Electrical Performance, Miniaturization and EMI Advantages of Very High Capacitance Density Laminates in PCBs and IC Packaging

Presented at PCB West 2011, September 29, 2011, Santa Clara, CA

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Agenda

- Background on Embedded Capacitance
- Electrical Performance/EMI Data
- Capacitor Elimination Metrics
- PCB Fabrication Compatibility
- Cost Considerations
- Summary

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Background on Ultra-Thin Embedded Capacitance Materials

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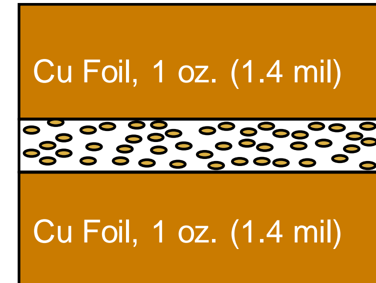
Ultra-Thin Embedded Capacitance Material

Product Description

Sheets of Cu-clad laminate
Thin, high Dk dielectric

- Ideal for high frequency decoupling
- Eliminates discrete capacitors
- Dampens plane resonances



Uses

Power-ground innerlayer (distributed capacitance) for rigid and flex PWBs and IC packages

Singulated (discrete-like) capacitors for decoupling, filtering and other functions in rigid and flex PWBs and IC packages

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Ultra-Thin Embedded Capacitance Technology

Capacitance/Area = 0.885 k/t (nF/cm^2)

- Capacitance per unit area (C/A) is proportional to dielectric constant k and inversely proportional to t
- Maximize C/A by decreasing thickness (t) and increasing dielectric constant (k)

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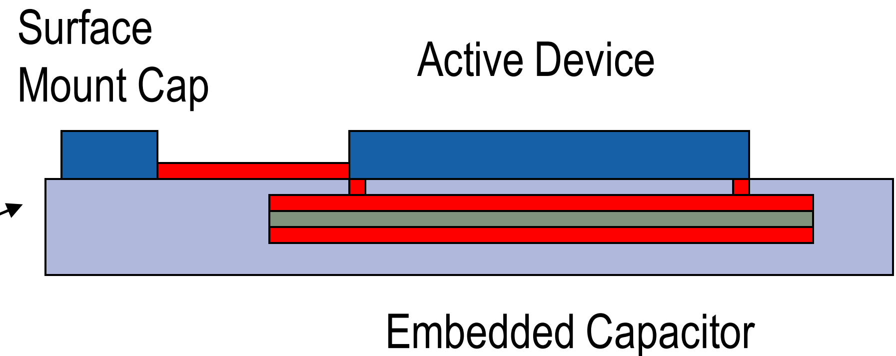
Why Embedded Capacitance?

1. Performance

- Faster charge delivery
- Effective noise dampening
- Reduced power bus noise



2. Space

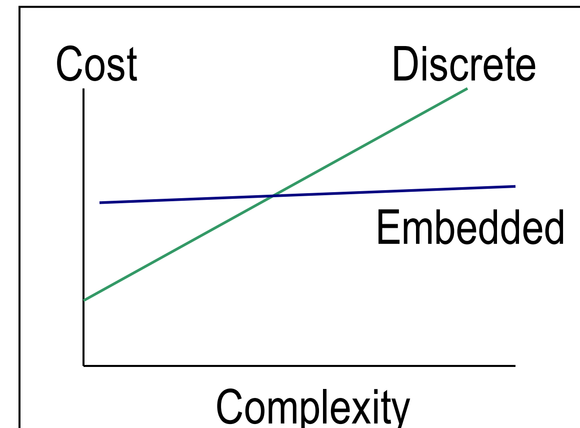
- SMT caps and vias eliminated

3. EMI

- Power bus noise is a leading cause of EMI

4. Cost

- Board size reduction
- Reduced assembly costs



5. Reliability

- Elimination of solder joints/vias

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3M™ Embedded Capacitance Material (ECM)

Miniaturization | Performance | Component Reduction

Telecom
Routers, Base Stations, Switches

Computer
High-end servers, Supercomputers, Storage

Test & Measurement
Automated Test Equipment

Military / Aerospace
Aircraft & Missile Avionics, Satellites

Chip Packaging
Processors, Memory Modules

Consumer Electronics
Mobile Handheld Devices, Video, MEMS Microphones

Very high C/A needed in these applications due to space constraints

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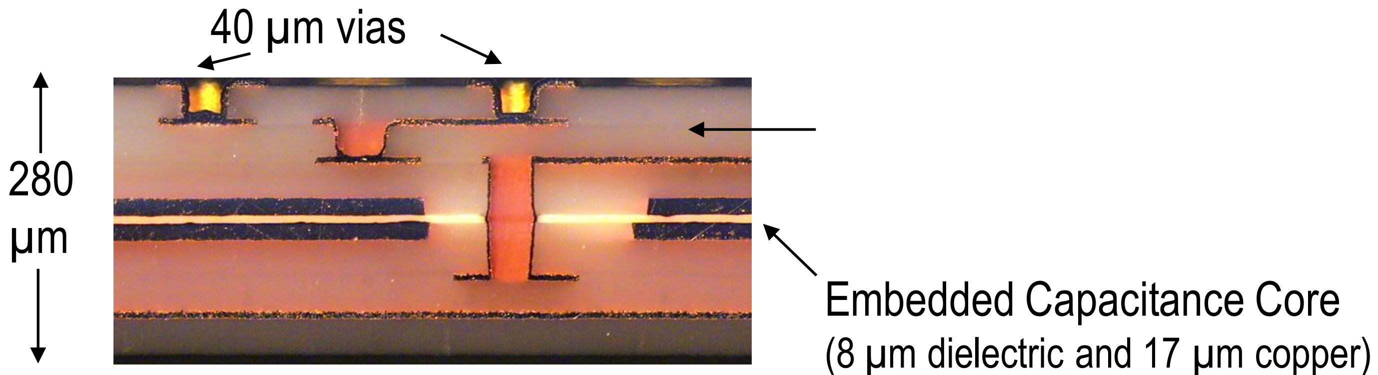
High C/A Needed IC Packaging

- Embedded Distributed Capacitance in high-speed digital IC package for high-end server



Eight Layer Package (42.5 mm X 42.5 mm) with 10 nF/in^2 ECM in middle

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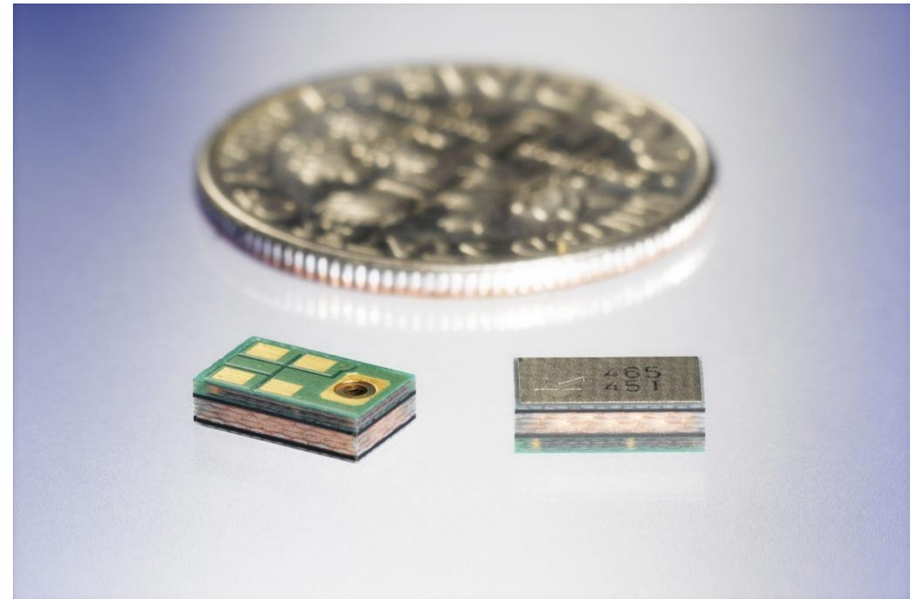
High C/A Needed in MEMS Module



Early design with 2 SMT caps (lid removed)

Later design with 3M™ Embedded Capacitance Material (ECM) replacing SMT caps

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Electrical Performance Data in High-Speed Digital Boards

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The Need for Electrical Performance

- High-speed digital electronics require **low impedance power distribution**, driven by trends in silicon
  - Lower voltages
  - Higher frequencies
  - Higher currents

$$\frac{\downarrow \text{Voltage}}{\uparrow \text{Current}} = \downarrow \text{Impedance}$$

- Very high C/A ECM is a very simple and effective way to lower the impedance of the power distribution system, even on small boards, modules and chip packages
  - Lowers voltage ripple
  - Dampens board resonances
  - Reduces EMI
  - Eliminates decoupling capacitors

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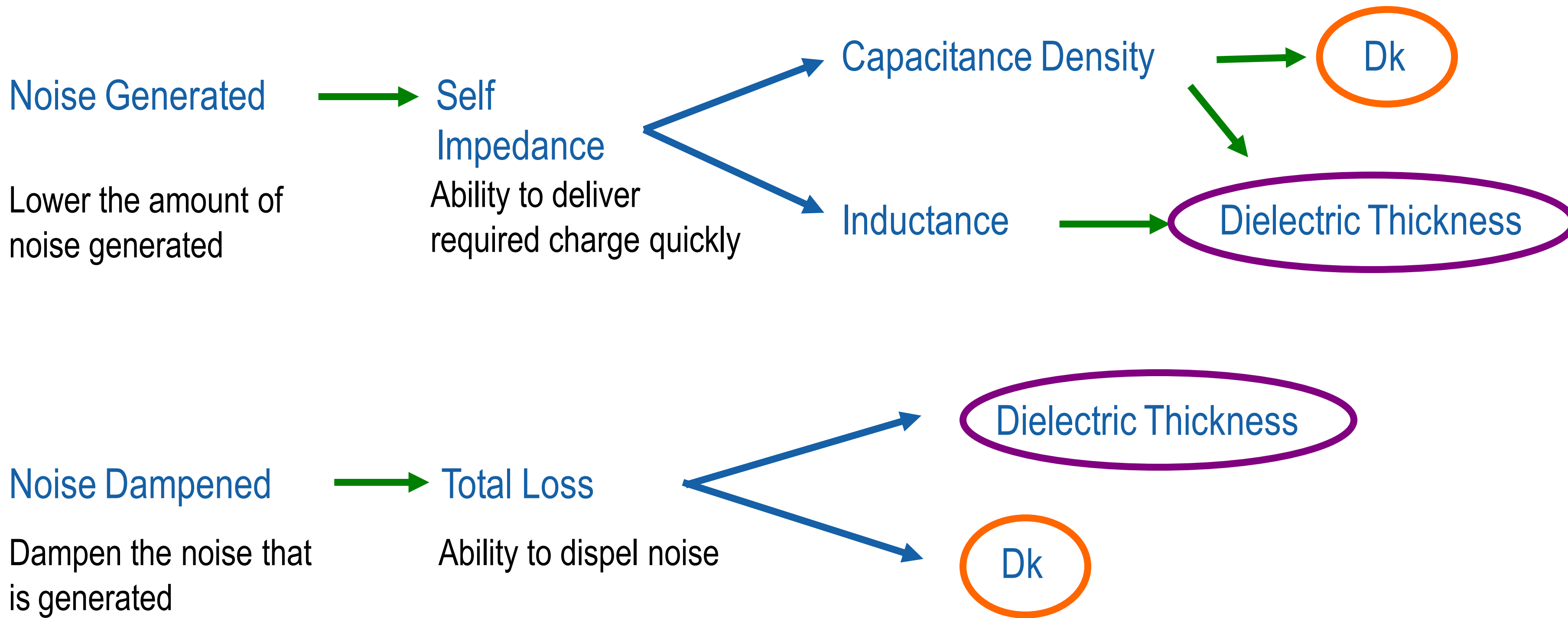
Key Factors for High Frequency Decoupling



Performance is driven by dielectric thickness and dielectric constant; thinner dielectrics and higher dielectric constants mean higher loss, higher capacitance and lower inductance.

Total Loss vs. Frequency (3M™ Embedded Capacitance Material (ECM)

D.F. vs. Frequency

Y-axis: D.F. (0 to 0.16)

X-axis: Log Frequency (3, 4, 5, 6, 7, 8, 9, 9.3)

Legend: Dielectric Loss, Copper Loss, Total Loss

Power-Ground Cores: Desire high loss at HF

Cu losses dominates at frequencies >150 MHz

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3M™ Embedded Capacitance Material (ECM) Key Properties

	C0614	C1012	C2006
Capacitance per Area	6.4 nF/in^2 (1.0 nF/cm^2)	10 nF/in^2 (1.55 nF/cm^2)	20 nF/in^2 (2.3-6.2 nF/cm^2)
Dk	16	22	22
Dielectric Thickness	0.55 mil (14 µm)	0.47 mil (12 µm)	0.24 mil (6 µm)
Dielectric loss @ 1GHz	0.03	0.03	0.03
Resin system	Epoxy, ceramic filler	Epoxy, ceramic filler	Epoxy, ceramic filler
TCC	Meets X7R	Meets X7R	Meets X7R
Dielectric Strength	~3300 V/mil (130 V/um)	~3000 V/mil (118 V/um)	~3000 V/mil (118 V/um)
Breakdown	>100V	>100V	>50V
Copper Thickness	1.4 mil (35 µm)	1.4 mil (35 µm) 0.7 mil (17 µm)	1.4 mil (35 µm)

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Power Bus Noise Reduction

- Reduce the dielectric thickness of the laminate between the power and ground planes
  - If >1.5 mils, 10 dB reduction per decade
  - If <1.5 mils, 20 dB reduction per decade
- Increase the dielectric constant of the laminate between the power and ground planes
  - If Dk <10, 7 dB reduction per decade
  - If Dk >10, 14 dB reduction per decade
- Changing from a 4 mil FR-4 power ground core to a 2 mil core will reduce power bus noise by ~4 dB
- Changing from a 4 mil FR-4 power ground core to a 0.5 mil core with Dk of ~20 will reduce power bus noise by ~20 dB

Modeling Noise on Printed Circuit Board Power Planes
John Grebenkemper, DesignCon 2004

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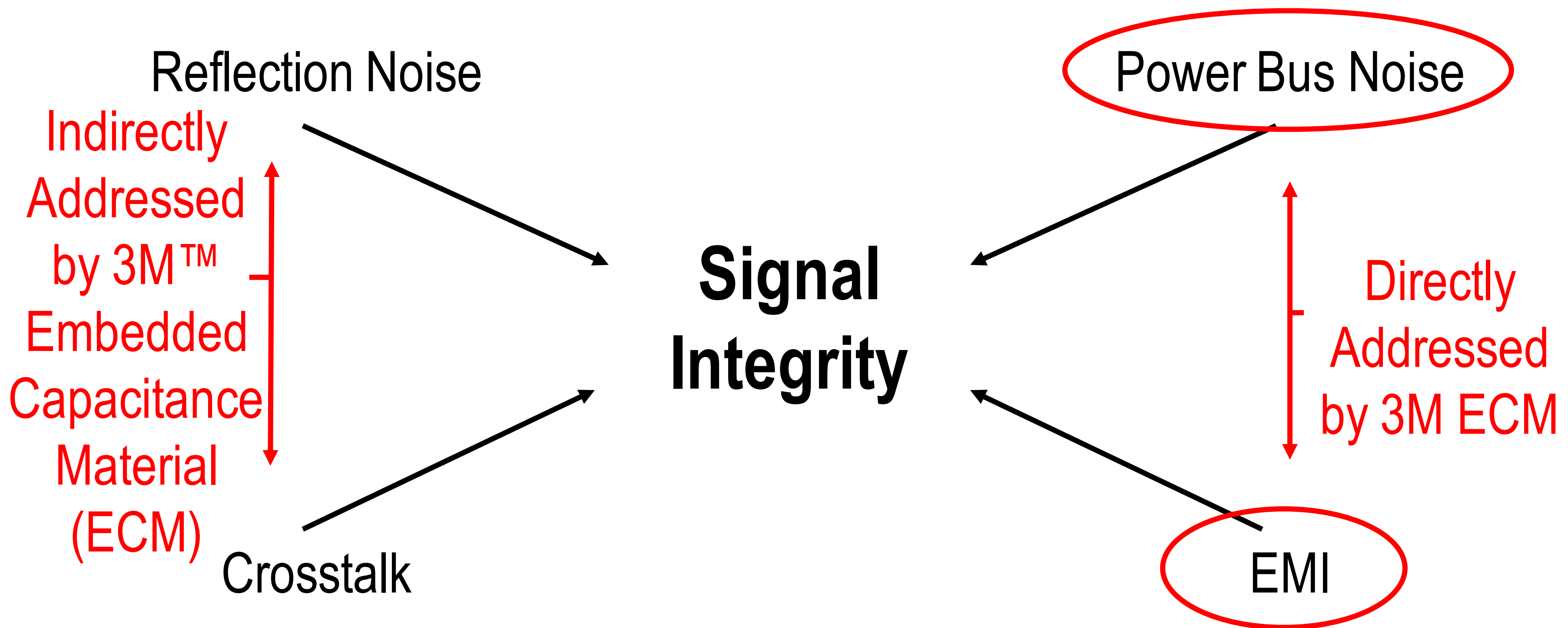
Four Factors Impacting Signal Integrity



Signal Integrity, Power Integrity and EMI are all interrelated

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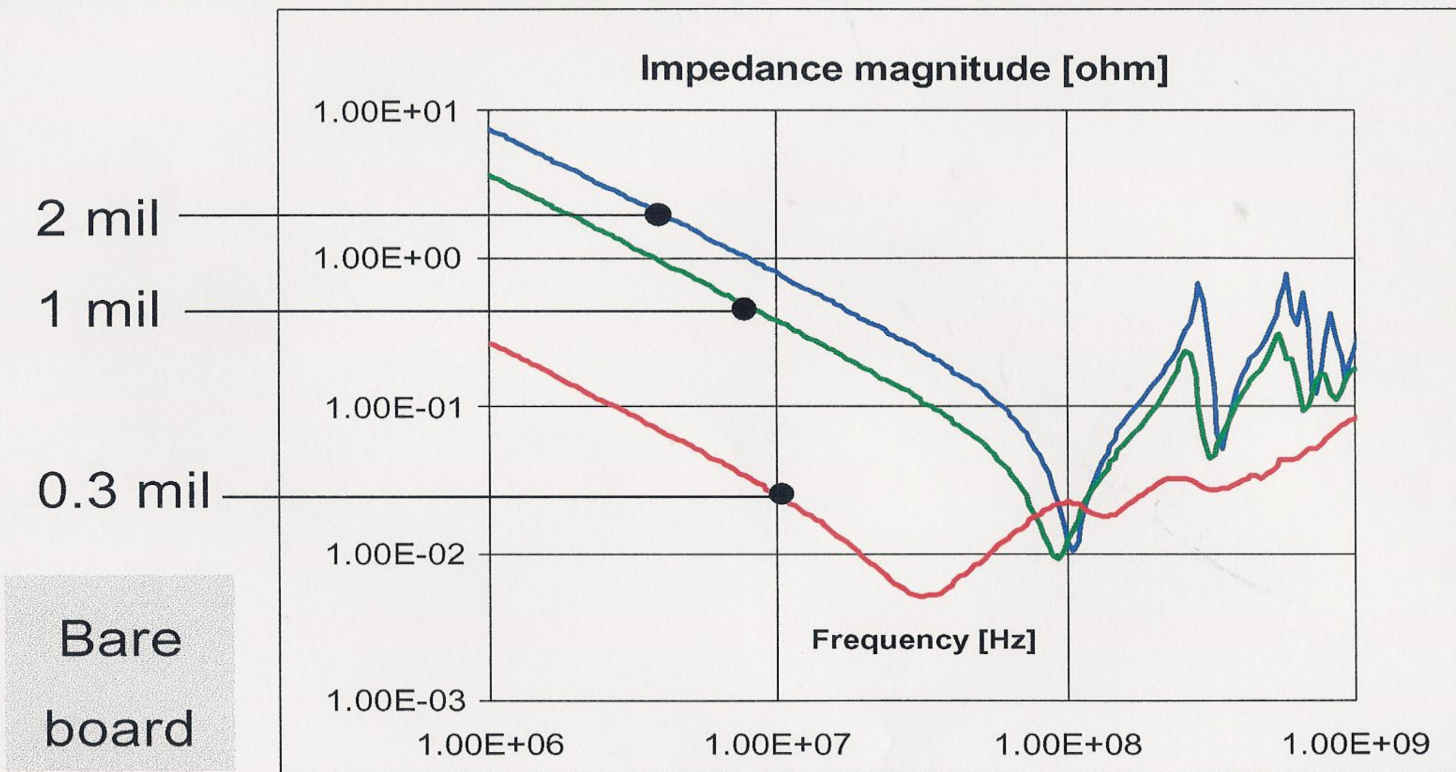
Impedance Comparison



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Self-Impedance Comparison

Impedance magnitude [ohm]

y-axis	1.E+00, 1.E-01, 1.E-02, 1.E-03
x-axis: Frequency [Hz]	1.E+07, 1.E+08, 1.E+09
Legend	50um, 24um, 12um, 8um

FR-4

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Courtesy of Sun Microsystems

Lower impedance across all frequencies with thinner /high Dk dielectric materials

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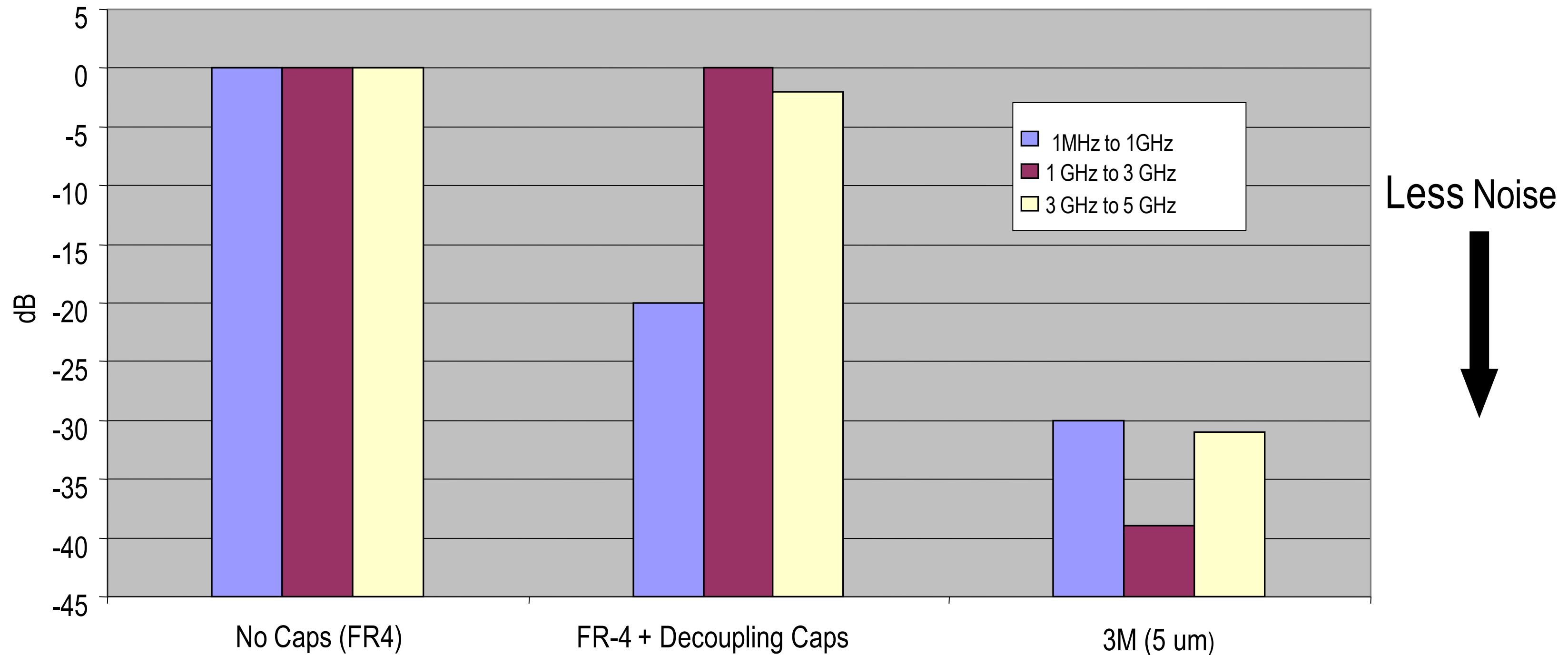
Power Bus Noise on Test Vehicle (EDC TV1)



- Traditional decoupling capacitors are not effective at frequencies above 250 MHz
- 3M has excellent performance to 5 GHz (and beyond)

Data from NCMS Embedded Decoupling Capacitance Project Report - 12/00

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Power Bus Noise

(Time Domain = 50 MHz

TV 1 FR4+dec.
TV 1 2 mil FR4
TV 1 3M

Volts

1.5
1
0.5
0
-0.5
-1
-1.5

-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5

50 Ohm mode, V=3.3v

x 10 ns

Data from NCMS Embedded Decoupling Capacitance Project Report - 12/00

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Power Bus Noise (UMR)

Power-Ground Core Material	Nominal Capacitance (nF)	Peak-to-Peak Voltage (mV)
FR-4 (with 33 discrete SMT caps)	330	214
BC2000™ (50 µm)	3	1,740
3M™ Embedded Capacitance Material (5 µm)	107	89

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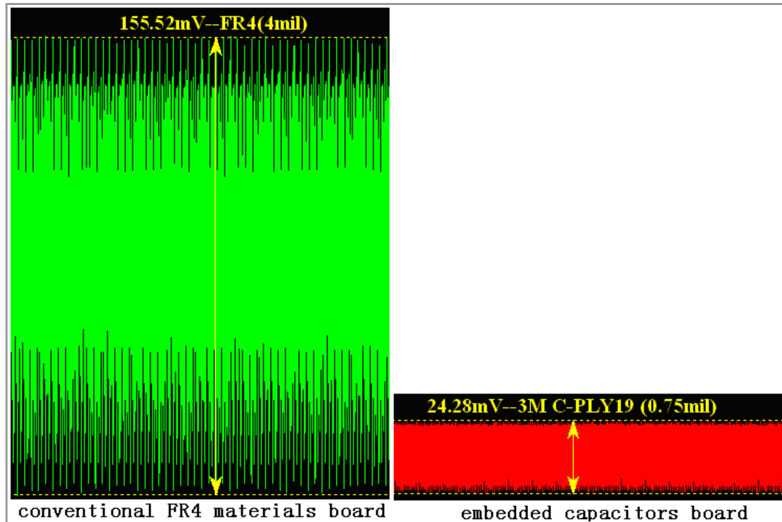
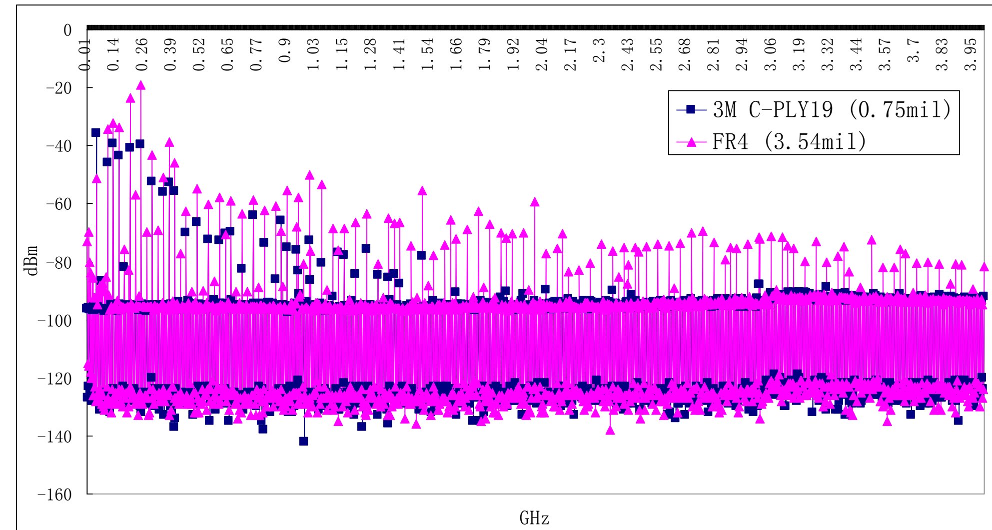
Comparison of Power Bus Noise on 6-Layer Board



Power ripple noise comparison in time domain



Power noise frequency spectrum comparison

- Power noise ripple of FR4 board is much higher than the 3M™ Embedded Capacitance Material (ECM) board (156 mV vs. 24 mV)
- ECM board shows superiority over FR4 on noise reduction in entire bandwidth (10MHz-4GHz)
- ECM board noise close to white noise of Spectrum Analyzer in higher frequency over 1.5GHz
- Very promising for ECM to improve power supply quality, digital /analog interference in board and board level EMI

Courtesy of Huawei

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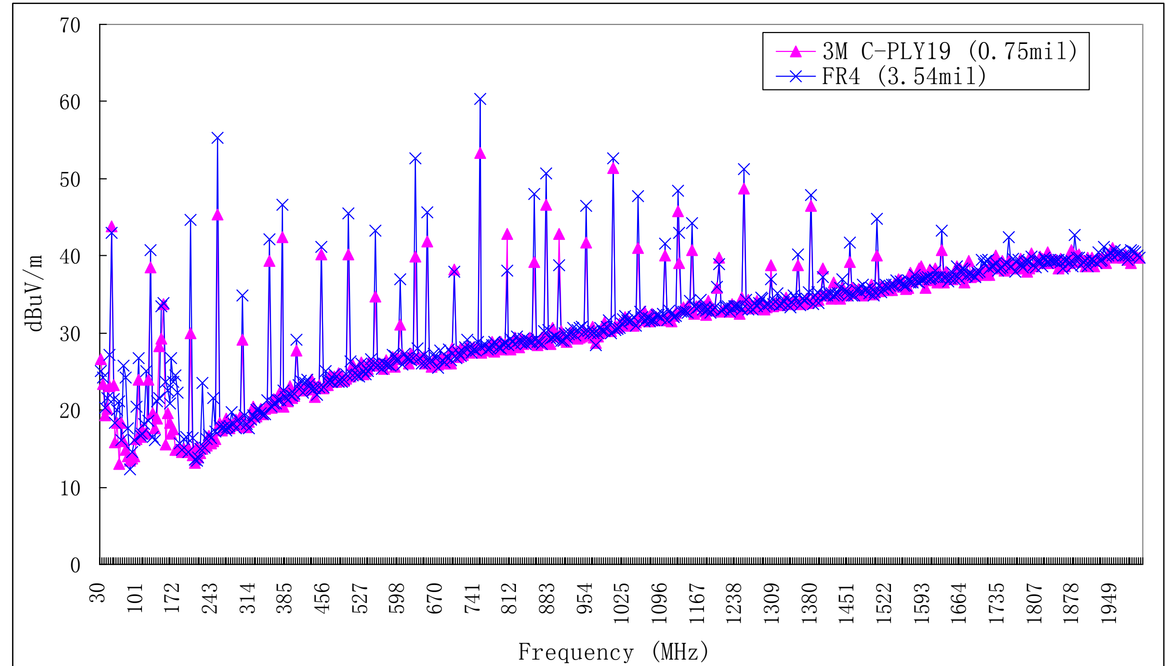
Board Level 3M™ Embedded Capacitance Material (ECM) Performance Comparison – Test Result

Full Wave Darkroom



Radiated Emission Test Result （30MHz - 2GHz ）

- Radiated Emission Test in standard full wave darkwave for FR4/ECM board.
- Obvious better performance of ECM board from 30M to 2G (only tested up to 2G)

Courtesy of Huawei

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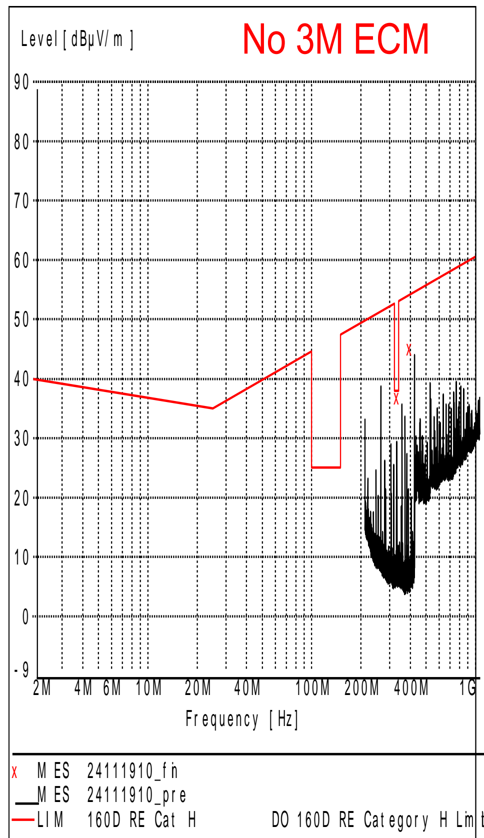
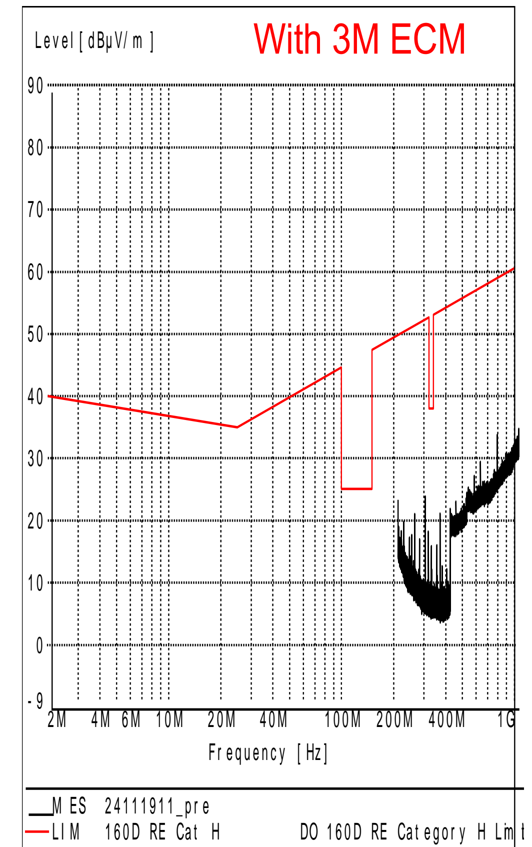
EMI Reduction with use of 3M™ Embedded Capacitance Material (ECM) on Rigid Multi-layer Board in Avionics Application





Courtesy of U.S. Defense Prime Contractor

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Electrical Benefits of Ultra-Thin Embedded Distributed Capacitance (Power-Ground)

- Lowers impedance of power distribution system
- Dampens board resonances
- Reduces noise on power plane
- Reduces radiated emissions
- High Dk significantly improves performance compared to same thickness with low Dk

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Capacitor Elimination Metrics

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Examples of How Many Discrete Caps Can be Replaced per Board Area

Design	Board Layers	No. of 3M ECM Power-Ground Cores	Approx. Board Area (in^2)	Total No. of Caps Removed	Caps Removed per sq in
EDC TV1	6	1	6	33	5.5*
OEM A	12	1	35	126	3.6
OEM B	10	2	17	73	4.3
OEM C	8	2	12	57	4.6
OEM D	14	2	121	529	4.4
OEM F	14	2	~100	443	~4.4*
OEM G	20	2	~80	~660	~8.2

*100% of decoupling caps removed

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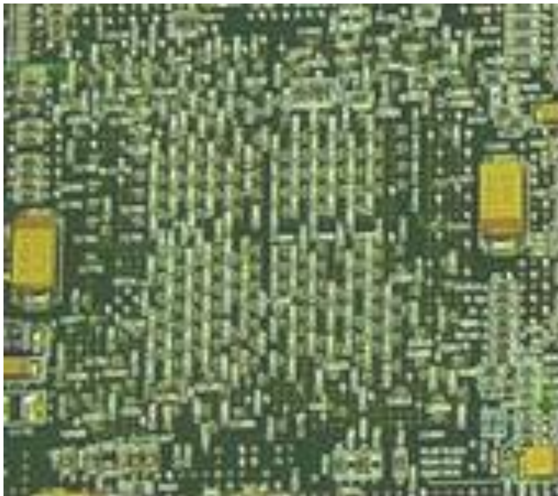
Discrete Capacitor Elimination on Telecom Board

Baseline Design (BGA1)

VS.

Embedded Capacitance Design (BGA1)



Baseline Design (BGA2)

VS.

Embedded Capacitance Design (BGA2)

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Cap Elimination Summary

- Surface mounted discrete capacitors are usually ineffective above several hundred MHz
- 3M™ Embedded Capacitance Material (ECM) can replace a large number of discrete decoupling capacitors from the board surface
- Results to-date suggest:
  – Typically ~75% of discrete decoupling capacitors can be removed
  – Typically ~4-8 decoupling caps per square inch can be removed
  – Only 1 – 10% of the amount of SMT capacitance removed is needed due to lower inductance
  – Even when large quantities of SMT caps are removed, electrical performance is still improved

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PCB Compatibility

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PCB Processing - 1

- Compatible with all standard rigid/flex PCB processing (includes laser drill, plasma de-smear and alternative oxides)
- Material handling is most significant issue
  - (compares to bare 2 ounce copper)
- A sequential lamination process is recommended
  - Pattern 1st side copper
  - Laminate patterned side to another layer of prepreg
  - Pattern 2nd side copper
- If a sequential lamination process is utilized, there are no design limitations

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PCB Processing - 2

- Typically 1 to 4 cores of material are used in a board stack up (2 is the most common)
- Typical locations in stack up are middle (one core) and layers 2/3 and n-1/n-2 (2 cores)
- Compatible with all common laminate/prepreg materials
  - Low and high Tg FR-4 (Epoxy-Glass)
  - BT/Epoxy
  - Nelco 4000-13/4000-13SI
  - Isola 370 HR
  - PPO/Epoxy (Megtron/Getek®)
  - Embedded Resistor Materials
  - Polyimide Film
  - Thermount® (Polyimide)
  - Polyimide-Glass*
  - Rogers 4450 and 4003
  - Gore Microlam™ 630
  - APPE

*Prepreg materials need max cure temp of 200C for some ECM materials

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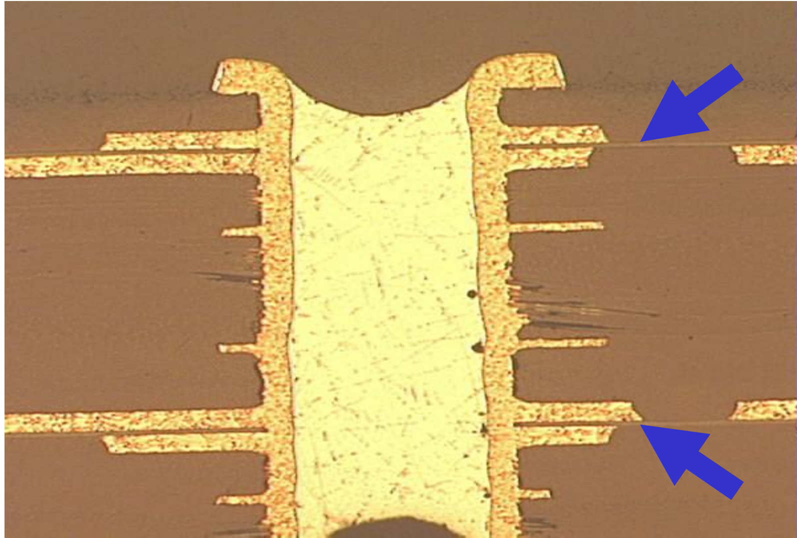
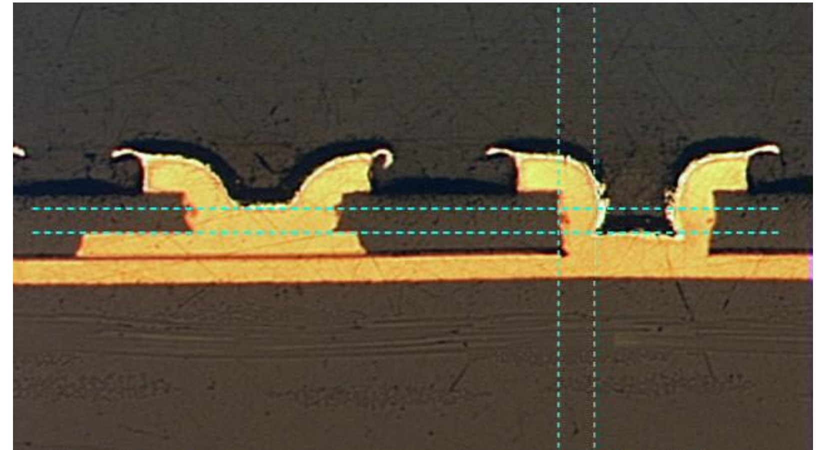
PCB Fabrication Results



Two 3M™ Embedded Capacitance Material (ECM) laminate cores (8 µm) separated by an FR406 core.



Microvias in test board.

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PCB Fabrication and OEM Acceptance

- Many PCB fabricators have successfully fabricated ECM in high volume commercial applications
  - Over 120 PCB fabs have used the material to-date
  - Used by PCB fabs in at least 15 countries to-date (including many in Asia)
  - Material has been used in backplanes, daughter cards, modules, IC packaging and flex circuits
  - Board layer counts from 2 to over 40
  - Boards have been built for military/aerospace, telecom, computer, handheld, IC packaging, automotive, medical, ATE market segments

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UL Testing/RoHS

- UL recognition (ECM C0614)

Test	Property	Result
Laminate	Flammability	94V-0
Laminate	Solderability Limits	288ºC/30 sec
Laminate	Relative Thermal Index	130ºC
Board	Flammability	94V-0
Board	Max Operating Temp	130ºC

- RoHS compliant
- Compatible with lead free assembly
- Does not contain bromine
- Halogen-free versions available

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Cost Considerations

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3M™ Embedded Capacitance Material (ECM)

Cost Reducers and Adders

	Cost Reducers	Cost Adders
Board	Smaller board sizes Reduced layer counts Fewer solder joints/vias	Material costs PCB processing costs Potential lower yields
Board Assembly	Eliminated capacitors Reduced assembly costs Improved yields	
System/Design	Fewer design cycles Faster layouts Eliminated EMI measures Improved reliability, service life	Difficult to alter embedded materials

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Cost Conclusions

- Bare board costs will typically increase
- System costs may increase or decrease
  - Design dependant
  - Higher component densities favor embedding
  - Boards with high panel utilization favor embedding
- The technology and supply chain infrastructures have matured greatly; the costs of embedded approaches have declined and opportunities for system cost reduction have expanded greatly compared to several years ago .

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Summary

- Ultra-thin/high Dk laminate materials used for power-ground cores (distributed capacitance) offer very significant electrical performance advantages compared to standard FR-4 laminate materials
- Ultra-thin, high Dk dielectric materials also offer many other advantages over standard FR-4 power-ground core laminates
  - Thermal
  - Reliability
  - Component and Space Reduction
  - Regulatory (EMI)
  - Easier/Faster Board Design
- New, even higher C/A products can achieve excellent decoupling and low pass filtering on even extremely small products such as chip packaging , handheld products and microphones

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Key Contacts

- Contact us or visit www.3Mcapacitance.com to…
  - Get samples for prototyping
  - Obtain a quote for purchasing
  - Set up a visit and/or conference call with a 3M engineer

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