AFRL

THE AIR FORCE RESEARCH LABORATORY

LEAD | DISCOVER | DEVELOP | DELIVER

"The Building Block Approach in the 21st Century - the role of ICME & UQ"

5 January 2015

Manufacturing & Industrial Technologies Division

AFRL/RXM

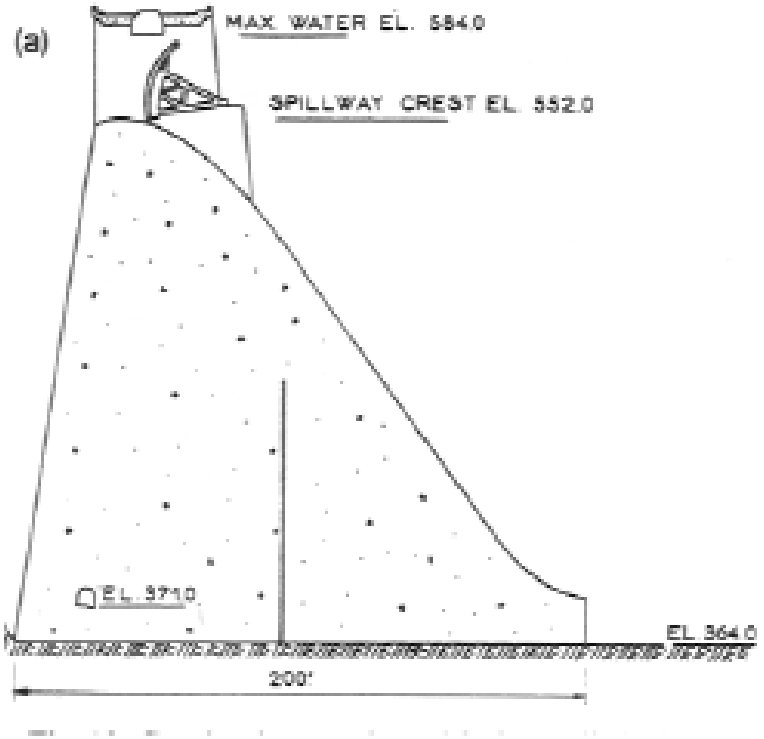
AF ManTech UNITED STATES AIR FORCE

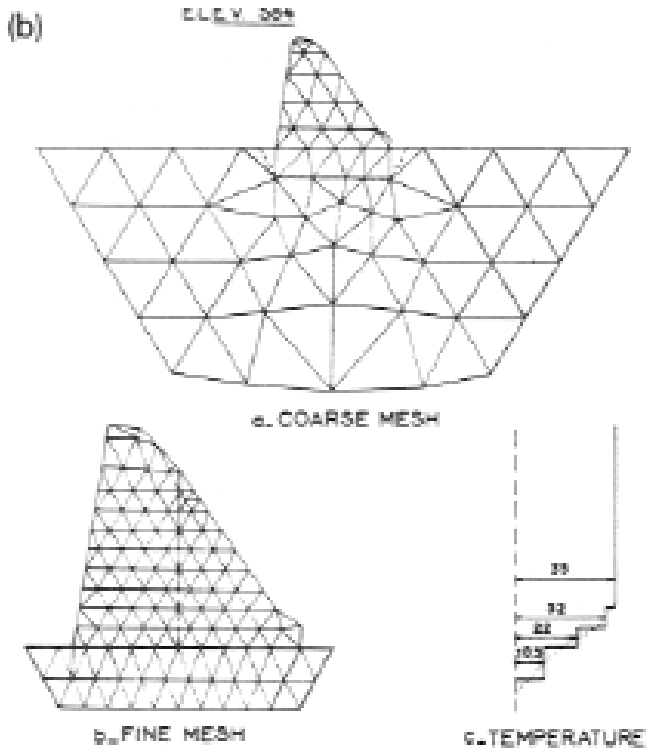
Topics

- Context
- The Building Block Method
- The Philosophy of Design
- Materials & Processes to the Rescue
  - Integrated Computational Materials Engineering
  - “Defect Species:” An example from Additive Manufacturing
- Steps towards a New Design Paradigm
- Takeaways

Norfolk Dam, Arkansas

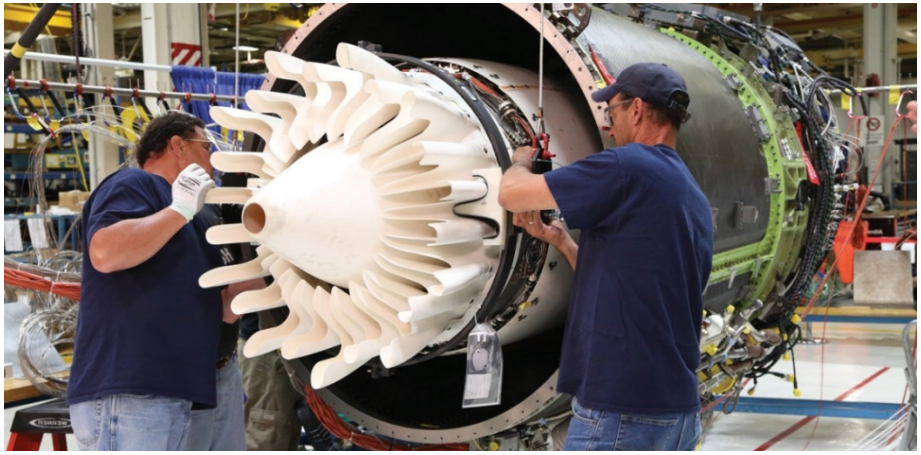
It’s the decision, not the model





Clough, R. W., “The Stress Distribution of Norfork Dam”, Institute of Engineering Research, Final Report to the Corps of Engineers, March 1962, Revised August 1962.

Materials & Processes = Performance



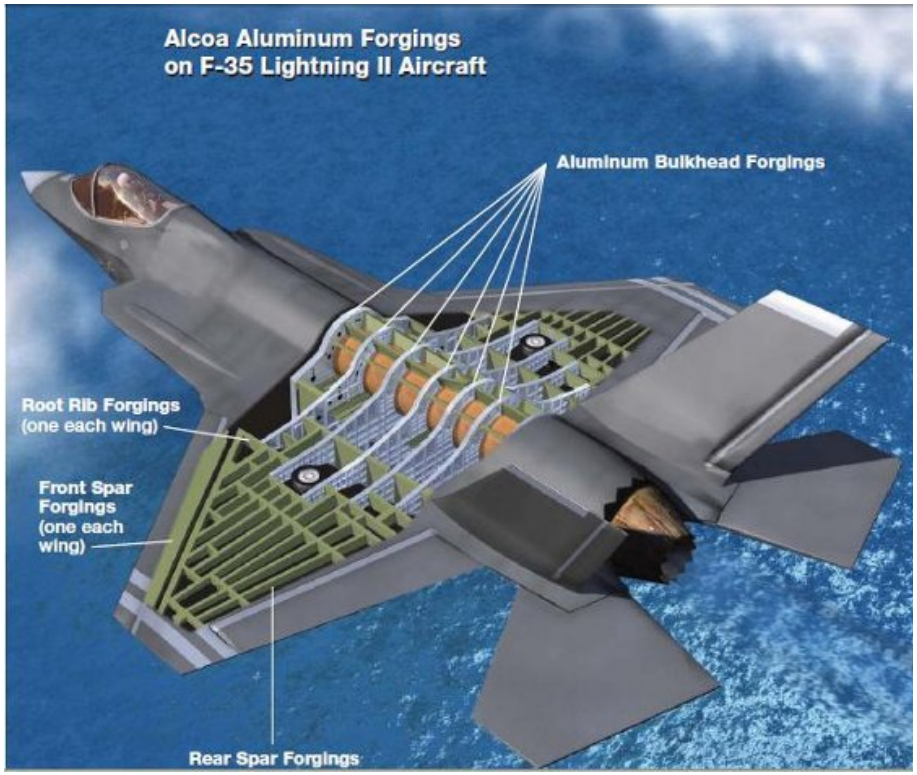
GE's Passport engine - the commercial debut of ceramic-matrix composites

CFM LEAP engine – Resin transfer molded fan blade

HondaJet – unitized composite fuselage

Increased use of Composites

Materials & Processes = Performance



Large Forgings

Additive Manufacturing

"Advanced manufacturing technologies are out-pacing structural analysis capabilities"

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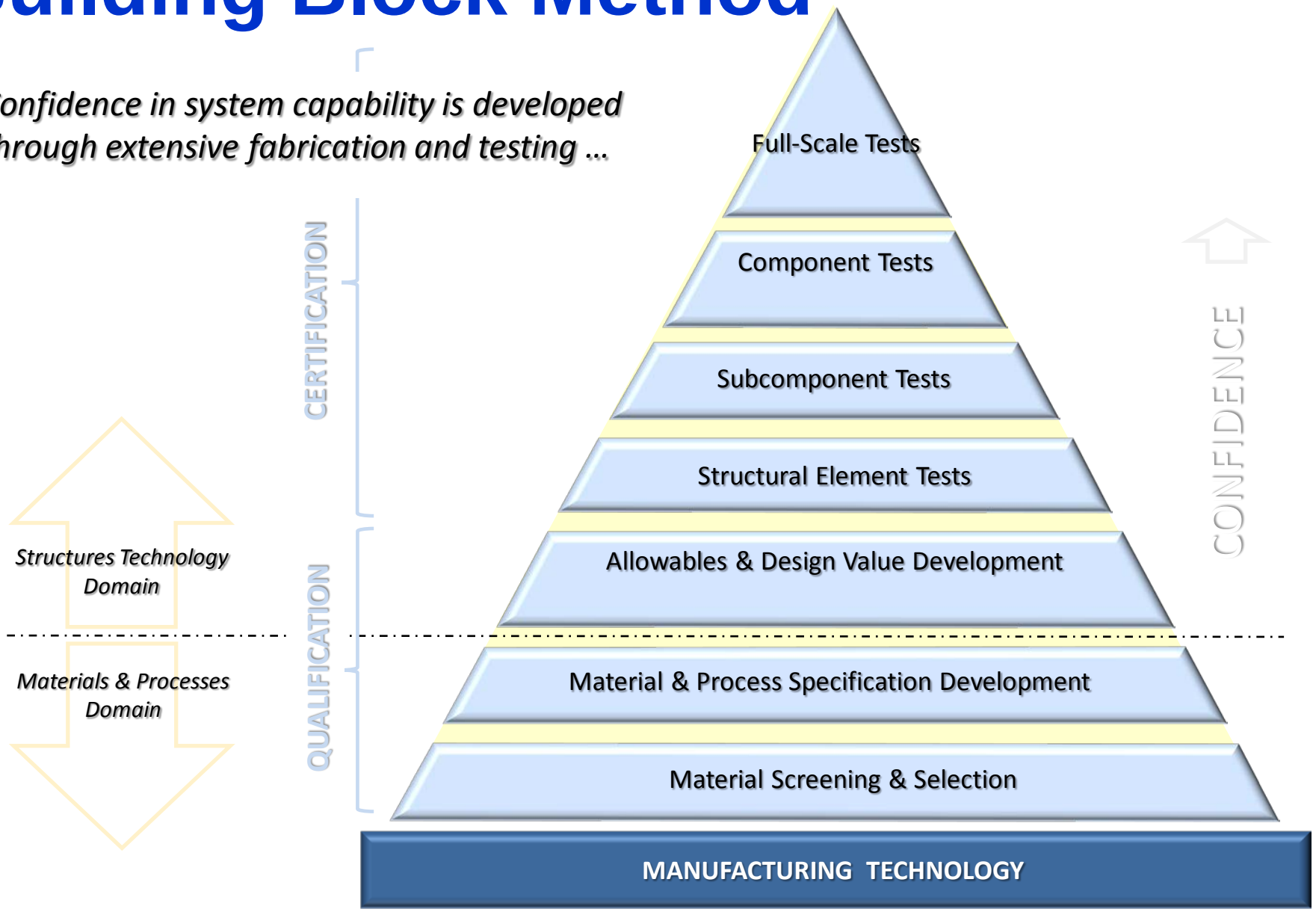
Building Block Method

Confidence in system capability is developed through extensive fabrication and testing …



COURTESY OF DAVE BOWDEN

Building Block Method

Full-scale tests

Component tests

Sub-component tests

Structural elements tests

Allowable development

Material specification development

Material screening and selection

Analysis validation

Design-value development

Material property evaluation

~ size of structural test programs

1980s	2000s
2	2
2	15
25	2,500
500	10,000
5,000	100,000

Major growth in cost & time

Building Block Method

Full-scale tests

Analysis validation

~ size of structural test programs

1980s	2000s
2	2
	15
	2,500
	10,000
5,000	100,000

Works fairly well for *evolutionary* design configurations, materials & manufacturing processes

Works less well when aircraft mission profiles & retirement dates *change*

Works poorly for *revolutionary* design configurations, materials & manufacturing processes

Allowable development

Material specification development

Material screening and selection

Material property evaluation

Major growth in cost & time

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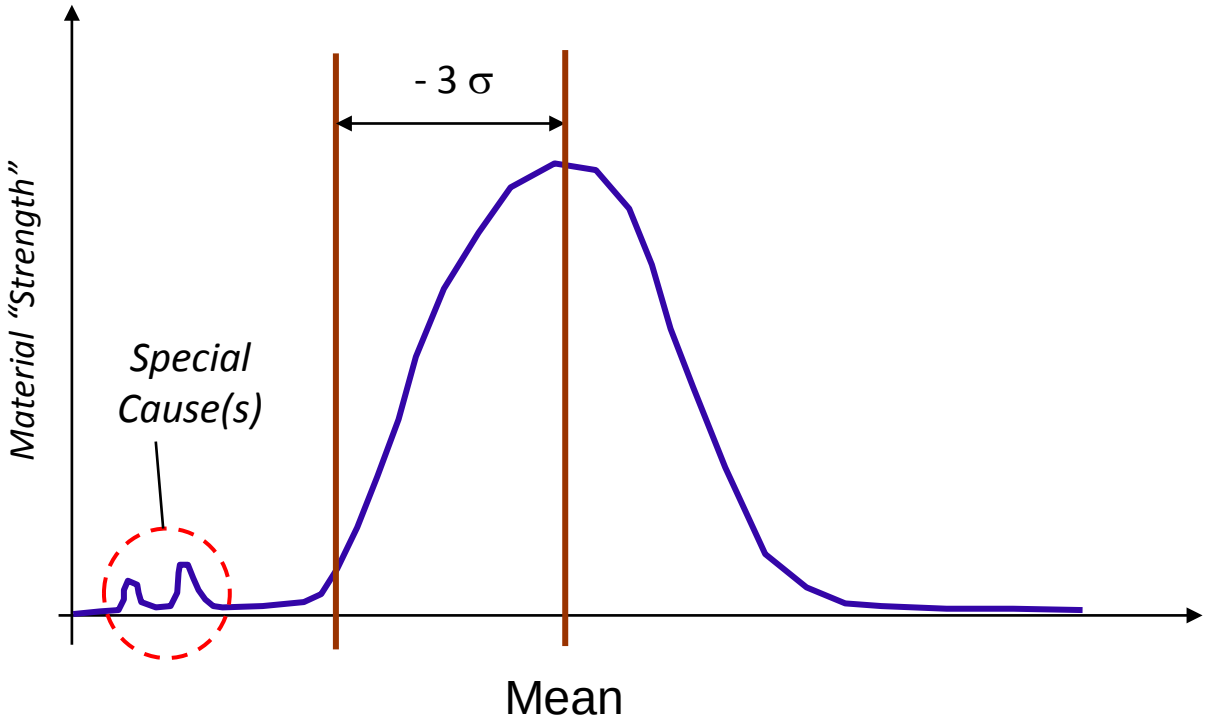
Philosophy of Design

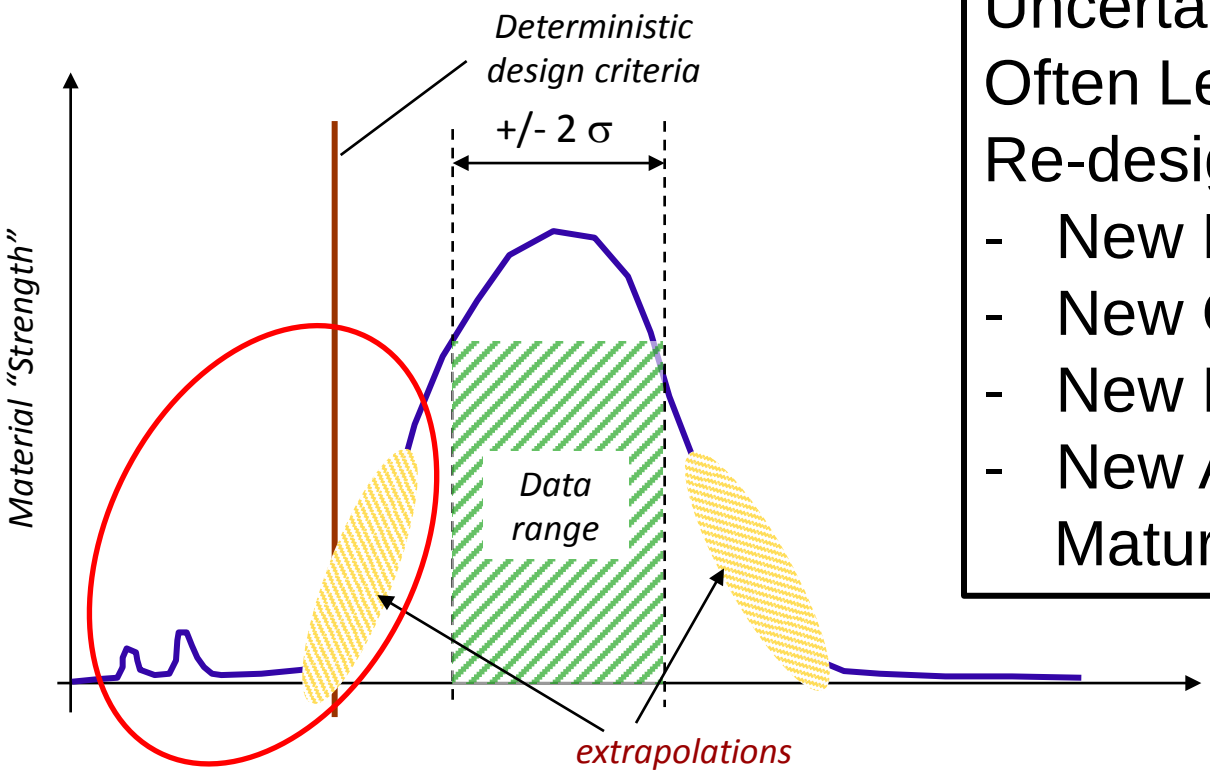
Common to All Structural Materials



Designs are Based on *Minima* - <u>not</u> *Averages*

Courtesy Michael Gorelick, FAA

We don't know what we don't know!



Uncertainty in Minima Often Lead to Expensive Re-designs, Especially:

- New Materials
- New Geometries
- New Processes
- New Application of Mature Processes

***Minima* are extrapolated - not measured**

Courtesy Michael Gorelick, FAA

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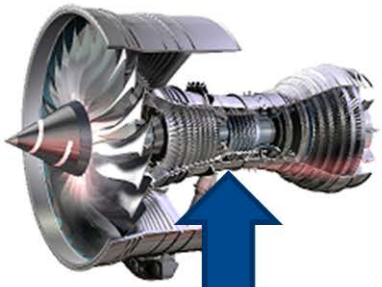
ICME is becoming a critical enabler for reducing the design/make cycle

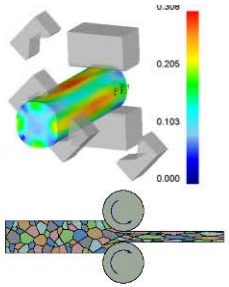
SX Casting | **Forging** | General Casting | Composites | Fabrication | Forming

Design Requirements

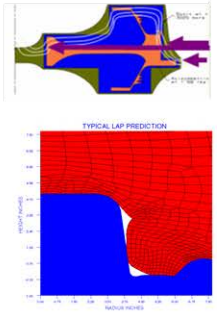


Alloy Design

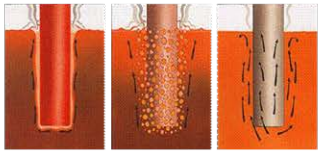
Cogging



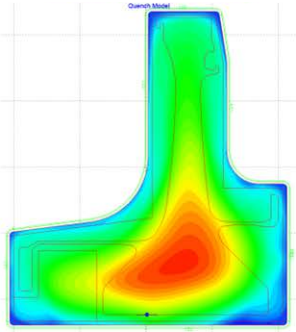
Forging



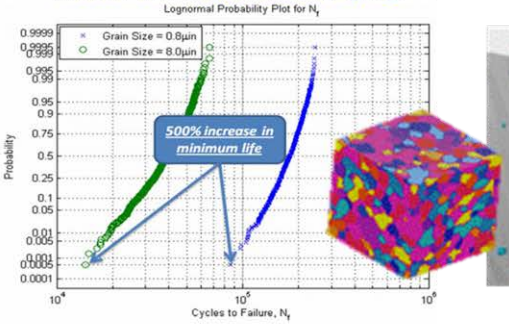
Quenching



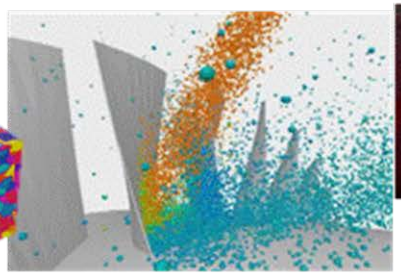
Heat treatment



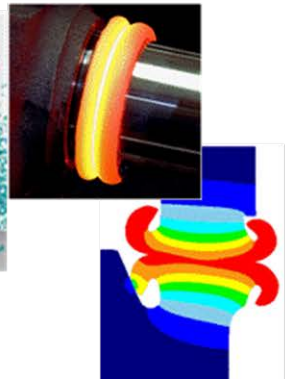
Material Properties & Lifing



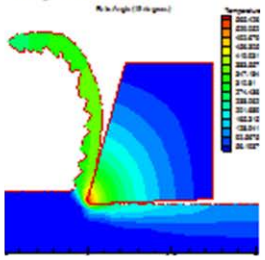
Surface Treatment



Joining



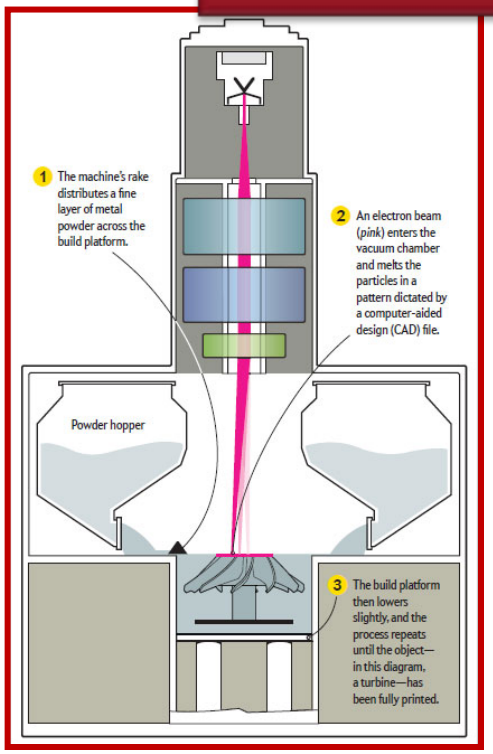
Machining



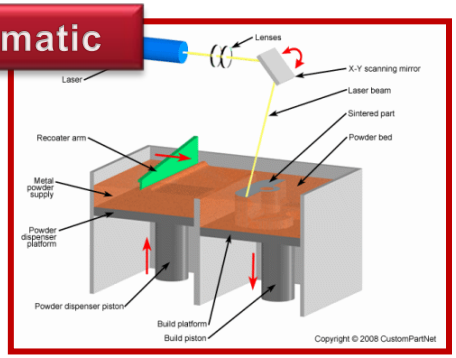
Courtesy John Matlik, Rolls Royce

Powder Bed Fusion

Process Schematic

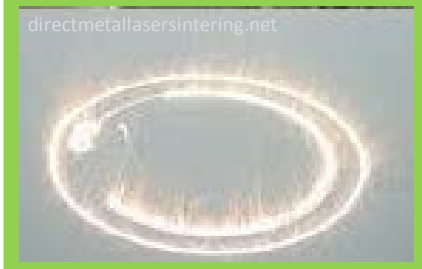


nature.com/scientificamerican/journal/



Equipment

Work in Process



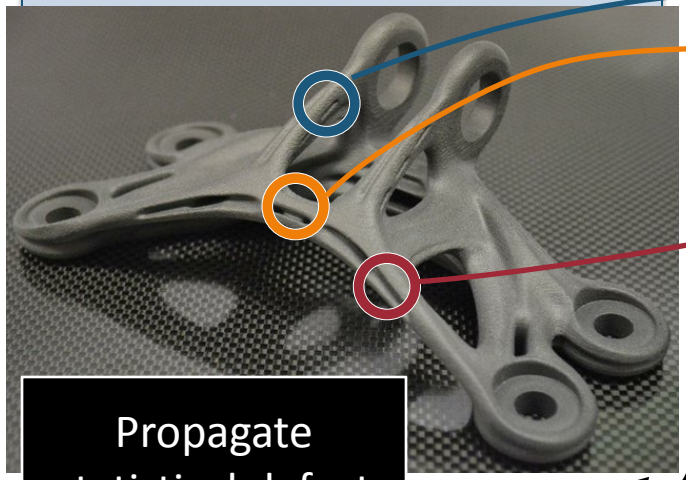
An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed

Finished Parts

Location-Specific Design: Building Block Vision & Motivation

Defect Likelihood = *f* (geometry,process)

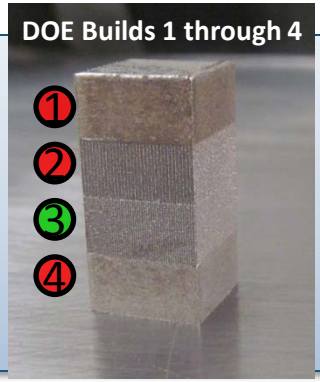
Optimized Design is Location-Specific and Assured through Digital Data & Informatics



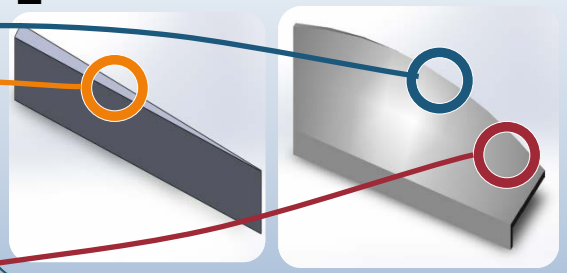
Propagate statistical defect prevalence and uncertainty

Phased Approach:

1
Effect of ***Process Parameters*** on Defect Species: DOE of Simple Shapes



2



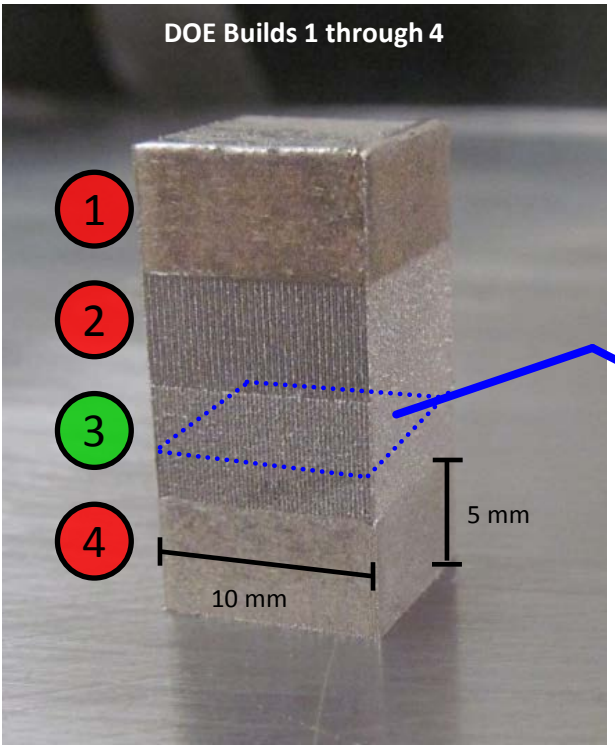
Effect of ***Geometry*** on Defect Species: "Canonical" Features connect process to feature

3

Effect of ***Process & Geometry*** on Defect Species

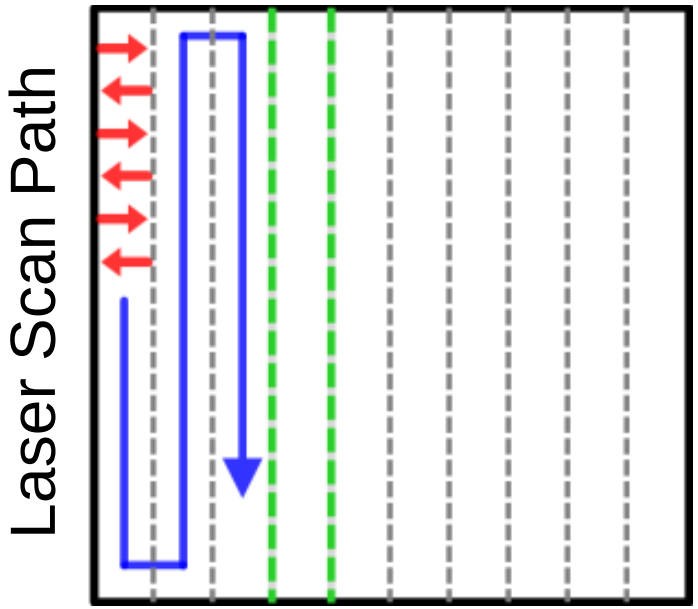
Develop Framework for Visualization & Analytics: integration of process data, in-situ data, inspection data with process models

Effect of Process Parameters on Defect Species



DOE # 3

- **Laser power (195 W)**
- **Laser diameter (70 µm)**
- **Laser speed (1,000 mm/s)**
- **Hatch spacing (0.1 mm)**
- **Stripe width (5 mm)**



hatch spacing

laser speed

stripe width

$$G = \frac{P}{S * H}$$

Where:
G=Global Energy Density
P= Laser Power
S= Hatch Speed
H=Hatch Spacing

Global Energy Density (GED): energy input density (J/mm^2) as laser beam is rastered across powder bed surface at constant speed

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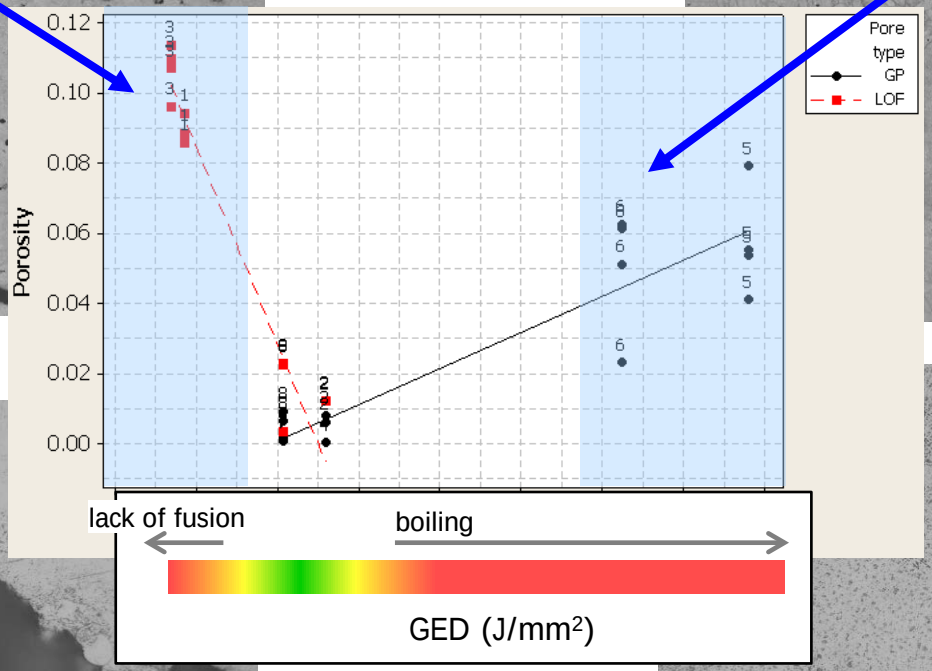
COURTESY OF MICK MAHER

Build Trials: As Built Defects

Low Energy- Lack Of Fusion

High Energy- Keyhole Porosity

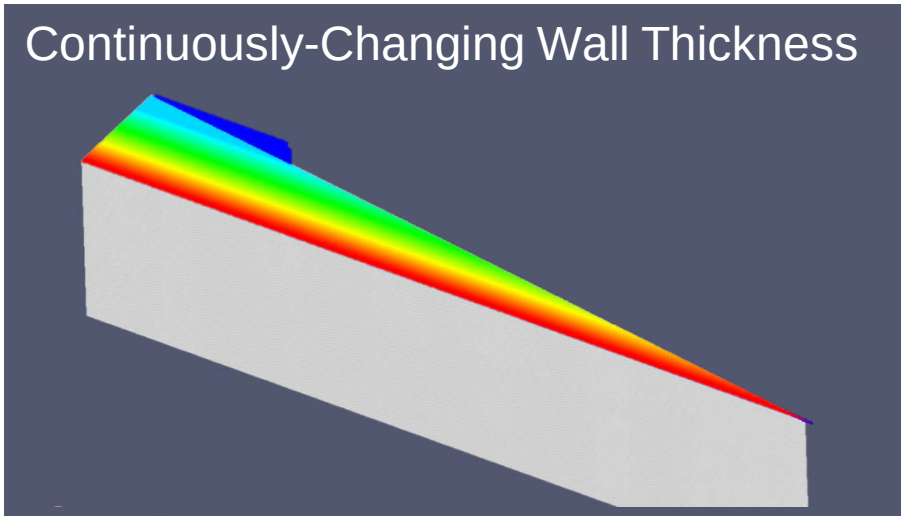


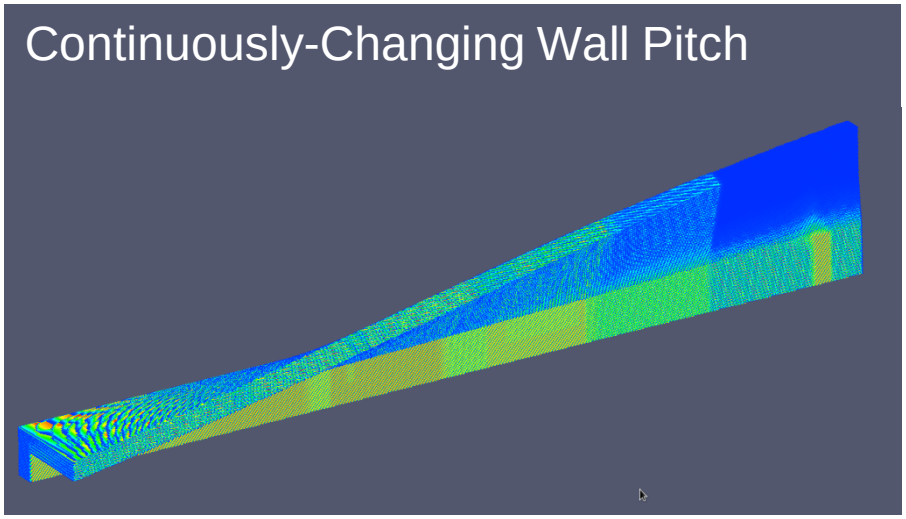
~ 150 μm

Avg = 22 μm

COURTESY OF MICK MAHER

Effect of Geometry on Defect Species



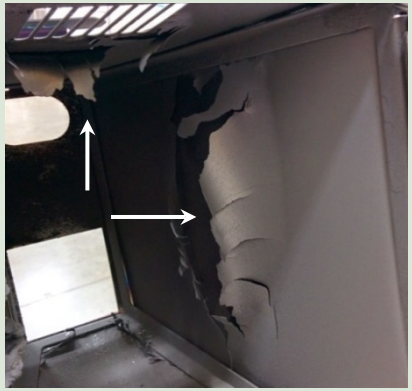


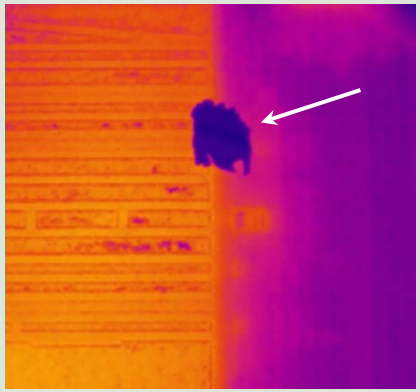
Process maps (beam current) for example geometries

Systematically vary geometrical features & local process parameters and catalog defect species

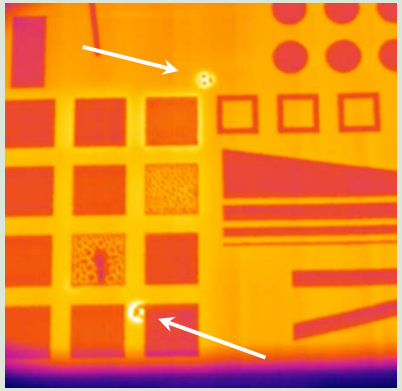
Defects in Full Scale Builds

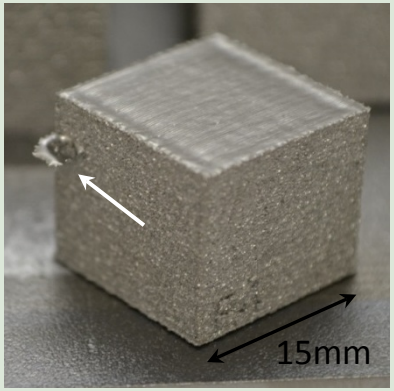
Metallization: build-up and contamination



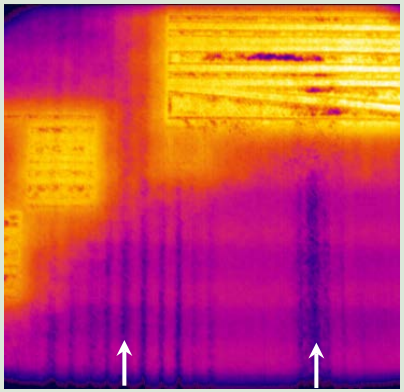


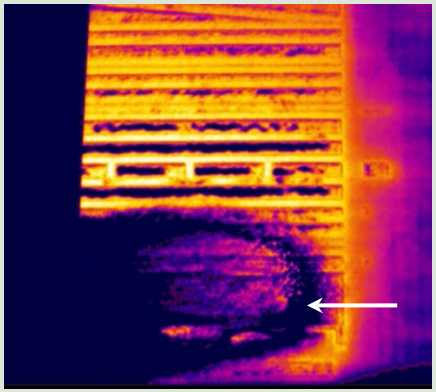
Anomalous melting

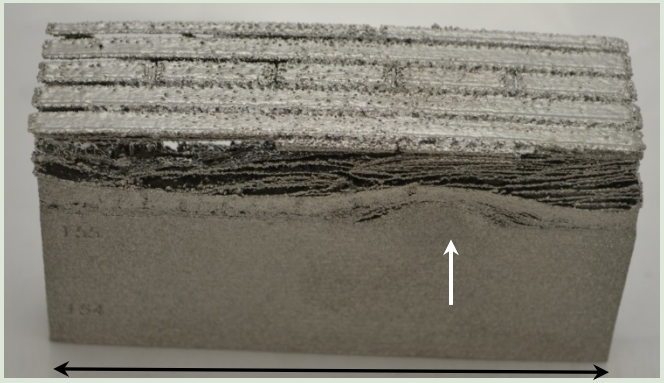




Raking: Powder distribution and swelling



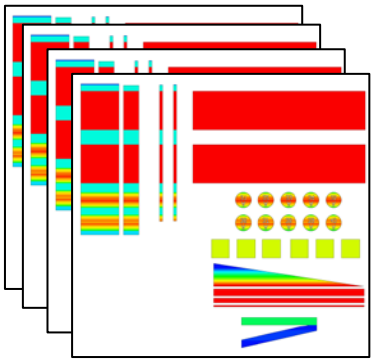




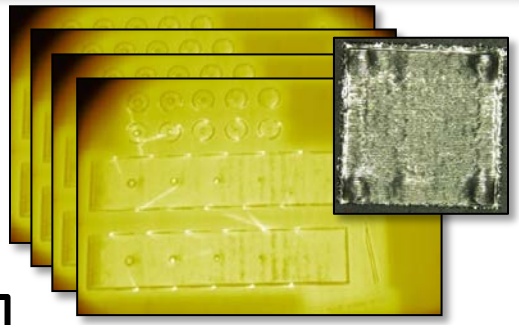
Scale Matters!

Fully Integrate Process Data & Models with Lifing Models

Beam Power & other parameters

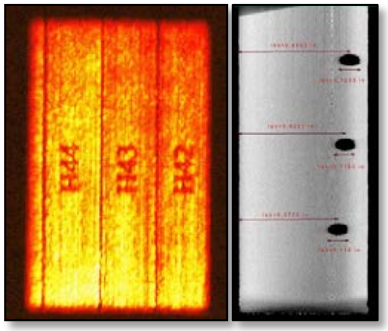


In situ data (Log-files, IR, Optical images)



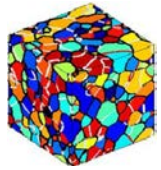
Intended Geometry

Process Data

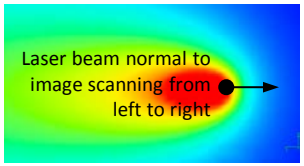


Characterization (Destructive & Non-destructive)

μ-structural Models

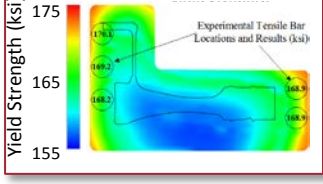


Process Models

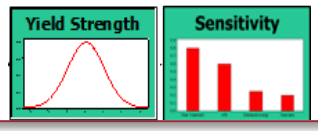


Process/Lifing Models

Property Models



Probabilistic Design and Performance Lifing



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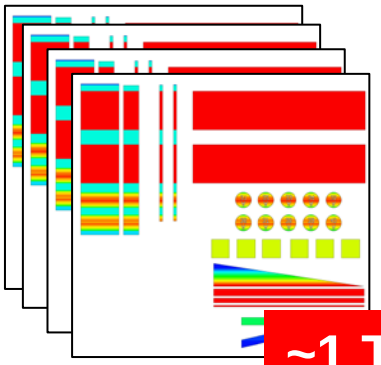
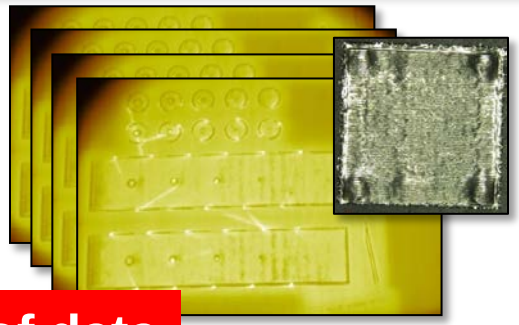
Fully Integrate Process Data & Models with Lifing Models

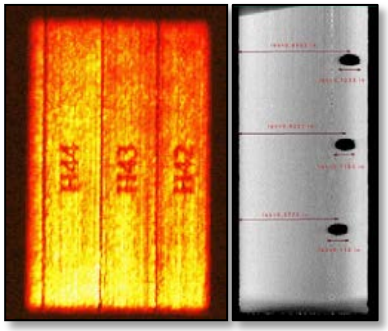
Beam Power & other parameters



In situ data (Log-files, IR, Optical images)



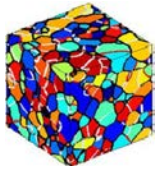
~1 Terabyte of data per Build!



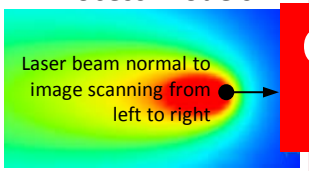
Characterization (Destructive & Non-destructive)

Intended Geometry

μ-structural Models

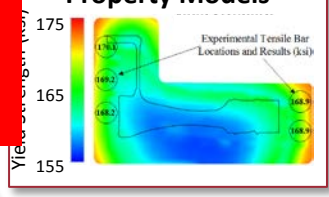


Process Models

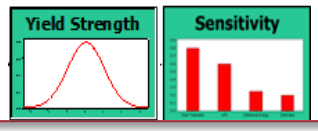


Over 60 Process Variables

Property Models



Probabilistic Design and Performance Lifing



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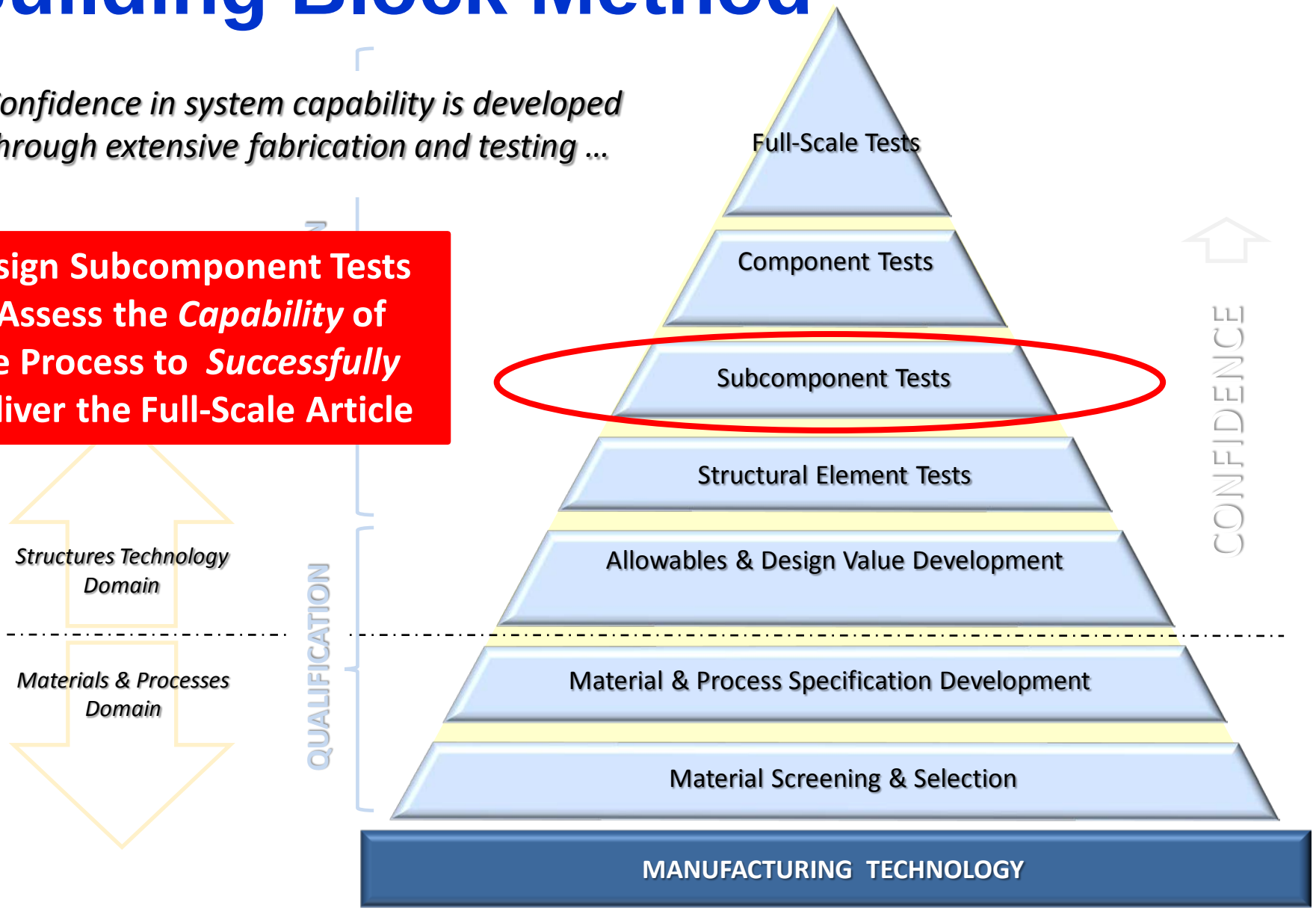
- ***Steps towards a New Design Paradigm***
- Takeaways

Building Block Method

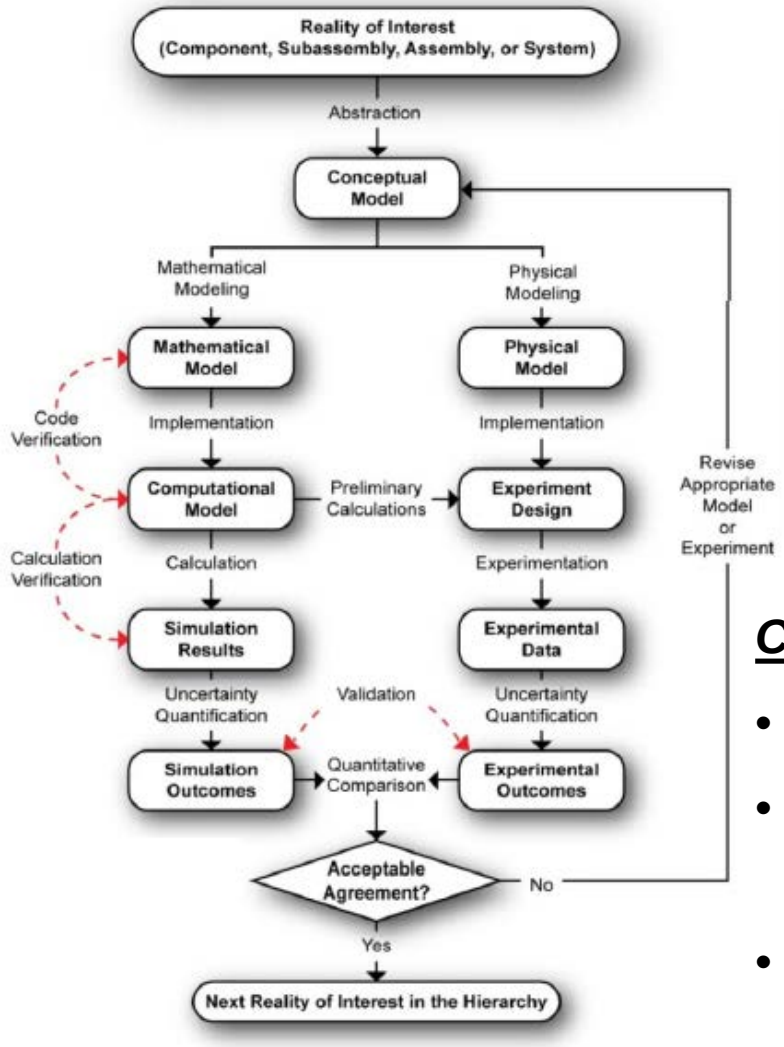
Confidence in system capability is developed through extensive fabrication and testing …

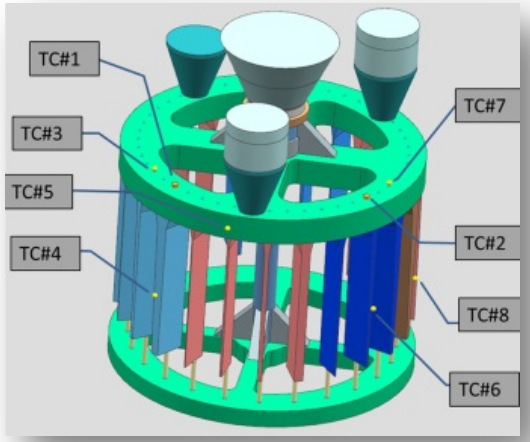
Design Subcomponent Tests To Assess the *Capability* of The Process to *Successfully* Deliver the Full-Scale Article



COURTESY OF DAVE BOWDEN

Change the Testing Paradigm: Use ICME to Design - 3 σ Validation Experiments that Delineate *Process Capability*





Combined Computational/ Experimental Approach

- **Vary material & process parameters**
- ***Simulate fine-scale behavior, homogenize to higher level models***
- **Estimate impact of M&P variability on system performance**
- **Iterate**

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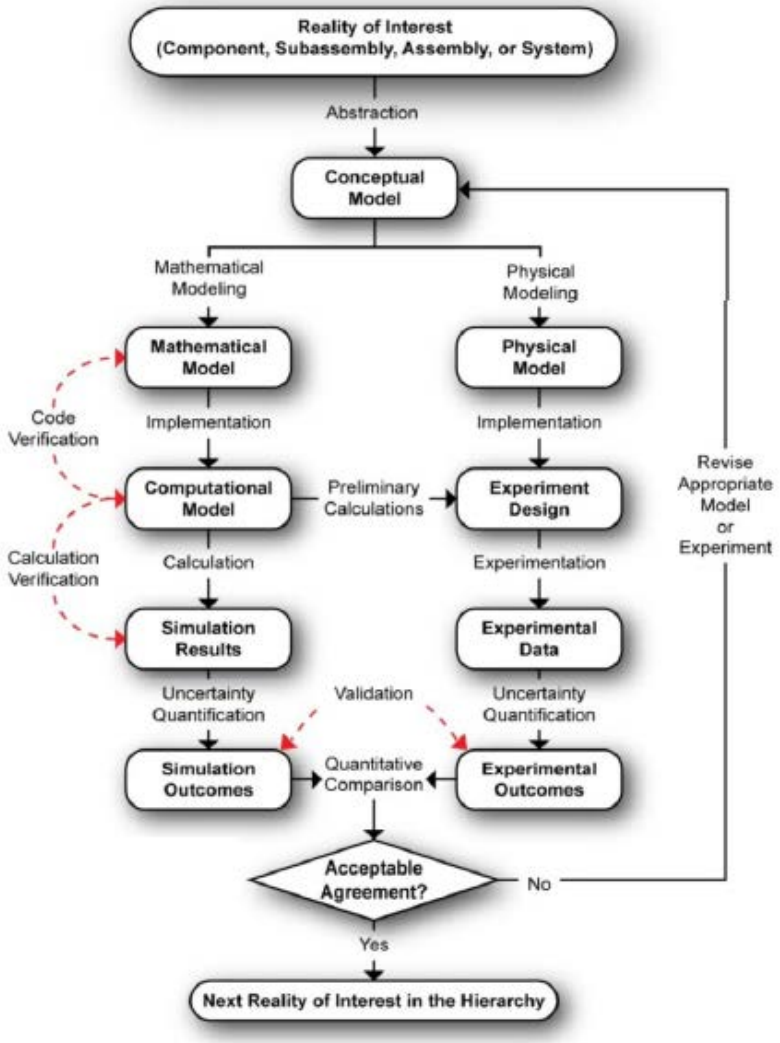
Change the Testing Paradigm: Use ICME to Design - 3 σ Validation Experiments that Delineate *Process Capability*



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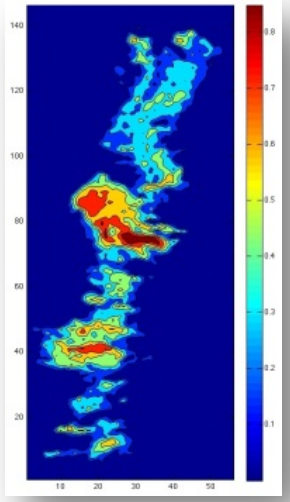
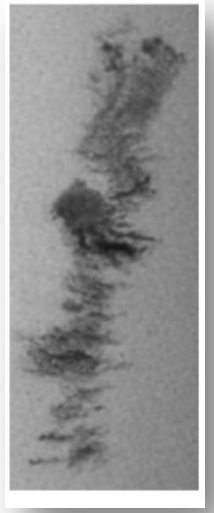


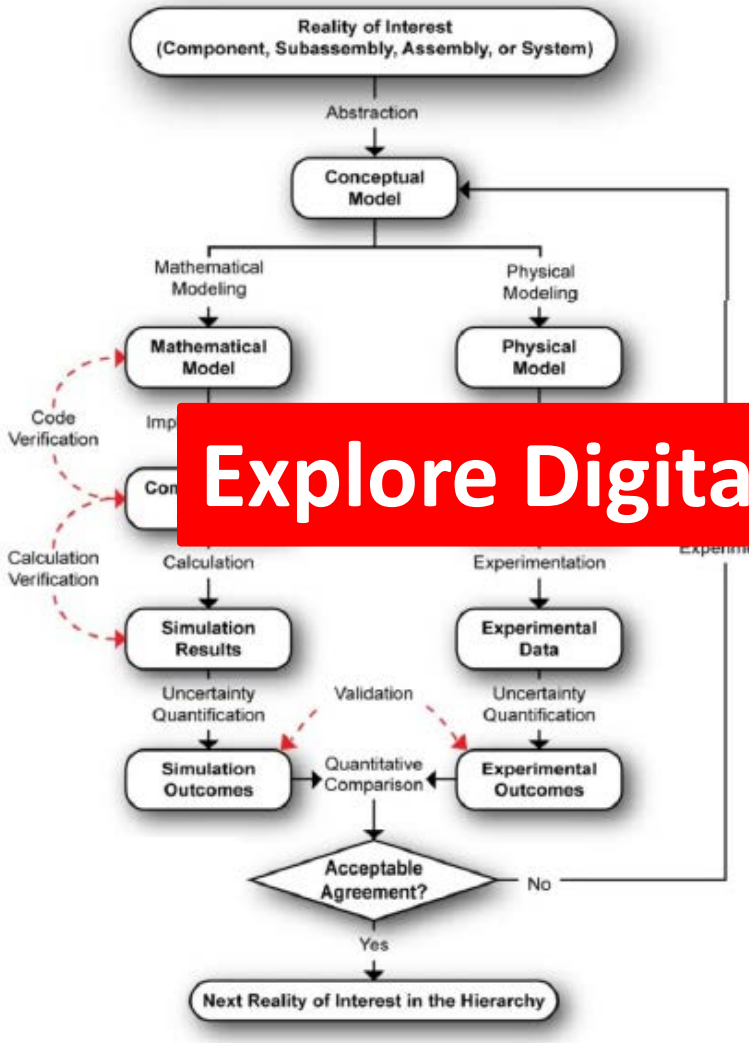


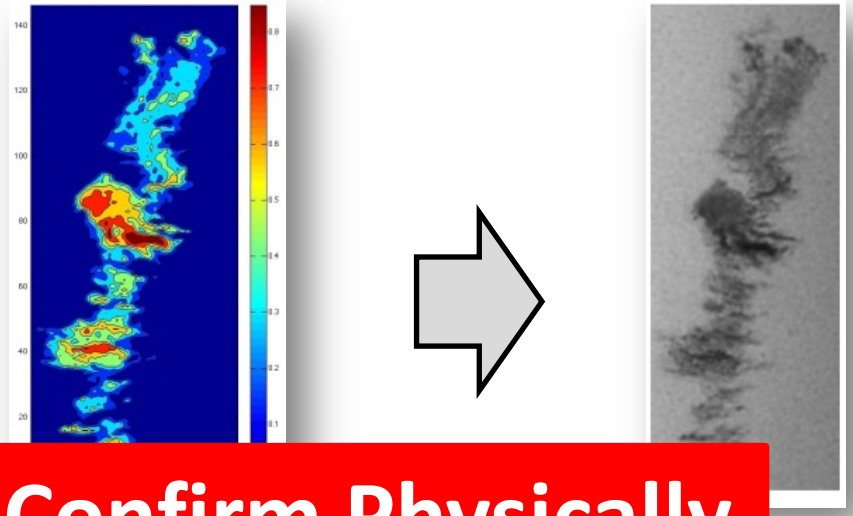
Model Predictions Of Defect Occurrences

X-ray Inspection

Use ICME to understand processing effects & sensitivity due to scale up in size, manufacturing volume, and component complexity

Change the Testing Paradigm: Use ICME to Design - 3 σ Validation Experiments that Delineate *Process Capability*





Explore Digitally – Confirm Physically

Of Defect Occurrences

Inspection

Use ICME to understand processing effects & sensitivity due to scale up in size, manufacturing volume, and component complexity

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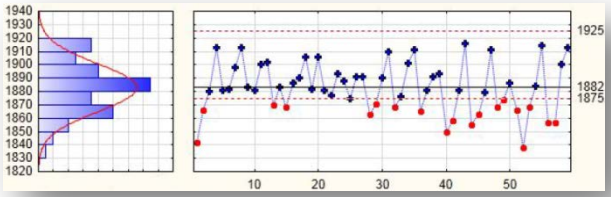
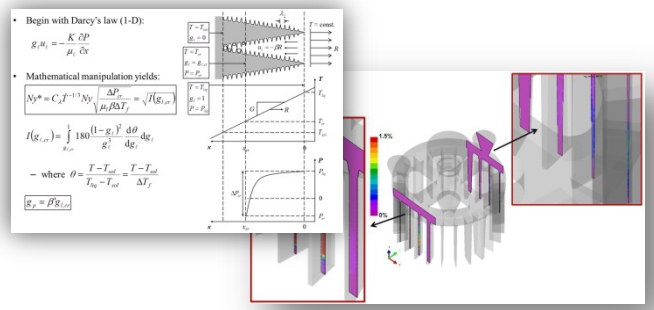
TODAY: Fully Integrate Manufacturing with Design & Risk Analyses

– **Data Informatics/Analytics**
  - Empirical/data-driven modeling
  - e.g. ICME, statistical process modeling, etc.

ICME = Integrated Computational Materials & Manufacturing Engineering

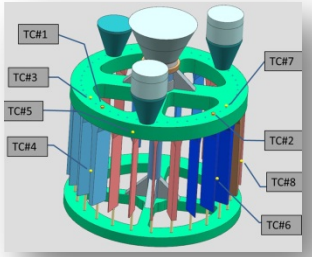


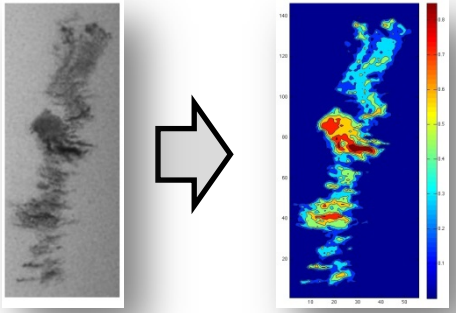


– **Material/Process Modeling and Simulation**
  - Advanced physics-driven modeling
  - e.g. ICME, FEA, CFD, etc.

FEA = Finite Element Analysis; CFD = Computational Fluid Dynamics

– **Intelligent Process Monitoring/Control**
  - Linking math/physics models to process control
  - e.g. process monitoring parameters as model input



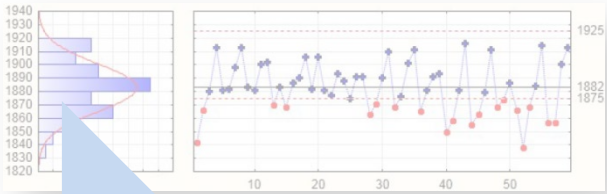


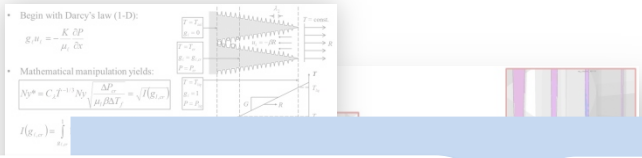
– **Integrated Quality Testing**
  - Inform modeling & simulation with quality test results
  - e.g. calibrating process models & process control

TOMORROW: Link Materials & Manufacturing to Fleet Management

– **Data Informatics/Analytics**
  - Empirical/data-driven modeling
  - e.g. ICME, statistical process modeling, etc.

ICME = Integrated Computational Materials & Manufacturing Engineering





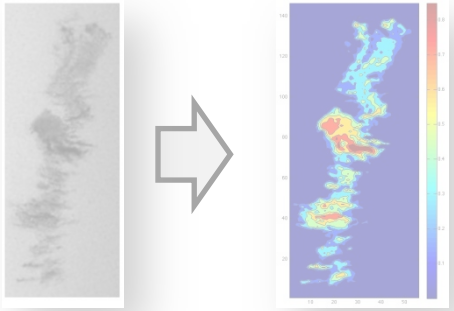
– **Material/Proce eling**

Quantifying & Understanding Manufacturing Variability

Performance-based Decision Making in Manufacturing

State Awareness & Prediction for Each Tail Number in the Fleet

- e.g. process monitoring parameters as model input



– **Integrated Qua Testing**
  - Inform modeling simulation with quality test results
  - e.g. calibrating process models & process control

Topics

- Context
- The Building Block Method
- The Philosophy of Design
- Materials & Processes to the Rescue
  - Integrated Computational Materials Engineering
  - “Defect Species:” An example from Additive Manufacturing
- Steps towards a New Design Paradigm
- *Takeaways*

Takeaways

- **The Building Block Approach doesn't work well for new M&P**
  - **Surprises happen too frequently**
  - **We're leaving too much information on the table**
- **Link Mfg to Design - it's much more than Design for Mfg!**
  - **Fully exploit the emerging capabilities of ICME models**
- **Change the testing paradigm to better elucidate minima**
  - ***Design validation tests that accurately estimate the relevant physics of the full-size article***
- **Change the value proposition for manufacturing!**
  - **Quantify the impact of manufacturing variability on system capability**
  - **Reduced Design Iterations = $$$$$$$ in cost savings**
- **It's not the model, it's the decision you make using the model results!**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