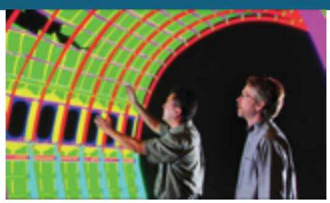
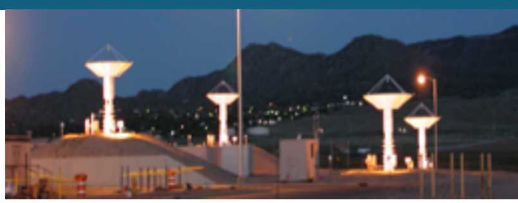
Sandia National Laboratories

SAND2019-5969PE

Sandia's Digital Twin: Dielectric Strength Experiment (DSE) Component





PRESENTED BY

John Emery

Team: Coleman (co-PI), Boyce, Bucy, E. Carroll, J. Carroll, Conroy, Ford, Grisham, Haskins, Lam, Long, Lovejoy, Moore, Noell, Olson, Pressly, Reedy, Roach, Rodriquez, Strong, Swiler, Tupek, and others (sincere apologies if I missed someone)

PM: Reno Sanchez

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Sandia's Digital Twin (DT) Effort: An Overview

30,000': Sandia is developing digital twin technology. The long-term goal is to develop high-fidelity prognoses on a per-serial-number basis for as-built, as-deployed systems and the associated tools and capabilities to support it. The prognoses will integrate systems models, computational simulation models of varying fidelity from reduced-order to high-fidelity, including multi-scale, multi-physics, aging and environments, and all available data from physical simulation, development and production builds, and remote sensing and non-destructive evaluation (NDE). The prognoses are necessarily statements about the probability of future performance.

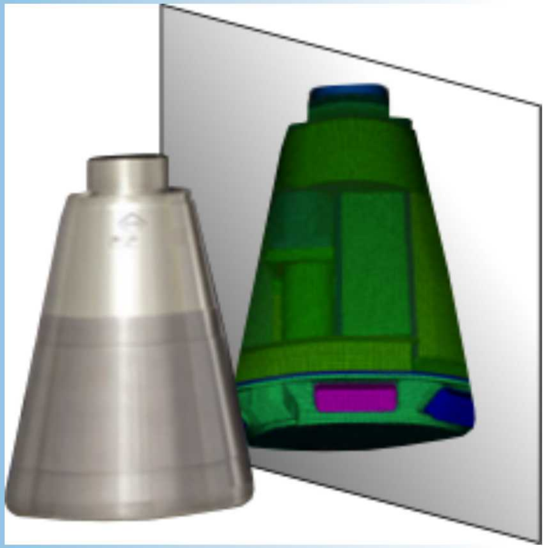
15,000': Among our present focuses, one line of investigation is considering a component that is subject to dielectric breakdown. Breakdown has been studied to various extents but models to predict it based on manufacturing defects do not exist. Further, it is not known how or if materials aging affect the associated uncertainties.

Ground level: Our present effort is developing a discovery experiment to emulate dielectric breakdown. The experimental "component" design will follow the digital twin paradigm for the entire "life" of the component, from feasibility through end of life (breakdown measurement). Our dielectric strength experiment (DSE) component will include 4 design variants: defect free, small delamination, large delamination, and non-planar defect. The defects are intentionally added with a controlled indentation technique. We are combining model-based systems engineering concepts and software, with CAD models, with mesh generation tools, and with finite-element analysis for component prognosis. We are collecting x-ray computed tomographic measurements to inform the models about the size and shape of existing manufacturing defects with a high degree of certainty. And we will be predicting the performance (dielectric strength) of the DSE based on as-built properties. A second round of DSE experiments will explore aging effects.

Digital Twin: Long Term Vision

Sandia's DT provides accurate, multi-physics-based prognosis

- Integrated hierarchy of increasingly complex models including precise as-built details, e.g. geometry and materials properties
- Assimilates data from surveillance, sensing and non-destructive evaluation ("physical twin")
- Statistically accurate materials and manufacturing data
- Multiscale, multi-physics, probabilistic prognosis
- Prognoses for all environments plus aging
- Serial-number specific



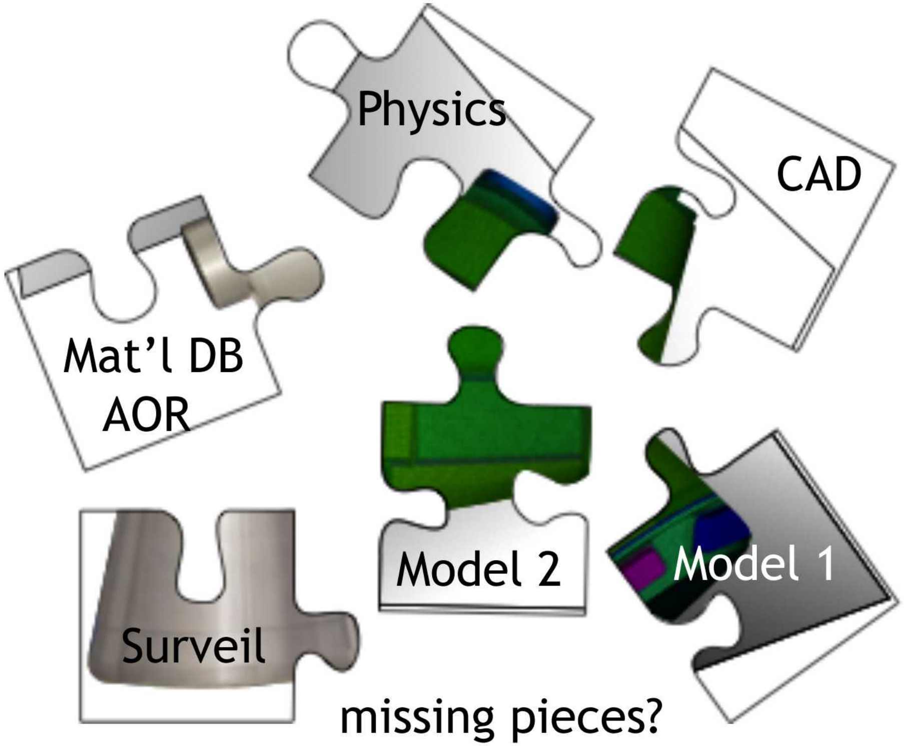
Revolutionary outcomes for design, assessment and lifetime:

- Enables agility for mission responsiveness
- Helps modernize the surveillance program
- Reduces development cycle time
- Transforms the annual assessment activities
- Predicts Significant Findings Investigations (SFIs)
- Provides a virtual environment to evaluate future weapon systems and features (CONOPS)

Transforms business operations

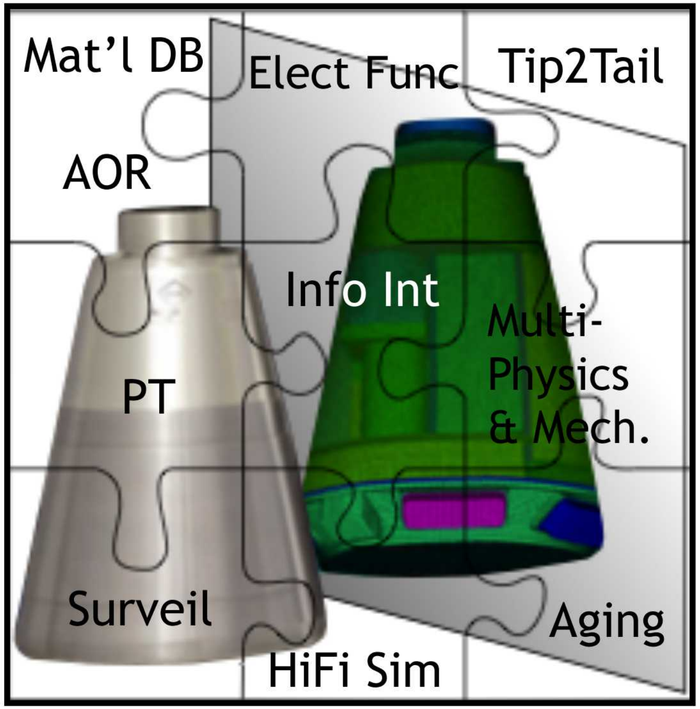
Business Today

- LEPs & ALTs use disconnected, single-physics models starting late in development
- Annual Assessment is largely test based with comp sim playing a supporting role in SFIs or addressing focused knowledge gaps
- Lessons learned are transferred via the technical library or word of mouth

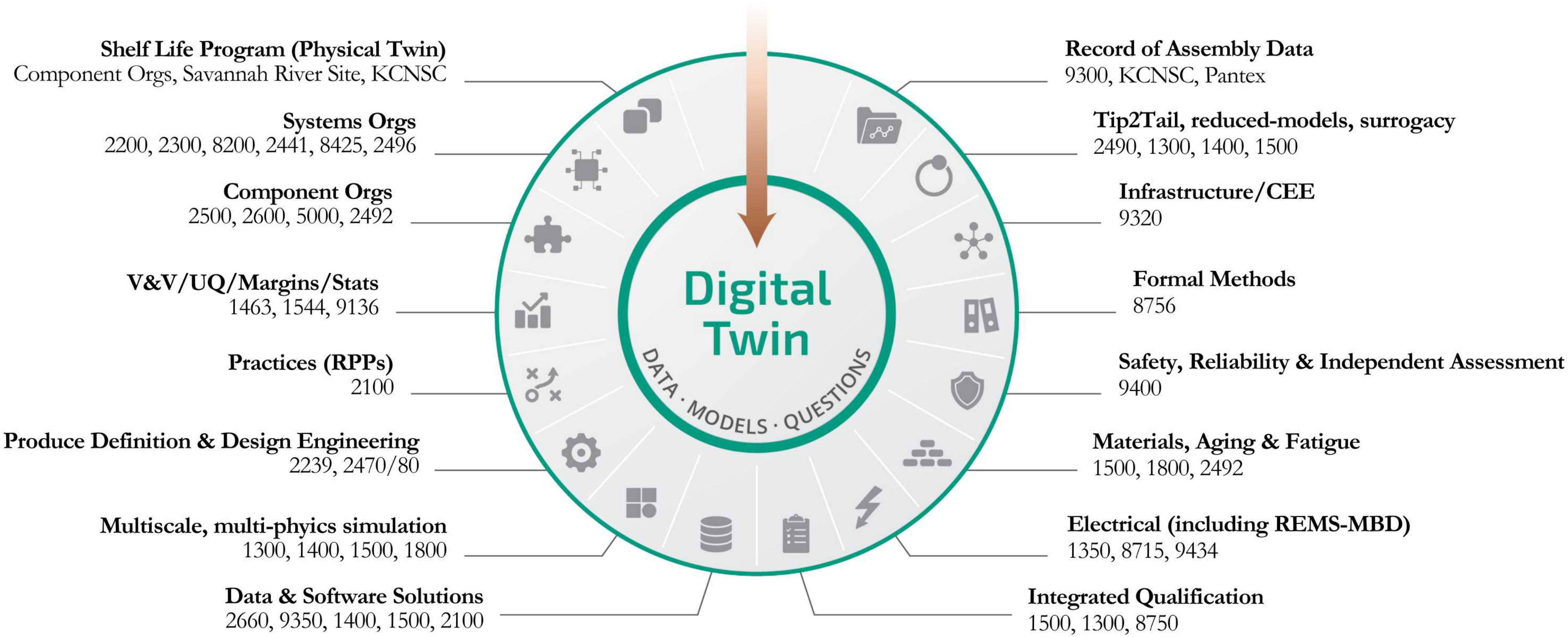


Business w/ NWDT

- Integrated information connecting multiscale, multi-physics models with data from surveillance and physical surrogates
- High-fidelity prognosis with physics-based, mechanistic underpinnings
- Connected physics and engineering models
- Leverages surveillance activities for physical surrogacy (a physical twin, PT)



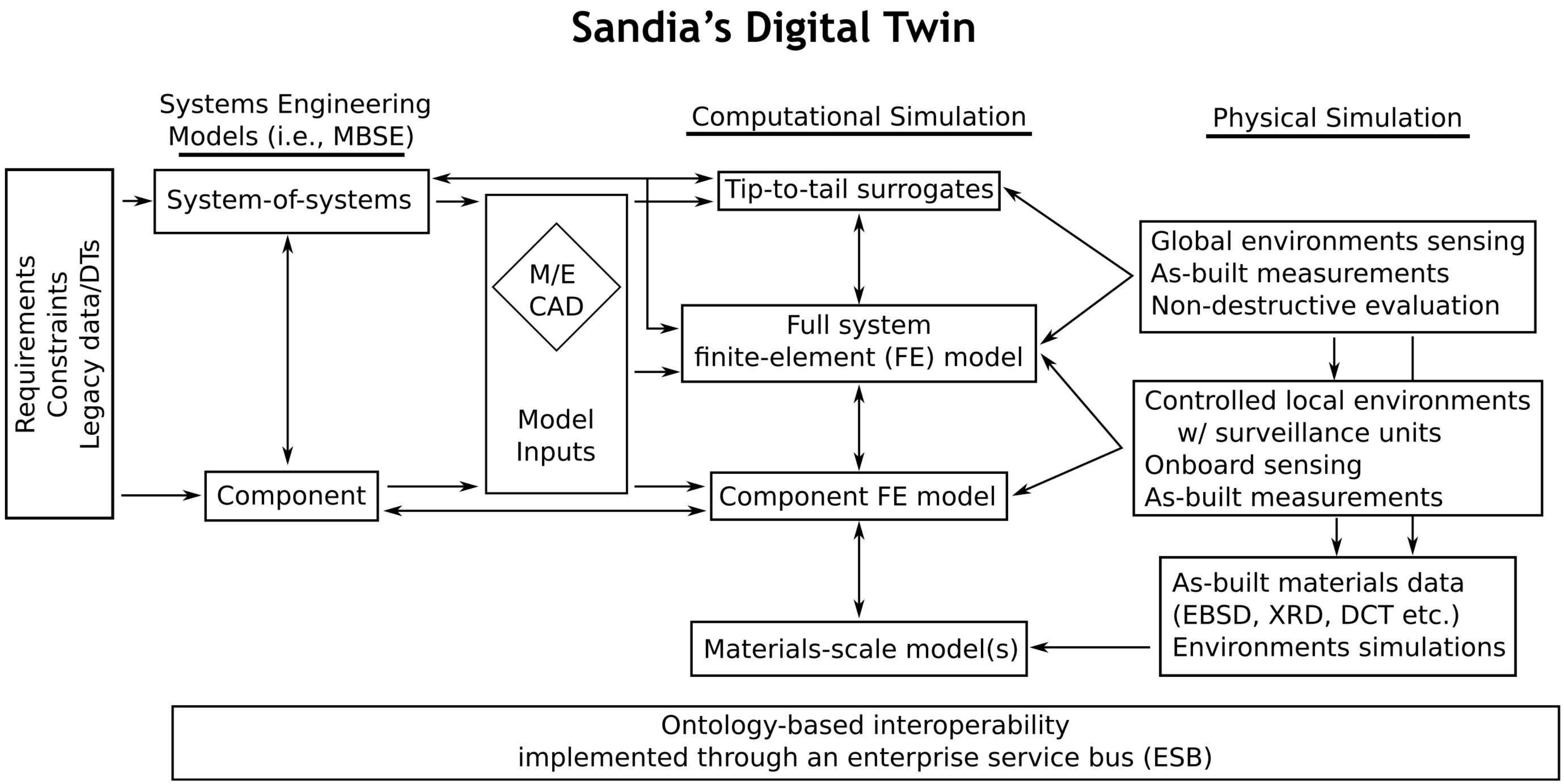
Digital Twin Engagement



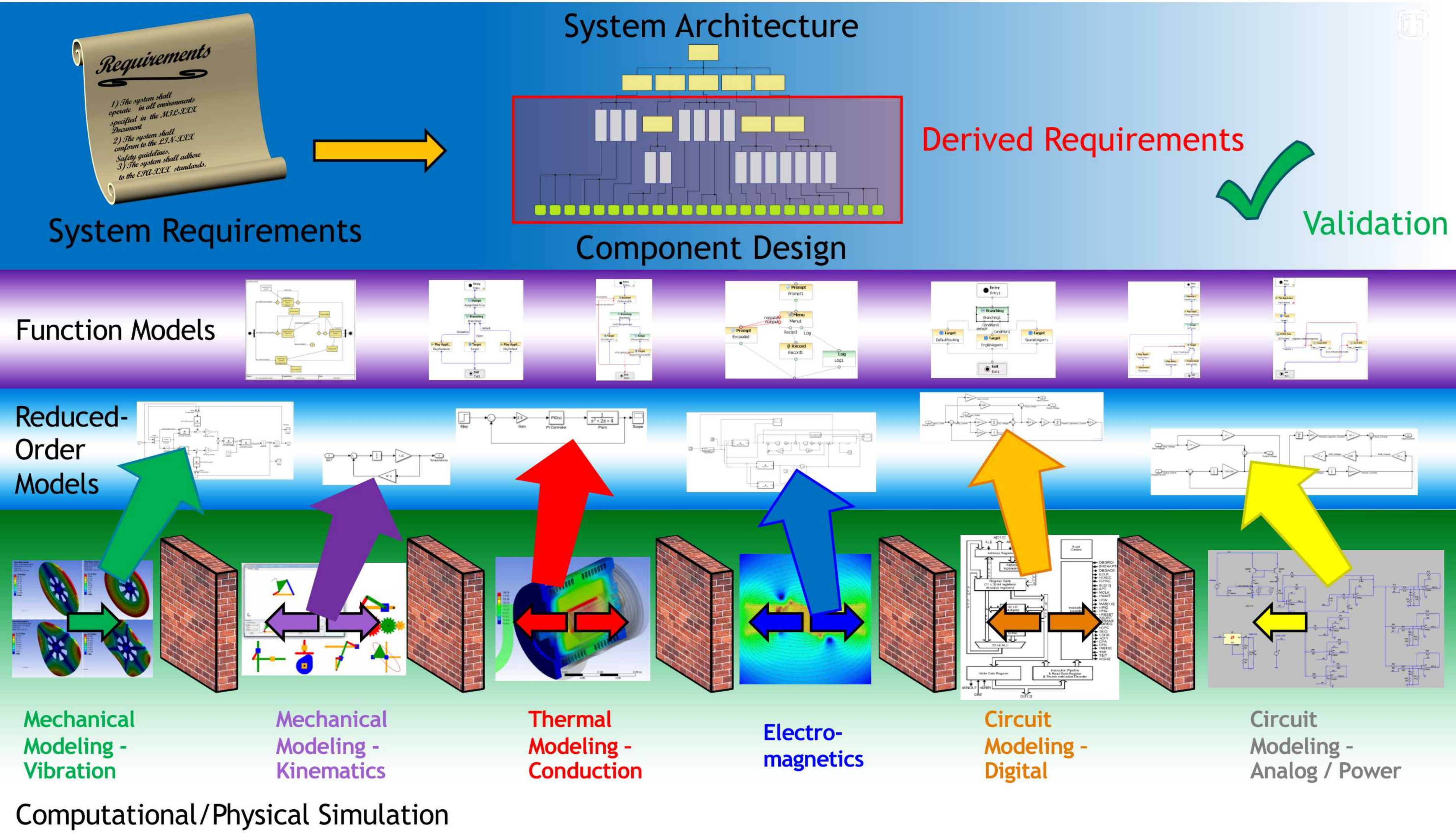
A Digital Twin is a collaboration platform across the laboratory, which **engages our people**.

We seek to transition from a document-based process to a **model-based process,** creating a working system for storing and integrating computational simulation models, physical simulation data, and systems engineering information.

Implementation



The DT relationship between MBSE and Simulation



slide & Tip2Tail ROM modeling effort by: Erik Olson

FY19 Details: Dielectric Strength Experiment (DSE) Component

We are developing an experiment to investigate dielectric breakdown, which will have a simplified geometry and relevant materials. The experiment will include an indentation technique that adds a "controlled" surface delamination to simulate a manufacturing defect. We will then characterize the defect with CT, and test the dielectric strength and compare to nominal strength.

For development and motivation, we will treat this like a digital twin (DT) / physical twin (PT) pair.

Objectives of/questions for the experiment:

1. Design a test specimen that allows us to determine how well uCT can characterize manufacturing defects in electrical encapsulants, e.g., delamination.
2. Design the test specimen so that, following the uCT scan, we can measure its dielectric strength (and measure apparent strength of nominal design).
3. Can we use this to develop a relationship between measured defects size/shape and dielectric strength? Can small-signal capacitance describe damage (perhaps by inverse methods)?

Our testing procedure will span a series of defects, varying in size and shape, and identify a limiting size/shape detectable via CT and develop the relationship between dielectric strength and defect size/shape.

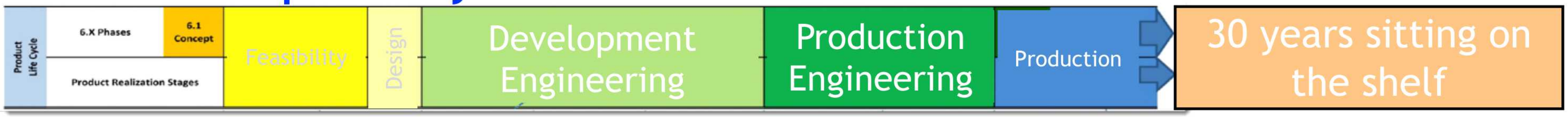
Our tests are designed to span a wide variety of applications.

Our tests shall be designed to remain in the appropriate range of voltages (appropriate for available strength tester).

Next steps: we will repeat the experiments with artificial aging to explore age effects.

DSE Component – A simple component to learn from

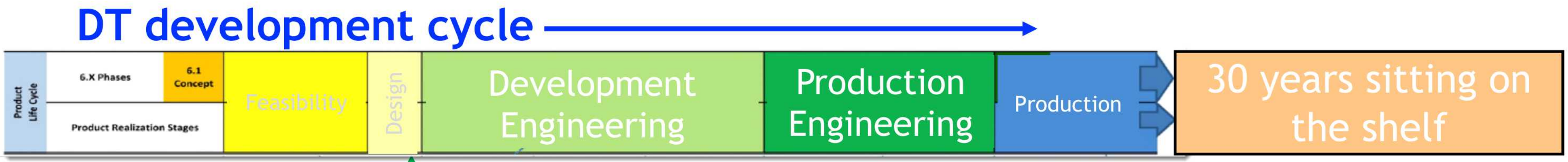
DT development cycle

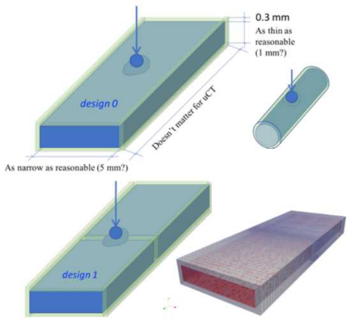


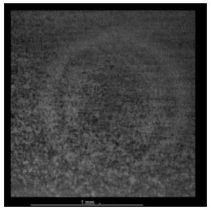
Steps:

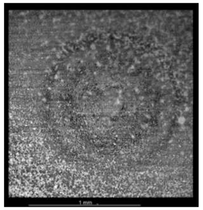
1. Write "systems requirements"
2. Build the systems model (GENESYS)
3. Develop design, e.g., M/ECAD models of the proposed geometry/geometries
4. Develop capabilities to connect SM w/ CAD w/ computational simulation (CS)
5. Demonstrate requirements verification via the SM-> CAD-> CS-> SM workflow. For example, encapsulation shall have no surface flaws greater than 1 mm – Verify via encapsulation simulations estimating residual stress in the epoxy.
6. Iterate 1 – 5 to design the experiment
7. Collect uCT measurements to characterize the manufacturing defects
8. Incorporate the defects into the CS models
9. Compute serial-number specific predictions of strength
10. Measure strength

DSE Component – A simple component to learn from

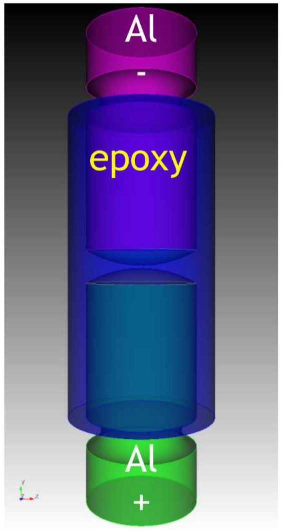








We're here



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Requirements of the test & test specimen

Includes relevant materials

- Encapsulants:
  - EPON epoxies
- Substrates:
  - Alumina
  - Polyamide coated copper

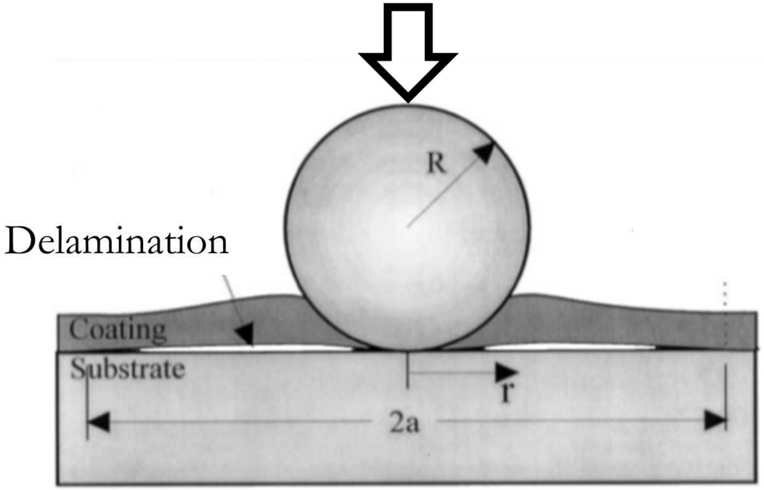
Controllable delamination size

Suitable for uCT (i.e., fits in the test apparatus)

Suitable for simple dielectric strength tests (future could include in situ temp / mechanical / rad insults?)

Encapsulation stresses reasonable to avoid cracking

Indentation for a delamination at an epoxy/electrode interface

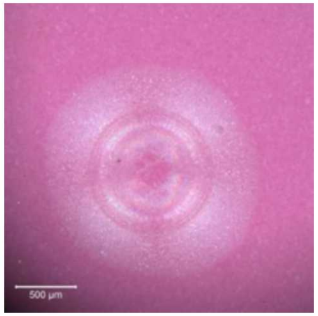


In theory, delamination forms outside of contact area.

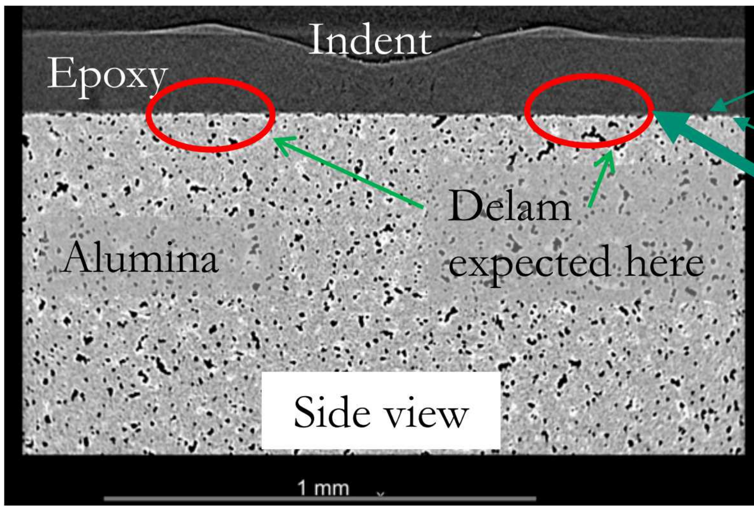
Can we measure size of delamination using X-ray tomography?

Controlled delamination size/shape allows us to validate the uCT measurements. Once we have validated the measurement, controlled delamination size/shape is not necessary but may still be desired.

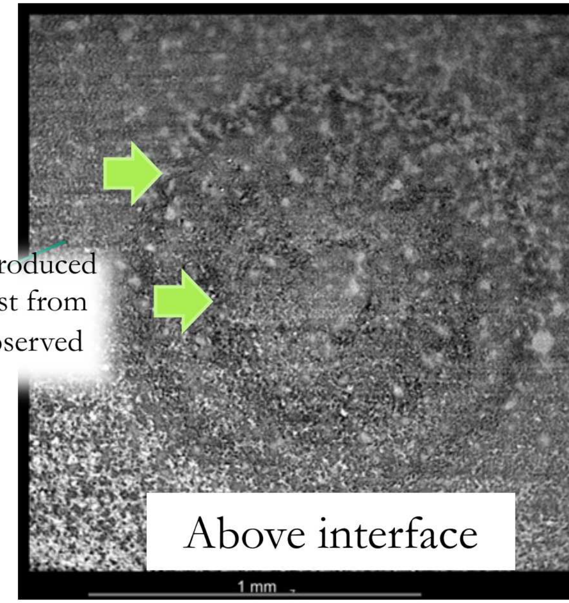
Philip's preliminary results: Phase contrast tomography



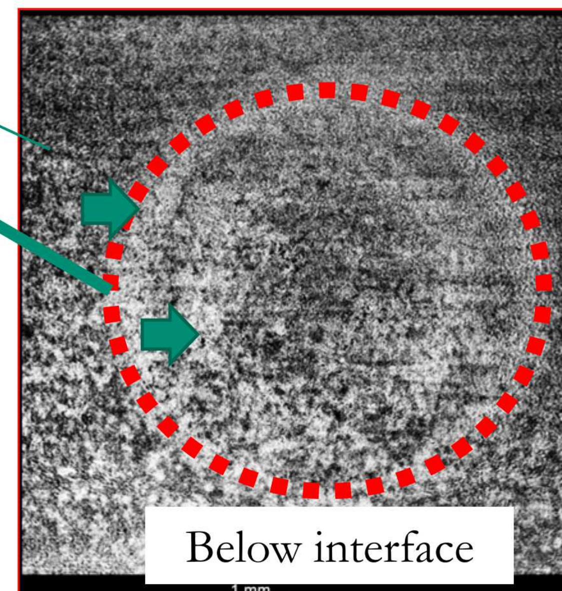
- Mockup with delamination similar to the pictured sample scanned using phase contrast tomography
- Unlike conventional X-ray tomography, which is based on differences in absorption for contrast, phase contrast highlights interfaces in the material



Top down views



"Rings" likely produced by phase contrast from delamination observed at the interface.

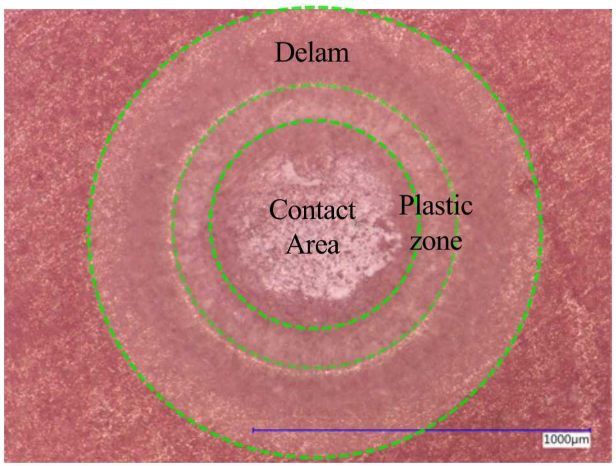


Early findings: It looks promising that we can detect the delamination and measure it for <u>unfilled epoxy & alumina</u> using X-ray CT!

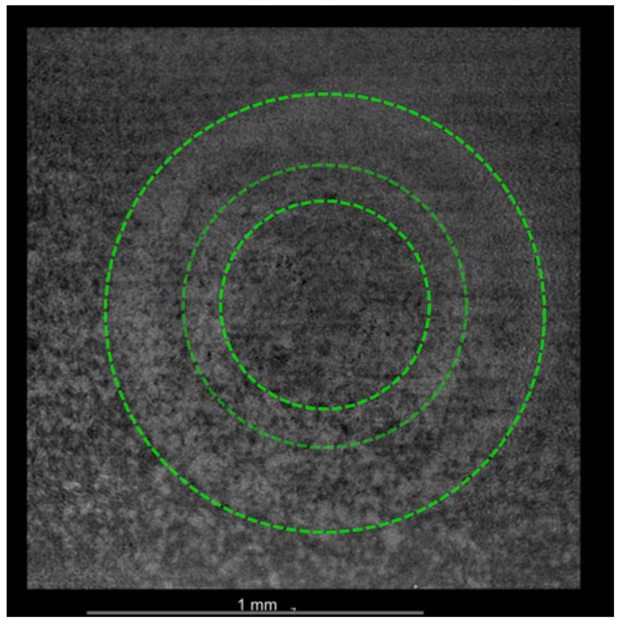
Comparing optical and X-ray tomography measurements

For <u>unfilled epoxy and alumina</u> using X-ray CT!

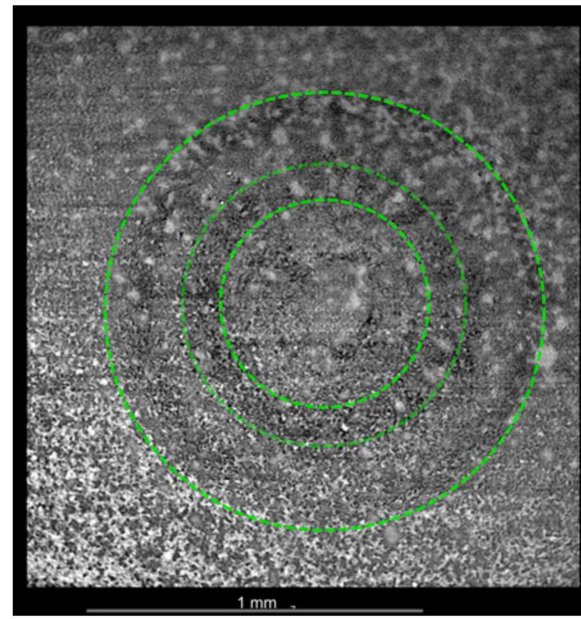
Optical image of indented Alumina/Epoxy sample



X-ray tomography data of indented Alumina/Epoxy sample (slice above alumina/epoxy interface)



X-ray tomography data of indented Alumina/Epoxy sample (slice below alumina/epoxy interface)



**All images at the same scale

- Measurements from optical indicate that the delamination is 248 μm wide ± 10 μm
- Measurements from X-ray CT indicate that the delamination is 233 μm wide ± 18 μm

Specimen Design Schematics

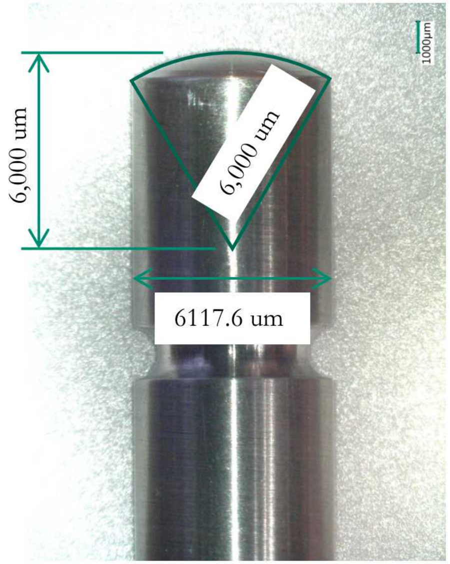
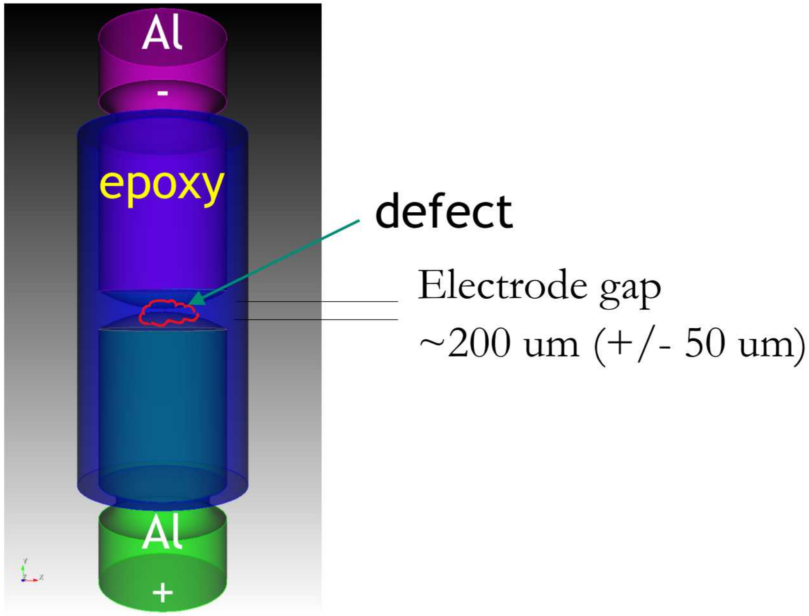


image of aluminum electrode



design 4

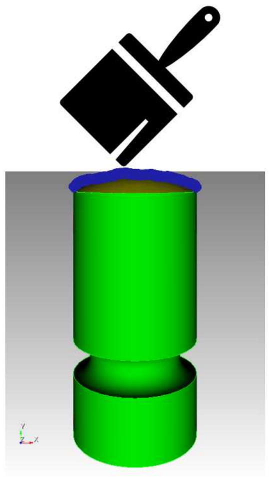
The specimen design ideas requires a _validated_ uCT capability. Note that Al has a higher z-number than alumina, so that the uCT measurement will be harder.

Defects may be achieved by incremental manufacturing:

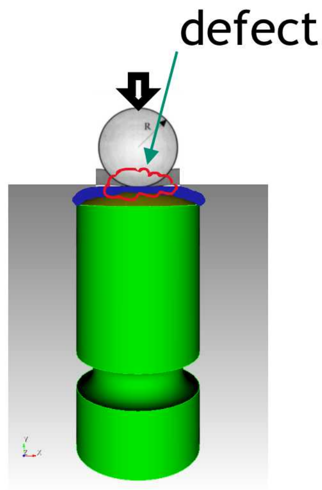
1. Fingernail paint epoxy on Aluminum electrode
2. "Insert" manufacturing defect, *e.g.*, by indentation
3. Encapsulate within greater electrode assembly

Other ideas: can the manufacturing defect be inserted by a mechanical loading of the electrodes? For example, picture applying a tensile load to electrodes.

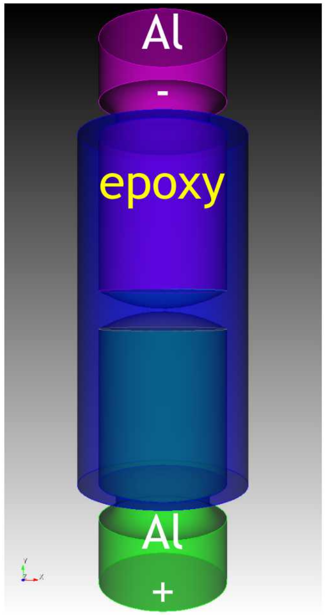
How do we build it



1. Build-up an epoxy layer with paintbrush



2. Add "defect" with indentation experiment



3. Encapsulate the full specimen

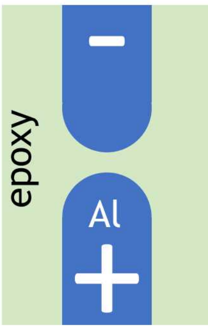
Notes:

1. Assume a cylindrical specimen.
2. Build a set of samples skipping step 2 to understand the dielectric strength of the undamaged part that was manufacture in the multi-step epoxy curing process.

Experiments

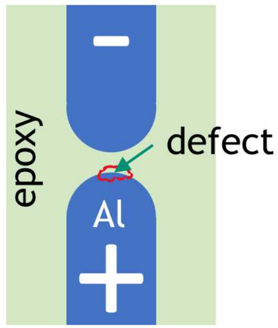
Initially, we will have a series of 4 experiments w/ 2 repeat samples in each category. Here are the proposed experiments:

Experiment #1



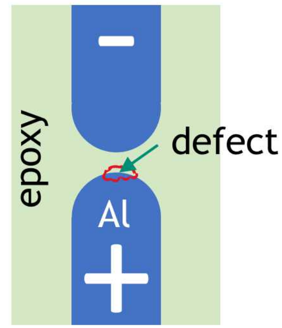
2 experiments, defect free

Experiment #2



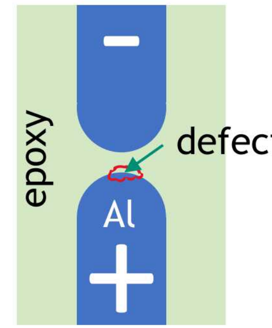
2 experiments, defect at P N indentation force

Experiment #3



2 experiments, defect at 2P N indentation force

Experiment #4



2 experiments, defect at P N indentation force, different shape indenter

Hopefully experiment #1 is a fairly repeatable measure of the inherent dielectric strength of the epoxy. Experiments #2 and #3 give us data to plot strength versus defect size (assumes defect size scales with indenter load). Experiment #4 explores effects of defect shape (assumes some way of normalizing defect size/shape based on indenter load).

Breakdown calculations

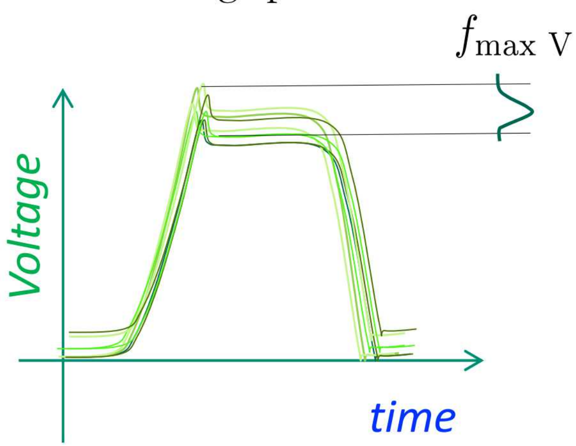
INPUT:

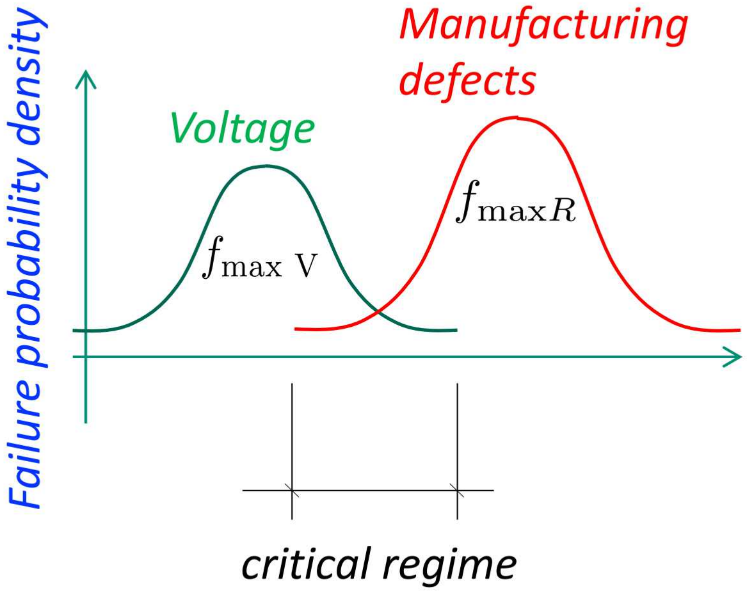
- Mesh/geometry/void /flaw description
- electron/neutron chemistry
- Outgassing in void
- Relative permeabilities
- Particle BCs at surfaces
- Voltage profile

→ **Aleph/EMPIRE (transient analysis)** →

OUTPUT:

- Energy flux, current to outer casing / wall
- Electron density
- Temperature





*** Figures are notional

Breakdown FE model

The first model for dielectric breakdown will be a 45-degree wedge containing a 1-um radius, semi-spherical pore at the tip of the bottom (positive) electrode.

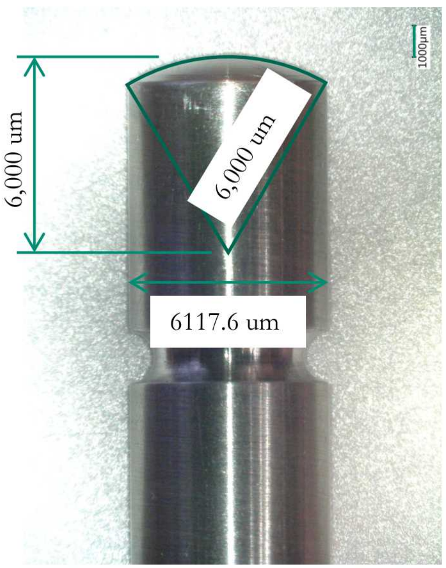
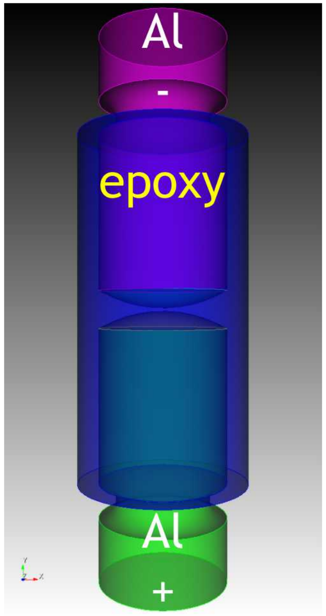
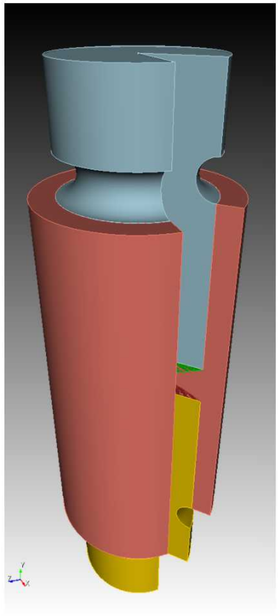


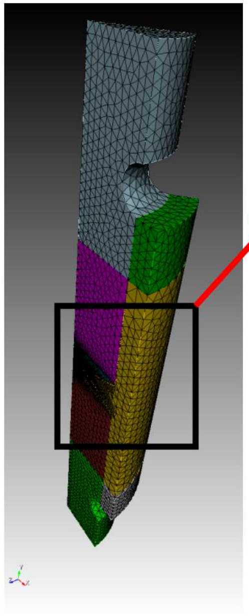
image of aluminum electrode



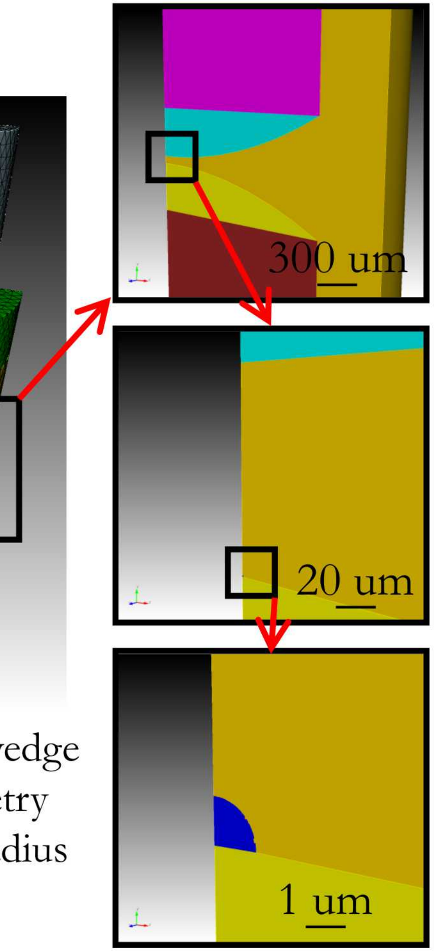
solid model



remove this part



45-degree wedge with symmetry and 1 um radius pore



Summary

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We are collecting x-ray computed tomographic measurements to inform the models about the size and shape of existing manufacturing defects with a high degree of certainty.

We will be predicting the performance (dielectric strength) of the DSE based on as-built properties. A second round of DSE experiments will explore aging effects.

Blank

Dielectric strength measurements

JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 5 1 MARCH 2002

Effects of void size and gas content on electrical breakdown in lightweight, mechanically compliant, void-filled dielectrics

R. A. Anderson,[a] R. R. Lagasse, E. M. Russick, and J. L. Schroeder
Sandia National Laboratories, Albuquerque, New Mexico 87185

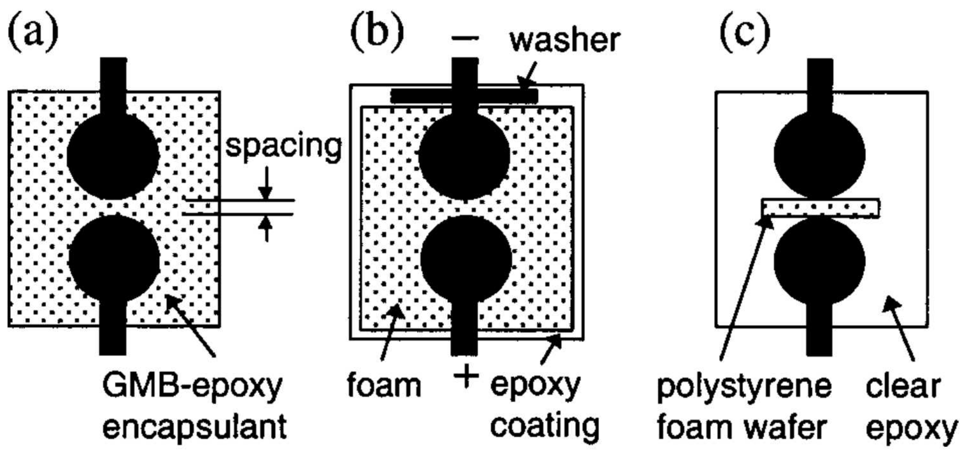

FIG. 4. Test specimens used to measure breakdown strength: (a) 12.7 mm diam spherical steel electrodes cast in GMB-filled epoxy. (b) Similar electrode arrangement, used with the gel-derived and urethane foams, which includes an epoxy coating to exclude the dielectric liquid in the high-voltage test chamber. A field-shielding metallic washer was needed with the gel-derived foams to prevent breakdown along the foam/coating interface. (c) Wafer of CO_2-blown polystyrene foam, in contact with the electrodes, cast in clear epoxy.

Dielectric strength measurements

JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 9 1 MAY 2002

Pulsed electrical breakdown of a void-filled dielectric

R. A. Anderson,[a)] R. R. Lagasse, and J. L. Schroeder
Sandia National Laboratories, Albuquerque, New Mexico 87185

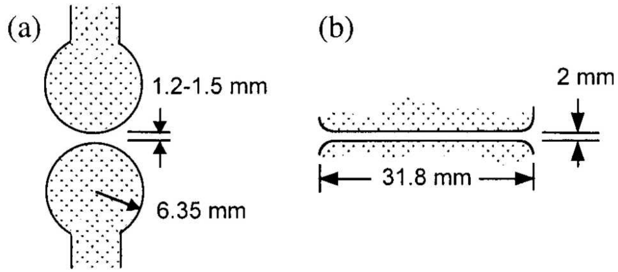

FIG. 1. Uniform-field electrode geometries: (a) 12.7 mm diam spheres. (b) Electrode geometry which produces uniform electrical stress in a volume of approximately 1400 mm^3.

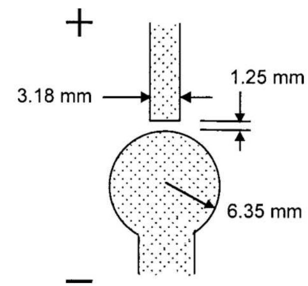

FIG. 2. Electrode geometry which produces local regions of concentrated electrical stress. The peak field at the edge of the square-cut cylindrical anode (with an edge radius of curvature of approximately 30 μm) is roughly three times as large as that along the gap centerline. In a second set of similar test specimens the diameter of the square-cut cylinder was 6.35 mm.

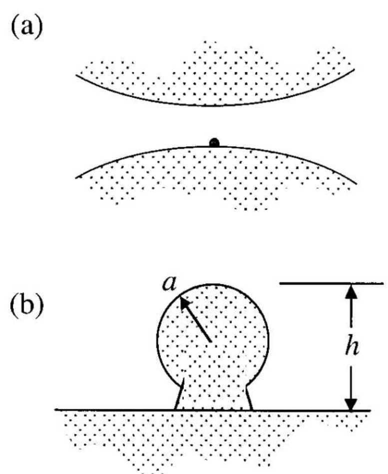

FIG. 3. Spherical-electrode geometry with a small conductive protrusion on one electrode: (a) sketch of the 12.7 mm diam spheres showing a protrusion, (b) closeup of the protrusion which defines its height, h, and tip radius, a.

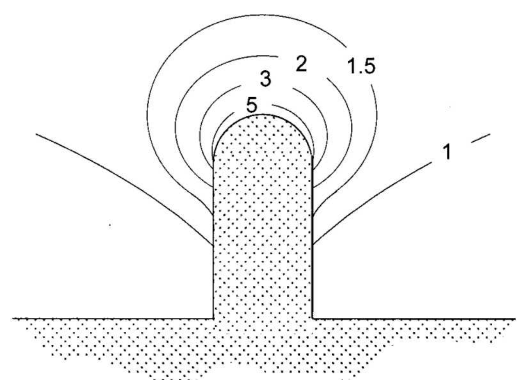

FIG. 4. Computed field-magnitude distribution near the tip of a dome-topped cylindrical protrusion on a conductive surface with $h/a=4$. Numbers on the contours indicate the local field magnitude relative to the uniform field further away. The ratio reaches 6.3 at the protrusion tip, which is close to the Eq. (1) prediction of 6.0.

Residual stress in epoxy are manageable