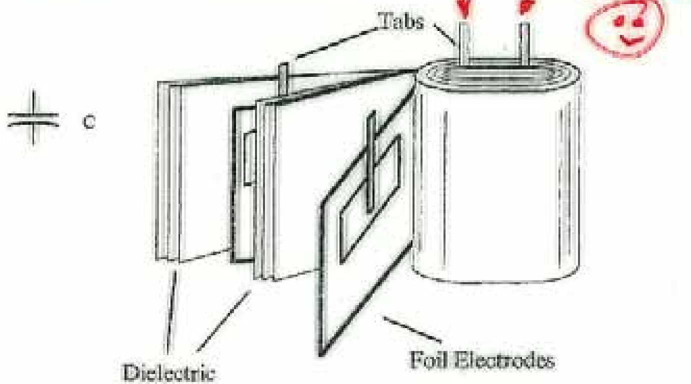
Busted caps: capacitors oozing a brownish crud as on this motherboard, provided by custom computer builder Carey Holzman, have led to the failure of hundreds of PCs. A faulty electrolyte formula is to blame.


Polypropylene
Film Dielectric
Metal Foil
Double-Sided Metallized
Polyester Carrier Film
Polypropylene
Film Dielectric

More tabs
Lower ESR
Lower L (parasitic)

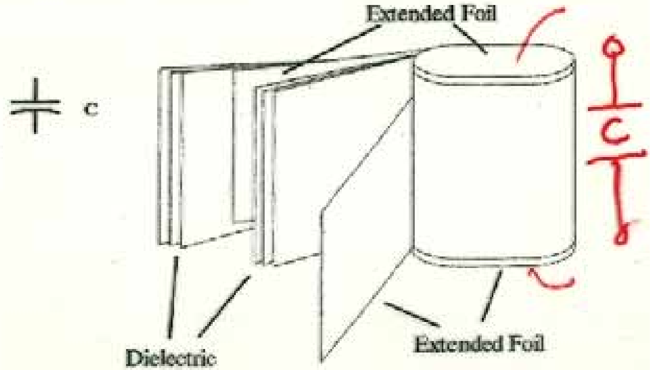
Short & fat desired

CAPACITOR WITH TABS



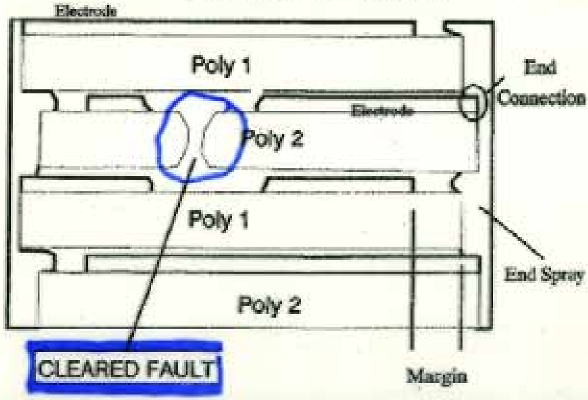
Inserted tab capacitors use thin (5.5 μm) aluminium foil electrodes conduct current through the capacitors and out through tabs to the load.

CAPACITOR
WITH EXTENDED FOIL ELECTRODES



Extended foil capacitors use thin (5.5 μm) aluminum foil electrodes to conduct current through high-current electrodes that are generally soldered to the extended foils on either end of the capacitor section.

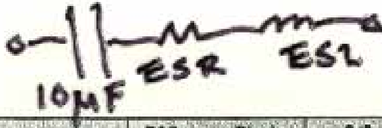
Metallized Polymer Capacitor Construction



Once the fault illustrated in Fig. 9 has been cleared, the capacitor will continue to function with the only measurable damage being a small loss of capacitance.

- Specialty Polymer Aluminum
  - Very Low ESR (10-50mohm)
  - High capacitance
  - Small size
  - Limited suppliers

Compare old "Lytics" to Metal Film Capacitors



Technology	ESR at 100kHz (mΩ)	Ripple Current (A_{rms})	Δ C/C 1 to 100 kHz (%)	Δ C/C at -55°C (%)	Leakage Current (μA)
Superior					
Metallized Polypropylene	<10	>6	<1	<1	<1
Aluminum Electrolytic	>100	<0.6	>-25	>-30	>50

Technology	ESR(mΩ)			
	-40°C	-20°C	+25°C	+85°C
Metallized Polypropylene	12.5	11	10	9
Aluminum Electrolytic	—	25,000	3,000	250

Performance of metallized polypropylene capacitors vs. aluminum electrolytics. Capacitance is 10μF, 450VDC.)

Lytics "dry up" over t-T

Lytics are <u>not</u> bipolar or stand reverse voltage

Metal/Film are self-healing on many failures reference

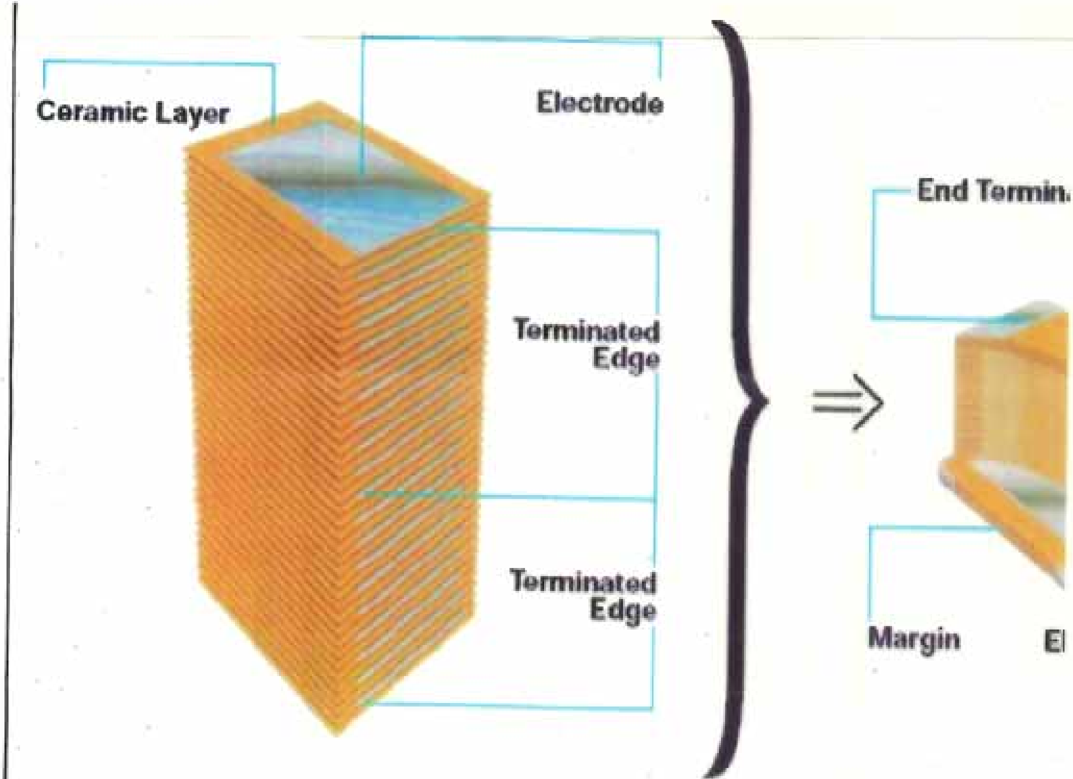
Low ESR

Parameter	Electrolytic	Metallised Polypropylene
Capacitance value (original)	32.4mF	
Capacitance value (final)		5.4mF
Configuration	48 caps, 24 in // x 2 in series	3 units in parallel
Nominal dc voltage	480V x 2 (800V)	1000V
r.m.s. current	1000A at 2kHz	900A at 2kHz
Max. thermal rating		456A (x3) at 50°C
Max. operating temperature	50°C	50°C
Overall volume	86.4 litres	28.5 litres
Inductance		~20nH for 3 units in parallel
ESR (total)	2.1mΩ	0.1mΩ
Surge voltage	1.1 x Un	2 x Un
Price comparison (caps only)		95% of electrolytic solution

6x

x3 smaller

x20 smaller



Multilayer Ceramic Capacitor

Figure 1

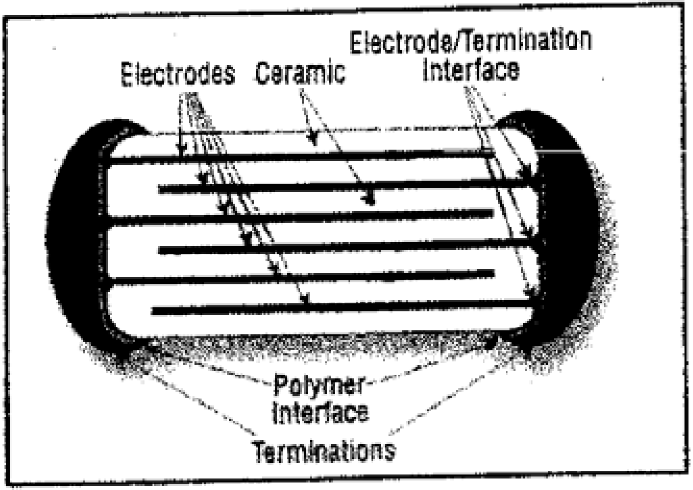


Fig. 3. *The addition of a conductive polymer termination layer improves the mechanical flexibility of a ceramic capacitor.*

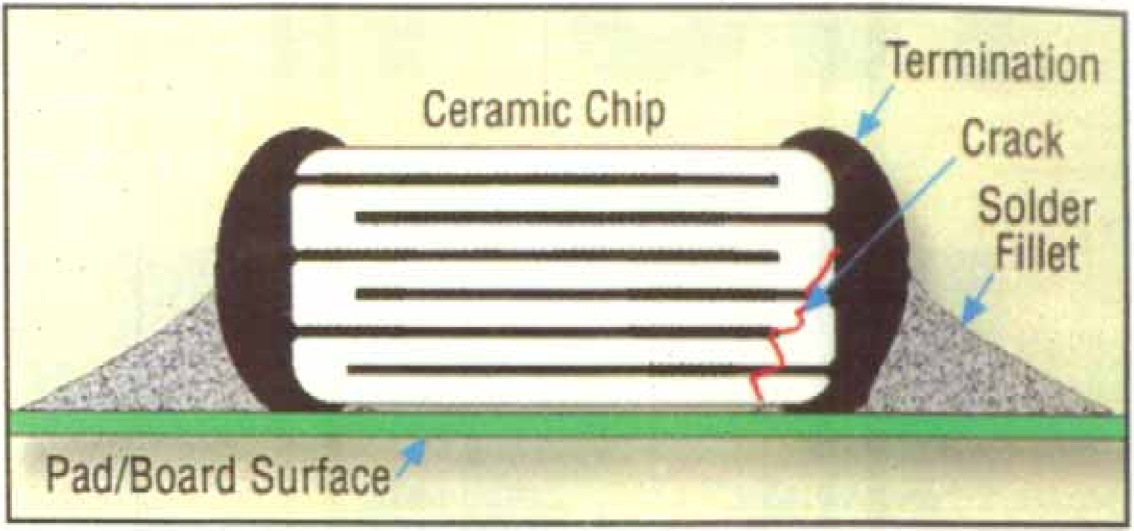
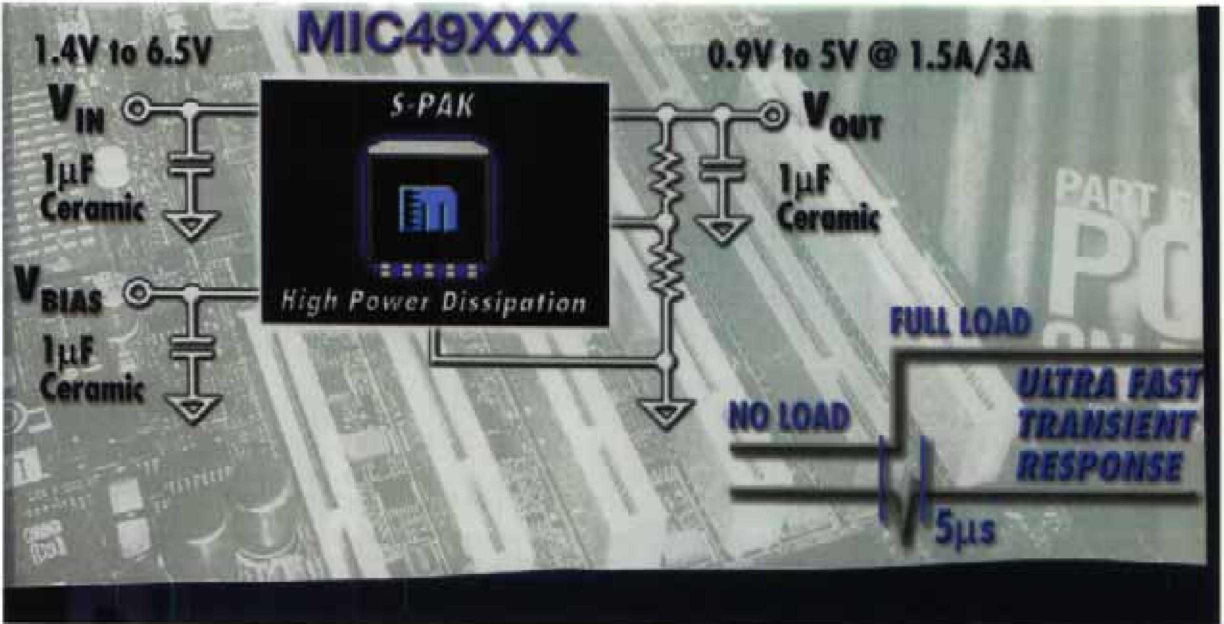


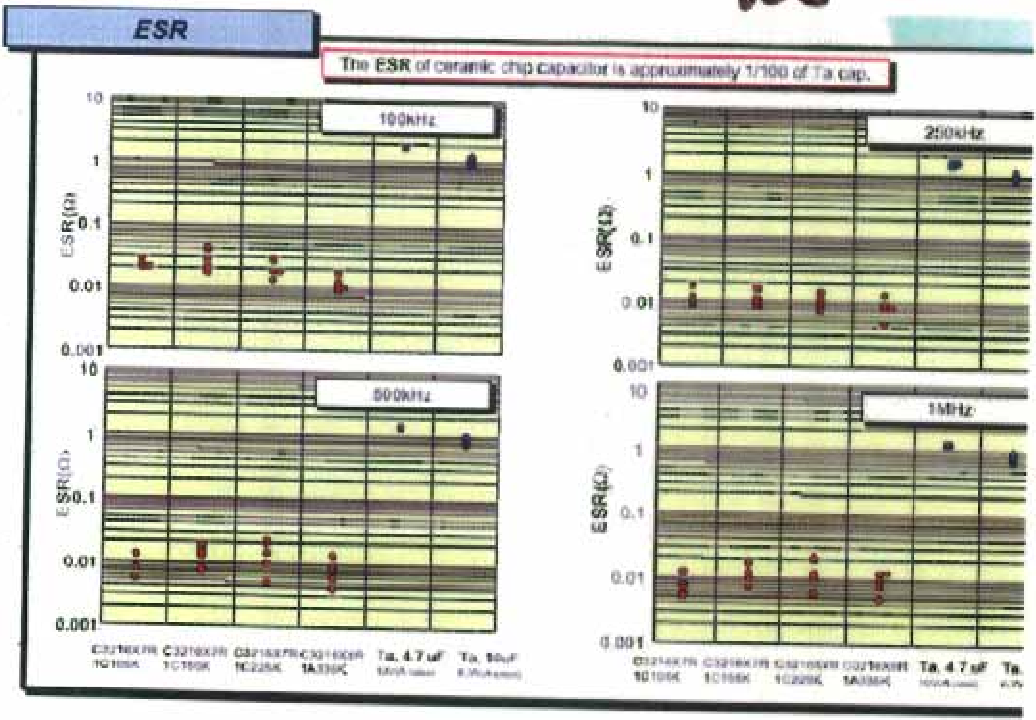
Fig. 1. *A multilayer ceramic capacitor exhibits cracking.*

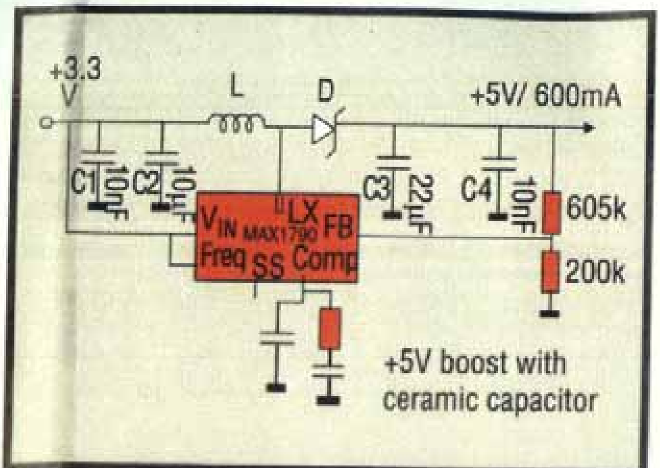
- Ceramic
  - X5R or X7R best temperature coefficient
  - Lowest ESR (1-10mohm)
  - Can generate audible noise in some applications

  - DC Bias reduces capacitance
  - Small size, Low cost

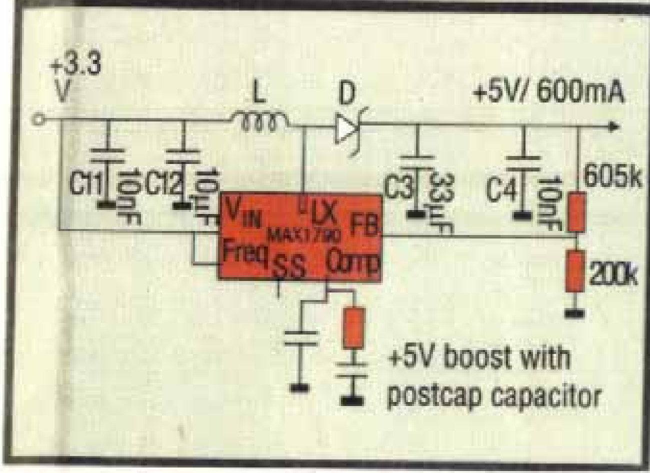

MIC49XXX
1.4V to 6.5V
0.9V to 5V @ 1.5A/3A
VIN
1µF
Ceramic
S-PAK
High Power Dissipation
VOUT
1µF
Ceramic
VBIAS
1µF
Ceramic
FULL LOAD
NO LOAD
ULTRA FAST
TRANSIENT
RESPONSE
5µs

$R_{ESR}^{Ceramic} < \frac{R_{Tantalum}}{100}$





+5V boost with ceramic capacitor



+5V boost with postcap capacitor

"Mechnical" Properties

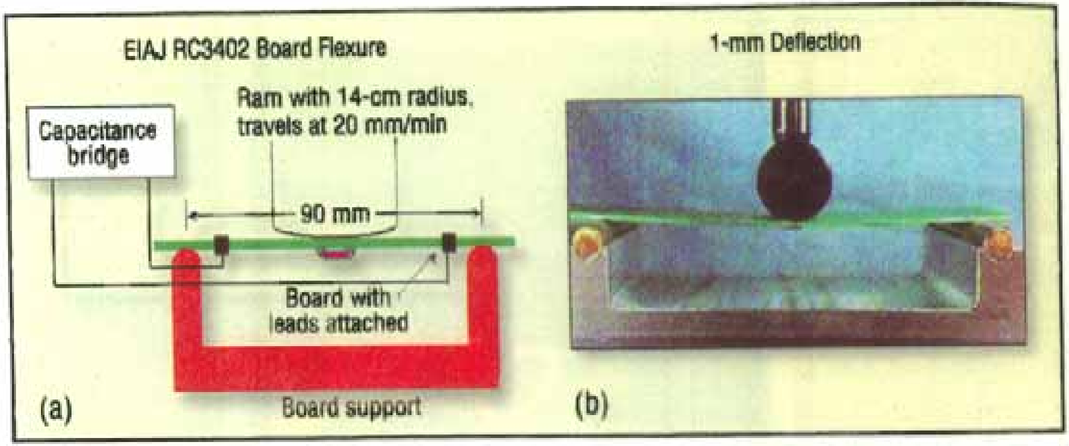


Fig. 4. *EIAJ RC3402 specifies the above setup (a) to measure a capacitor's ability to withstand flexing. If deflection produces a capacitance shift, the capacitor fails. A 1-mm deflection is used as an acceptance level for no failures (b).*

C(t) C↓ t↑

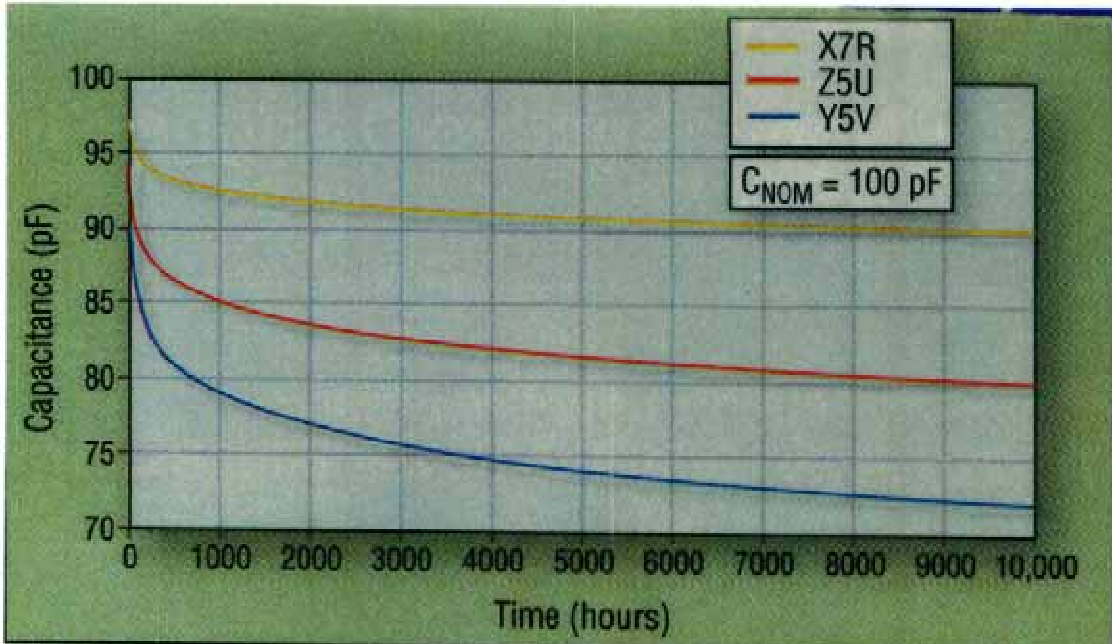


Fig. 7. *Aging for ceramic capacitors varies according to the type of dielectric used.*

Dielectric/ capacitor type	Typical dielectric constant	Typical aging rate (%)
Ceramic NPO	65	None
Ceramic X7R	2000	1.5 to 2.5
Ceramic BX	4000	3 to 4
Ceramic Z5U	8000	4 to 5
Ceramic Y5V	10,000	6 to 7
Ceramic (BP) capacitors		±21* (-2.5 to -4 per decade hour)
Ceramic (BP) capacitors	—	1.25 to 2.1
Tantalum (CSR) capacitors	—	±10

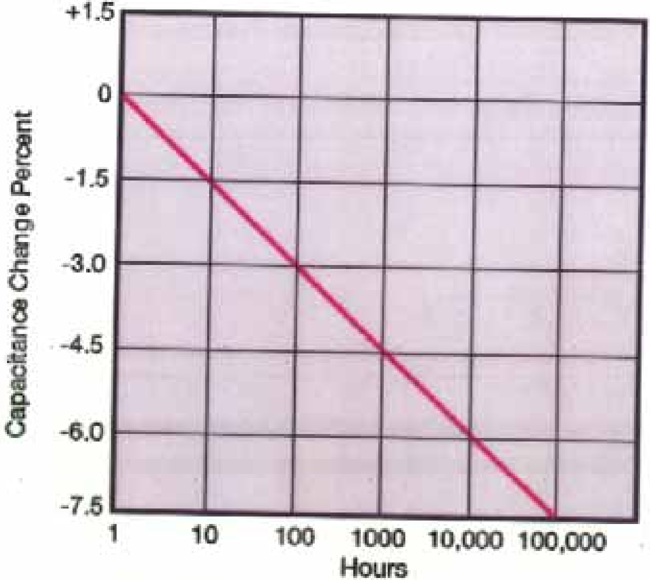
Table. *Aging rates of various dielectric types. *MIL-HDBK-1547A is considered overly pessimistic.*

$(1-A \quad)$

C(t)

…ile to use in spite of this voltage dependency.

Typical Curve of Aging Rate X7R



Characteristic	Max. Aging Rate %/Decade
C0G (NP0)	None
X7R, X5R	2
Y5V	7

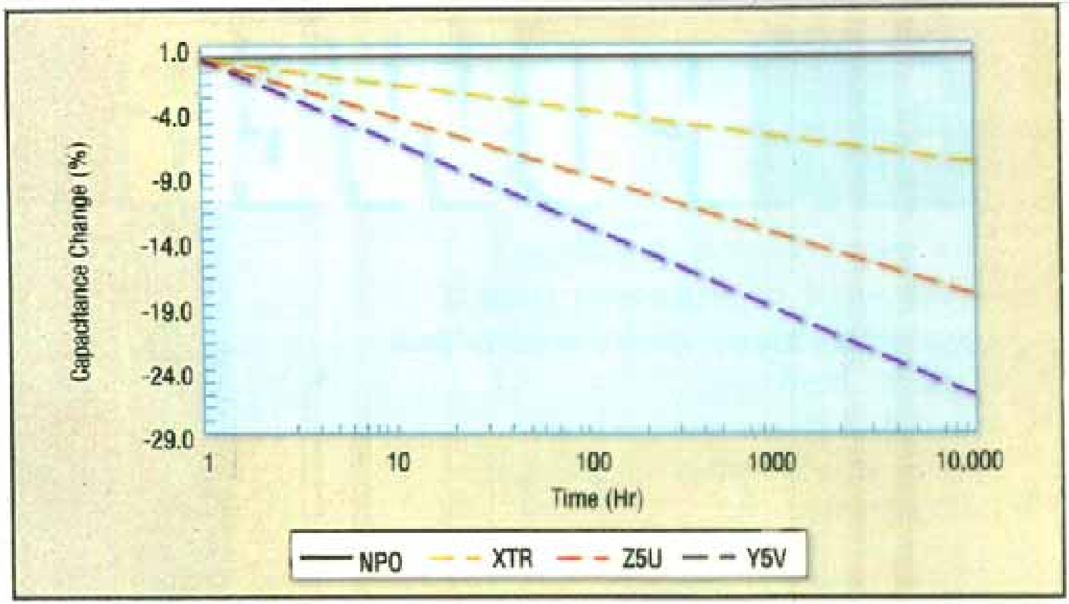


Fig. 6. *The choice of dielectric material influences the loss of capacitance over time in ceramic capacitors.*

Capacitance vs Temperature

Dielectrics vary in their response to the temperature and voltage. EIA created classifications of material called Class I and Class II and further nomenclature for the amount of variation in the Class II dielectrics. Due to the inherent ESR, the capacitor self heats during operation raising its temperature. The capacitance value chosen to be used in the application must include this potential change over the temperature.

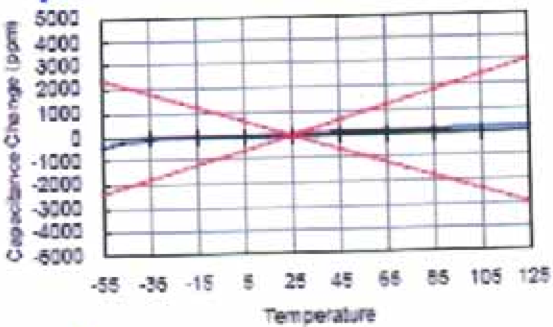
- The variation in the Class I materials is specified in ppm (parts per million). It is typically less than 3000ppm (< 0.3%), so it will be ignored in this discussion. EIA standard EIA-198-D specifies a 3digit code to name classI and classII materials. See the netlink for the details of classI naming. One particular noteworthy classI type is C0G (C stands for 0, 0 often confused as letter O is multiplier of 0 and G stands for +/- 30ppm). This type is also called NPO (negative positive zero, meaning zero change for either positive or negative change in temperature). EIA standard The table below lists codes used for Class II materials, more commonly seen.

C (T)

negative
positive
zero

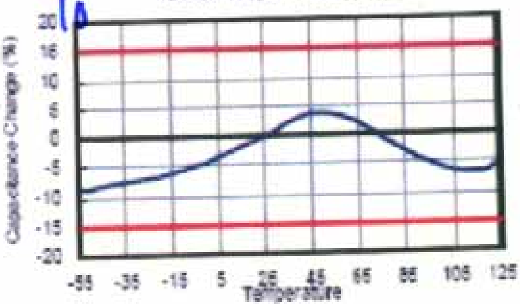
ppm

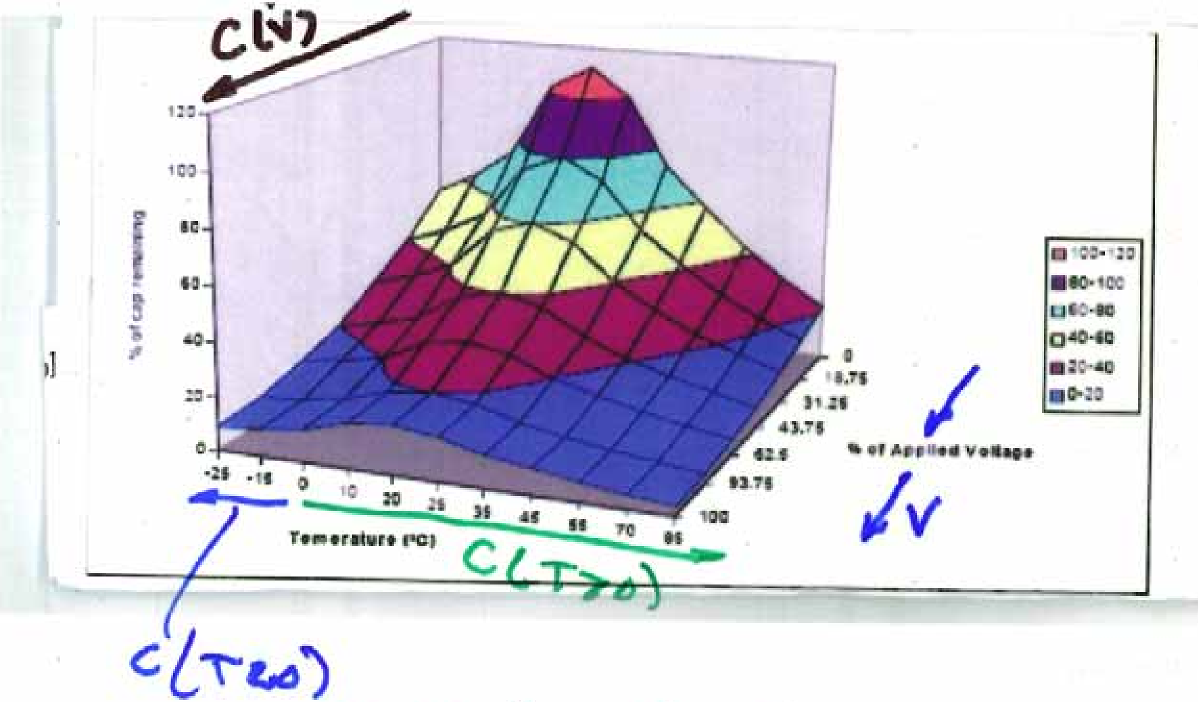
NPO of Temperature Coefficient



%

X7R of Temperature Coefficient



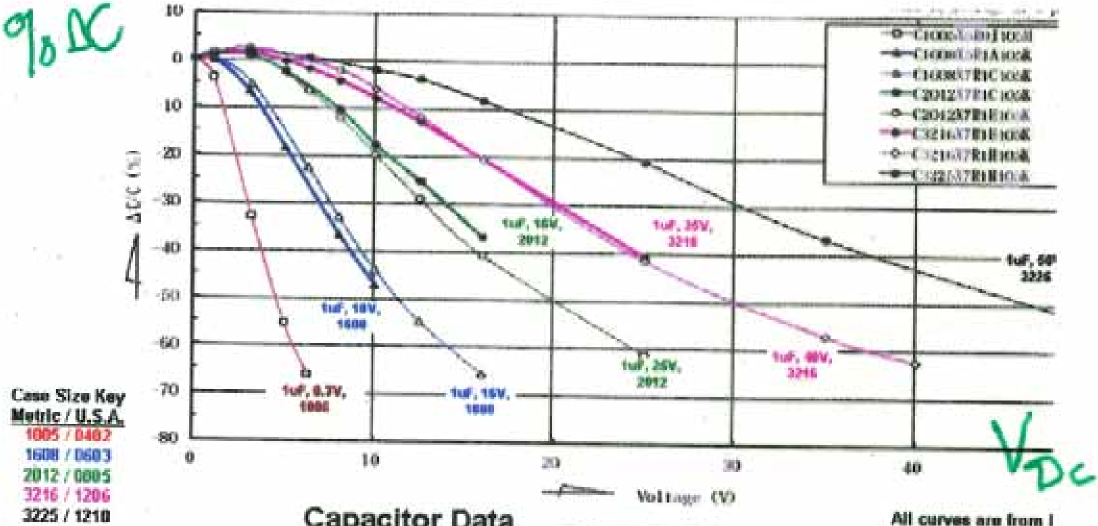


Just for starters
C(V, T, f, time, material choices)

Capacitance vs Voltage

ClassII dielectric materials also change their capacitance value over time and with applied DC voltage, AC voltage. The effect over time is called aging and tends to lower the capacitance. The application of DC voltage tends to lower the capacitance, whereas the application of AC voltage (within a small signal range) tends to increase the capacitance.

C (V DC) not same as C (V AC)



Capacitor Data Provided By: TDK

All curves are from h
quality ceramic capa
with good X5R or X
temperature coeffici

% ΔC(V) plots for Ceramic Caps

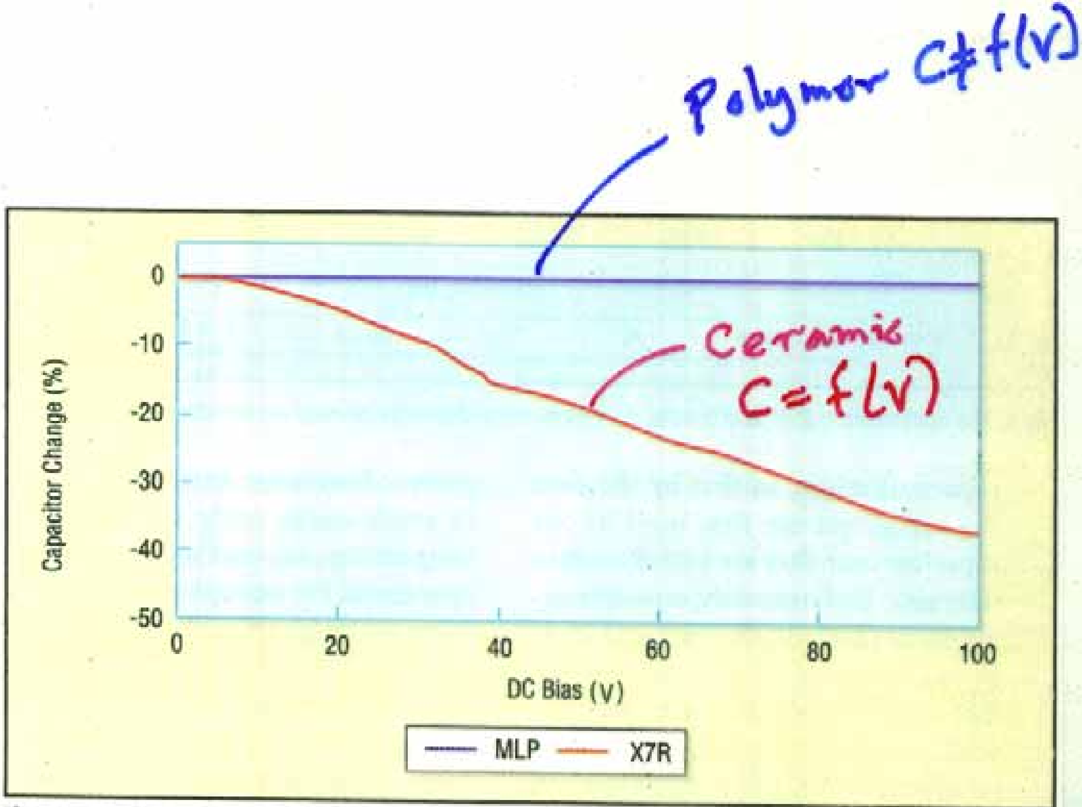


Fig. 7. *A multilayer ceramic capacitor loses capacitance as the dc bias voltage increases, while a multilayer polymer capacitor maintains a constant value.*

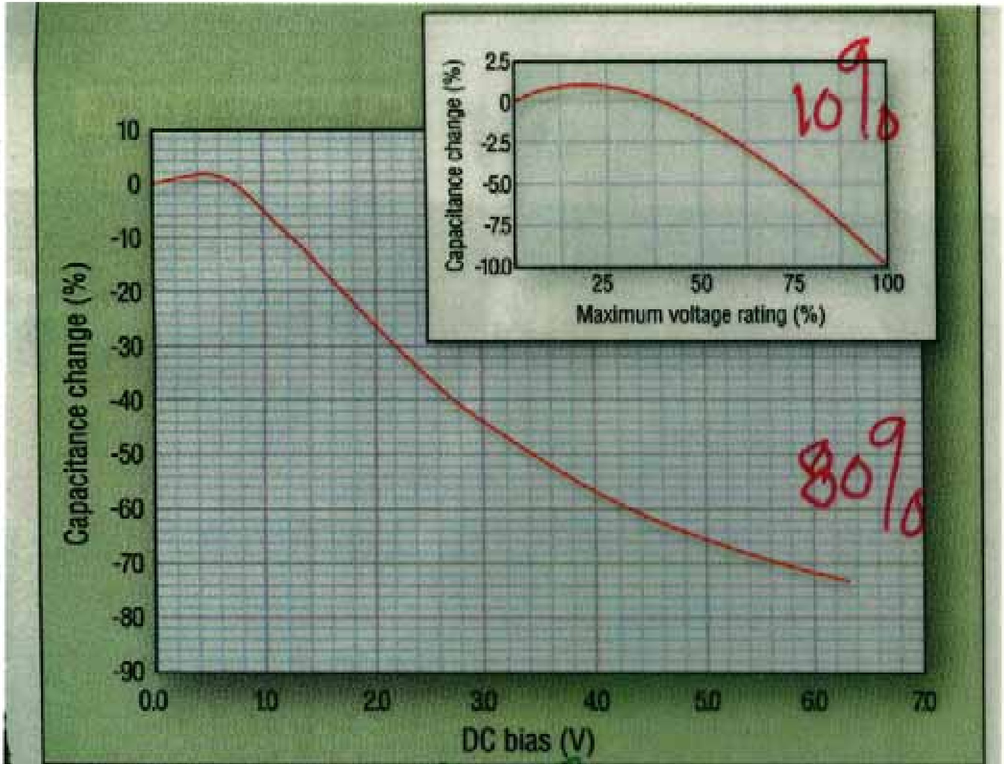
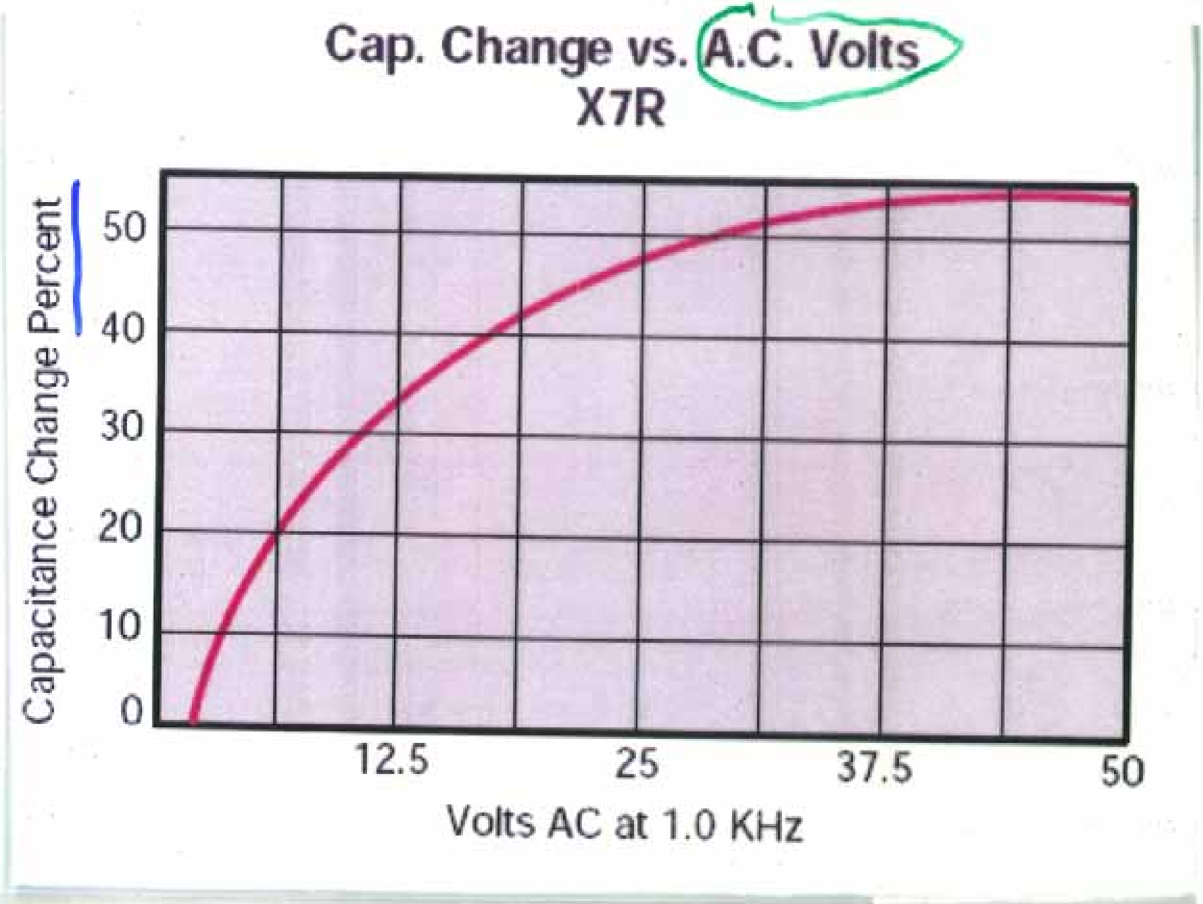


Fig. 2. *DC-bias effects for the X7R and X5R paint a dramatically different picture. At 28% of rated voltage, the capacitance is down almost 25% for the X5R.*

C vs V_{DC}


Cap. Change vs. A.C. Volts
X7R
Capacitance Change Percent
0
10
20
30
40
50
12.5
25
37.5
50
Volts AC at 1.0 KHz

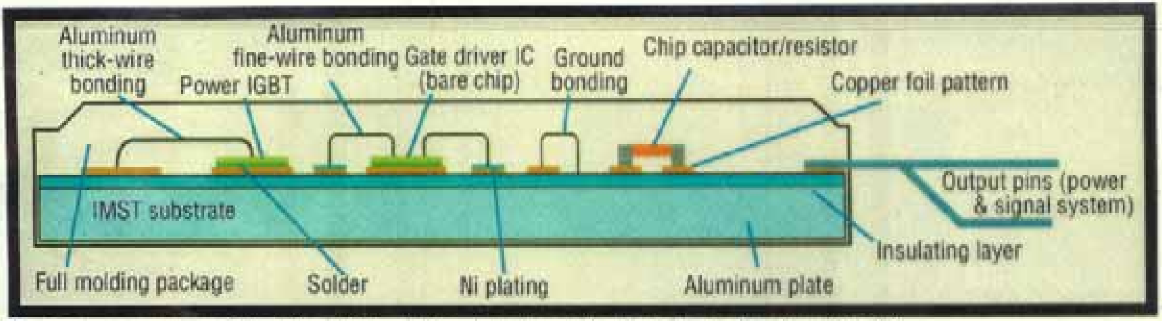
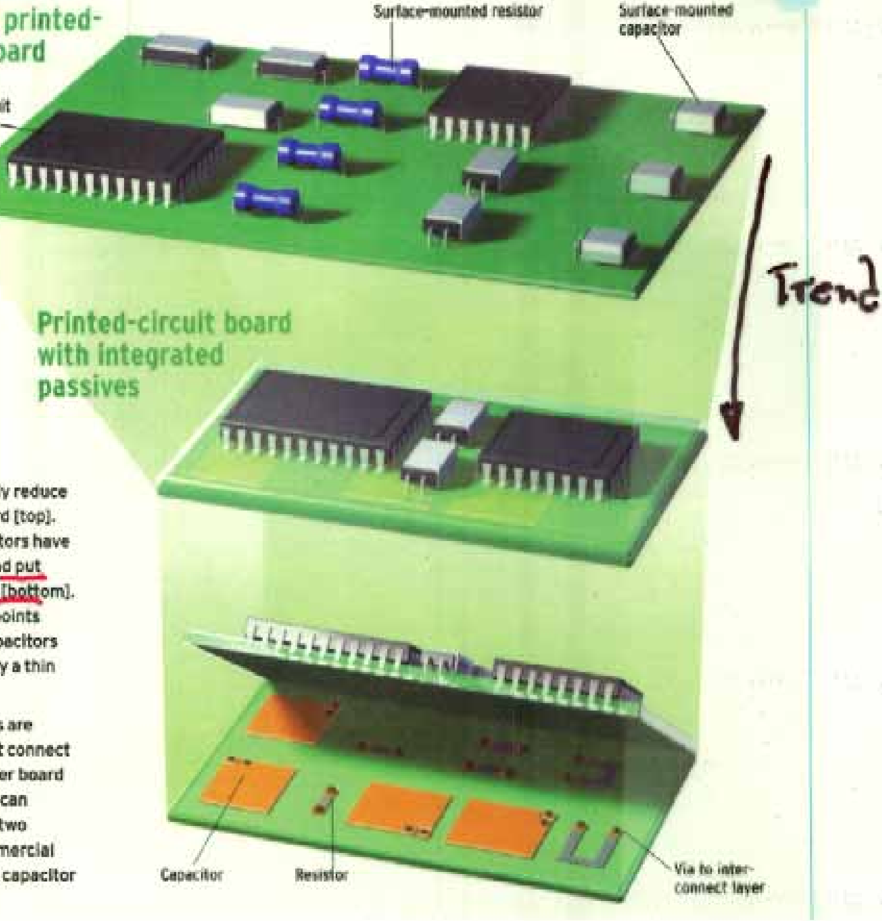


Fig. 5. *Cross-section of the PlugNDrive™ insulated metal substrate technology (IMST).*

a
p
c
la

st
w
o
fo
h
to



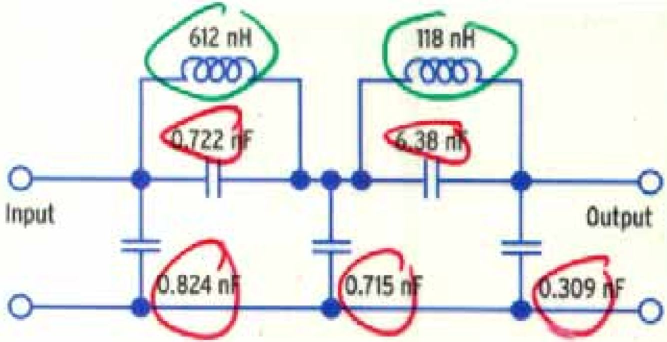
Size Matters

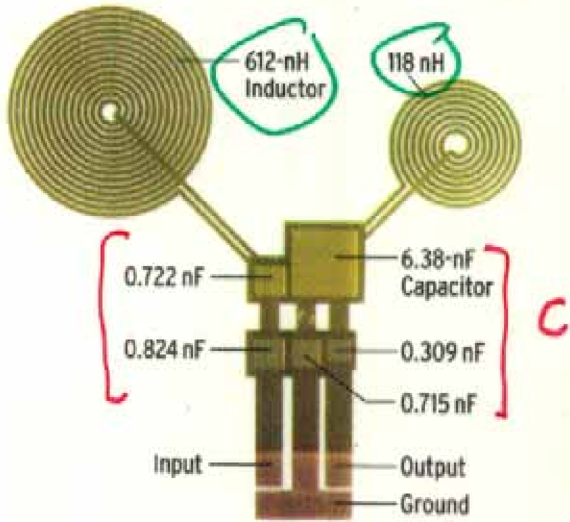
Integrating passives can drastically reduce the size of an ordinary circuit board [top]. Here, four capacitors and six resistors have been removed from the surface and put into an extra layer of circuit board [bottom]. Resistors are copper connection points bridged by a resistive film, and capacitors are conductive plates separated by a thin film of dielectric material.

After the board is laminated, holes are drilled and plated to form vias that connect the integrated components to other board wiring. Not every value of passive can be replaced by an integrated one; two remain on the surface. Some commercial processes would require separate capacitor and resistor layers.

A Very Flat Filter

Inductors are angled away from each other to avoid crosstalk in this low-pass filter that fits between the layers of a circuit board. Designed by one of the authors, and built by Integral Wave Technologies (Fayetteville, Ark.) for NASA's Langley Research Center, the thickest part of this filter is less than 6 μm. Capacitors are made from a thin-film oxide, inductors from copper.





C huge Farads small
Kilo-F

PLUSES AND MINUSES: An ultracapacitor depends on highly porous carbon. The carbon becomes electrically charged when connected to a battery; pink here means a positive and light blue indicates a negative charge. The carbon then attracts oppositely charged ions from the electrolyte solution. The ions move through the paper separator if necessary to get to the appropriately charged carbon, and they insinuate themselves into the porous material's many nooks and crannies. The arrangement provides the two features needed for high capacitance: electrodes with huge surface areas, and charges separated by very small distances.

Super Capacitor Theory

KF values

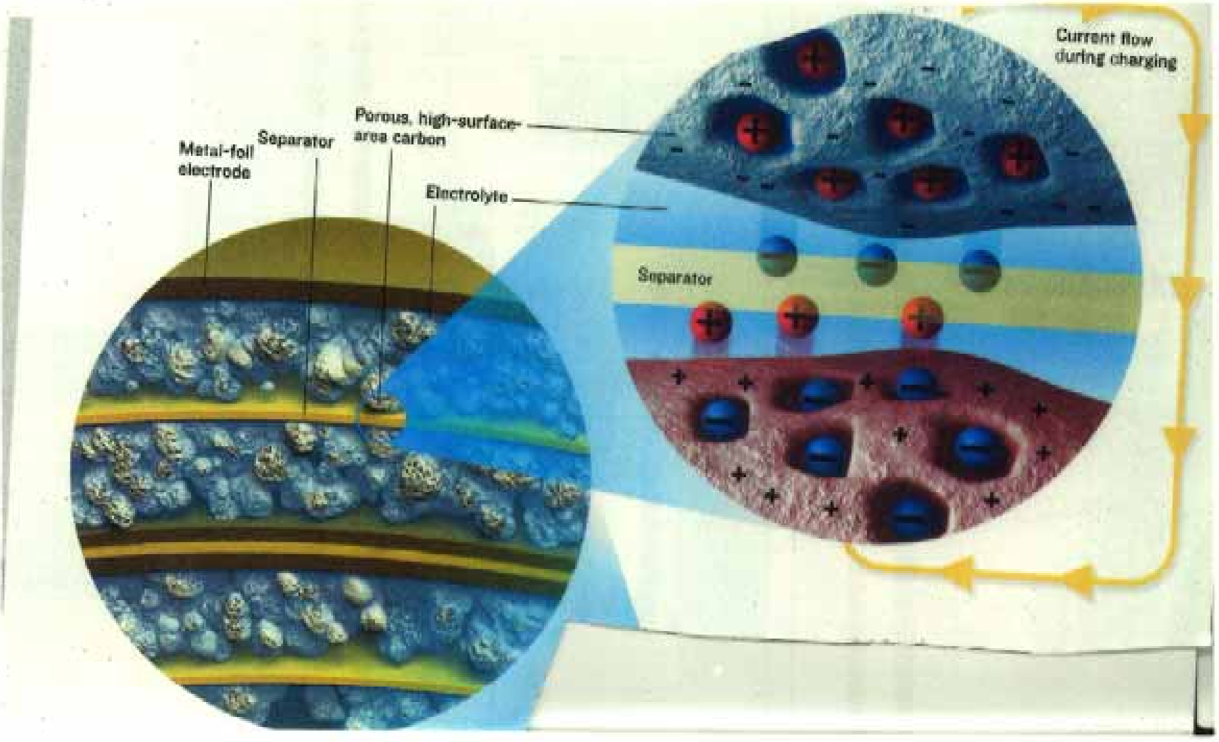
- Instead of ratings such as micro-farad, mili-farad, or pico farad, rated as kili-farad
- Large Capacitance in small package.
  - 5000 Farad, 27 Volts, in Coke bottle
- Efficiency
  - No chemical energy storage
  - No die off like batteries
  - Increased Efficiency, resulting in longer life span

50 soccer fields in cm^2

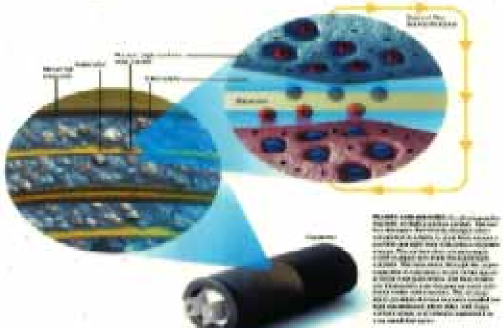
$$C = \frac{\epsilon A}{d}$$

A↑ porous media

d↓ nm scale


Metal-foil electrode
Separator
Porous, high-surface-area carbon
Electrolyte
Separator
Current flow during charging

Super Capacitor Theory



- Key Ingredient
  - Activated Carbon
  - Large surface area
- Activated carbon is porous
- Positive and Negative ions
  - Allowed to get extremely close
- Surface area of around 1500 square meters per gram
  - A typical electrode weighing 250 grams, the total area would be 375,000 square meters-or roughly 50 soccer fields

$C = \frac{\epsilon}{d\,(\text{small})} * A\,(\text{big})$

sources. Because of high price and manufacturability is-

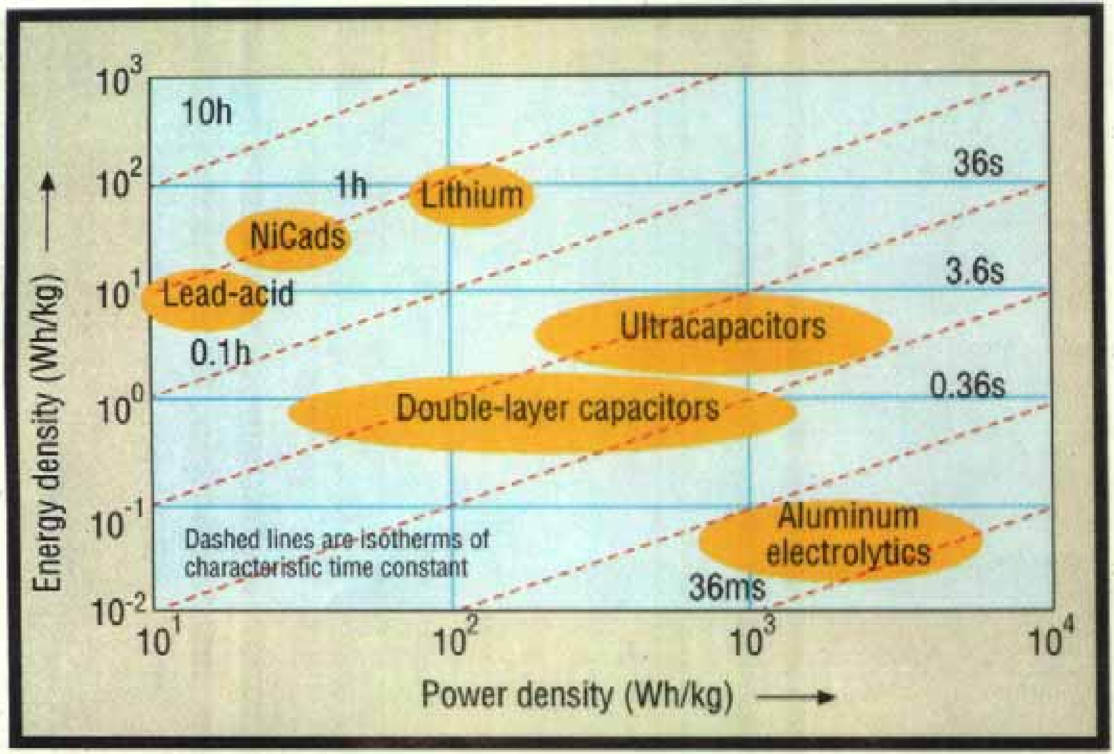
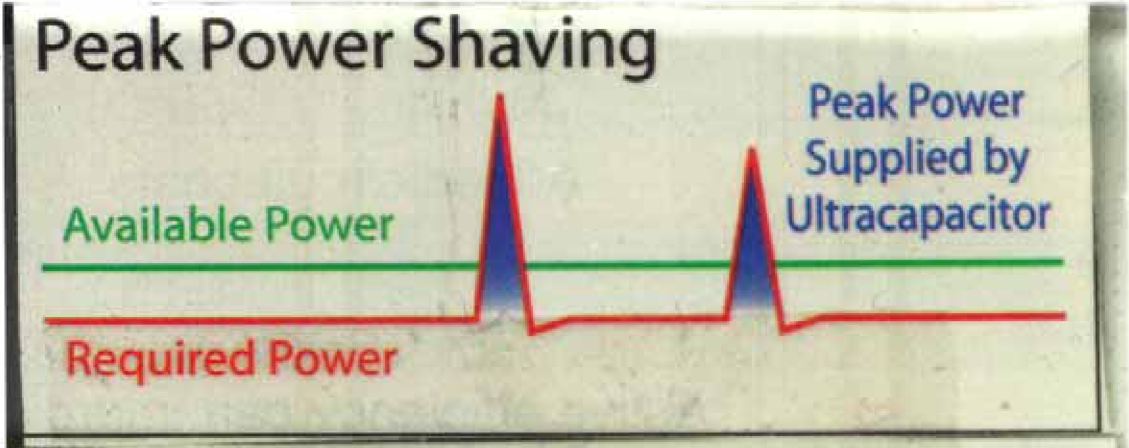
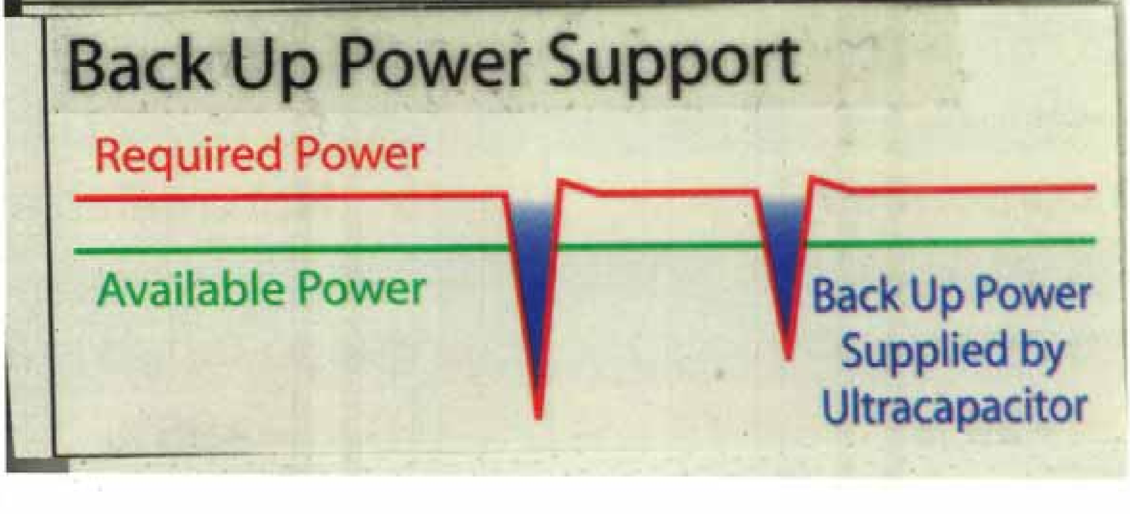


Fig. 1. *Power vs. energy characteristics of energy-storage devices.*


Peak Power Shaving
Peak Power
Supplied by
Ultracapacitor
Available Power
Required Power


Back Up Power Support
Required Power
Available Power
Back Up Power
Supplied by
Ultracapacitor

In its V28 line of power tools, Milwaukee Electric Tool is replacing 18-V NiCd battery packs with slightly lighter 28-V Li-ion packs that deliver higher power and up to twice the run time of the NiCd packs.

Batteries in parallel with Super C

Super-capacitor Applications

Portable Power Tools

- Super-capacitors vs. Batteries
  - Batteries absorb ~60%
  - Super-capacitors absorb ~95%
  - I^2*R losses
  - Super-capacitors have a longer lifetime
  - Operate over a larger voltage range
  - Much larger Power Density (W/kg)
  - Limited Energy Density (W*h/kg)
- Used together battery life increases by about 250%

recharge Sup C: 1hr

Recharge vs Batt: 10hr

10x faster

ENERGY CONTENT

TECHNOLOGY	ENERGY DENSITY (MILLIWATT-HOURS/MILLIGRAM)
Lithium-ion in a chemical battery	0.3
Methanol in a fuel cell*	3
Tritium in a nuclear battery**	850
Polonium-210 in a nuclear battery**	57 000

*Assuming 50 percent efficiency

**Assuming 8 percent efficiency and 4 years of operation

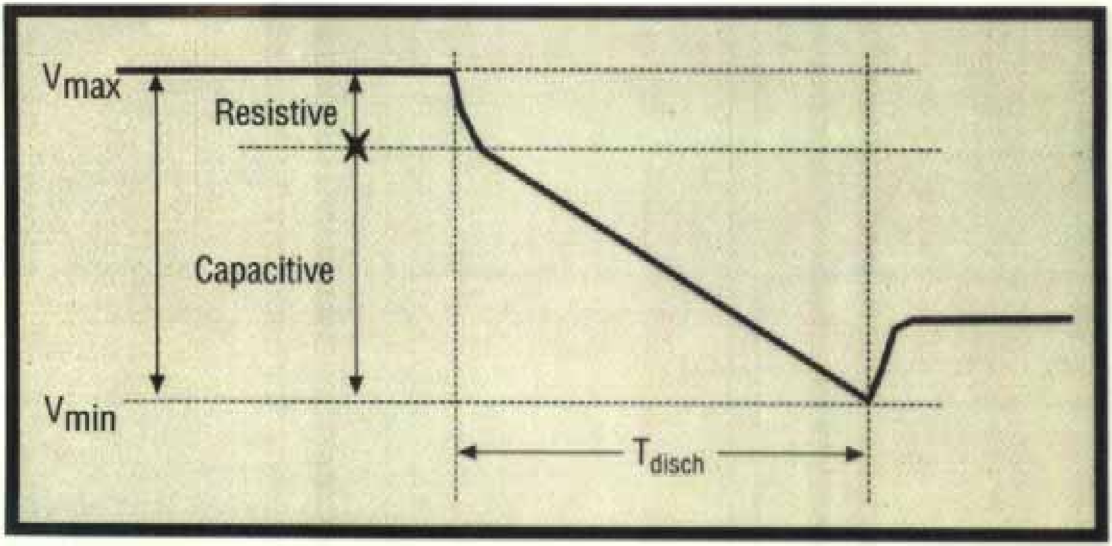


Fig. 5. *Discharge profile of an ultracapacitor.*

rating. Because sustained overvoltage can cause an

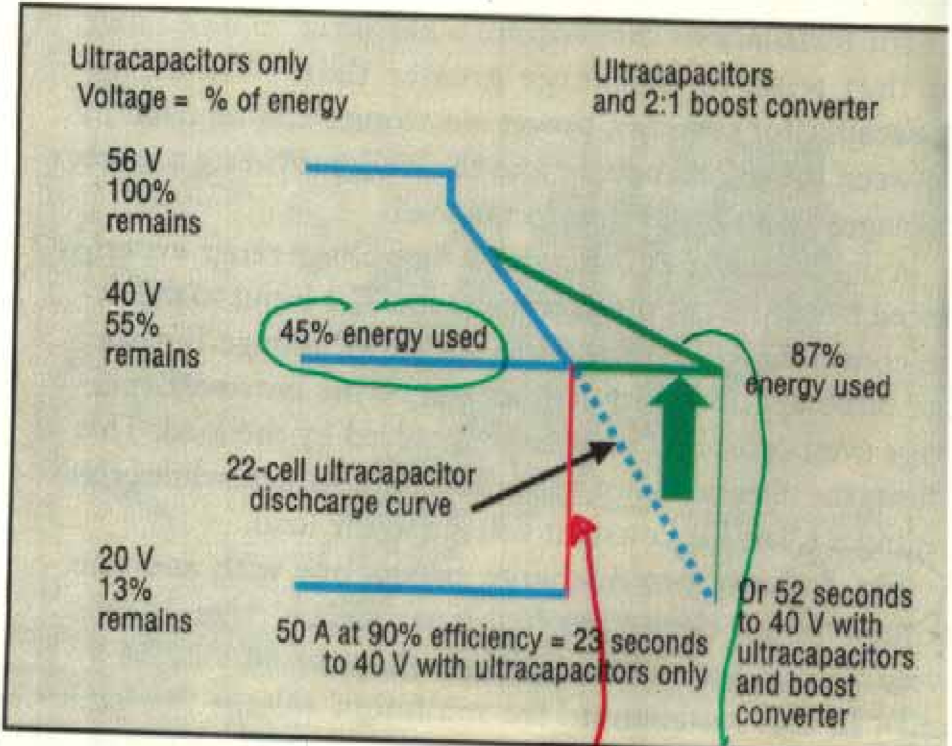
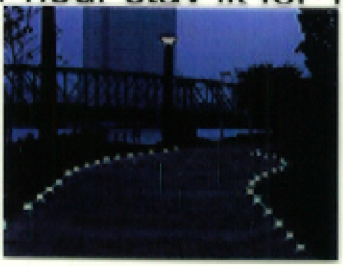


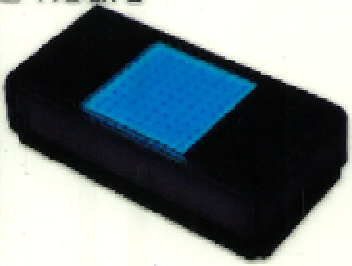
Fig. 4. *Discharge curves for ultracapacitors with and without power electronics.*

line), the actual output is limited

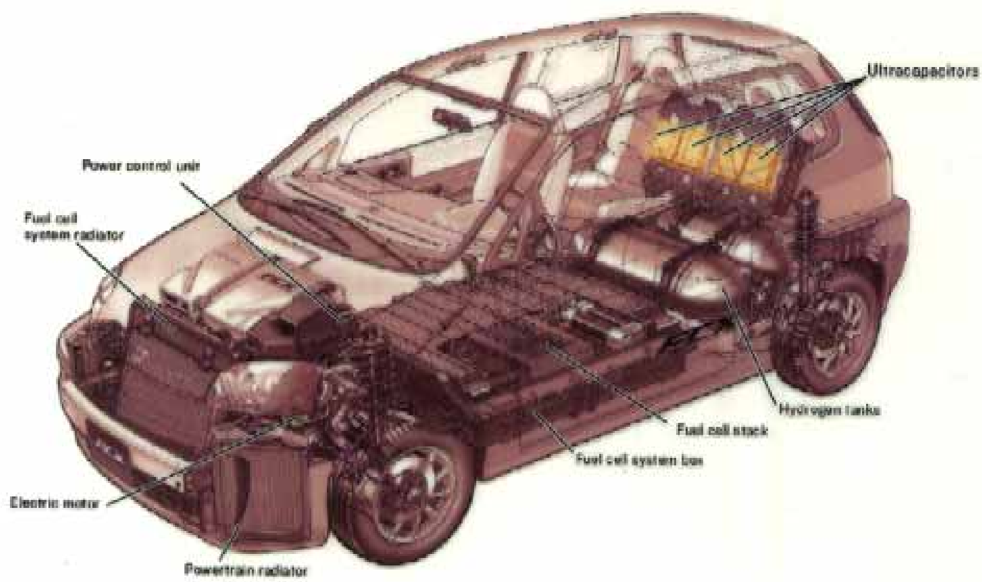
Super-capacitor Applications

- Solar Tiles
  - Batteries last ~1-2 years
  - Super-capacitors over 10 years
  - Charge in 1 hour stay lit for 12 hours



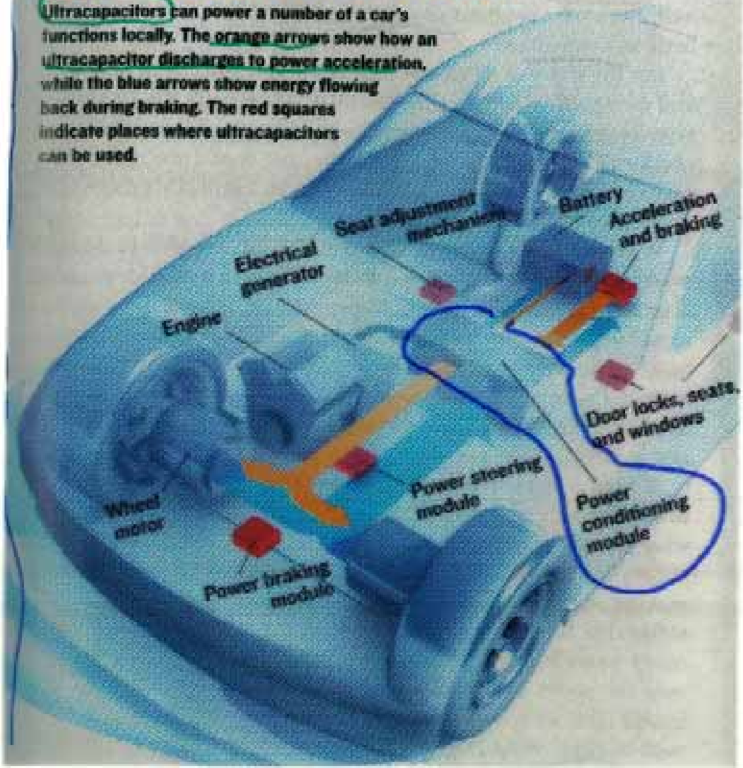


Super-capacitor Applications



HOW TO ULTRACAP A CAR

Ultracapacitors can power a number of a car's functions locally. The orange arrows show how an ultracapacitor discharges to power acceleration, while the blue arrows show energy flowing back during braking. The red squares indicate places where ultracapacitors can be used.



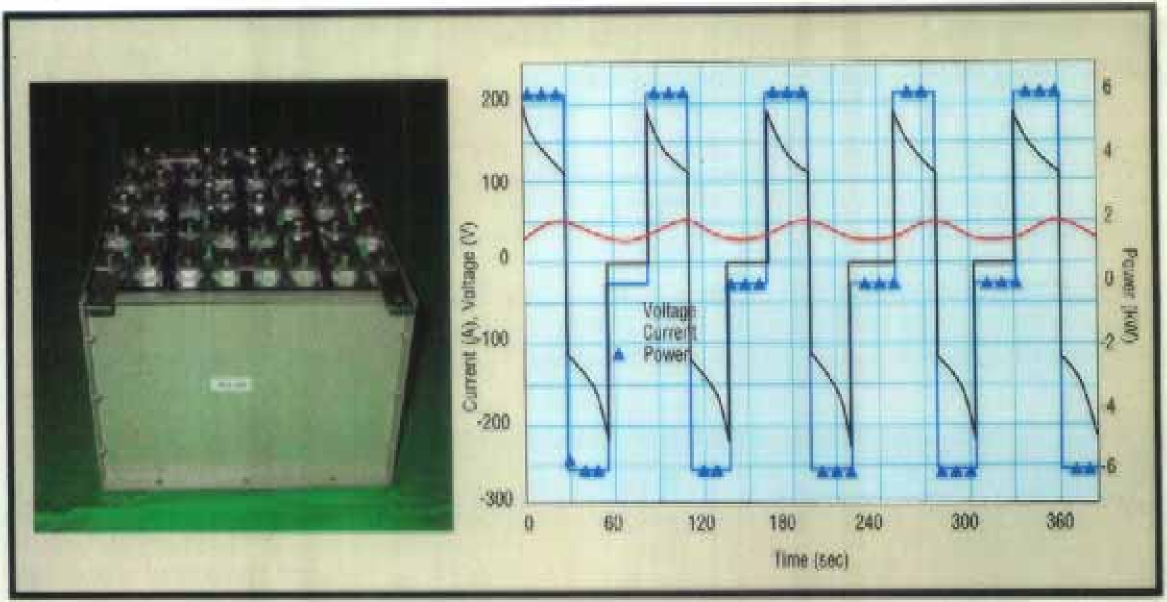


Fig. 6. *A 54-V/175-F NESSCAP ultracapacitor bank module and 6-kW cycling data for 42-V vehicle application.*

1KW – sec

10KW – 10 sec

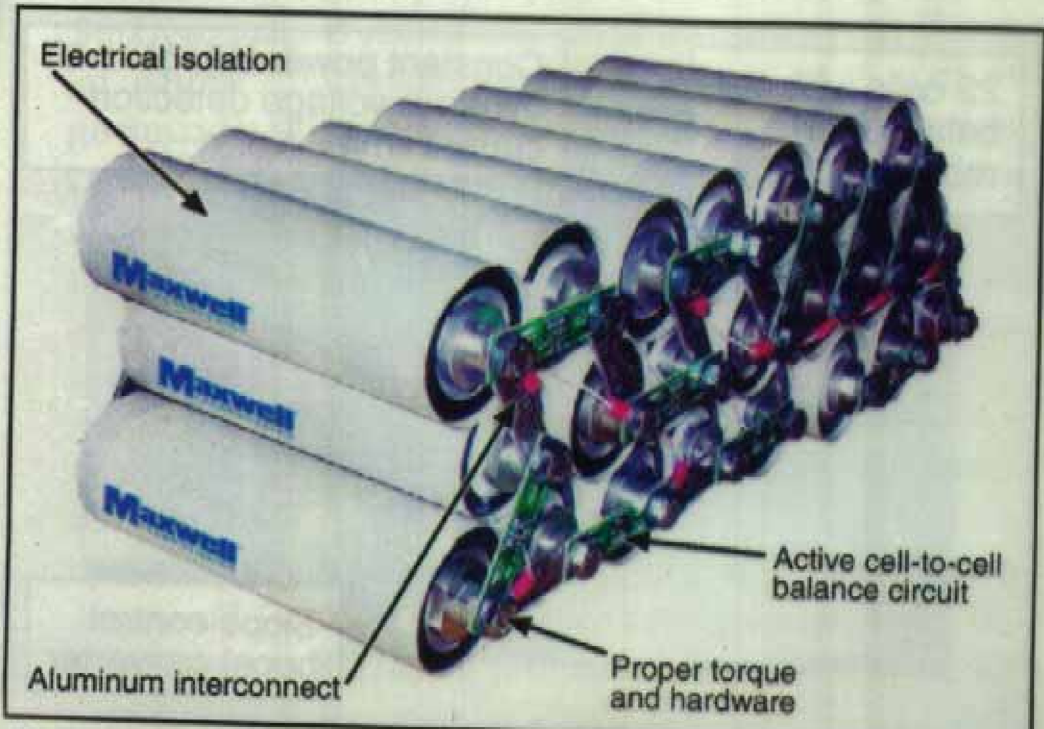


Fig. 3. *Packaging.*

F
or t
ultra
betw
man
A
ence
dc c
the u
haps
allow
vidir
Fi
with
were
cell)

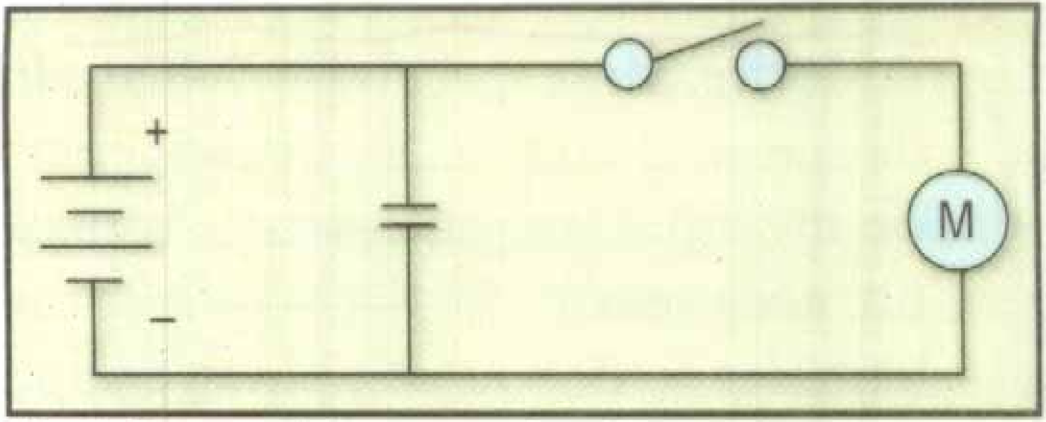


Fig. 1. *Battery/ultracapacitor/motor arrangement.*

Super-capacitor Applications

- A few example used in Power Distribution
  - Wind Power
  - Electric Bus Lines
- New but not on the market
  - Electric Toothbrushes
  - Electric Bicycles
  - Smoke Detectors