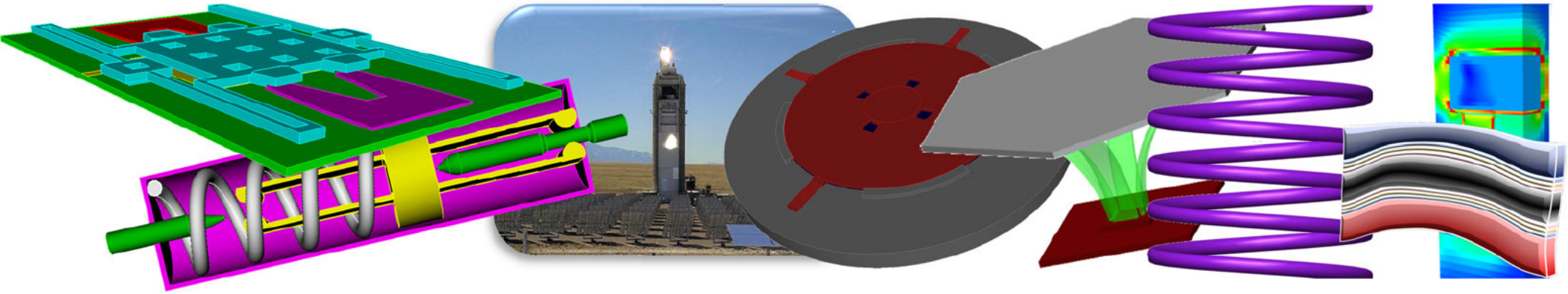
SAND2016-6800PE

Exceptional service in the national interest

Sandia National Laboratories



Uncertainty-enabled Thermal Stress Management of Engineered Multilayered Structures

Drs. Jordan E. Massad & Robert J. Kuether

Sandia National Laboratories
Albuquerque, NM

Raleigh, NC
July 19, 2016

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

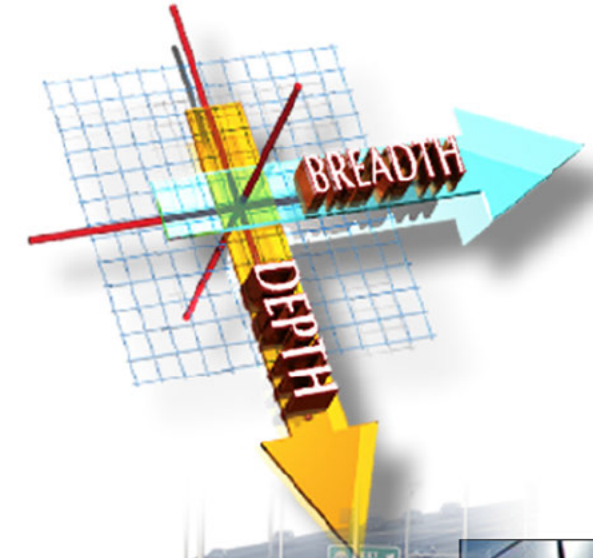
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corpora ion, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

- Core Purpose: **help our nation secure a peaceful and free world through technology**.
- Provide objective, multidisciplinary technical assessments for complex problems.
- Focus on solutions with large science and technology content.
- Create prototypes for subsequent production and operation by industry.

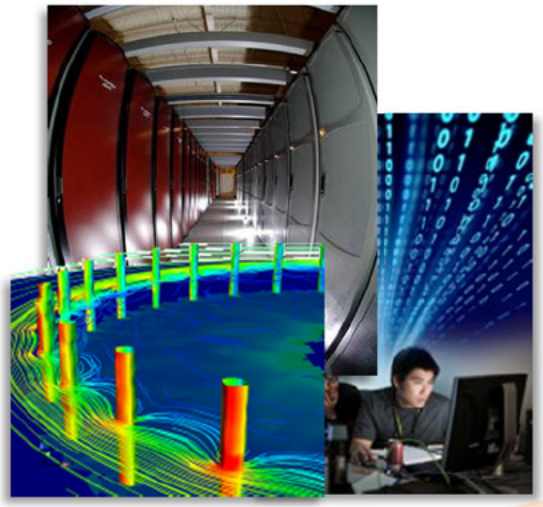
U.S. DEPARTMENT OF ENERGY

Scope & Complexity of National Security

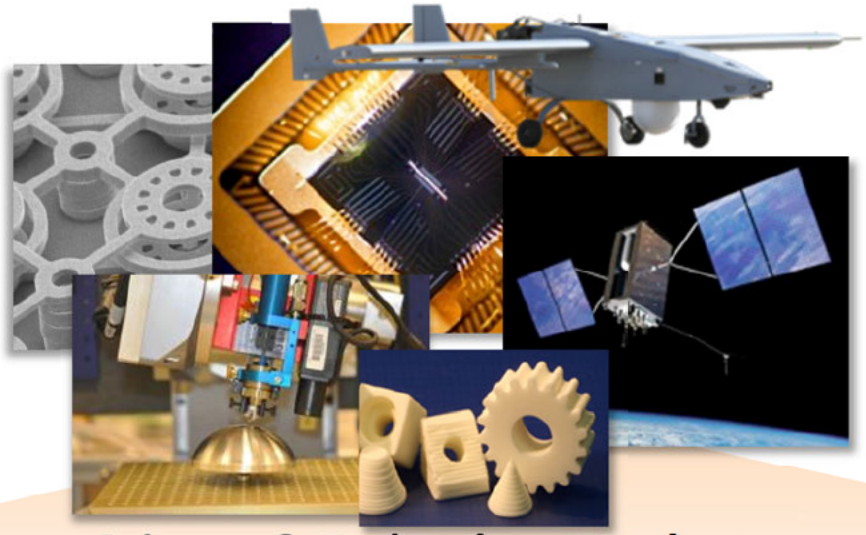


SNL Applies both BREADTH & DEPTH to solving our nation's most challenging problems.

Research Disciplines Drive Capabilities



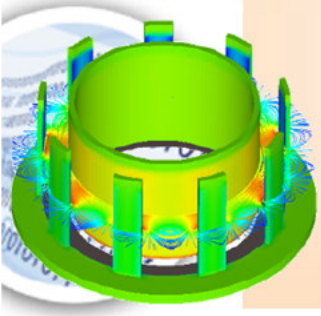
High Performance Computing



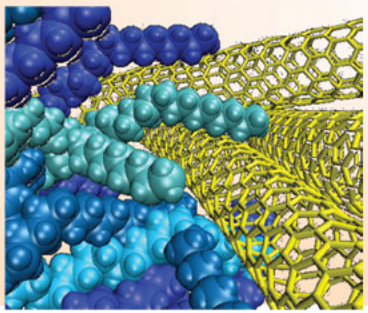
Science & Technology Products

Renewable Systems & Energy Infrastructure

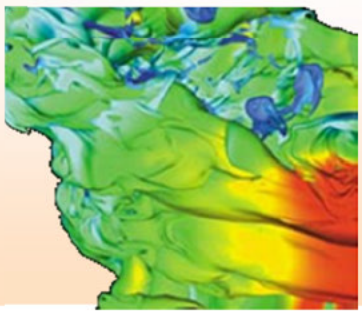
Computer Sciences



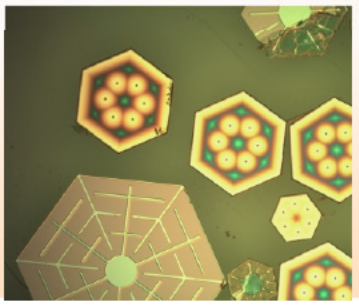
Materials



Engineering Sciences

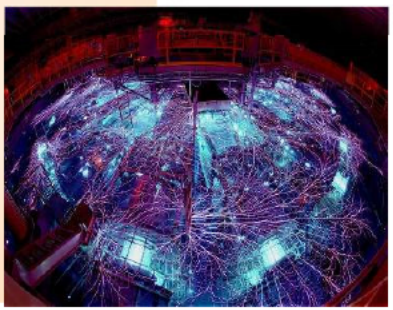


Nanodevices & Microsystems



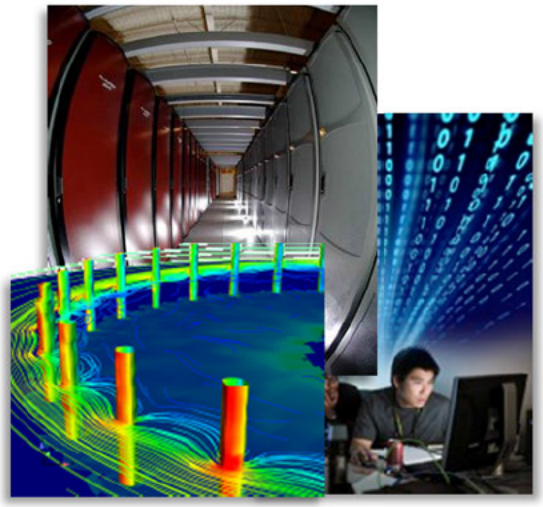
Bioscience

High Energy Density Science

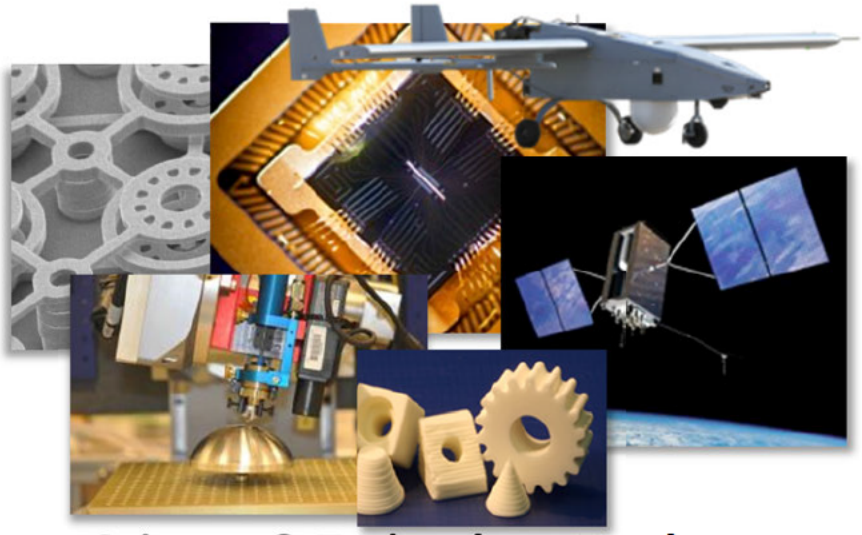


Research Disciplines

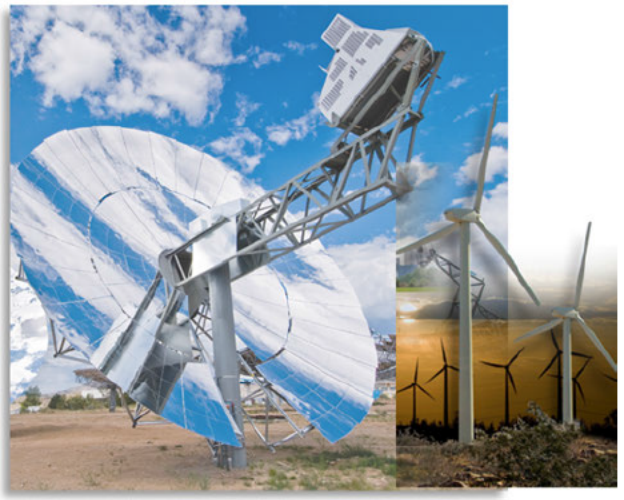
Research Disciplines Drive Capabilities



High Performance Computing



Science & Technology Products

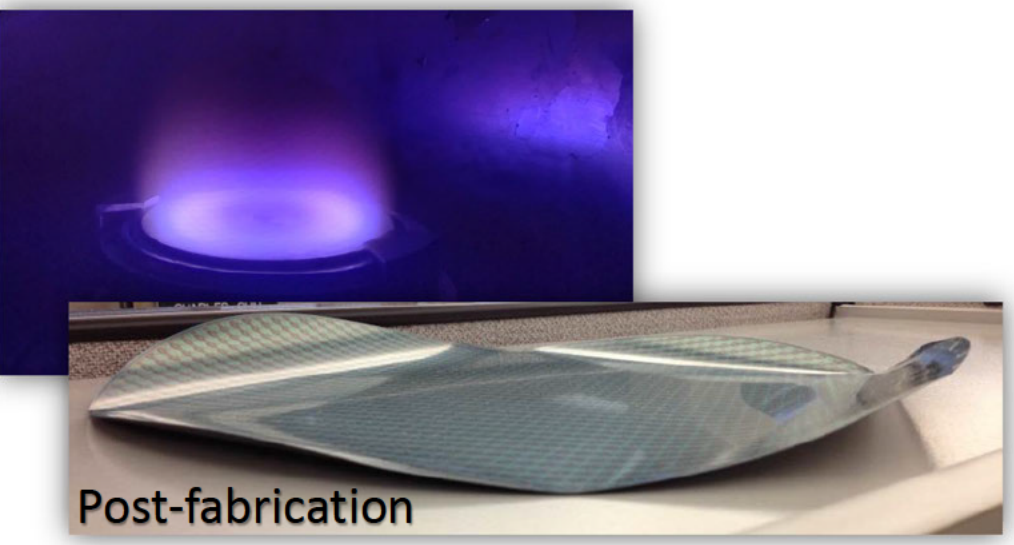


Renewable Systems & Energy Infrastructure

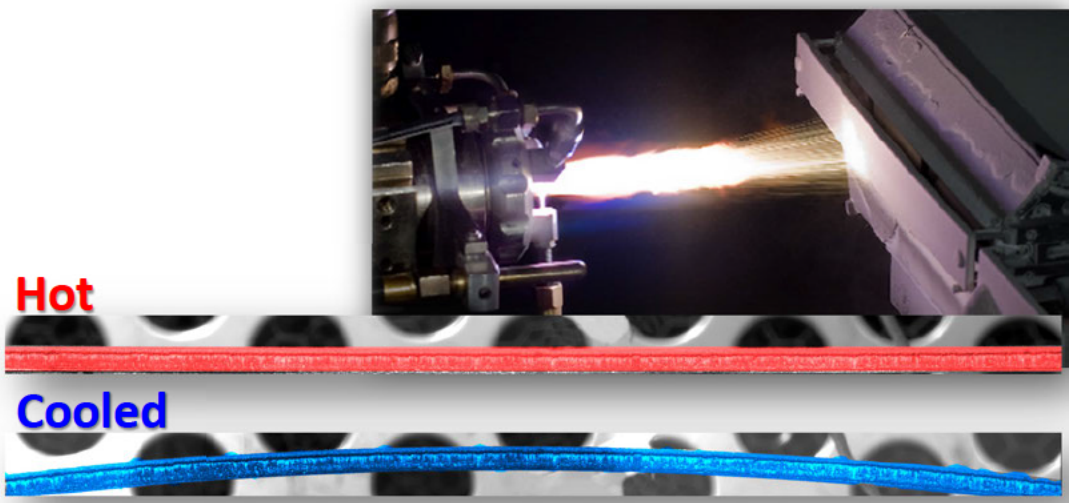
What happens when parts are attached and then their temperature changes?

Warpage!

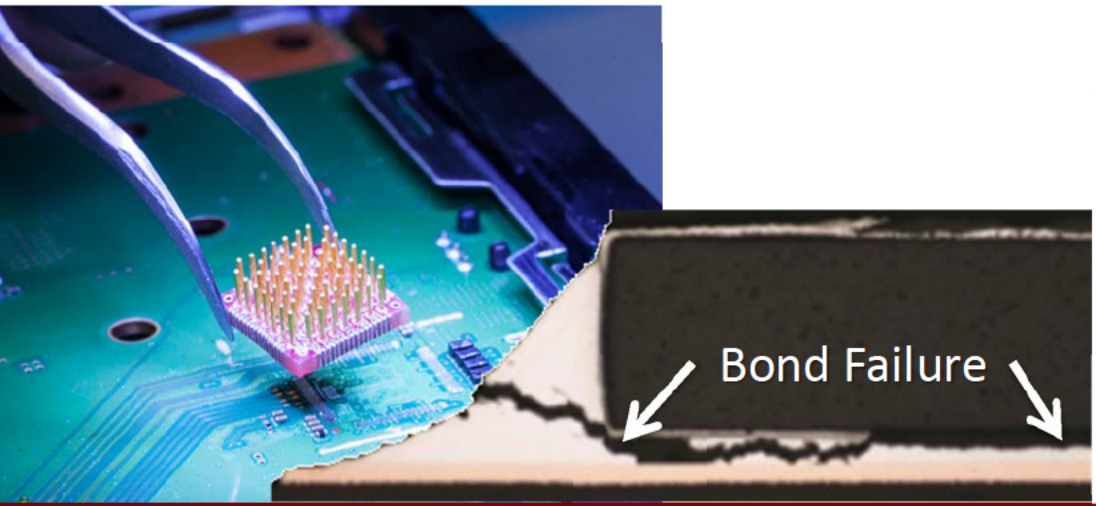
Integrated Circuit (IC) & Thin Film Fabrication on Silicon Wafers



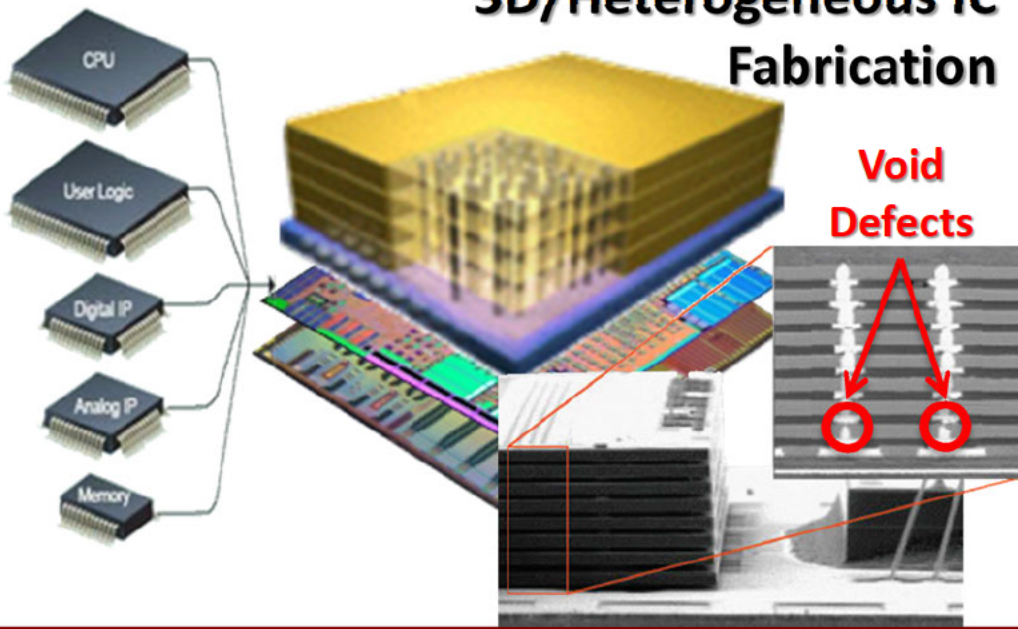
Thermal Spray Additive Manufacturing



Solder & Epoxy Bonding on Circuit Boards



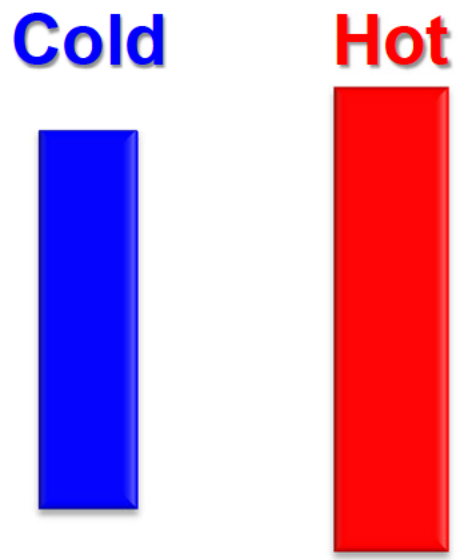
3D/Heterogeneous IC Fabrication



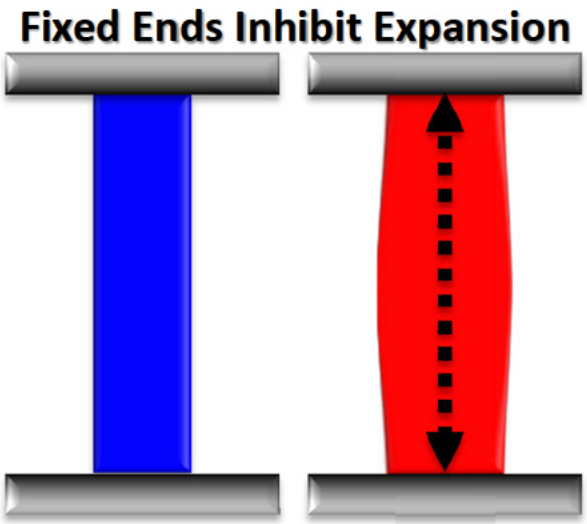
Images: Abdelnaby (2013), SNL, ReliaCoat Technologies, IBM, Micron, Luxtera, ACM

Thermal Deformation & Stress 101

- Materials expand/contract due to temperature changes; most expand as temperature increases.
- **Coefficient of Thermal Expansion** (**CTE**): relative dimension change per temperature change.
- CTE of metals is $O(10^{-3})$ %/K; generally depends on temperature.

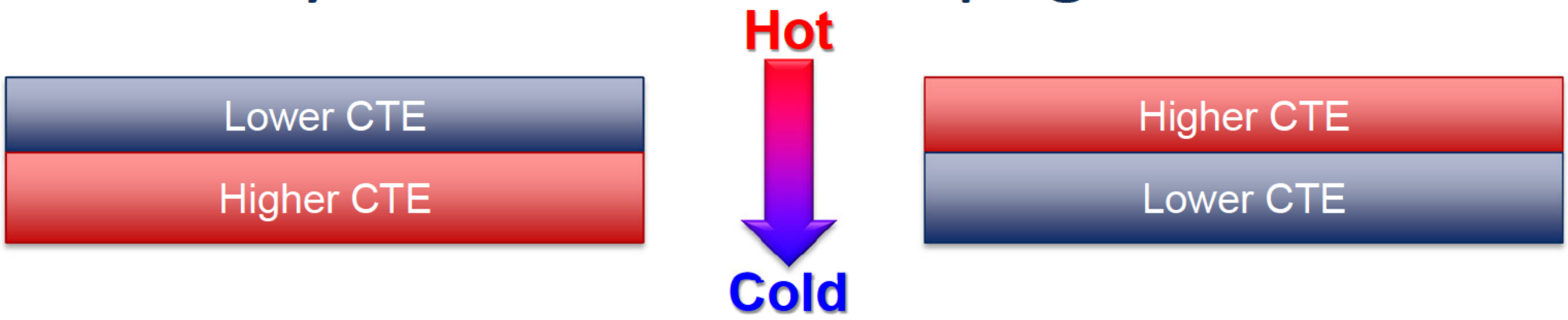


- **Stress**: force normalized by the area on which it acts; a measure of force intensity.
- **Thermal Stress**: stress generated when thermal expansion/contraction is inhibited.
- Thermal deformation/stress of a structure depends on
  - geometry,
  - material properties,
  - temperature environment,
  - interaction among parts/materials.



Thermal Stress Develops due to Heating

Multilayer Structure Warpage



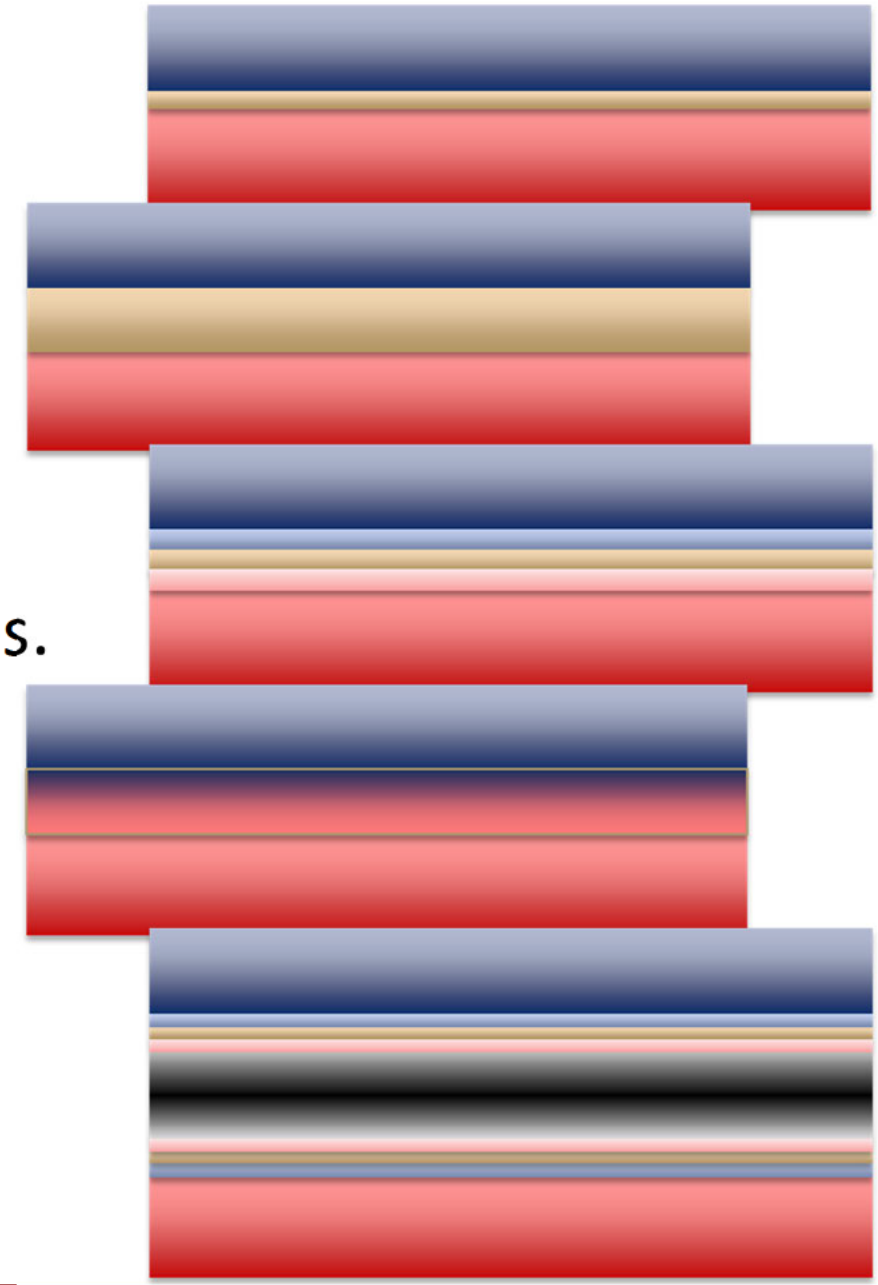
NON-ATTACHED LAYERS

ATTACHED LAYERS

Case is more complicated for >2 layers, but essential principle holds.

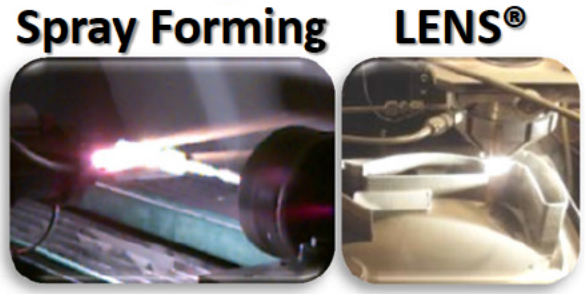
Manage Thermal Warpage & Stress?

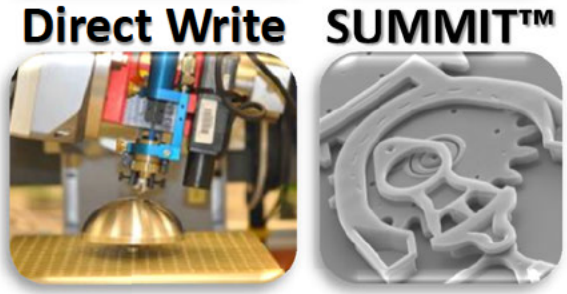
- Modify layer and bond thicknesses.
- Re-arrange layers.
- Add interstitial layers.
- Employ layer gradation.
- Change materials.
- Modify effective material properties.
- Adjust attachment temperature(s).
- Any mitigation approach is constrained by design, fabrication, processing, and performance limits and requirements.

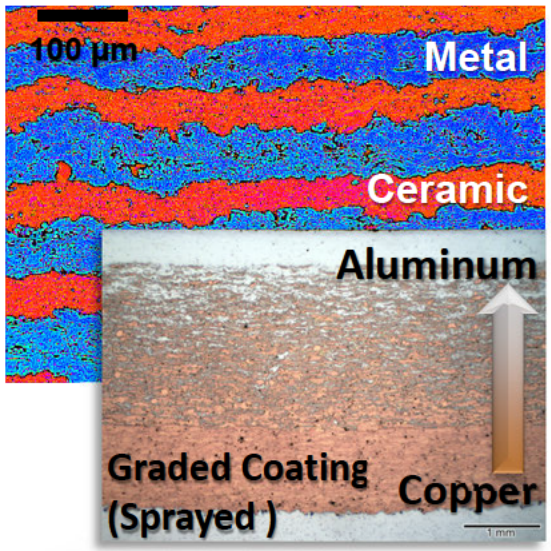


Advance Manufacturing Resources

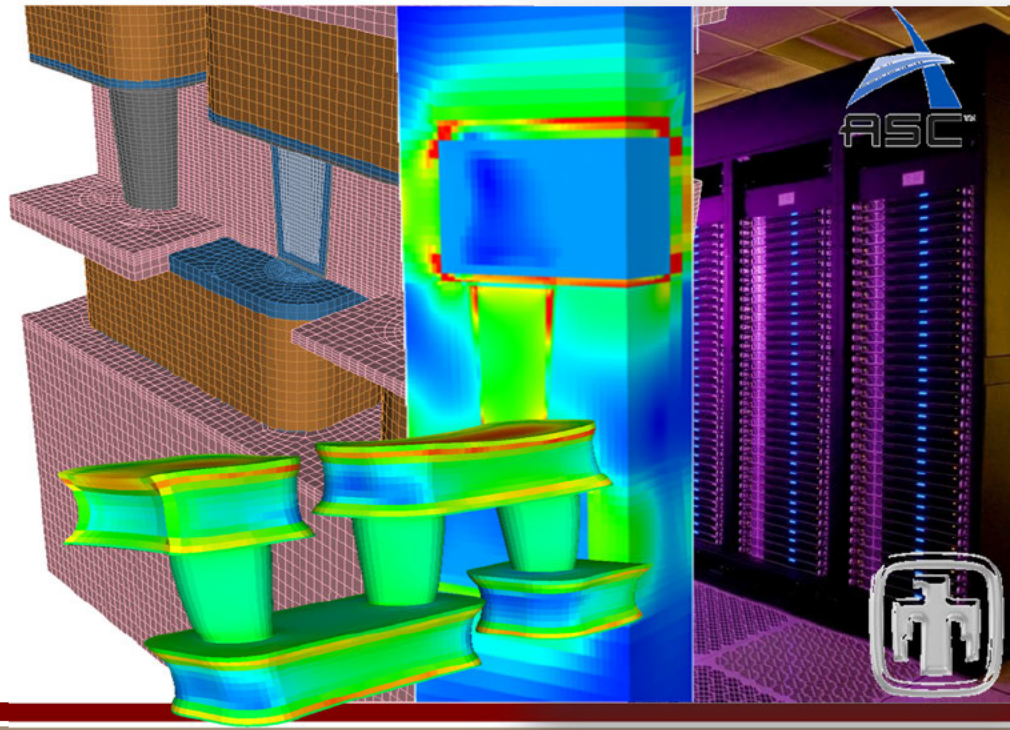
- Advanced manufacturing techniques enable enhanced control over multilayer fabrication.
- Industry often uses trial-error approach to build design rules.





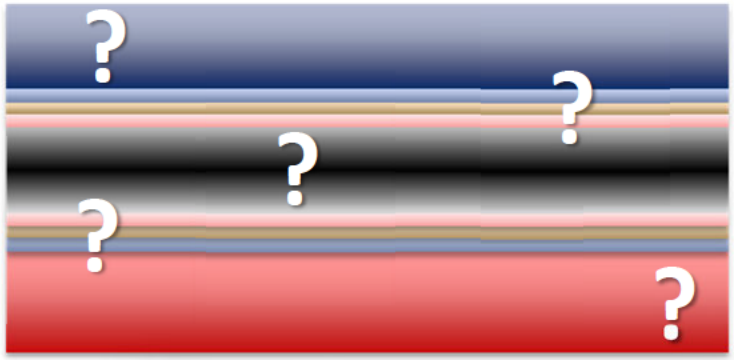


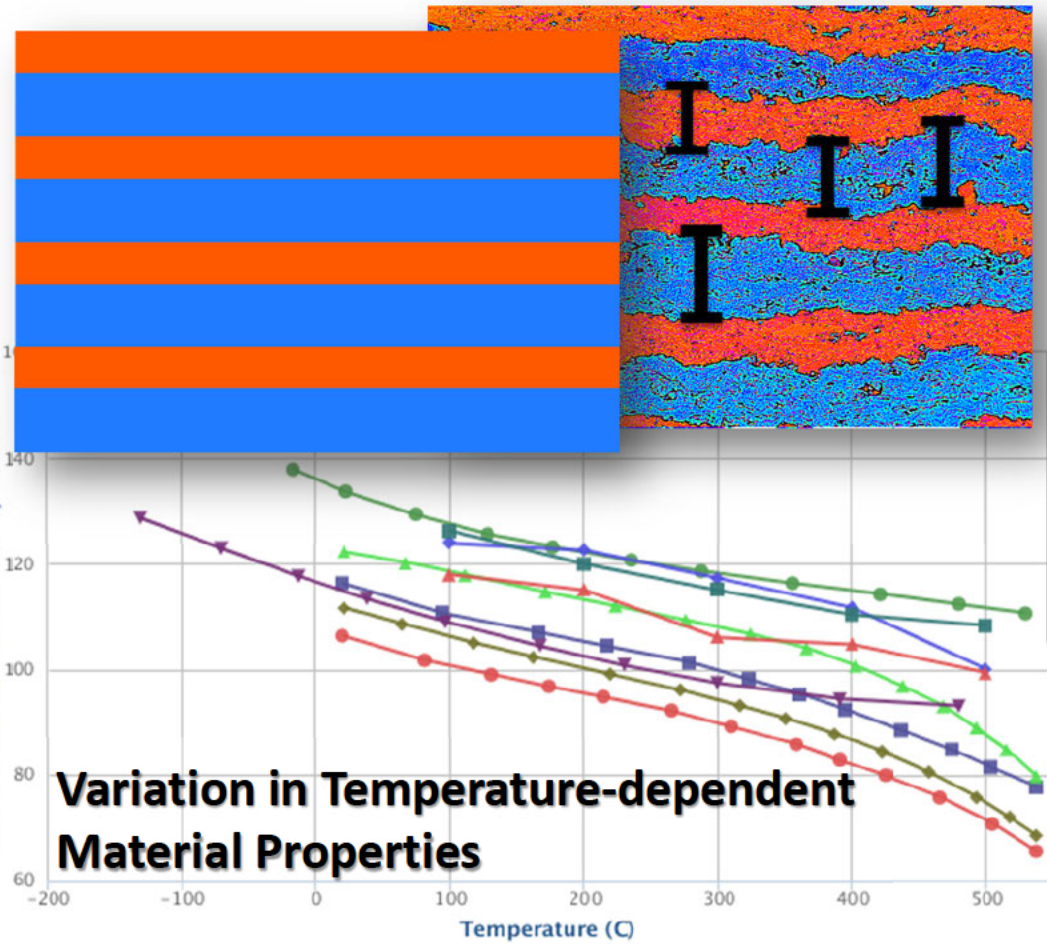
- Enabled by massively parallel hardware/software, Finite Element Analysis used to evaluate multilayer design and fabrication.
- Structures with fine features and thin layers necessitate *gigantic* meshes.
- Ideal for design evaluation, but not for design proposal or optimization.



Uncertain Design & Properties

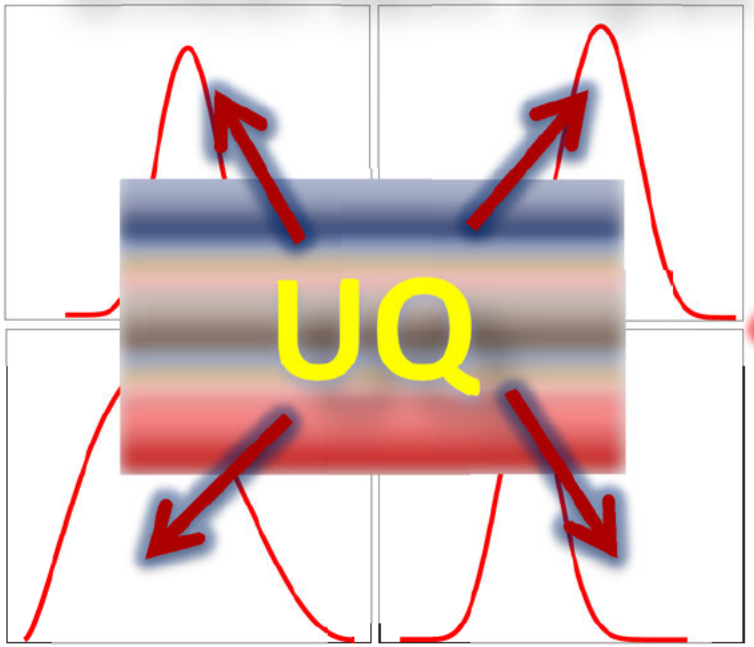
- In early design stages, some materials may be unknown, properties incomplete, and layers partially-defined.
- Geometric tolerances are process-dependent.
- As-designed is not as-built!
- Building material from the small-scale and gradation can lead to uncertainty in material behavior.
- Process temperatures are toleranced, may be merely suggestions.

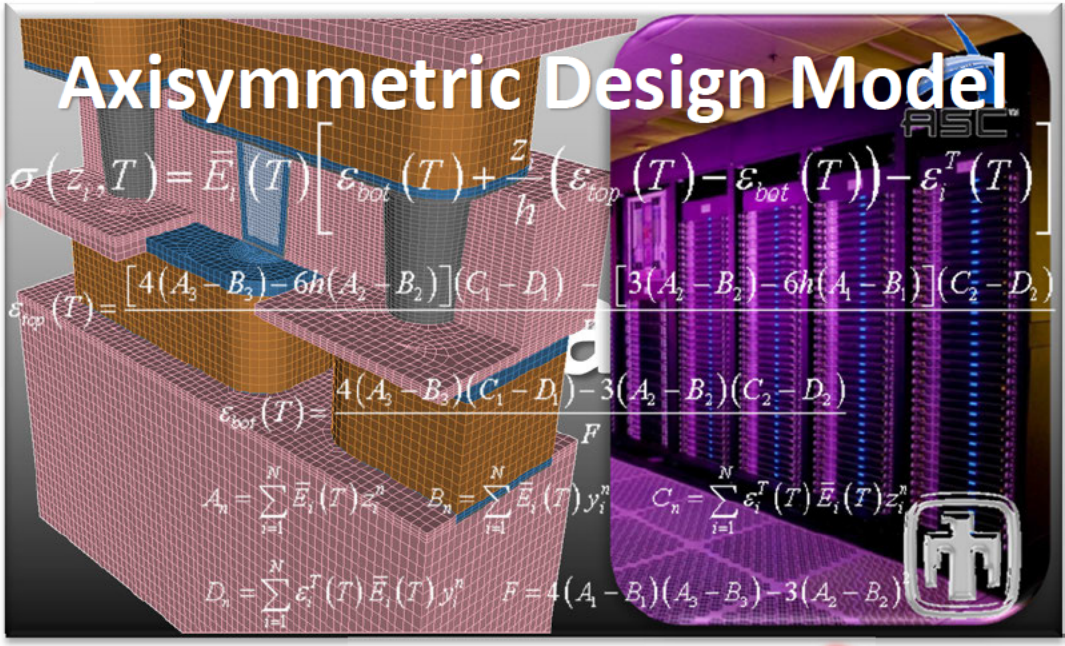




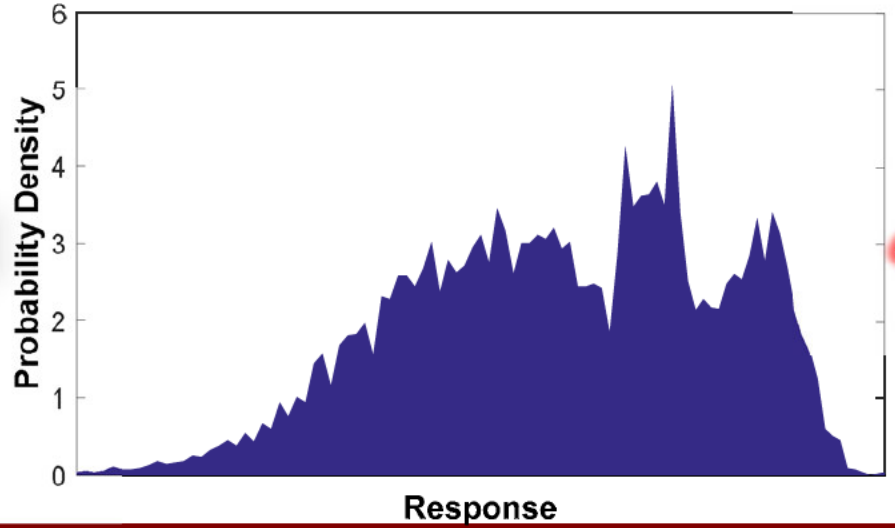
Impact of Uncertainty

Uncertain Input





Probabilistic Output



What Sandia Wants to Know

Given a conceptual design of a multilayer structure,

What is a design with optimized thermal warpage and stress?

- Questions to address include:
  - What is an estimate of warpage and stress with an arbitrary number of uniform and graded layers and temperature-dependent properties?
  - What is an efficient algorithm that configures the layers to manage the warpage and stress?

Addressing this problem can help us accelerate development of a wide range of multilayered structures.

- *Mr. Goodbar: are there multilayer designs that maximize the probability of structural performance under uncertain conditions?*
- *Dr. Greatbar: can you develop a solution for multilayer structures of various fundamental geometries?*