AM Discussion
National Academy of Sciences
Aeronautics and Space Engineering Board

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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.
Sandia National Security Mission Areas

Sandia’s Nuclear Weapons Mission

- Maintain the current U.S. nuclear weapons stockpile
  - Annual Assessment, Surveillance, Limited Life Component Exchanges, Significant Finding Investigations
- Sustain the stockpile into the future
  - Life Extension Programs, Alterations, Technology Maturations
- Steward the long-term viability of our capabilities, infrastructure, and operations
  - Persistent commitment to multi-disciplinary staff, state-of-the-art science, equipment, facilities, and safe/secure/quality/affordable operations

Defense Systems & Assessments Programs

- Space Mission
- Remote Sensing and Surveillance
- Integrated Military Systems

Energy & Climate

- Energy Research
  - ARPAE, SES, Chem Sciences, ASCR, CINT, Gen Bio Scien, BES, Material Science
- Climate & Environment
- Nuclear Energy & Fuel Cycle
  - Commercial Nuclear Power & Fuel, Nuclear Energy Safety & Security, DOE
- Managed Nuclear Waste Disposal

International, Homeland, & Nuclear Security

- Global Security
- Remote Sensing and Verification
- Homeland Defense & Force Protection
- Cyber and Infrastructure Security
- WMD Counterterrorism and Response
Q1 - How is additive manufacturing used in your field/application area today?

- Strong Nuclear Weapon Mission Area driver supporting future agile & affordable capabilities foundation for uncertain and unknown future
- Strongly supported as a corporate level objective by Sandia, NNSA, and DOE
- Multiple $M’s of projects are being funded at Sandia to explore and define Additive Manufacturing (AM) in support of our mission
Current Uses of AM at Sandia & KCNSC

- AM 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 at Sandia (NG’s) and KCNSC

Digital Manufacturing Initiative Impact

- **FY14**
  - 3D Printed development items made: 5,000
  - Total cost savings/avoided: $13.4M

- **FY15**
  - 3D Printed development items made: 12,000
  - Total cost savings/avoided: $22.6M

- **FY16**
  - 3D Printed development items made: 16,000
  - Total cost savings/avoided: $28.9M

Example
- Made additively out of glass-filled Nylon in 2 weeks
- Polymer AM version cost $2,758
- A metal (cut aluminum) version would have cost ~$27,000 and delivered in 3 months
- Had a metal mold been the only option, scheduled deliveries would have been missed by over 9 weeks.

- Exploratory efforts underway to evaluate when and if AM parts are adequate for use in weapons components
- Today’s Goal - Integrate AM early with design projects as we continue developing background and expertise
Q2 - How do you expect additive manufacturing to be used in 5 years?

- Continued growth in use of AM for Tooling, Gages, Fixtures, Molds and Mass Mocks
- First use in design and manufacture of weapons components
- Continued expansion of R&D in AM
- In 15 years new Qualification paradigm centered around AM
Answers to Questions:

• Q3 - Why have you chosen to move into additive manufacturing, and what technical capacities are you focused on?

• Q4 - What do you believe the major challenges are to more effective use of additive manufacturing?

➢ Overview of Sandia project titled:
Born Qualified Overview & Vision

- Strong NW 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 Certified*

- Born Qualified is a 15-Year Vision and this project is a 3-Year step in that direction

- Born Qualified also provides the long term ability for materials and components to be “Born to be Surveilled”
Paradigm Change

**Why Additive Manufacturing (AM) as driver for design, manufacturing, and qualification revolution?**

- Disruptive technology that allows simultaneous creation of part and material
- Inherently flexible and agile
- Ability to create near-net shape parts
- Ability to tightly control and monitor manufacturing process at the voxel level
- AM is ideal for low volume, high value, high consequence, complex parts
- Common challenge:
  
  “qualification and validation of materials and processes is an important dimension for integrating 3D printing into production. Removing this barrier is a recurrent theme” Mick Mahler, DARPA 8/2/2016
Qualification Approach

- Drive Qualification revolution by
  - Predicting Performance Probabilistically
  - Tightly controlling and monitoring process at voxel level
  - Accelerated cycles of learning
- Integrate validated, predictive capability with real-time and ex-situ diagnostic tools to create the Capability Base to realize UQ driven qualification of design and process
- Utilize Capability 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

Notional example of margins and uncertainty quantification for every part/material
Overview of our Approach

Using Metal Powder Bed Example

Quantify & Optimize

Performance Predictions

Exemplar Performance

Complex Data:
- Regression
- Classification
- Density Estimation
- Statistical Estimation
- Dim reduction

AM Process

In-Situ Measurements

Alinstantiate Properties

Property Aware Processing

Predict

Exemplar Models

Process Models

Materials Models

Measure

Densified Structure

Powder bed

Shear lip

Lack of fusion

Voids

Fracture across print layers

Failure at 2% elongation, Vendor 1 H900

100 µm
Accelerate Qualification

For New Designs and Materials, BQ will accelerate time from TRL 1-9 and MRL 1-9

R&D

Technology Maturation, Design Definition, & Production Engineering

- Accelerate Process Development
- Accelerate Material Assessment
- Simplify Production Capability Assessment
- Reduce Development Builds
- Accelerate Testing
Impact on Sandia

- **Goal** - After 6 years of investment, demonstrate concepts and approaches to reduce timelines for:
  - R&D from 3-5 to 2-4 years
  - Tech maturation from 12-15 to 8-10 years
  - Cost savings could easily approach 25% with reduction in development builds and testing

- **Funding** for the 15-year vision would allow us to:
  - Reach ultimate goal to be “Born” qualified
  - Take tech maturation and qualification beyond current process

- **Complications**
  - Not all components will use AM (nor should they)
  - New qualification paradigm will need to cover all manufacturing including traditional

- Already working in close collaboration with Sandia assessment and analysis groups
- Also communicating and collaborating with non-Sandia organizations to go beyond NW
AM has had a significant impact already with bright future

Significant investment planned in the next 5-10 years

Entering year 2 of 15-year Born Qualified vision to change design and qualification paradigm

Collaboration with universities, industry, and government agencies will be key to our success
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 **AM shortcomings**, such as dimensional tolerances or surface finish which could dilute the focus from the goals
AM Process Development

- Sandia Core AM Capabilities are world-class

**FY16 Highlights**

- Ceramic insulator ring process evaluation and down-selection was completed with build of initial coupons for evaluation
- Multi-material printing demonstration
- Direct Laser Melting of 99.5% \( \text{Al}_2\text{O}_3 \)
- Fabricated an initial set of valve housings using powder bed platform and performed dimensional analysis to obtain initial data on part relaxation and residual stress
- Teaming with collaborators for Neutron Diffraction measurements at LANSCE to look at defect structures
Science Challenges

- Develop innovative, real-time diagnostic tools of AM

**FY16 Highlights**

- Testbed capability needs and design #1 complete, construction underway
- Leveraging IR techniques developed in LDRD “Born Certified Additive Manufacturing: Predicting the Performance and Reliability of Laser Engineered Materials”
- Project with MIT initiated for mm-wave capability originally developed for plasma diagnostics
- Calibration strategy developed for IR temperature measurements
Science Challenges

- 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 AM materials

**FY16 Highlights**

- Designed and built a 1\textsuperscript{st} generation diagnostic artifact that is easily inspected to quantify printability limits and material / build properties
- Characterization techniques and tools identified
- Filed a Technical Advance and obtained approval for a patent filing regarding a non-destructive characterization technique for additively manufactured materials
- Filed a Technical Advance regarding a concept for a flexible automated robotic workcell for high-throughput materials and manufacturing process evaluation

![Diagram showing the process and material analysis cycle](image-url)
Science Challenges

- Ability to relate microstructure to bulk measurable properties to Translate AM process results to material properties & ultimately predict component performance

FY16 Highlights

- Phase Field solidification modeling: multiple grains/orientations, solid-liquid and solid-solid interfaces, far-field heat reservoirs
- Random walk model of electrical conductivity applied to 3D grain structures, working on comparison to experiments on AM cylinders
- Kinetic Monte Carlo models improved to do more complex geometries and scan patterns
- Developing capability to atomistically predict thermal conductivity in powder beds to improve KMC and continuum models
Science Challenges

- Ability to incorporate **material & process variability in AM process and exemplar models** to predict performance probabilistically, calibrate models, and optimize design

**FY16 Highlights**

- Initiated various modeling efforts to characterize LENS and molecular dynamics of powder beds coupled to thermal models
- Multiscale material modeling to understand difference between Type 1 and Type 2 residual stress (macroscale vs microscale)
- Devoted considerable coordination efforts to form interdisciplinary teams across the entire project that to date have resulted in deeper understanding of AM process, numerical modeling at different scales, mathematical analysis to achieve optimal designs, quantification of uncertainties, and the ultimate integration
Science Challenges

- **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

**FY16 Highlights**

- Initiated development of foundational capabilities for PDE-constrained optimization under uncertainty, with capability established for phase-modeling, solidification, multiscale phenomena, and residual stress inversion

- Completed initial data characterization of powder-bed AM tensile bars; statistical analysis of multiple attributes is now being performed