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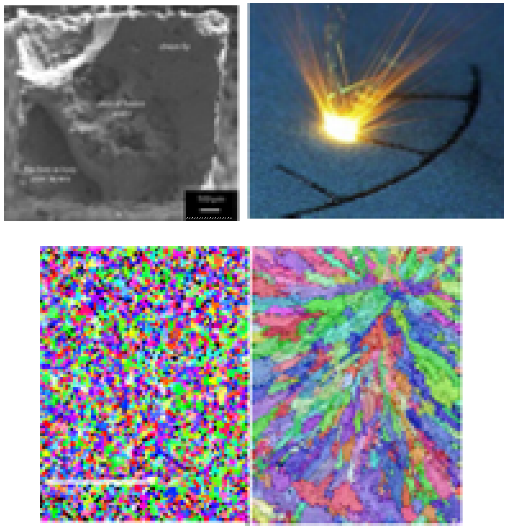

Changing the Engineering Design & Qualification Paradigm in Component Design & Manufacturing (Born Qualified)

R. Allen Roach, Principal Investigator

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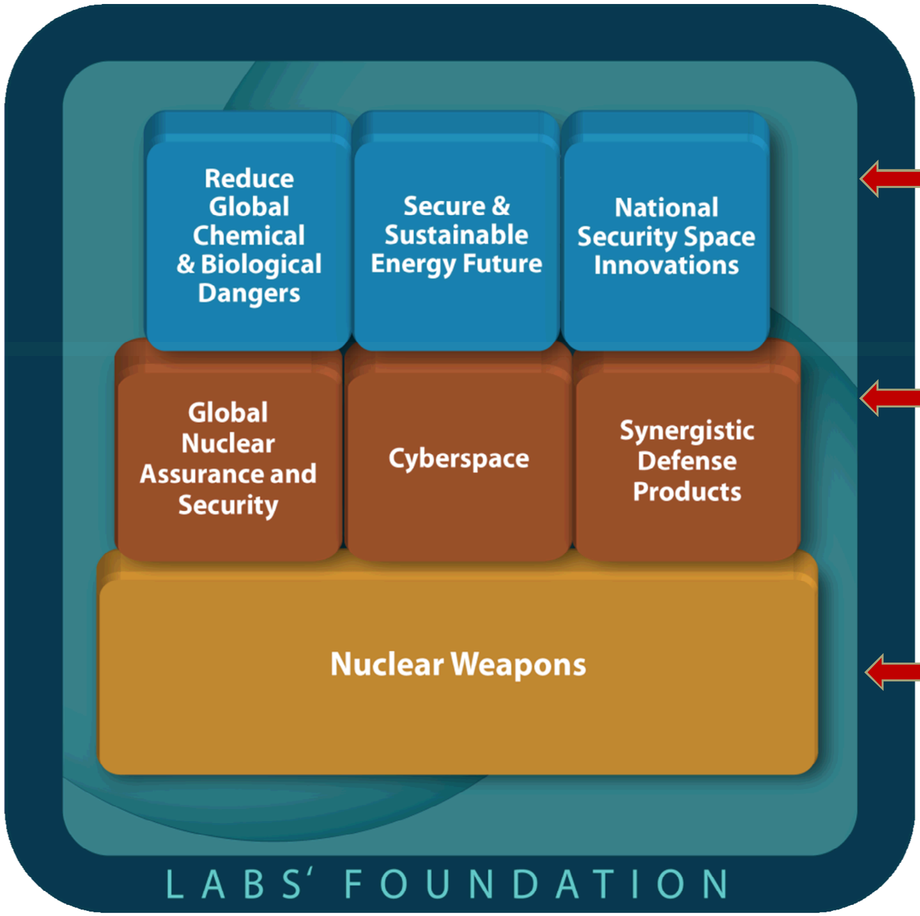
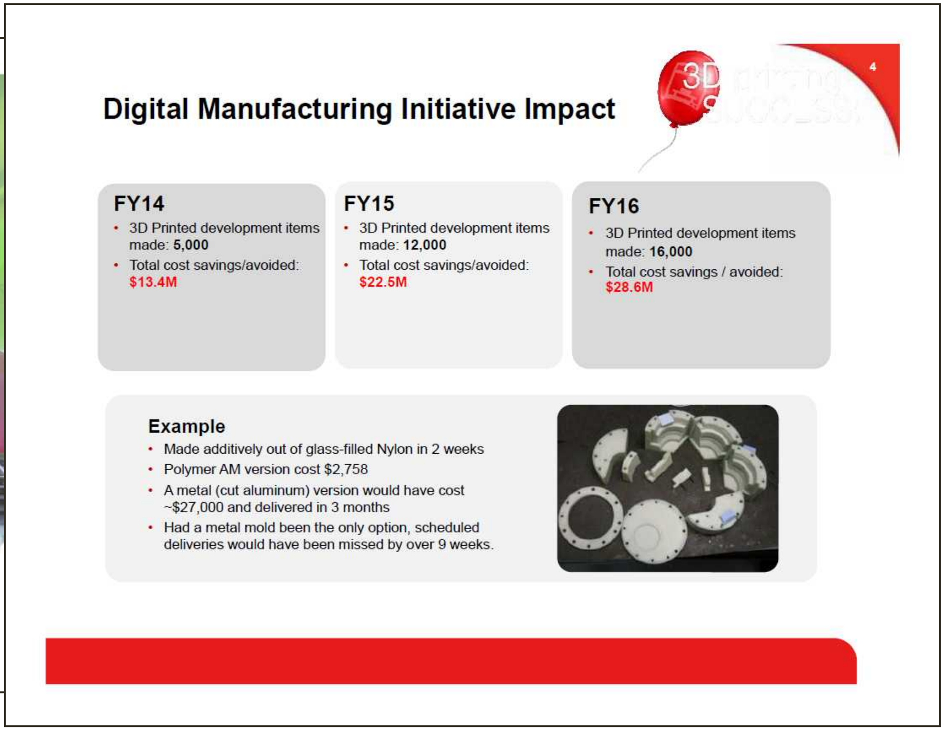
Sandia National Security Mission Areas



- Top row: Critical to our national security, these three mission areas leverage, enhance, and advance our capabilities.
- Middle row: Strongly interdependent with NW, these three mission areas are essential to sustaining Sandia's ability to fulfill its NW core mission.
- Bottom row: Our core mission, nuclear weapons (NW), is enabled by a strong scientific and engineering foundation.

Current Uses of Additive Manufacturing at Sandia & KCNSC

- Additive Manufacturing has become a well-accepted tool for the design, prototyping and production of Tooling, Gages, Fixtures, Molds and Mass Mocks
- Significant cost-avoidance already achieved in production



- Exploratory efforts underway to evaluate when Additive Manufacturing parts are adequate for use in weapons components
- Today's Goal - Integrate Additive Manufacturing early with design projects as we continue developing background and expertise

Born Qualified Overview & Vision

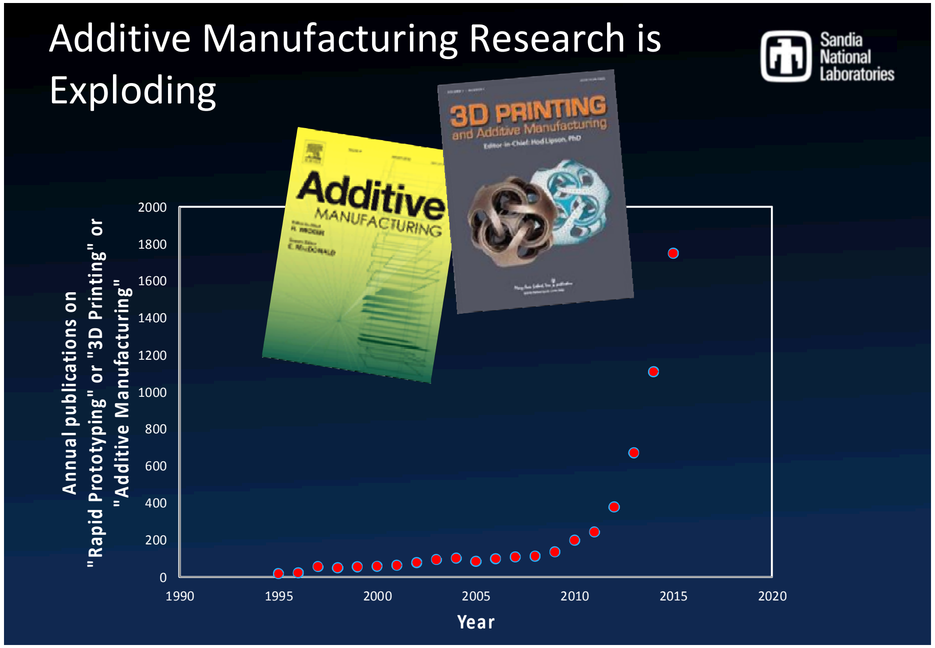
- Strong Sandia Mission Area driver supporting future agile & affordable capabilities foundation for uncertain and unknown future

- ***Goal:*** Combine promise of **additive manufacturing** with **deep materials & process understanding** to revolutionize design, manufacturing, & qualification paradigms
  - Materials, designs, and ultimately components are *Born Qualified*

- Born Qualified is a 15-Year Vision and this Grand Challenge Laboratory Directed R&D project is a 3-Year step in that direction

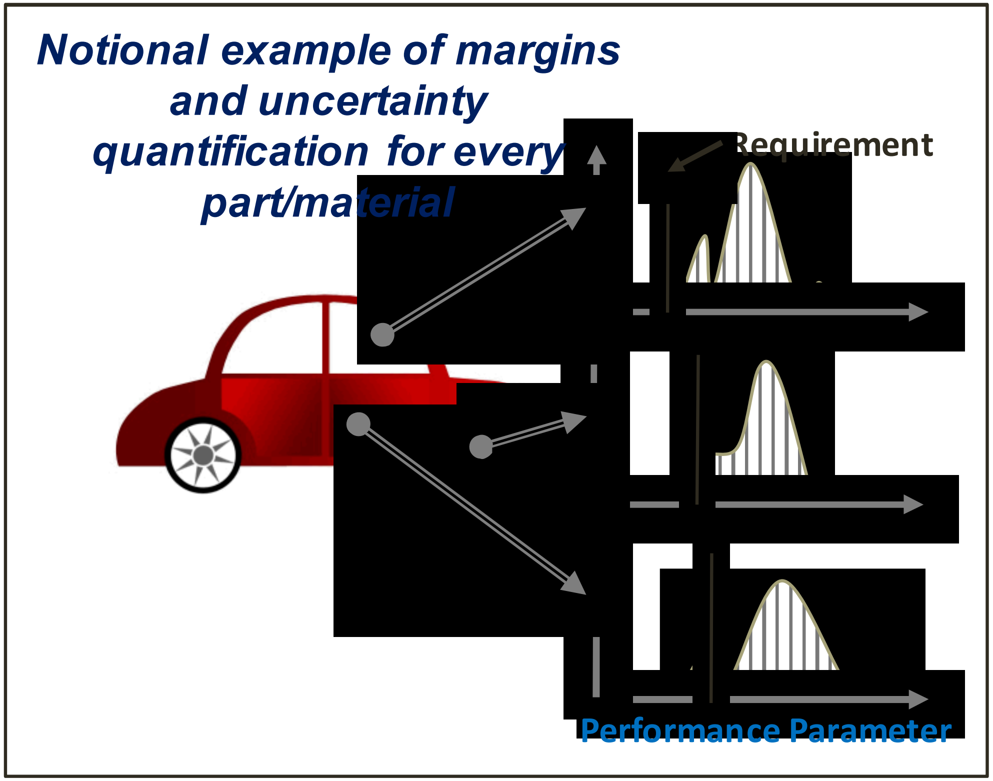
Paradigm Change

- ***Why Additive Manufacturing as driver for design, manufacturing, and qualification revolution?***
  - Disruptive technology that allows simultaneous creation of part and material
  - Ability to tightly control and monitor manufacturing process at the voxel level
  - Additive Manufacturing is ideal for low volume, high value, high consequence, complex parts (weapons, energy, aerospace, medical)
  - Inherently flexible and agile

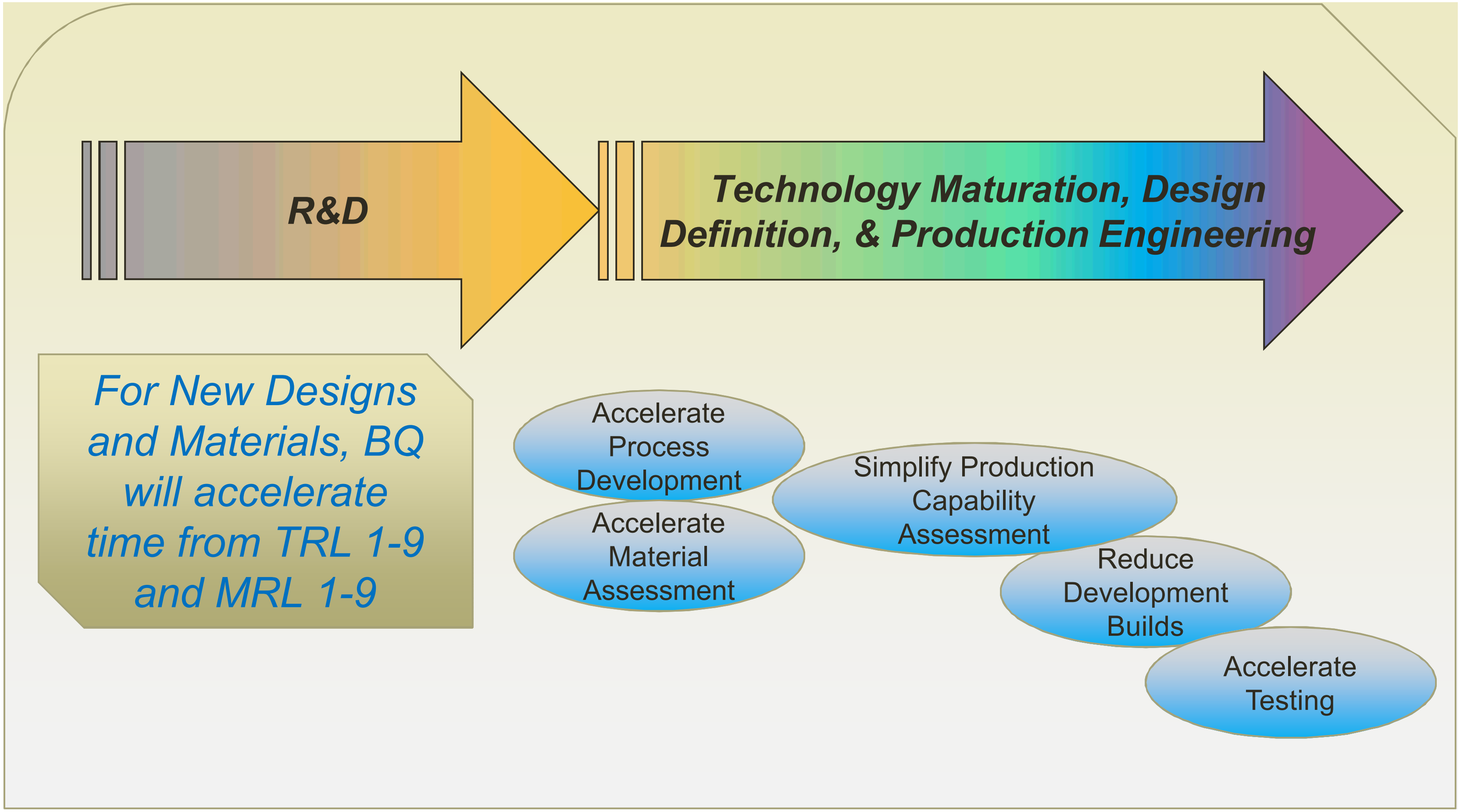


Approach to Paradigm Change

- Drive Qualification revolution by
  - Predicting Performance Probabilistically
  - Tightly controlling Process
  - Accelerated Cycles of Learning
- Integrate validated, predictive capability with real-time and ex-situ diagnostics to create a broad science-base to realize Uncertainty Quantification driven qualification of design and process
- Utilize science-base and diagnostic artifacts to verify materials and process assurance
- At the end of 3-years, test with 3 Exemplars to evaluate progress and future investment needs

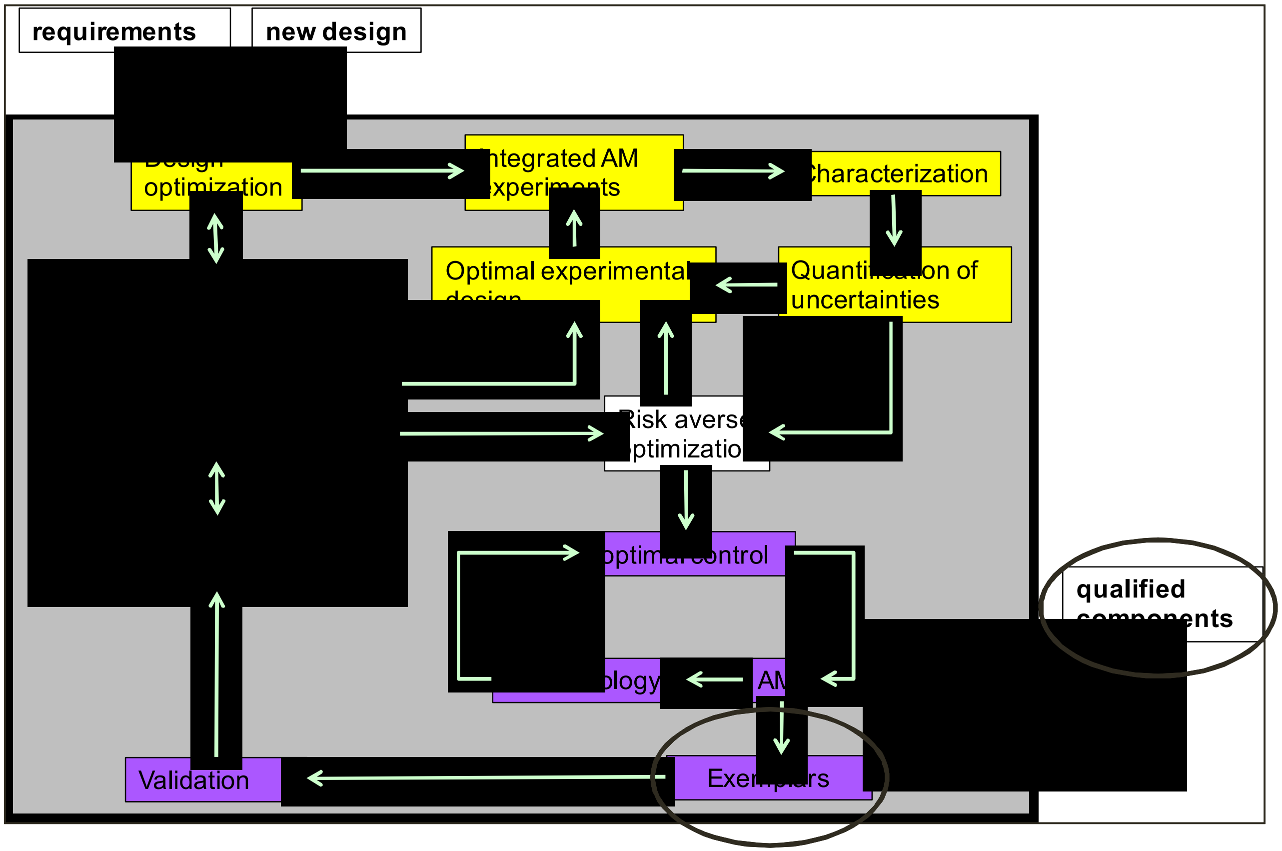


Accelerate Qualification



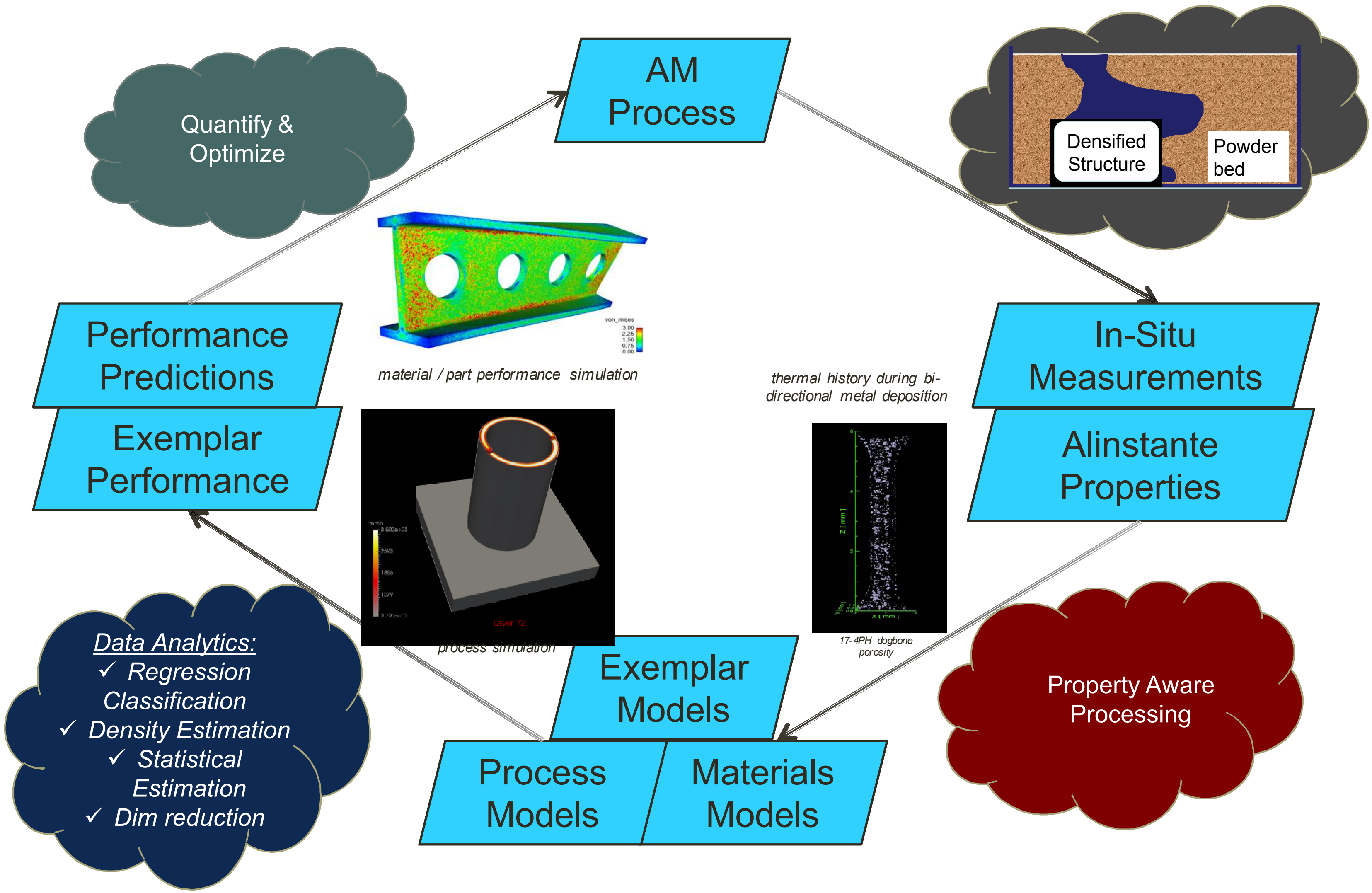
Strategy

Goal: Develop ability to translate Additive Manufacturing <u>process</u> results to material properties by relating micro<u>structure</u> to bulk measurable <u>properties</u> to ultimately predict Exemplar <u>performance</u> (P-S-P-P)



Overview

Using Metal Powder Bed Example



Sandia's AM Process Expertise

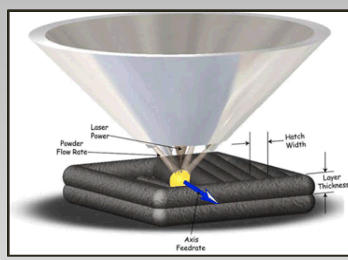
Strong capabilities and history

Examples of Polymer AM Tools

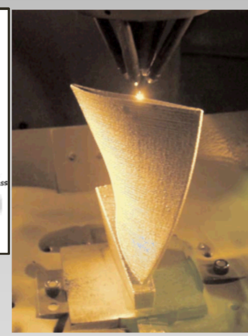
MakerBot

PolyJet

Examples of Metal, Ceramic AM Tools



LENS®*

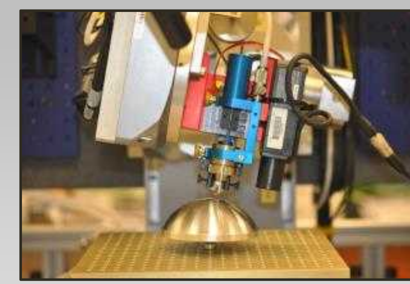


Recoating Blade

Build Platform

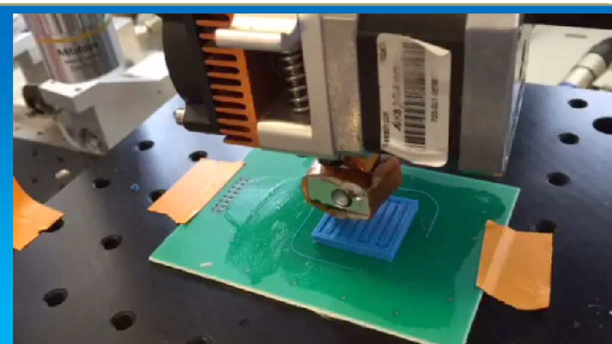
Dispenser Platform

Powder Bed



Direct Write

Examples of Multi-Material AM Tools



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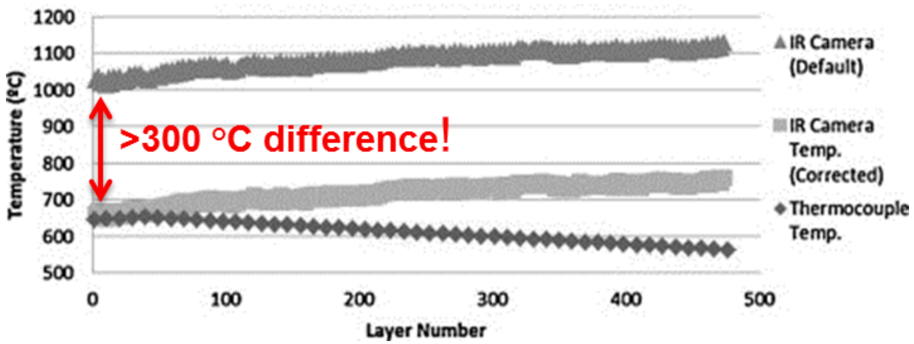
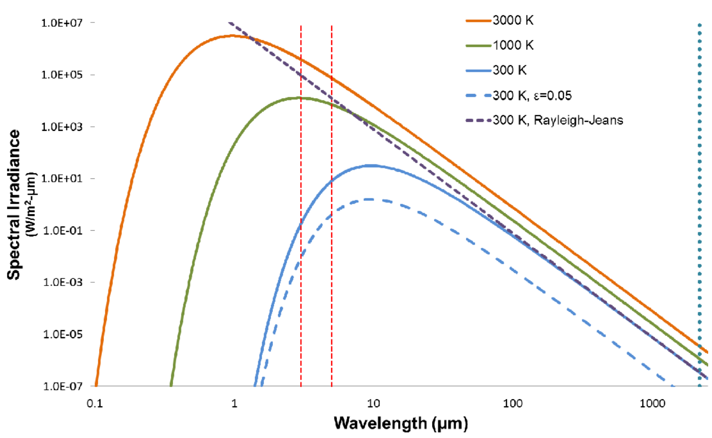
Step 1: Temperature Measurement Problem

- Accurate determination of powder bed, melt pool, and part temperatures during build is critical for:
  1. Predicting performance and parameters such as residual stresses.
  2. Validating and verifying physics-based models.
  3. Feedback control for real-time Additive Manufacturing process optimization.
- Layer-wise temperature measurement requires non-contact methods, but achieving accuracy a key challenge.
- Exploring mm wave techniques to reduce errors introduced by emissivity variation
  - Expected accuracy ~ 10°C
  - MIT collaboration
- Also have multiple efforts looking at spectroscopy techniques and neutron diffraction



Observed temperature errors in powder bed process using IR Camera with factory calibration. ***Rodriguez et al., Add. Mfg., 2015.***



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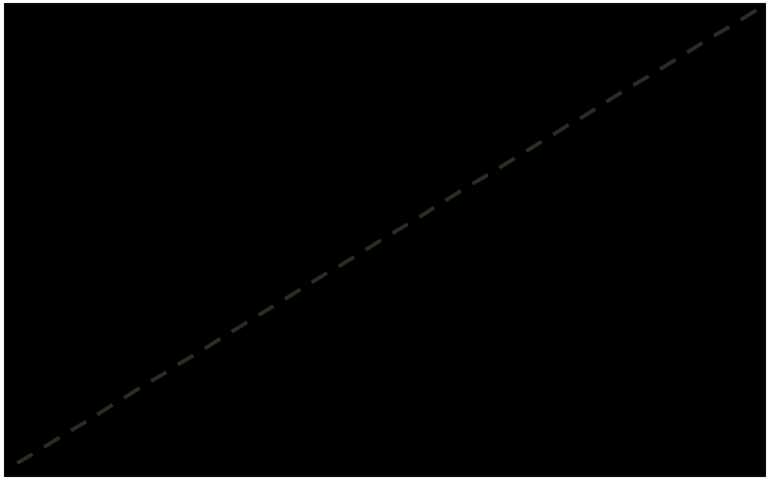
Alinstante Challenge

- Development of innovative experimental techniques for "Alinstante" high-throughput, real-time measurements, in tandem with detailed, lower throughput, measurements to efficiently establish the structure, process, and property relationships of Additive Manufacturing materials
- "Material Scientist in a box"
  - Automate many existing material tests
  - Make it easy to continue to extend automated testing
  - Introduce the ability to do regression testing against gold standard



Diagnostic Artifact

BORN QUALIFIED

Sandia National Laboratories

Objective: Develop a 80 mm x 80 mm artifact that is easily inspected to quantify both printability limits and material/build properties. This artifact can track differences between builds, materials, printers, or Additive Manufacturing processes.

Material & Structural Properties

Mechanical Properties
Arrays of tensile bars used to investigate stochastic tensile properties. Arrays of two different-sized tensile bars allow exploration of size-dependent mechanical properties

Structural Dynamics
Several cantilever beams of two heights can be used to test the resonance frequency of the material.

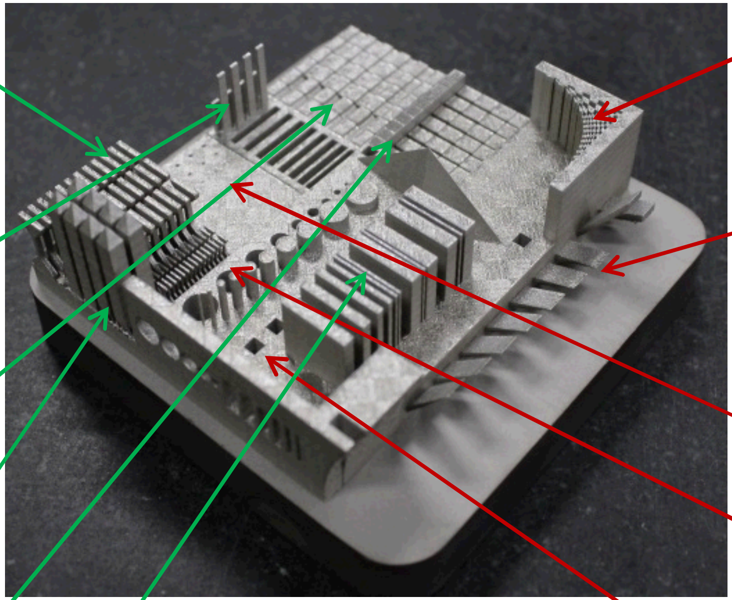
Notched Features
Arrays of notched features intended to explore stress-concentration effects on reliability and develop break-away coupons

Material Chemistry
Coupons to readily verify the composition and monitor contaminant levels.

Surface Roughness
Several features explore the interplay between geometry and the resulting surface roughness

Residual Stresses
Several features may be used to quantify the stress-induced warpage. Also, regions of the part exacerbate internal residual stresses to be measured by x-ray/ neutron diffraction or hole drilling.

Sandia Artifact printed in stainless steel alloy 17-4PH using a commercial vendor (Fineline) with a ConceptLaser Mlab Printer



Printability Limits & Metrology

Minimum Feature Dimensions
Evaluate printability and dimensional accuracy for a wide range of feature types including theoretical sharp corners

Overhangs & Bridges
Incrementally sized features intended to determine the maximum dimension that will maintain structural integrity of the part. Features push printer to failure point.

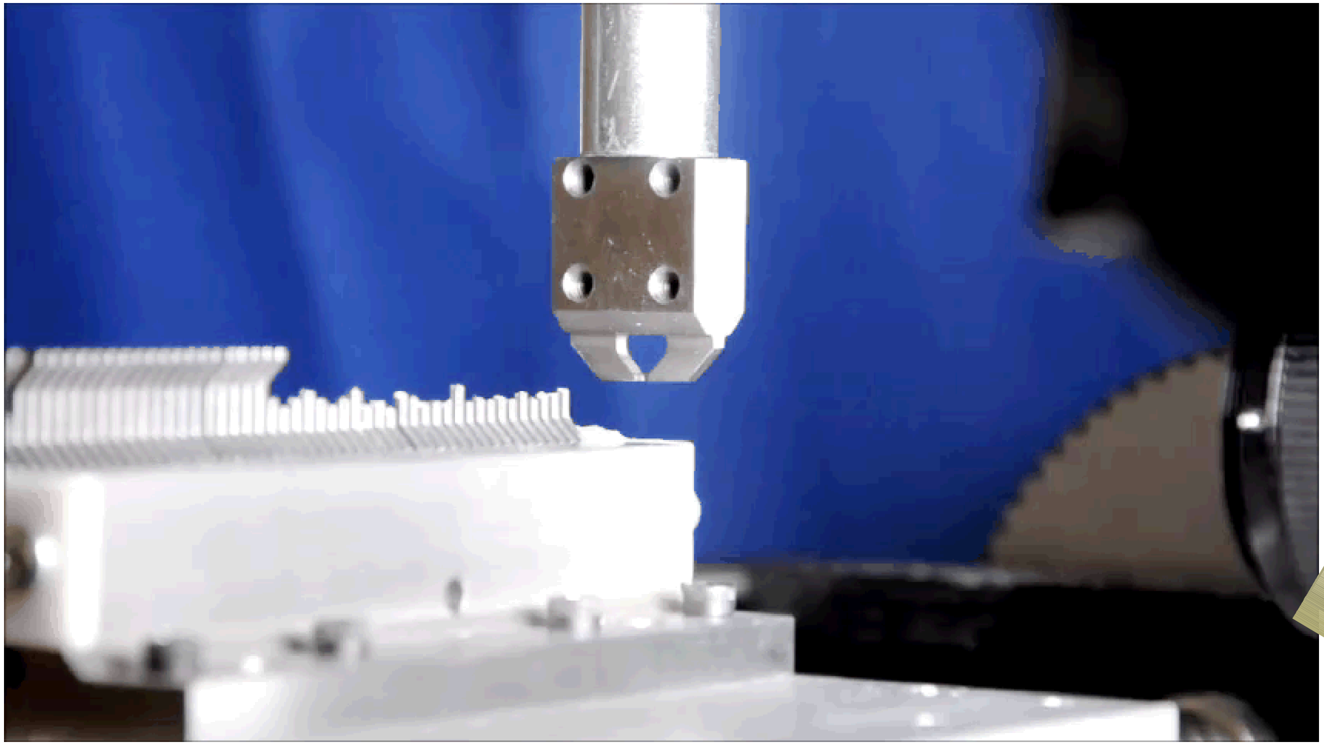
Internal voids
Intentional internal void arrays of varying dimension allow inspectability assessment

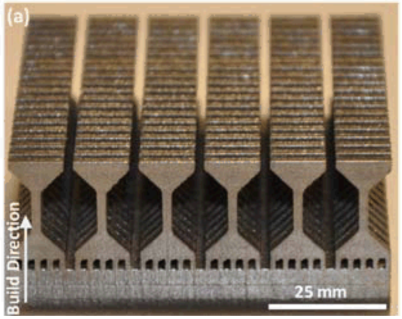
Aspect Ratios
A wide range of aspect ratios explores the printability limits of positive and negative features

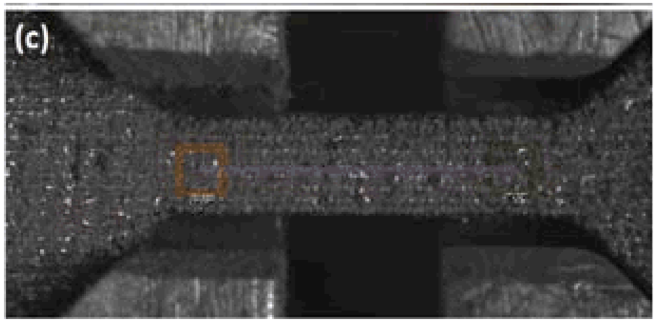
Consistency features
Arrays of nominally identical features allow evaluation of repeatability

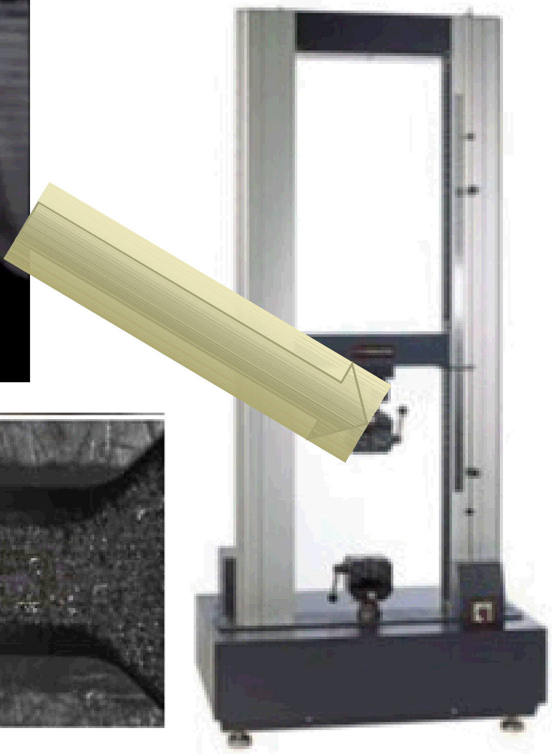
Most existing artifacts (e.g. NIST Additive Manufacturing artifact) emphasize dimensional metrology and ignore material/structural properties. This compact array employs many dual-purpose features and many arrays of features for statistical repeatability analysis.

Automated Tensile Testing

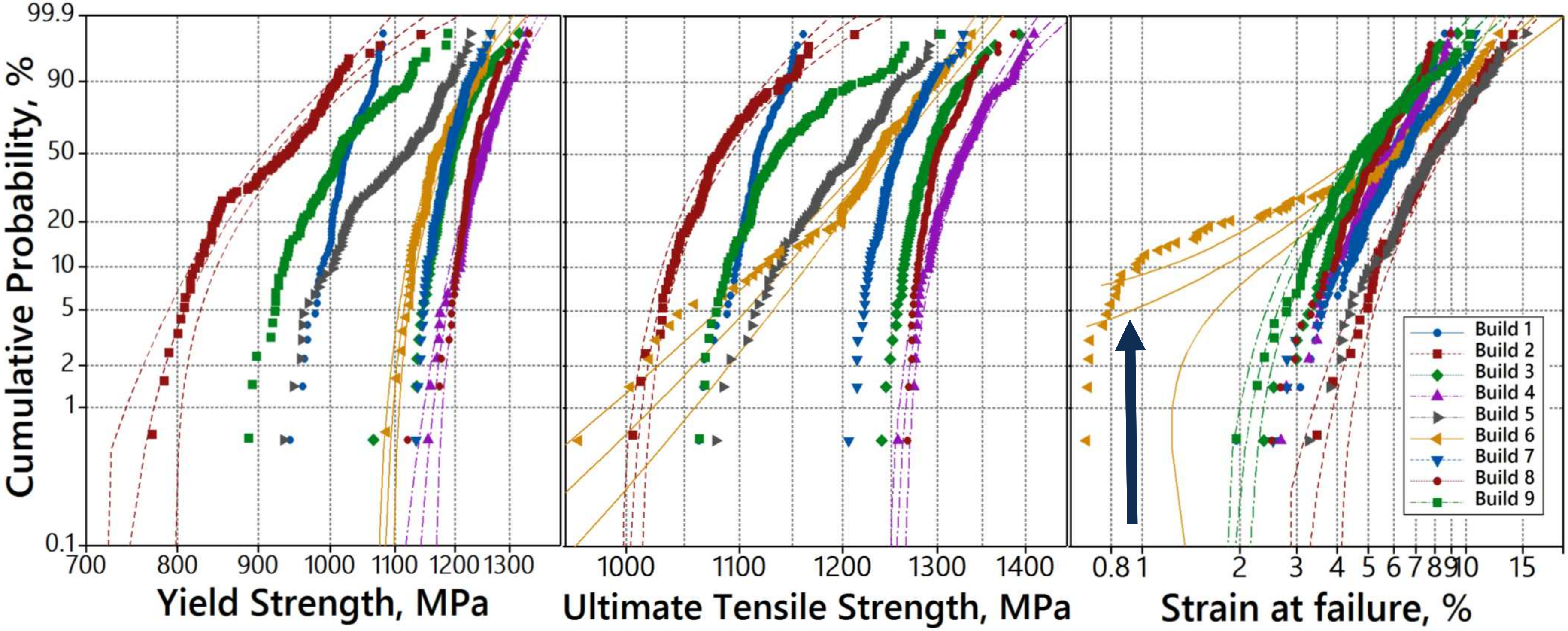








High-throughput Tests



- Tested 9 builds, each one with 6 columns by 20 rows of tensile bars, 1065 individual tensile specimens
- Build 6 contained 25 instances of failure strains below 1.95% whereas the other eight builds all exhibited values above 1.95%. The loss of ultimate strength was caused by the low ductility.

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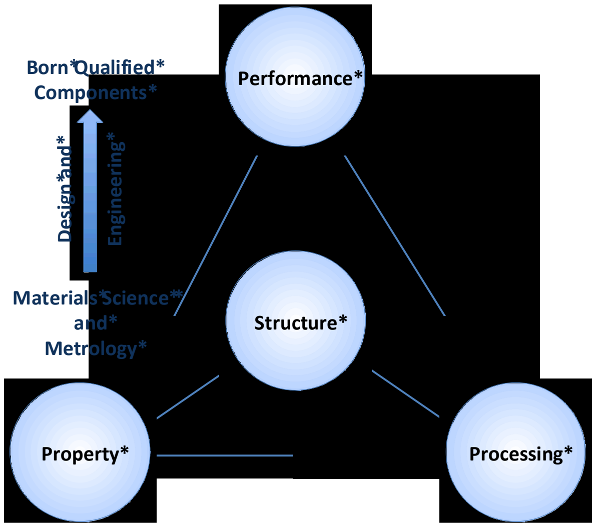
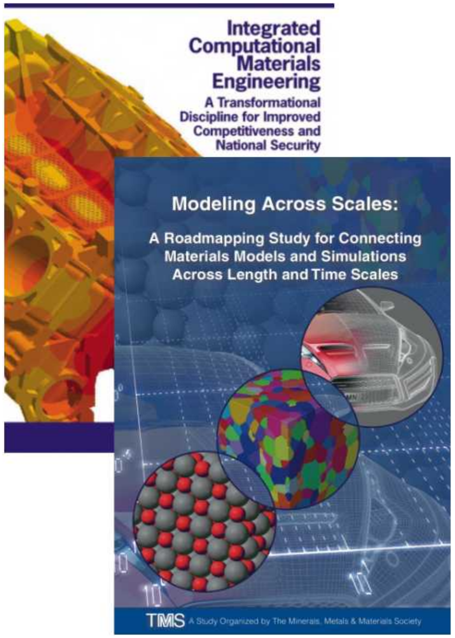
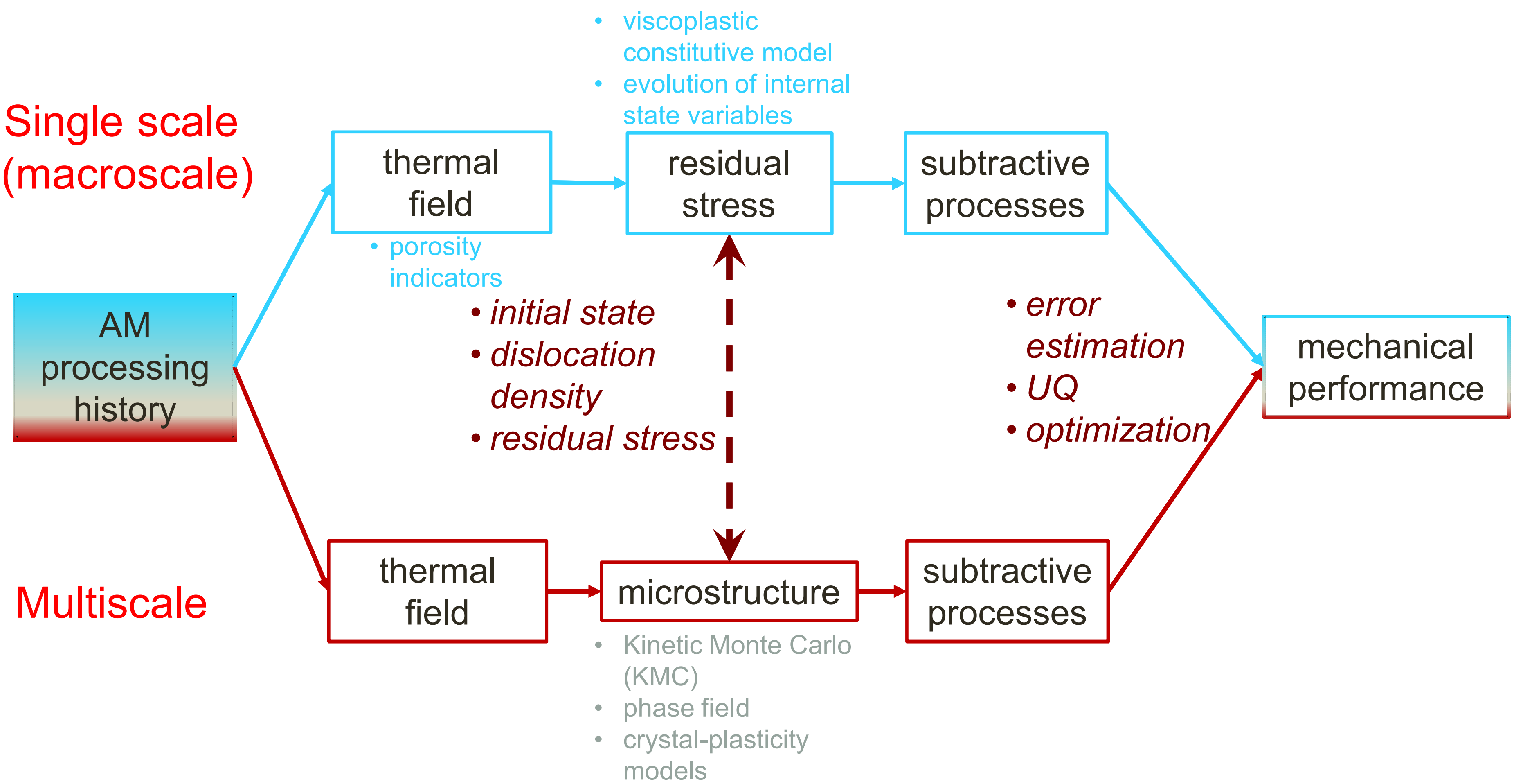
Modeling Challenges

- How to establish process-structure-property-performance models/relationships?
- How to approach multiscale uncertainty quantification for metal Additive Manufacturing?
- What are the errors in quantities-of-interest in assuming homogeneous constitutive behavior?
- Importance of residual stress field to component performance?

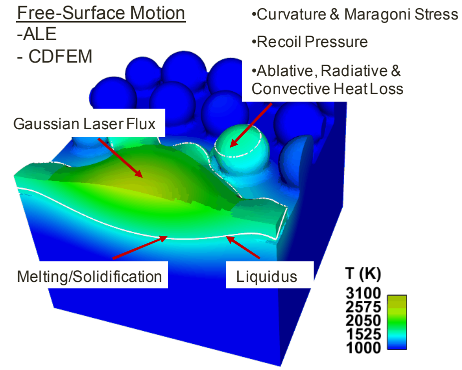




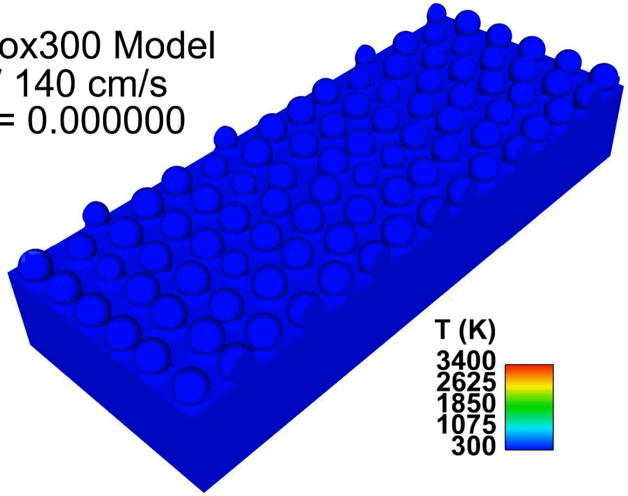
Process - (micro) Structure - Performance (PSP) Linkages



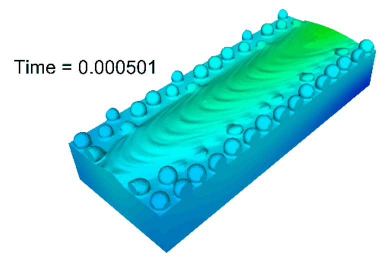
Process Models
Powder Bed Physics Model



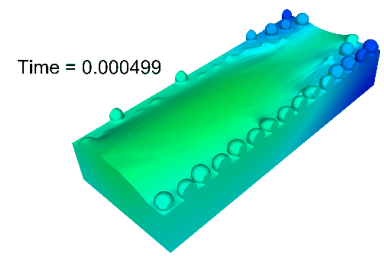
SNL Prox300 Model
50W 140 cm/s
Time = 0.000000



25W

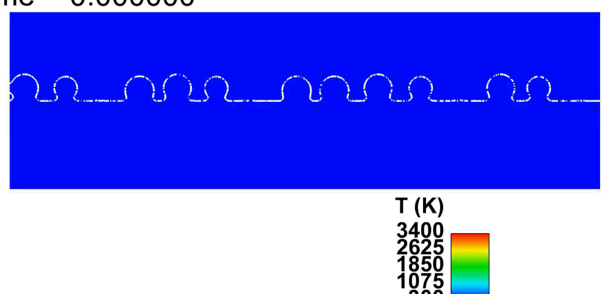


50W

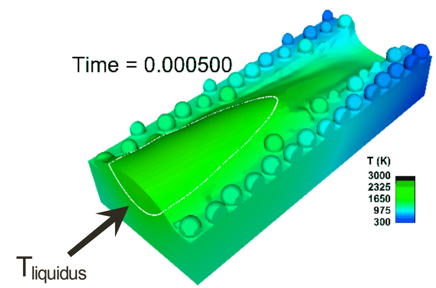


Gas and melt pool dynamics

Time = 0.000000



100W

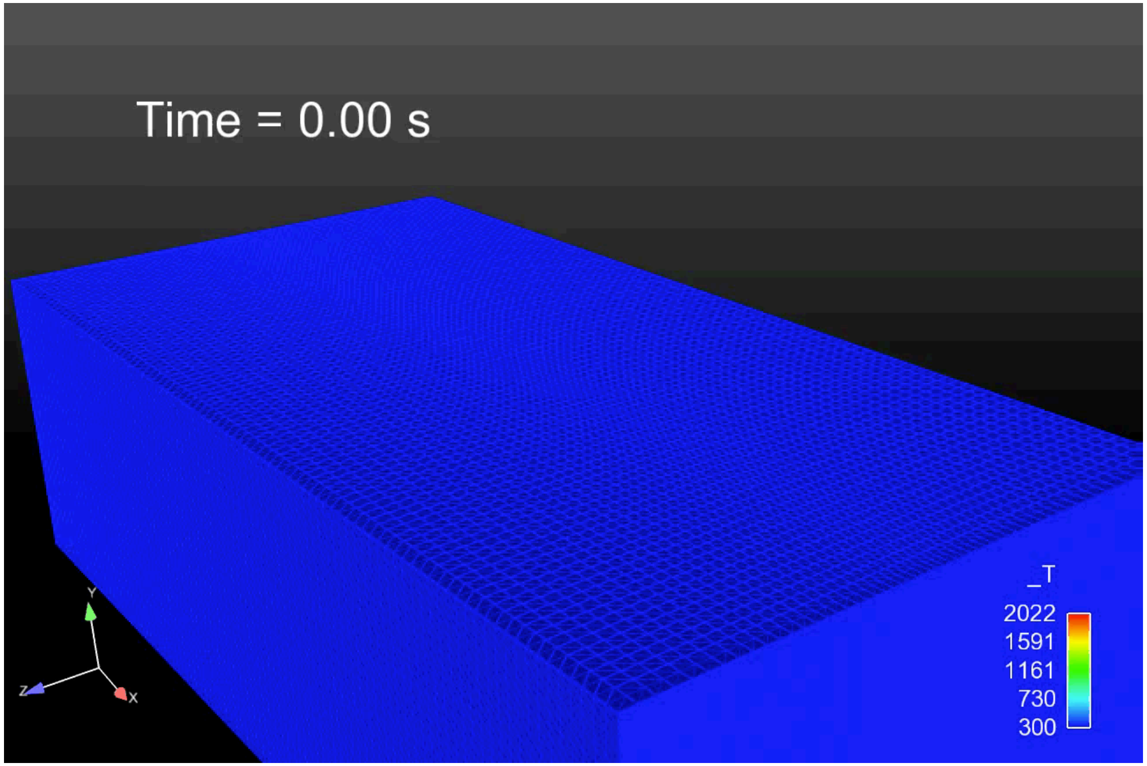


R_{eff}=2.0

Notes:
- SNL Prox 300 Model - Impact of power for fixed hatch spacing
- Stainless steel 304L, 25 micron powder
- Hatch spacing 150 μm center to center
- 500 micron powder bed traversed in 357 microsec.
- Sloshing-driven gas dynamics entrains ambient gas

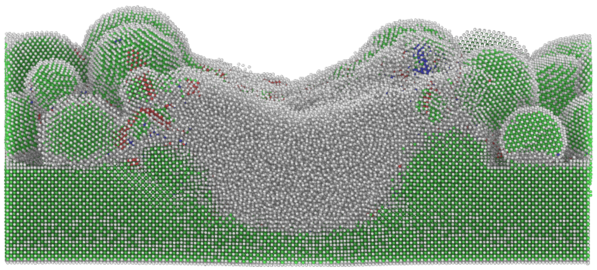
Process Models
LENS Physics Model

- 3D mesoscale thermal/fluid simulation of multi-layer LENS powder deposition process
- Hatch Spacing simulation

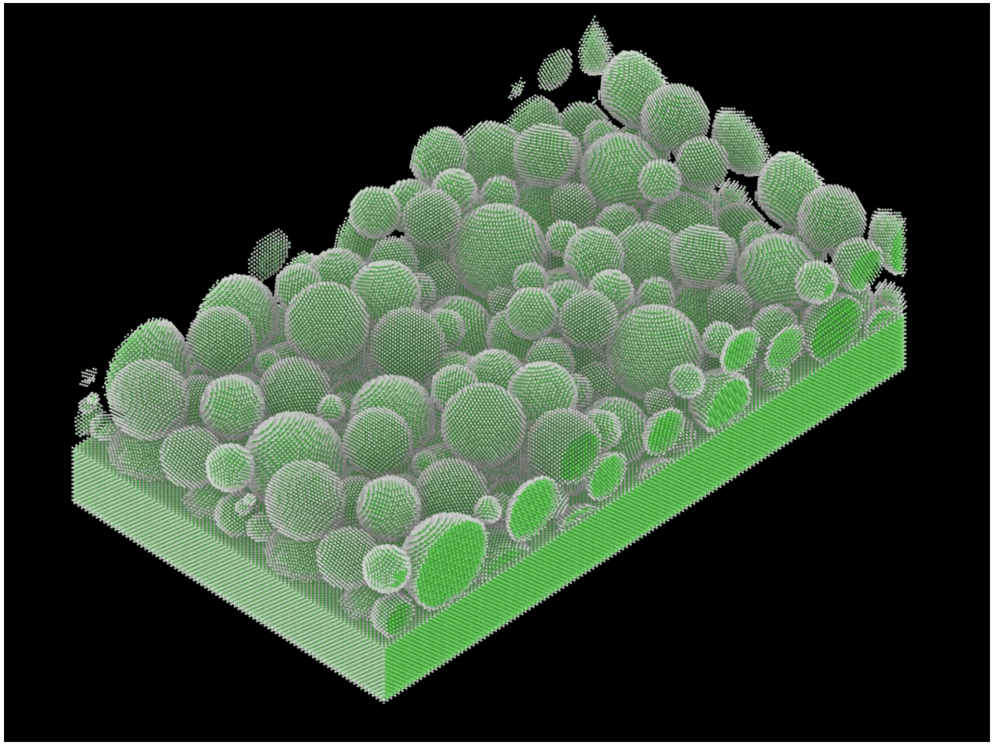


Incorporating Complex Thermal Histories in Microstructure Simulations of 304L SS

- Predicting microstructure evolution due to the rapid solidification and complex thermal histories is key to process-structure-property relationships
- Implemented atomistic scale model of powder bed during laser melting

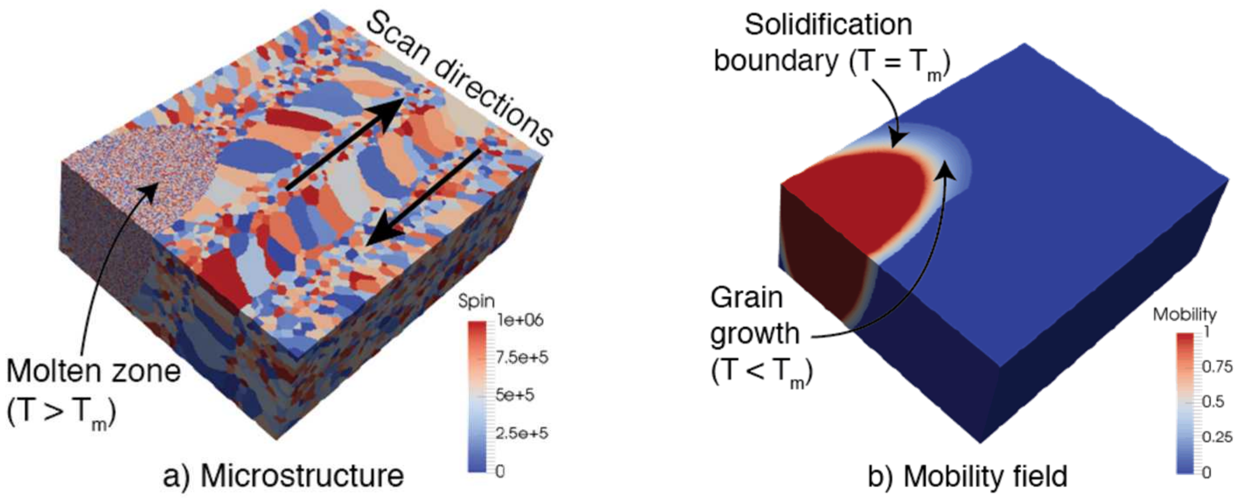


Green atoms are FCC, white are locally amorphous, red are HCP and blue are BCC



Incorporating Complex Thermal Histories in Microstructure Simulations of 304L SS

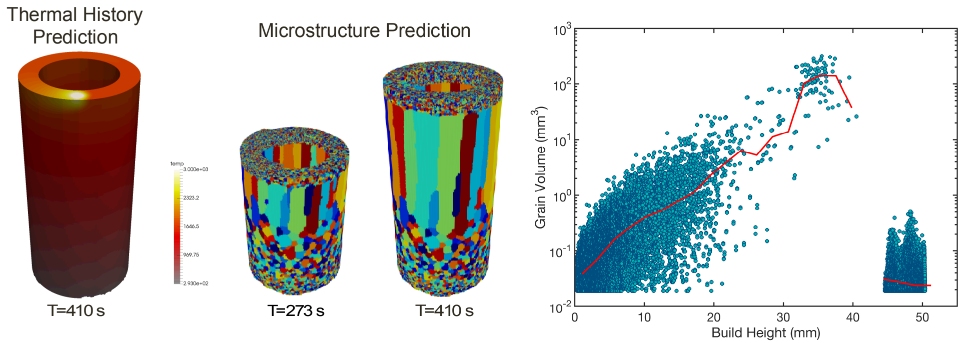
- Employed numerical heat transfer modeling combined with kinetic Monte Carlo (KMC) simulations

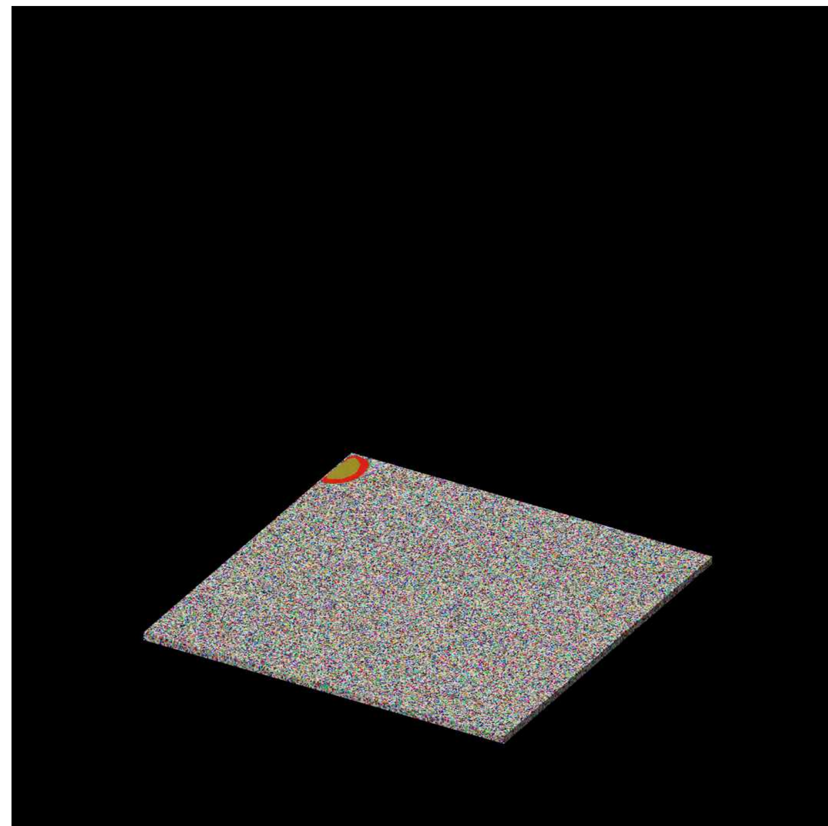


- In situ IR thermal imaging underway for model validation

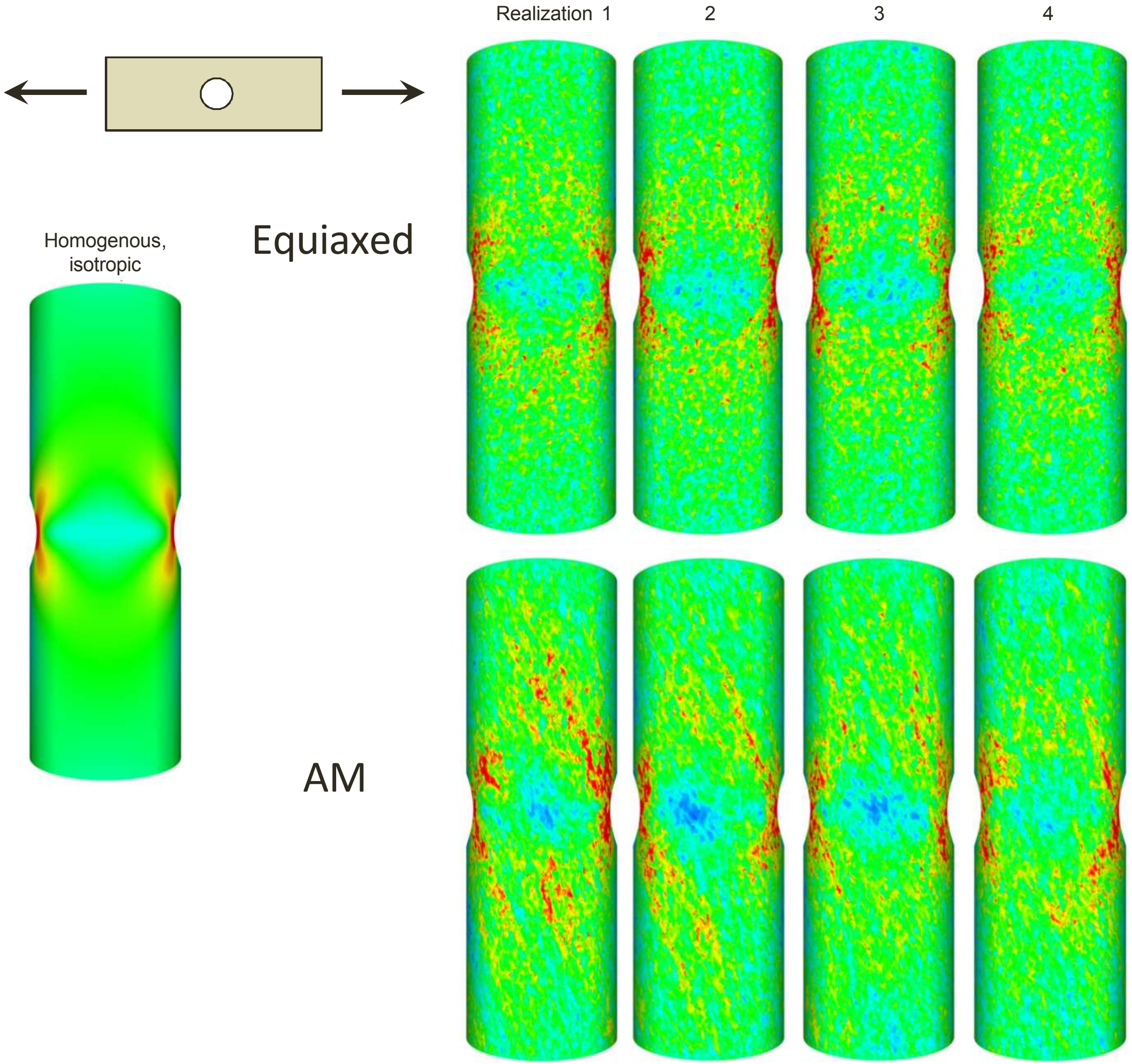
Microstructure Prediction (KMC)

- At the beginning of the build, relatively small, equiaxed grains form due to the baseplate serving as a heatsink
- As the build continues and heat accrues, grains begin to enlarge





Mechanical Performance – Stress results

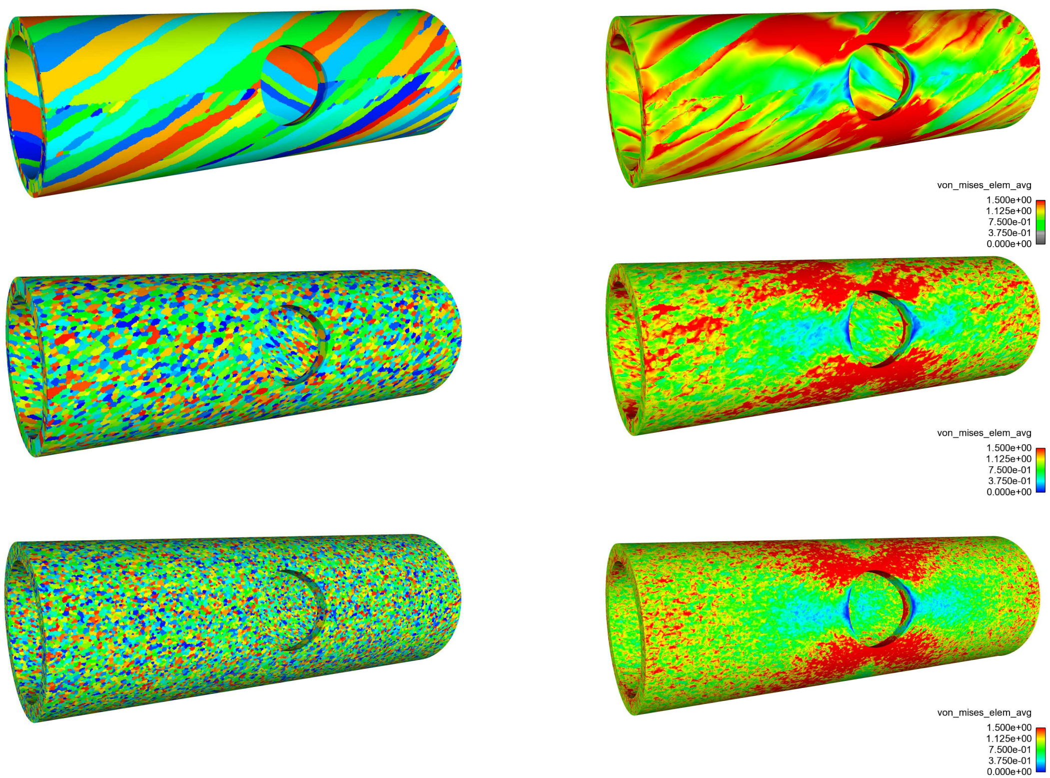


- Looking at effects of Additive Manufacturing microstructure (using KMC/SPPARKS) on mechanical performance
- 2 synthetic microstructures selected with 4 different microstructure realizations

Mechanical Performance – Stress results

- Looking at effects of laser speed on mechanical performance

grain structure *stress field in uniaxial tension*



laser speed = 5 voxels/mcs

laser speed = 10 voxels/mcs

laser speed = 20 voxels/mcs

Optimization and Uncertainty Quantification – Research Strategy

- Intelligent data collection & analysis of diverse sources (experiments, diagnostics, models) which requires filtering, selecting, sampling, & generating data to provide maximal information to create robust solutions in the face of uncertainties
- **Goal** - control Additive Manufacturing processes to achieve predictable material properties at all length scales
  - Optimization provides the interface between numerical simulation, experiments, data, and uncertainties
  - Map numerical capabilities to real experiments
  - Use data science to ask questions, not just answer questions
  - Use data science in each part of the process-property-structure map

Data Science Techniques in Born Qualified

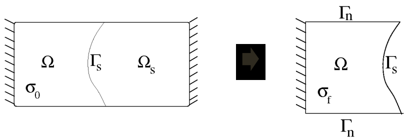
1. Statistical Analysis Techniques of both Process Data and Coupon/Part Data
2. Microstructural Analysis
3. Design of Experiments
4. Surrogate models
5. Data management/archiving and dimension reduction methods
6. Optimization: control, design of parts and processes, experimental design

- Process Development and Control (LENS, Powder Bed, Direct Write)
- Prototype Evaluation (Three exemplars)
- Predict Performance

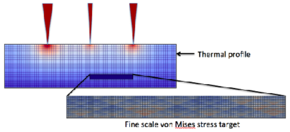
Optimization Strategy

- Address large scale optimization spaces
- Plagued by many uncertainties
- Perform verification and validation
- Implement different optimization formulations
- Implement complicated adjoint and Hessian-based sensitivities
- Address complex data: errors, inhomogeneities, incomplete, voluminous
- Many capabilities needed to enable a range of physics, multiscale

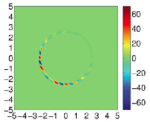
- Residual stress inversion implementation in Sierra-SD



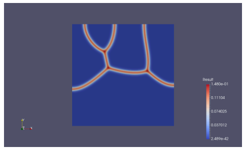
- Mortar multi-scale/parameter/physics optimization



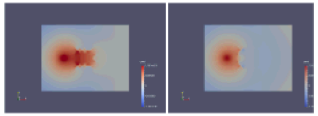
- Risk averse control



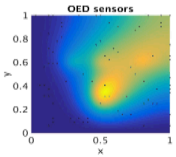
- Phasefield modeling and solidification



- Topological optimization thermal and Helmholtz

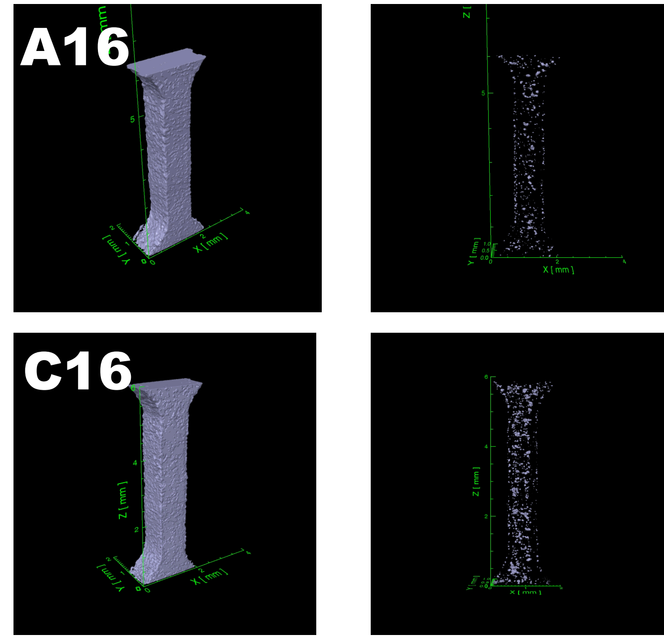


- Optimal experimental design, trace of Covariance

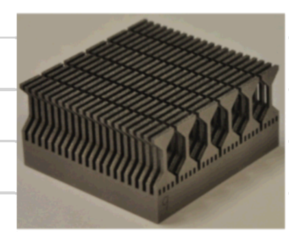


Example - Data Analysis of 120 Dogbone Specimens

- 15 scalar attributes, including density, mass, Z-score statistics, Top face, initial and unloading modulus, yield and tensile strength, ductility
- Correlation matrix with most important correlations in yellow, next most important in orange
- Few very high correlations but overall we expected more significant correlations



	Density	*Mass*	*Modulus, initial*	*Modulus, unloading*	*Strength, yield*	*Strength, ultimate*	*Ductility*
Density	1.00						
Mass	0.27	1.00					
Modulus, initial	0.00	0.26	1.00				
Modulus, unloading	0.03	-0.03	0.21	1.00			
Strength, yield	-0.04	0.25	0.76	-0.24	1.00		
Strength, ultimate	0.02	0.09	0.27	0.29	0.13	1.00	
Ductility	0.17	0.24	-0.34	-0.08	-0.33	0.18	1.00



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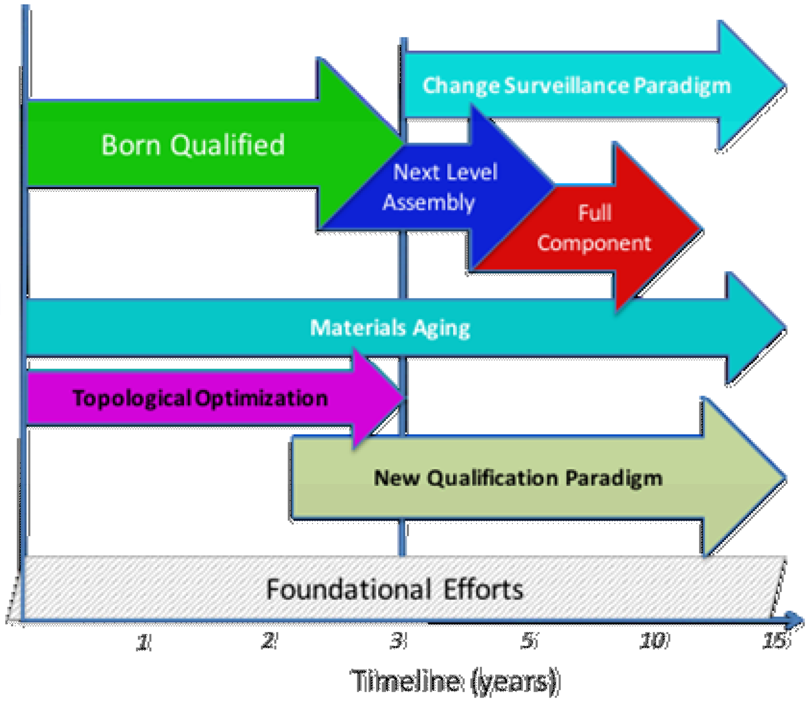
Closing Slide - Final Product and Impact

3 Yrs

FY16-FY18 Main Deliverables

1. Deliver science-base (models, in-situ and Alinstante measurements, Optimization, UQ) to predict AM part performance
2. Produce, test, and evaluate 3 single material exemplars where performance was predicted during manufacture using science-base



15 Years

- Science-Based & Born Qualified Design
  - Identify critical performance parameters, enhance design flexibility & agility
- Science-Based & Trusted Manufacturing
  - Verify manufacturing is the same every time
- Cost Effectiveness & Agility
  - Reduce number of builds by re-inventing component testing to validate, not discover, performance
- Improved Surveillance & Confidence in Lifetime Performance
  - Quantified birth data on all materials, track every material through its lifetime

Backups

Exemplar Selection Principles

- **Ceramic** and **Metal** exemplars each selected to provide unique material, design, and process challenges
- Applications with distinct opportunity for **enhanced functionality** using AM
- Applications that have **modest performance requirements**
- Applications that have **reliability which can be assessed** by measuring a limited number of relevant performance metrics / properties
- Consider **Additive Manufacturing shortcomings**, such as dimensional tolerances or surface finish which could dilute the focus from the goals