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MOU TCG-X
Safe, Arm, Fuze, and Fire Technology
LTCC Transformer

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Collaborations

- This work is done with the LTCC team at NascenTechnology (Watertown, South Dakota)
  - Daryl Schofield, Vice-president
  - Dave Abel, Staff Engineer

All Good Things Must Come to an End...

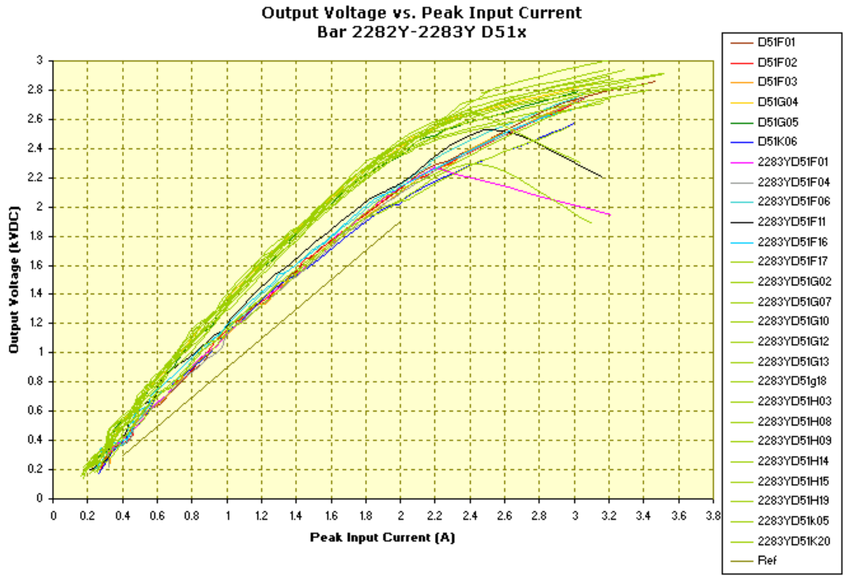
- It has been decided that the LTCC transformer work will end.
- Original goal of a manufacturable monolithic flyback transformer for DoD applications (1500 V) has been met.
- Past year's work will show that the current size is maxed out in performance.
- To increase performance above 3 kV, much time and money will need to be expended to develop new manufacturing processes.
  - Thicker parts
  - Higher permeability materials
  - Multimaterial integration

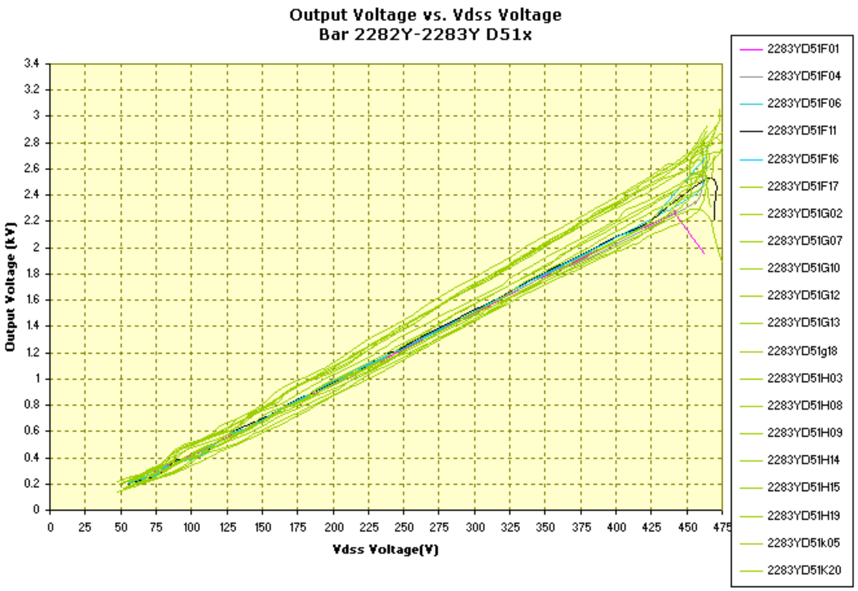
3-5 kV Flyback LTCC Transformer-Issues

- 3 kV design is more than likely doable in the near future for currents less than 4 A.
- The technology is still far off for a reasonable (primary currents) 5 kV design.
- To address these concerns, Sandia has funded work with NascenTechnology, Inc., to development a dielectric LTCC tape that is compatible with the ferrite tape. The potential advantages are:
  - Reductions in flux leakage, i.e. leakage inductance
  - More homogenous design (less wet constituents)
  - Thicker designs
  - Circuit integration
- NascenTechnology has bought a singulation router to make thicker parts for Sandia.
  - Higher inductance
  - Decrease leakage inductance

D51 LTCC Transformer (0.5” x 0.5”)

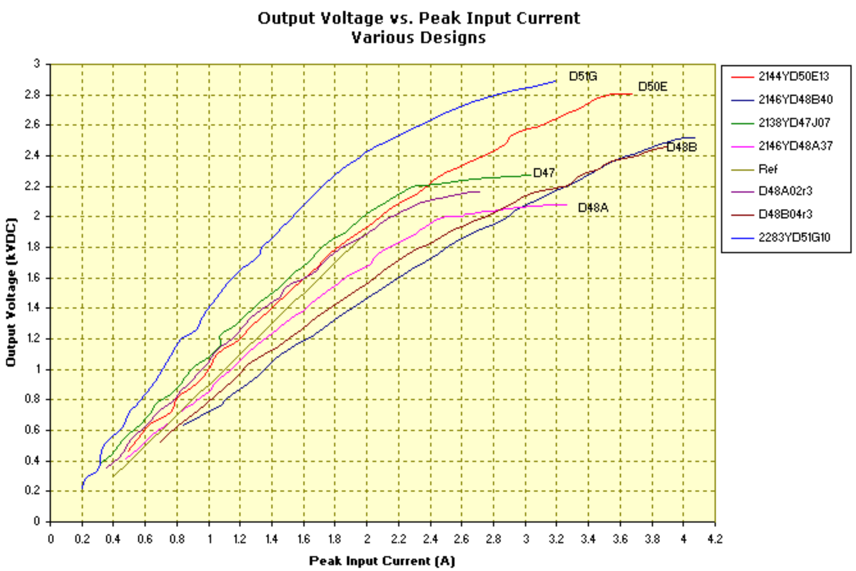
- **Basically the same design as the D48 and D50 transformers, just bigger footprint.**

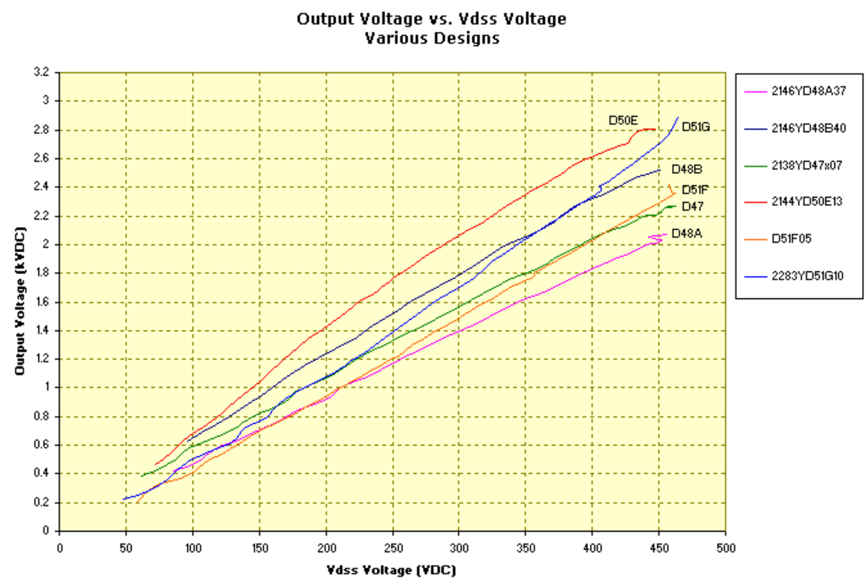




- **The green traces are for an experimental gap structure not used before (gap layers to the outside edge of the parts).**

D51 LTCC Transformer (0.5” x 0.5”)





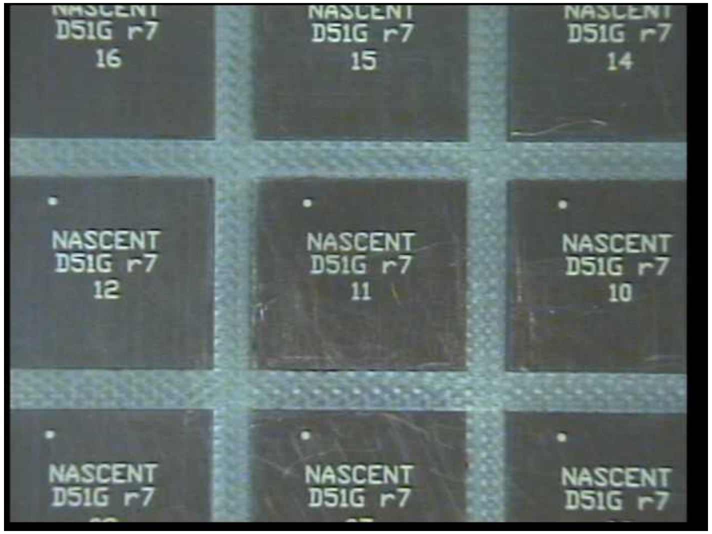
- In comparison to the previous smaller designs, the D51 transformer has higher output voltage for a given current. However, the D51 has a higher voltage stress for a given output voltage. Obviously, a design tradeoff is required.

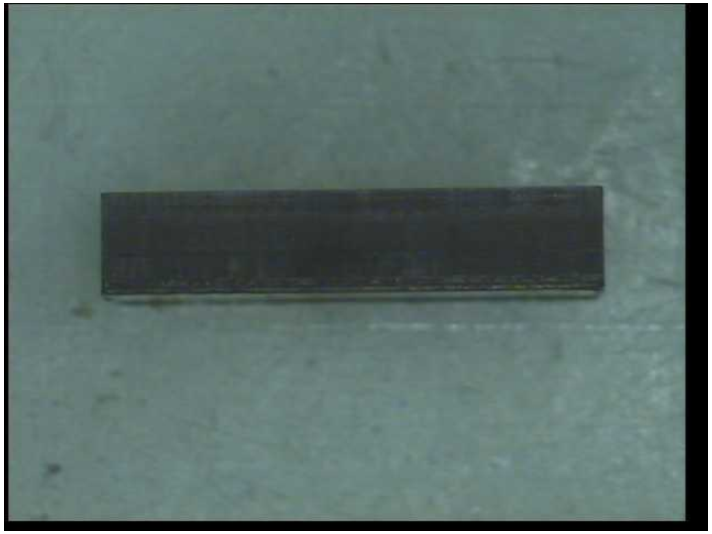
Dielectric LTCC Tape

- **Must be compatible with existing ferrite tape**
  - **CTE**
  - **Shrinkage during Firing**
  - **Reasonable Dielectric Strength**
  - **Firing Profile**
- **First version of dielectric tape matched well to ferrite tape but could be better**
- **Second version of dielectric tape AND modified ferrite tape had about 60% improved shrinkage difference.**
- **First proof of concept D50E showed promise. Subsequent builds of D51 sized transformers proved difficult.**

Router vs. Guillotine

- In order to fabricate thicker parts, the Guillotine method will have to be scraped. A router based approach must be used.
- 56 and 88 layer test samples were successfully routed and fired (ferrite only).
- Machine is in place to cut thicker parts if design/process allow.

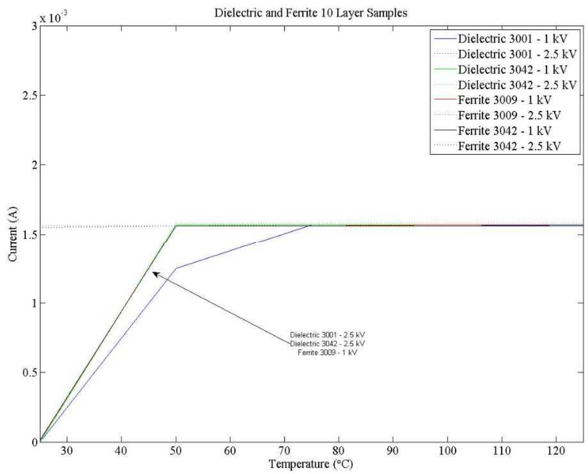


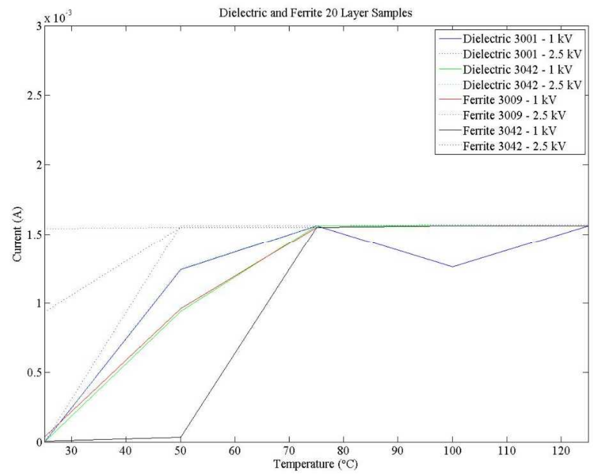


Insulation Resistance

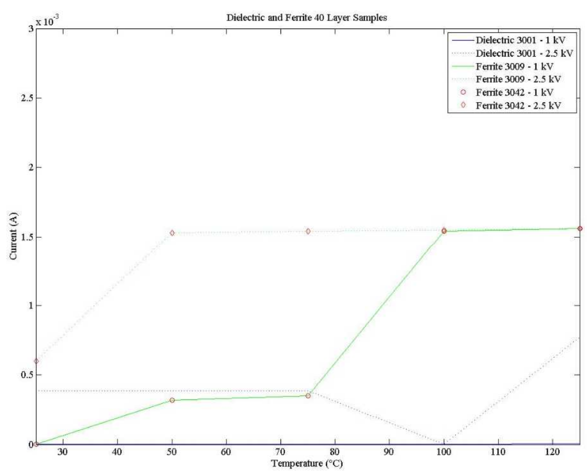
- In some testing, output voltage foldback has been seen in the dielectric ring coil transformers. Also for the traditional LTCC transformers, voltage drop has been seen as high primary currents and/or large run times.
- A series of test samples were made with the different ferrite and dielectric tapes blends at different thicknesses to test high voltage standoff with temperature.
- The data (following slide) shows that the system could be temperature sensitive and future work should study this further.

Insulation Resistance





Limit of tester was 1.5 mA.

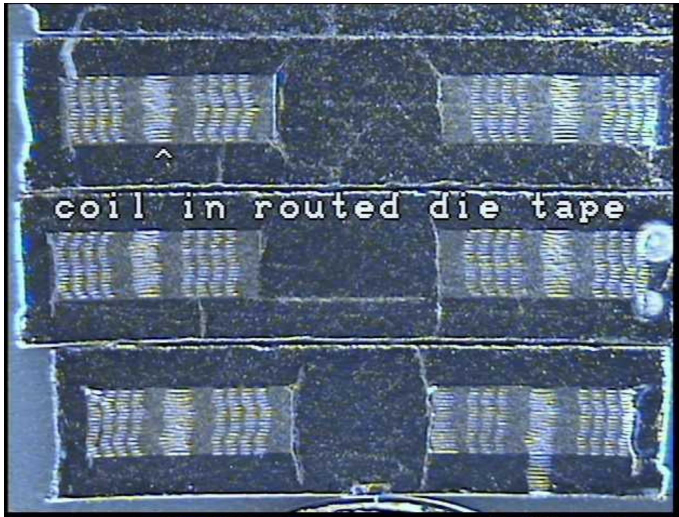


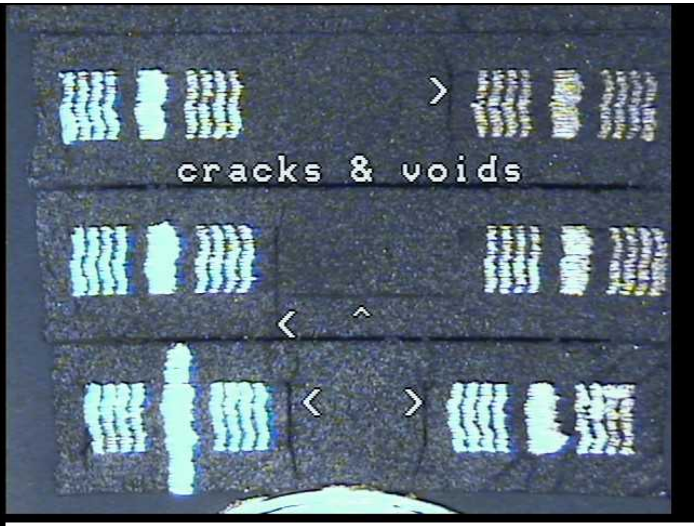
- There is a definite temperature effect on insulation resistance.
- As the samples get thicker the effect is delayed.
- The data shows that there could be energy lost from one end of the coil to the other at elevated temperatures such as from Joule heating.

Dielectric Ring Coil Transformer

- Since the first proof of concept done in late 2006 for the D50E design, much has been tried to decrease cracking which has severely affected the production yield and lowered the inductance (limited output).
- Early design had the central gapped core part of one of the end caps.
  - Cracks seen at dielectric ring coil ferrite interface around the central gap structure.
- The design has now evolved into a separate routed center gapped structure. This should give more mechanical degrees of freedom during the sintering process.
  - So far some minor improvement but cracking is still an issue.
- All designs that have continuity show a siginificant increase in coupling factor (lower leakage inductance). These designs have some internal cracking which have prevented the coupling factor from being higher.

Early Dielectric Ring Coil Transformers (I)





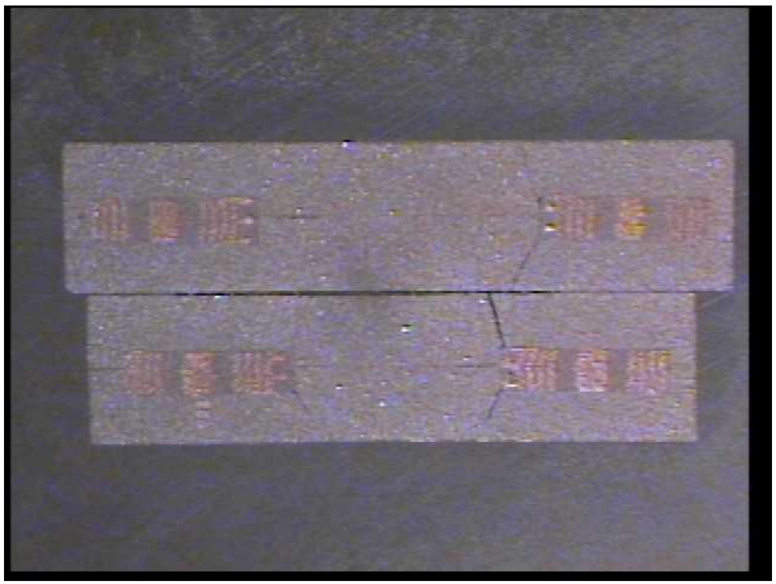
Need to optimize:

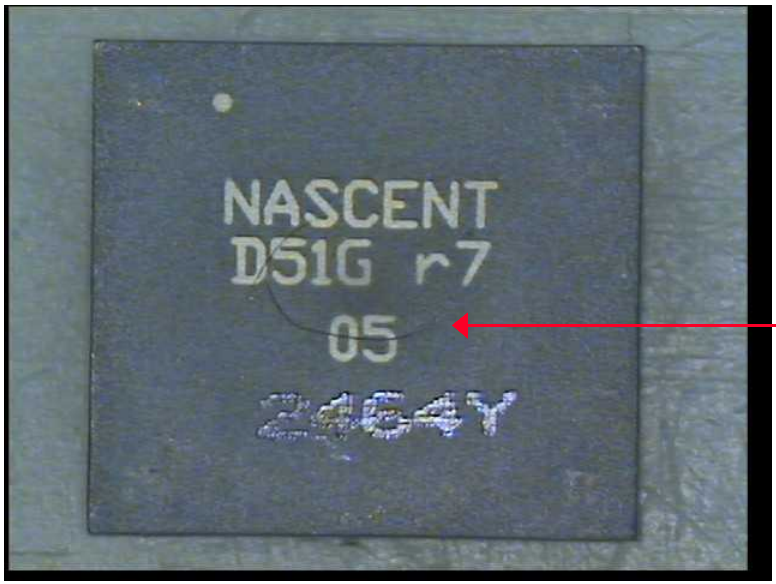
- **Clearances**
- **Pocket Depths**
- **Burn out profiles**

Use a router for singulation

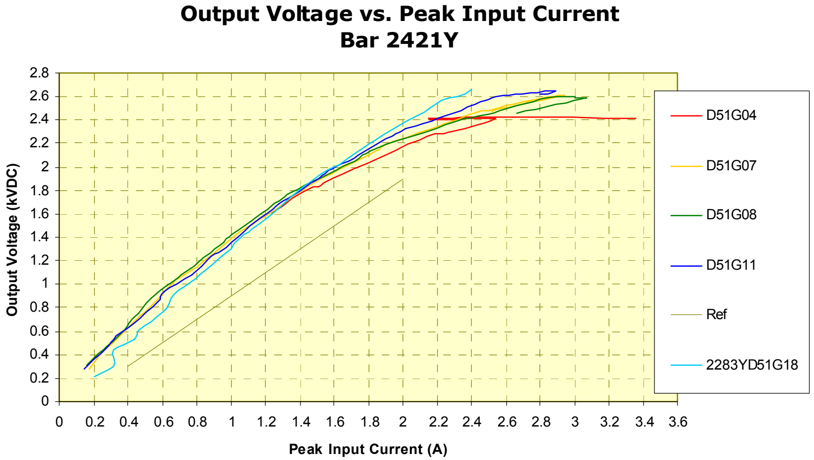
Early Dielectric Ring Coil Transformers (II)

- **When using a router to singulate the parts instead of razor in combination with extended burn out times, cracking improved.**
- **There was still cracking in the central core/gapped region, which lowered the inductance and decreased coupling from its highest potential.**



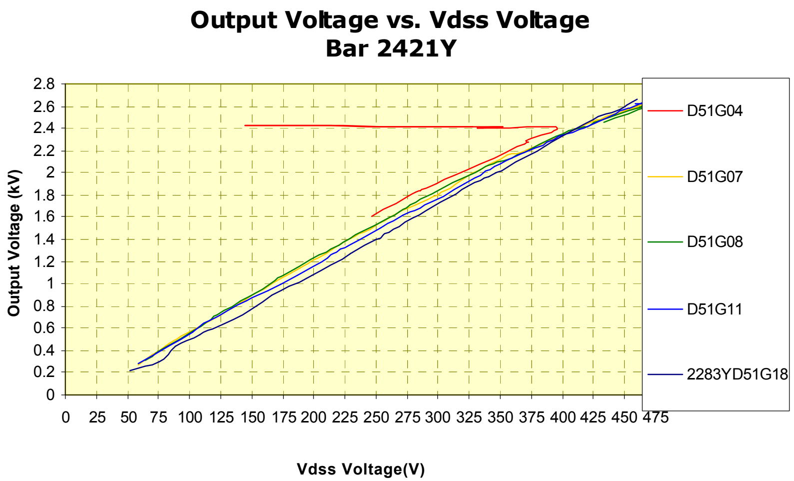


Early Dielectric Ring Coil Transformers (III)



Output voltage for dielectric ring coil design is higher than the traditional design (2283) up to about 1.4 A drive current then becomes worse.

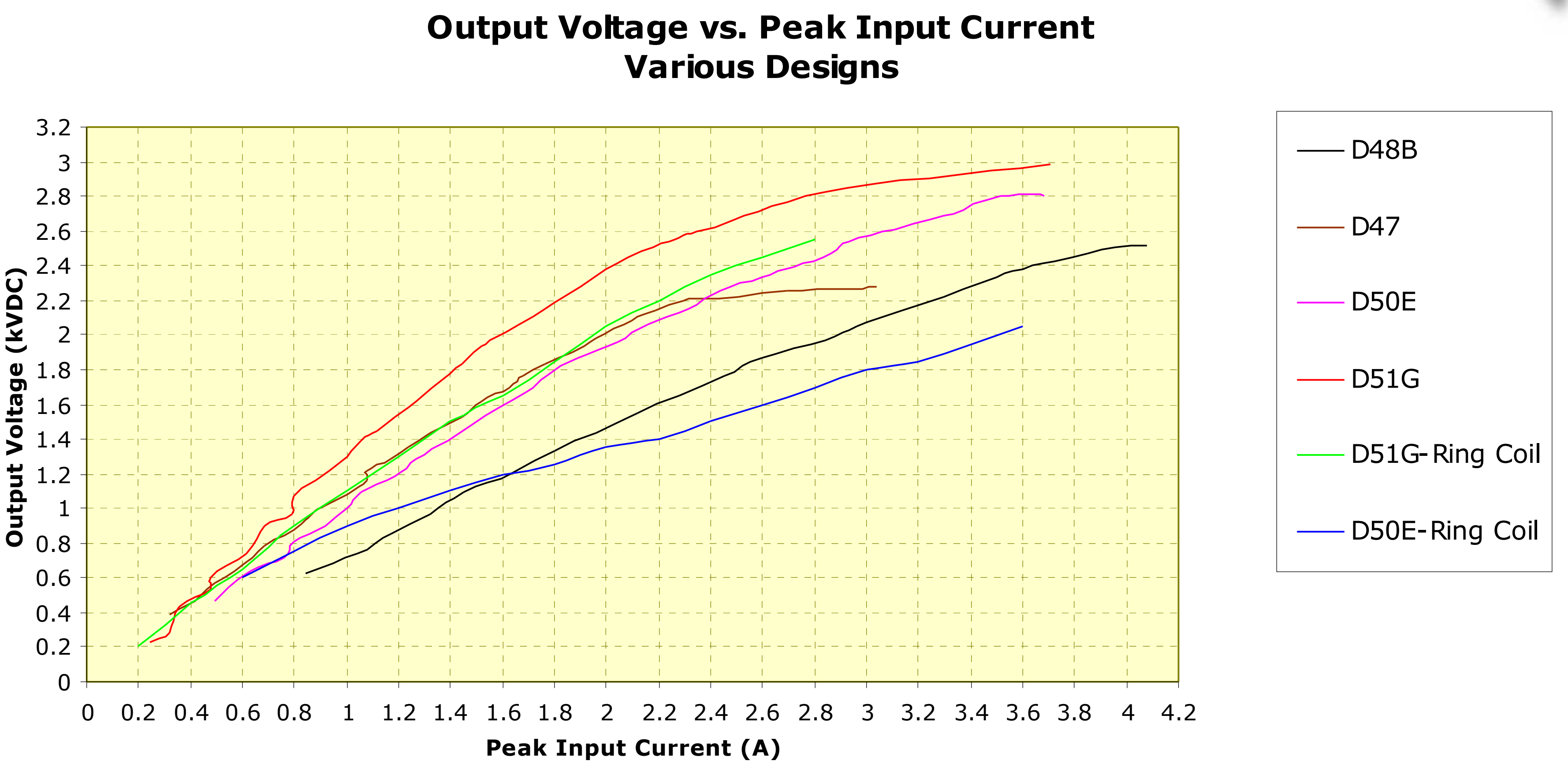
This is due to saturation in the core endcaps because the the leakage path through the coil region is decreased.



Voltage stress was lower for the novel dielectric rign coil design. This is due to the increased coupling (lower leakage inductance).

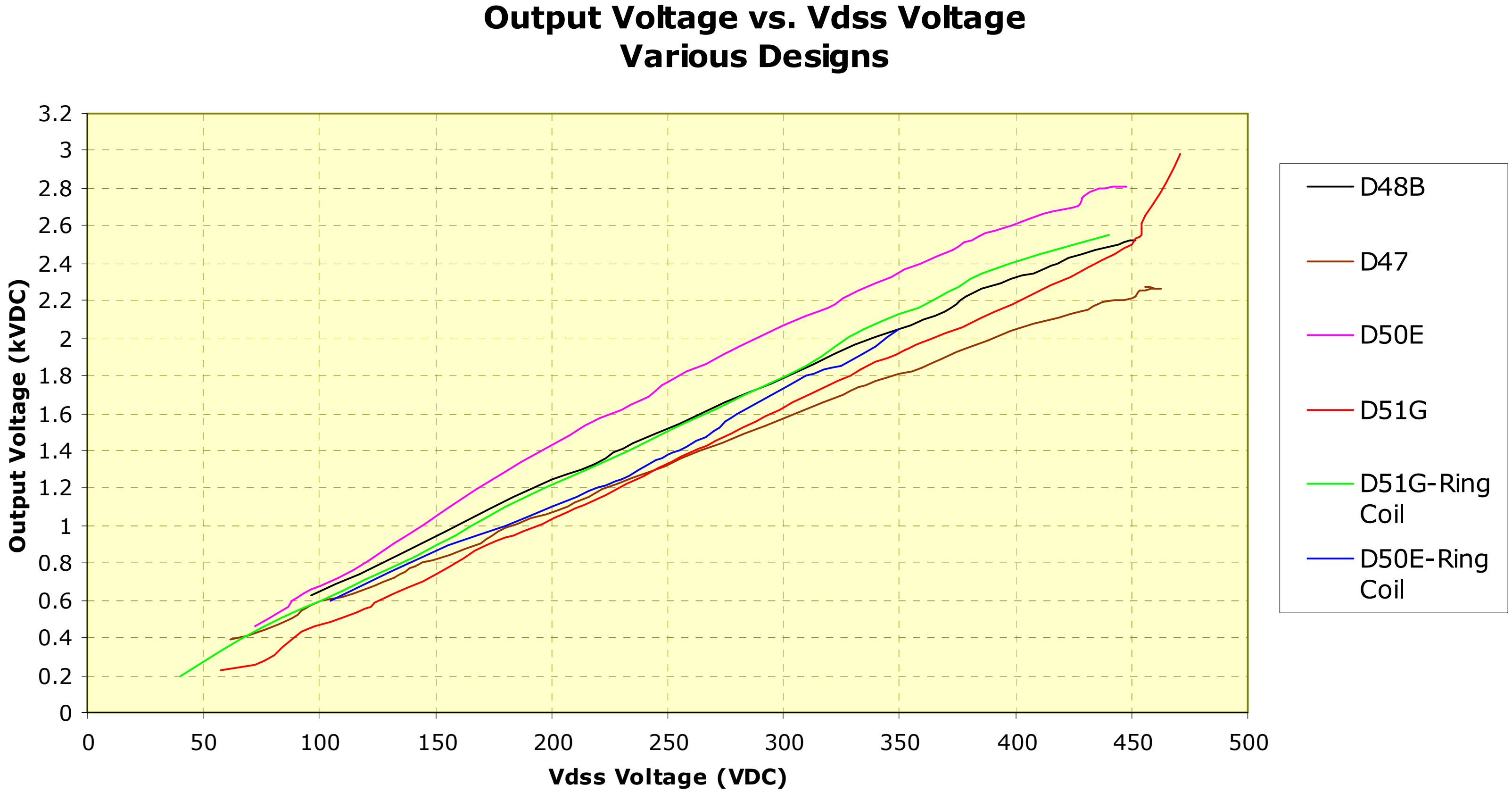
0.94 vs 0.8 (G design only – highest output capability)

Comparison of Designs: Output Voltage



Both D50E and D51G ring coil transformers had lower outputs compared to traditional LTCC transformers.

Comparison of Designs: Vdss



The D51G ring coil transformer had lower voltage stress compared to traditional design because of improved coupling. D50 ring coil was worse.

Dielectric Ring Coil Transformer Process Studies (I)

- After the first few panels of dielectric ring coil transformers, effort was placed on trying to minimize cracking and improve yield.
- Concentric cracking
  - The pocket for the ring coil was increased in size to increase clearances to try and decrease stress at the coil/central core interface.
    - Cracking did not improve. Still had concentric cracking.
    - Many more opens in the coil connections possibly due to increased misalignments from larger pocket.
- Separate central leg/gap slug
  - Instead of routing the central leg and end cap as one peice, route two separate pieces. The hypothesis is that this would relieve stress during stackup and burn out.
  - The result was end cap cracks were still occuring at the same places and numbers.
  - Edge cracks improved due to less voiding. This might be due to a more symmetric assembly for the stack up.

Dielectric Ring Coil Transformer Process Studies (II)

- Dielectric paste for gaps instead of tape
  - It is hypothesized that the large volume of unconstrained ferrite in the center leg and the dielectric ring coil have uneven shrinkage rates (although final CTE's are matched well) cause stress thus leading to cracking.
  - Cracking was no better than the previous sample
  - Another sample was run with higher air flow in the firing ovens with improved cracking.
    - No edge cracking observed. Probably because only ferrite layers at the edge.

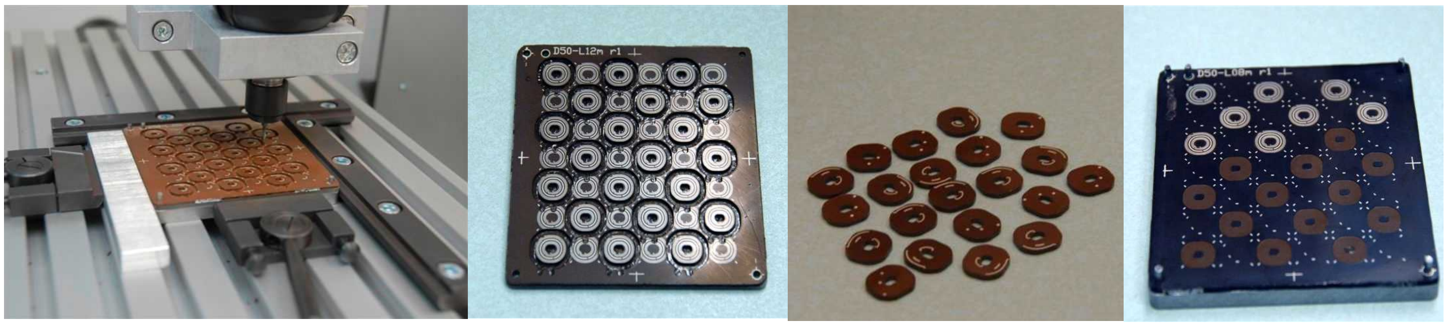
Dielectric Ring Coil Transformer
Future work to be Considered

- Some process improvements have been made but much work has yet to be done. Some things to try:
  - Press all parts in well fitted dies.
  - Consider firing the coil separate from the core.
  - Study the endcap thickness on cracking.
  - Use a separate pressed ferrite margin with routed holes for the coil. Use loose end cap layers.
  - Different burn out parameters.

LTCC Summary

- LTCC work started 5 years ago has produced a manufacturable 1500 V solution for DoD applications.
- D51 size has demonstrated an increase in output votlage and voltage stress per Amp of drive current than previous smaller design. This is due to increased leakage inductance.
- The material properties at elevated temperature shows signs of degradation. This should be studied in depth.
- The dielectric ring coil transformer shows promise in the increased coupling factor (lower leakage inductance) at the expense of output voltage when compared to the traditional D51 designs.
- Further process/design development on thicker LTCC dielectric ring coil parts might combine low leakage inductance with higher outputs.

Dielectric Ring Coil Diagram



Route Coils

Coils

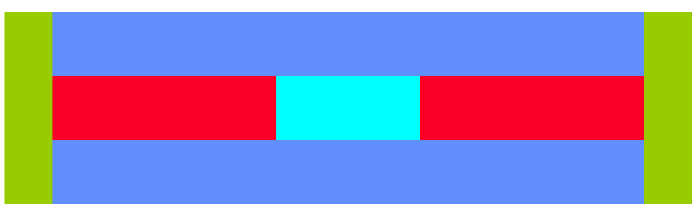
Coils in Routed Ferrite Margins and/or endcaps

Coils

Endcaps

Central Core

End Margin



Pocket depth is the height for the coils to drop into the routed out ferrite endcap/end margin.