A Transformative Epoch in Material Science & Engineering and Manufacturing

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Presentation Themes

- **The PEST Challenge -** Political, Economic, Social, & Technological (PEST)
- **Global Environment**
- **Industry 4.0**
- **Trends in Manufacturing & MS&E**
- **Knowledge Management –** The Great Enabler & Challenge
- **Exemplar Technologies**
- **Crystal Ball – What Might the Future Hold**

Complex Political, Economic, Social and Technological Forces Shape Global MS&E and Manufacturing

Political

- Democracy Vs Authoritarian
- Stability & Rule of Law
- Immigration Policy
- Alliances – Military, Reginal, Economic
- Mega Companies
- Public-Private Consortium

Economic

- Manufacturing Vs Service
- Agrarian - Industrialized
- Gross Domestic Product
- Distribution of Wealth
- Super Rich & Mega Corps.
- Trade & Tariffs
- Workforce - Knowledge Skills & Abilities

Political | Economic

PEST

Social | Techno-logical

Social

- Demographics - Sex, Age, Education, Race, & Ethnicity, Education
- Religion & Culture
- Fertility Rate
- Xenophilia - Xenophobic

Technology

- Industry 4.0 -> 5.0
- Artificial Intelligence & Machine Learning
- Modeling & Simulation
- Diverse Data Convergence
- In situ Sensor

Global Environment
Most Populated Countries

- Global Population: **7 billion** people in 2011; **8 billion** people in 2022
- **35%** of the world lives in **two countries**
- **56.8%** of the world's population live in **ten countries**
- **56.8%** these people live in Urban areas.

#	Country	Population 2025	Density (P/Km²)	Land Area (Km²)	Fert. Rate	Median Age	Urban Pop %	World Share
1	India	1,463,865,525	492	2,973,190	1.94	28.8	37.10%	17.78%
2	China	1,416,096,094	151	9,388,211	1.02	40.1	67.50%	17.20%
3	United States	347,275,807	38	9,147,420	1.62	38.5	82.80%	4.22%
4	Indonesia	285,721,236	158	1,811,570	2.1	30.4	59.60%	3.47%
5	Pakistan	255,219,554	331	770,880	3.5	20.6	34.40%	3.10%
6	Nigeria	237,527,782	261	910,770	4.3	18.1	54.90%	2.89%
7	Brazil	212,812,405	25	8,358,140	1.6	34.8	91.40%	2.59%
8	Bangladesh	175,686,899	1,350	130,170	2.11	26	42.60%	2.13%
9	Russia	143,997,393	9	16,376,870	1.47	40.3	75%	1.75%
10	Ethiopia	135,472,051	135	1,000,000	3.81	19.1	22.50%	1.65%

Source: Worldometer, 2025 data, https://www.worldometers.info/world-population/#religions, Downloaded 8/26/25

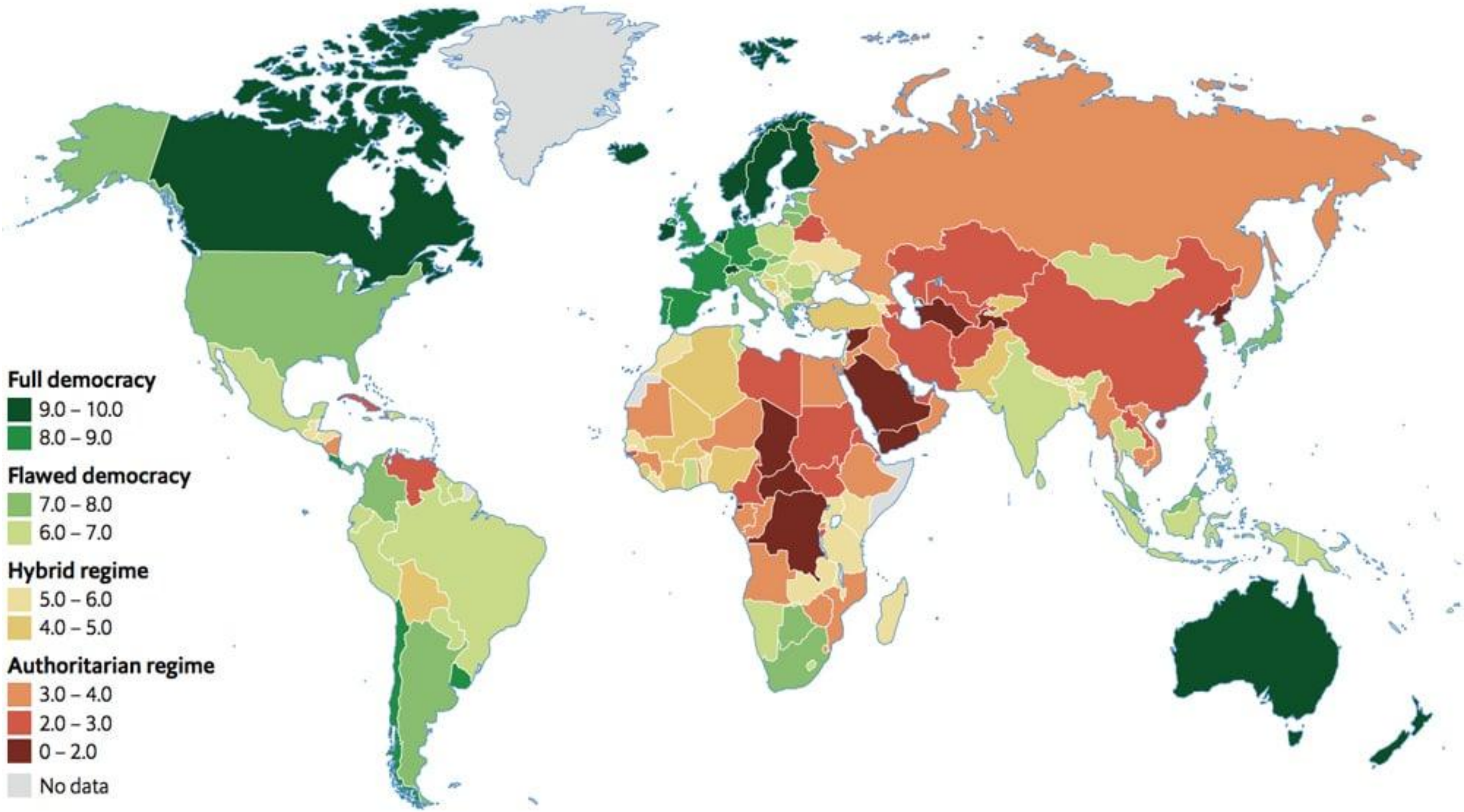
Economic
Global Productivity

Estimated GDP Nominal	Estimated GDP (PPP)
1. **United States:** ~$30.5 trillion	1. **China:** ~$40.7 trillion
2. **China:** ~$19.2 trillion	2. **United States:** ~$30.5 trillion
3. **Germany:** ~$4.7 trillion	3. **India:** ~$17.6 trillion
4. **India:** ~$4.2 trillion	4. **Russia:** ~$7.2 trillion
5. **Japan:** ~$4.2 trillion	5. **Japan:** ~$6.7 trillion
6. **United Kingdom:** ~$3.8 trillion	6. **Germany:** ~$6.2 trillion
7. **France:** ~$3.2 trillion	7. **Indonesia:** ~$5.0 trillion
8. **Italy:** ~$2.4 trillion	8. **Brazil:** ~$5.0 trillion
9. **Canada:** ~$2.2 trillion	9. **France:** ~$4.5 trillion
10. **Brazil:** ~$2.1 trillion	10. **United Kingdom:** ~$4.4 trillion

GDP – Gross Domestic Product uses market exchange rates compares the economic value of a country’s production

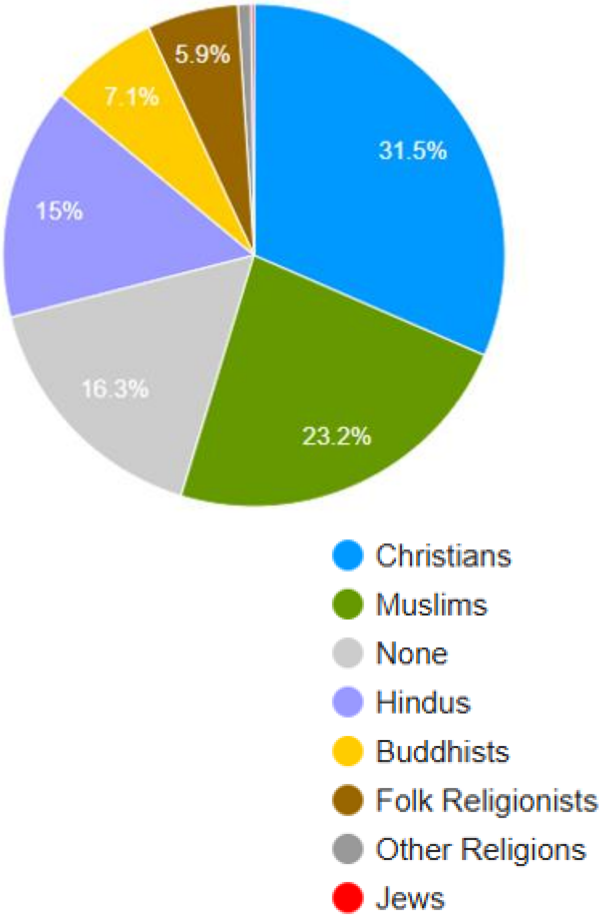
GDP (PPP) – Purchasing Power Parity adjusts for differences in cost of living between countries.

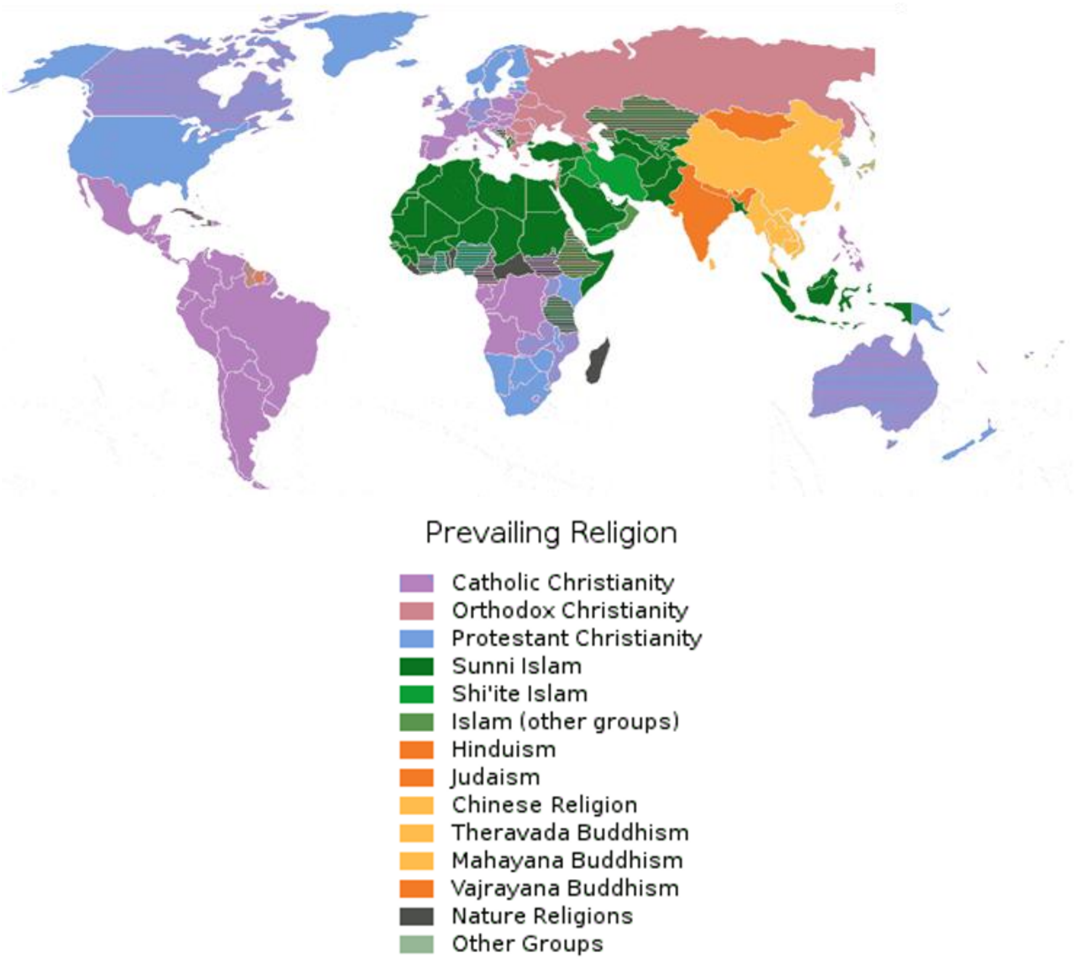
Politics
Global Democracy Vs Authoritarian



Source: https://www.atlasandboots.com/remote-work/worlds-most-democratic-countries/

Social
Global Religion Demographics





https://www.worldometers.info/world-population/#religions

Social
US Fertility Rate

Fertility Rate: The average number of children a woman would have in her lifetime.

United States Fertility Rate

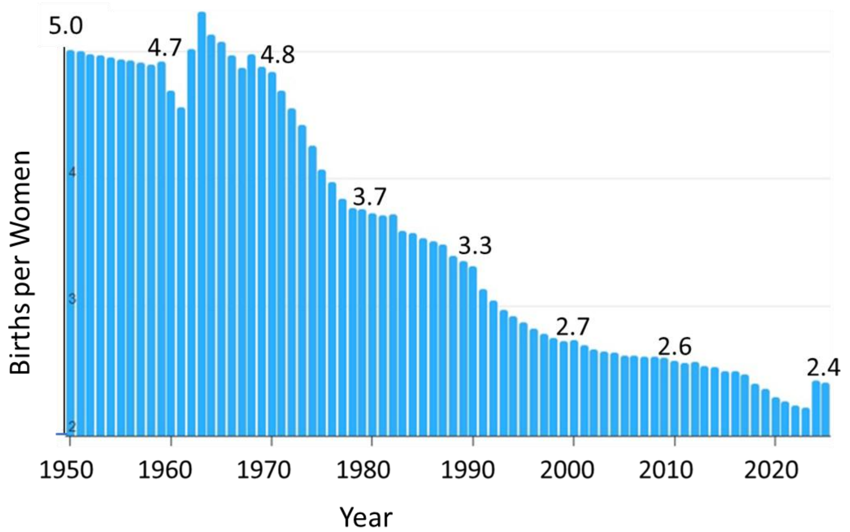
Trends

- Fertility rate dropped to a historic low of 1.599 children per woman in 2024.
- A fertility rate of 2.1 children per women is required to maintain the extant population.
- The US fertility rate has been declining since 2007

Possible Contributing Factors

- Women are delaying childbearing
- Financial insecurity, lack of affordable childcare, and paid parental leave
- Greater access to birth control

Global Fertility Rate



Sources: 1. Hamilton, Brady E.;Martin, Joyce A.;Osterman, Michelle J.K.; “Births: Provisional Data for 2024” National Center for Health Statistics (U.S.), 4/23/2025, URL : https://stacks.cdc.gov/view/cdc/174587, 2. https://www.cdc.gov/nchs/data/nvsr/nvsr74/nvsr74-3.pdf Macrotrends, 3. https://macrotrends.net/global-metrics/countries/wld/world/fertility

Mega Global Economic Trends

Demographic and Social Trends

- Aging population - silver economy
- Urbanization – by 2050, 68% of the world's population living in cities.

Sustainability and Energy

- Renewable energy (1.5 trillion in 2025)
- Energy transition – move to sustainability and environmentally friendly
- Circular economy – recycling and sustainability projected to reach 7.9 trillion in 2050

Technology and Innovation

- AI to drive economic growth. Estimates of 7.9 trillion by 2050
- Digitalization – projected to continue to drive growth and innovation. IoT projected to reach 3.35 trillion by 2030

Slowing and Uneven Global Growth

Shifting economic power

- Rise of Superstar Firms –consolidating market power and capturing a significant share of economic profits.

Geopolitical Tensions & Trade Fragmentation

- Shift in Supply Chains
- Trade barriers and Tariffs
- Impact on Economies

Inflation and Monetary Policy Divergence

- Uneven Disinflation. Emerging markets with higher inflation
- Central Bank Response

Public Debt and Fiscal Constraints

- Rising debt servicing costs
- Fiscal policy challenges

Top Ten: Companies & Richest Men
(Knowledge, Computational & Data Management Dominance)

Knowledge Management Technological Dominance

1. **Nvidia**: $4.4 T (Semiconductors)
2. **Microsoft**: $3.7 T (Software)
3. **Apple**: $3.4 T (Hardware)
4. **Alphabet (Google)**: $2.5 T (Communications)
5. **Amazon**: $2.4 T (Retail)
6. **Meta Platforms**: $1.9 T (Communications)
7. **Saudi Aramco**: $1.5 T (Energy)
8. **Broadcom**: $1.4 T (Semiconductors)
9. **TSMC**: $1.2 T (Semiconductors)
10. **Berkshire Hathaway**: $1.1 T (Financials)

TSMC - Taiwan Semiconductor Manufacturing

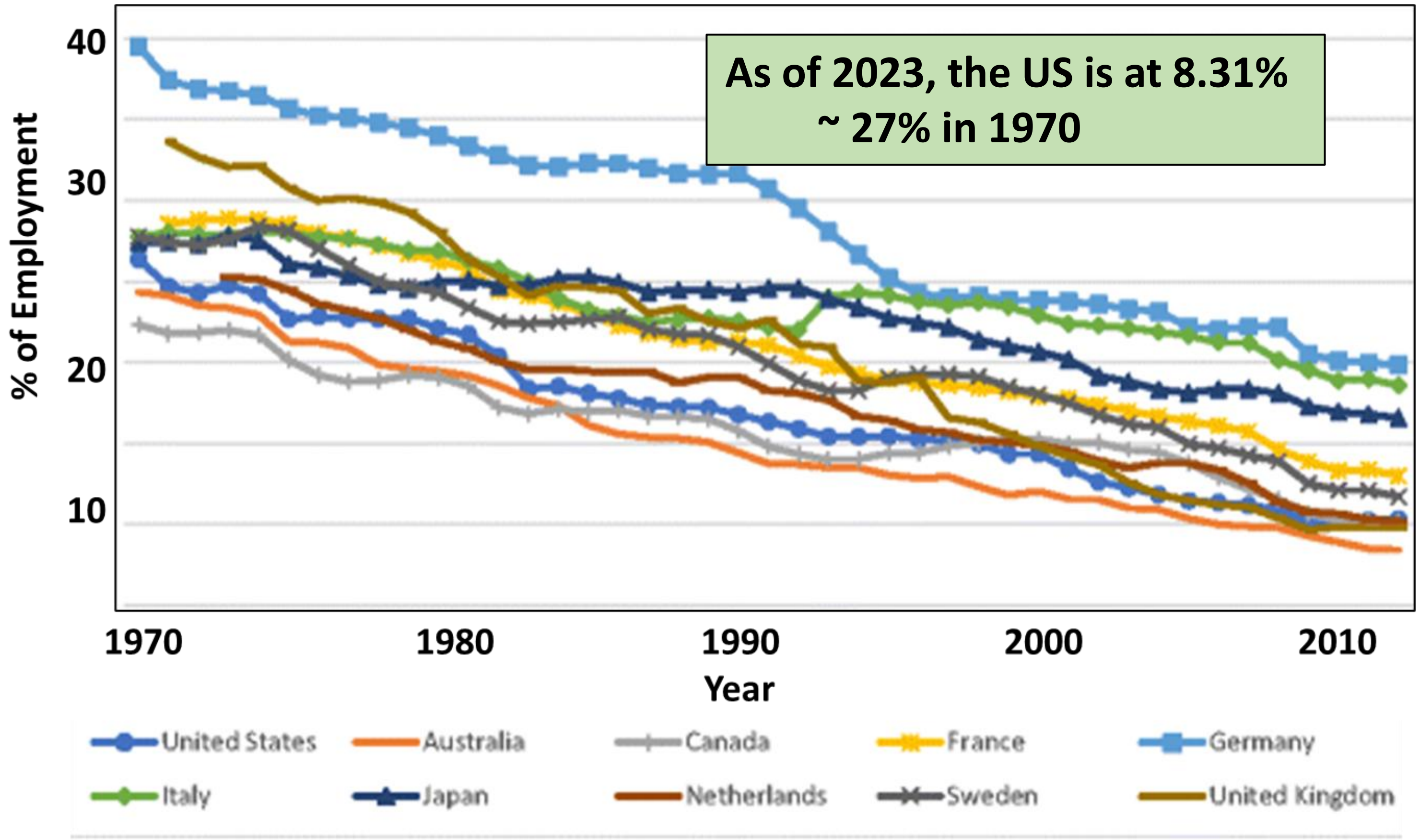
Sources: https://disfold.com/; https://companiesmarketcap.com/

1. **Elon Musk**: $400 billion, (Tesla, SpaceX)
2. **Larry Ellison**: $291 billion, (Oracle)
3. **Mark Zuckerberg:** $260 billion, (Meta)
4. **Jeff Bezos**: $230-244 billion (Amazon)
5. **Larry Page**: $156-179 billion, (Alphabet)
6. **Jensen Huang**: $135-152 billion (NVIDIA)
7. **Sergey Brin**: $149 billion, (Alphabet)
8. **Steve Ballmer**: $147-173 billion (Microsoft)
9. **Warren Buffett**: $142-151.8 billion (Berkshire Hathaway)
10. **Bernard Arnault**: $137-159 billion (Louis Vuitton, etc.)

Global Share of Workforce
Working in Manufacturing

Long-term, systemic decline in manufacturing workforce.

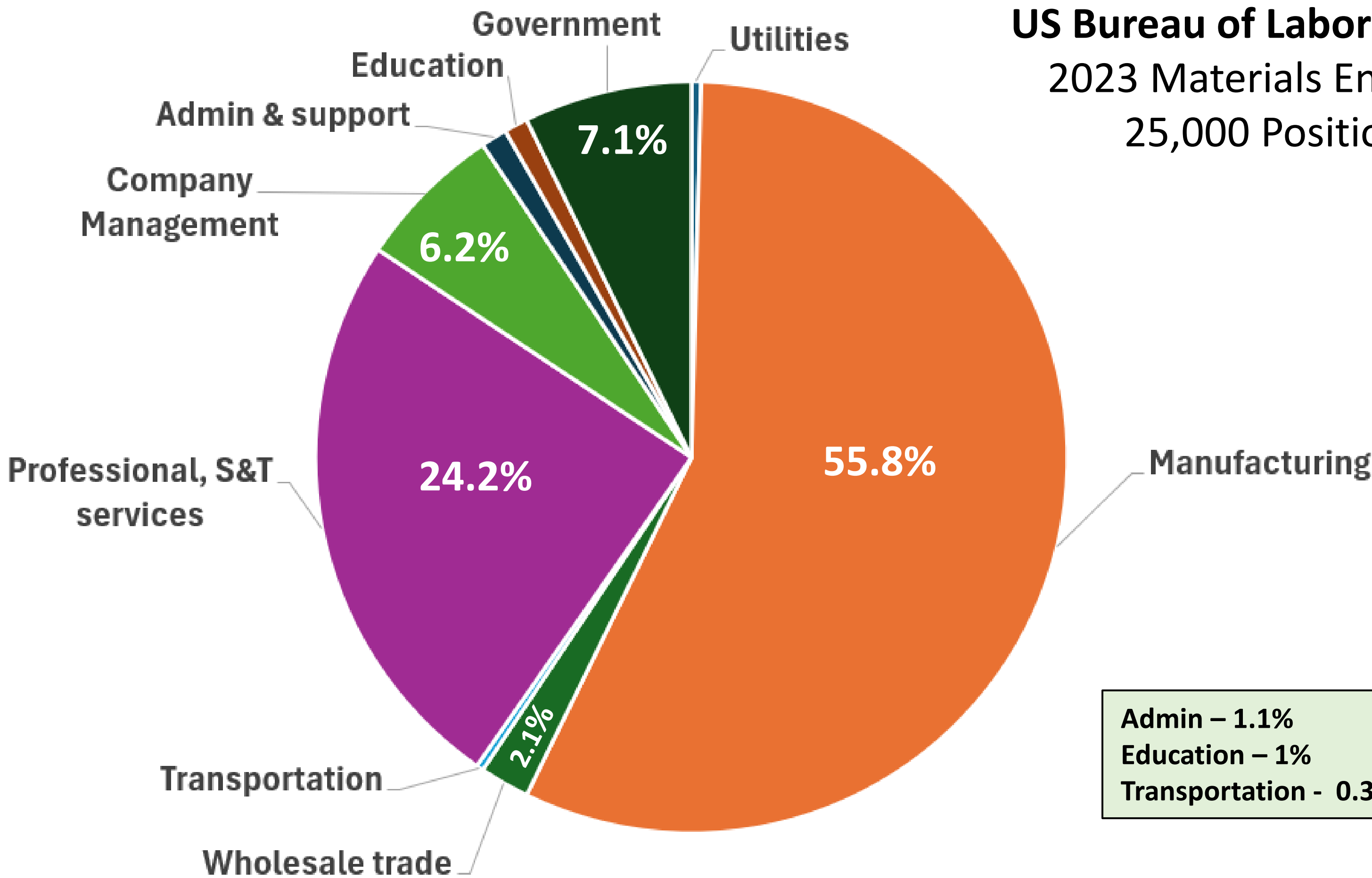
As of 2023, the US is at 8.31%
~ 27% in 1970



Source: Economies Review 29(3) July 2018,
Prosperousamerica.org 2023

Materials Engineers
Sectors of Employment

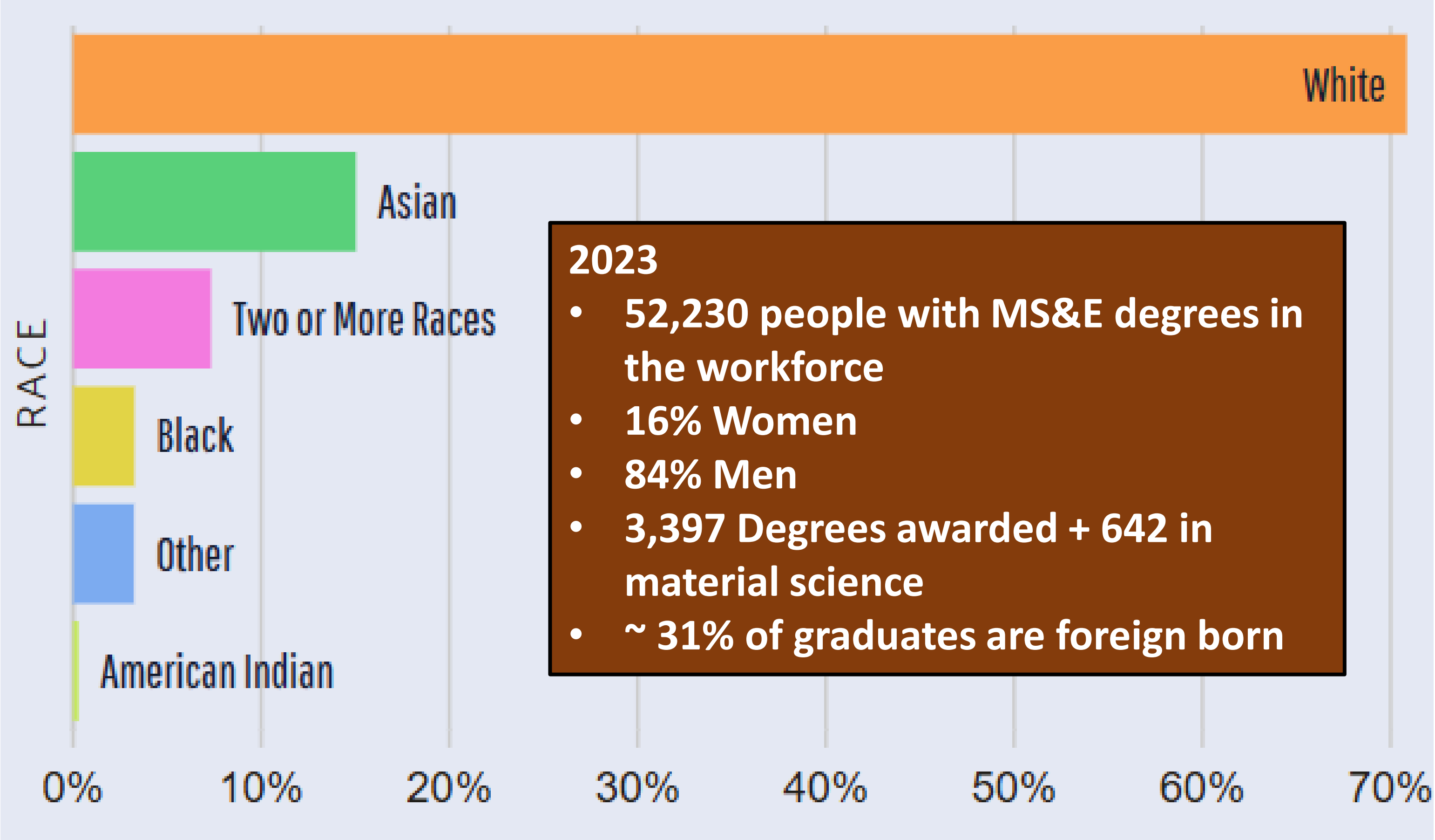
US Bureau of Labor Statistics
2023 Materials Engineers
25,000 Positions



Admin – 1.1%
Education – 1%
Transportation - 0.3%

United States
Race & Ethnicity of Materials Engineering Degrees

US Population (2024) - 57.5% White, 12.6% Black, 20% Hispanic, 6.7% Asian



2023
- **52,230 people with MS&E degrees in the workforce**
- **16% Women**
- **84% Men**
- **3,397 Degrees awarded + 642 in material science**
- **~ 31% of graduates are foreign born**

Sources: DATAUSA https://datausa.io/profile/cip/materials-engineering-141801
https://datausa.io/profile/soc/materials-engineers

Material Science & Engineer Publications
A Measure of Productivity

Country / Region	2003	2023	% in 2003	% in 2023
World	**37,400**	**91,511**	**100.0**	**100.0**
China	6,553	42,330	17.5	46.3
EU-27 & UK	10,659	15,836	28.5	17.3
India	1,475	10,742	3.9	11.7
United States	7,140	6,753	19.1	7.4
Japan	5,352	3,480	14.3	3.8
South Korea	1,532	3,010	4.1	3.3
Iran	143	1,956	0.4	2.1
Saudi Arabia	81	1,580	0.2	1.7
Australia	529	1,563	1.4	1.7
Canada	730	1,404	2.0	1.5
Brazil	862	1,320	2.3	1.4

China: 265% increase
India: 300% increase
US: 61% decrease
EU/UK: 39% decrease
Japan: 73% decrease

Source: National Center for Science and Engineering Statistics; Science-Metrix; Elsevier, Scopus abstract and citation database, accessed February 2025; World Bank Country and Lending Groups, accessed February 2025

Industry 4.0 & 5.0

Industry 4.0 a Term coined in 2011 (by the German government)

- Public–private funding
- Strategies for Tech. Implementation
- ID business drivers & barriers.

Core idea of Industry 4.0

- Digital technology to create "**Smart Factories**"
- Integration of production and operations
  - ✓Smart digital technology,
  - ✓Machine learning, and
  - ✓Big data.
- Enhances productivity, efficiency & reduces cost

Industry 5.0 the Fifth Industrial Revolution

- Builds upon Industry 4.0
- Emphasizes a human-centric, sustainable, and resilient approach to manufacturing and production.

Key Principles

- **Human-Centricity** –What technology can do for workers
- **Sustainability** – Active, efforts to create positive planet change.
- **Resilience** –robustness and adaptability in face of disruptions, e.g., pandemics, supply chain disruptions, etc.

What is Advanced Manufacturing?

Big Data & Analytics AI & ML

Material & Processes

Simulation

Augmented Reality

Additive Manufacturing

Advanced Manufacturing

Cyber Physical Systems

System Integration

Collaborative Robotics

Internet of Things

Cloud Computing

Pillars of Industry 4.0

Trends in Manufacturing

I. Hyper-Automation & AI-Driven Decision Making
(AI/ML adoption to promote productivity)

- **Smart Factories leveraging connected systems**
- **Sustainable & Circular Manufacturing**
  - Eco-friendly practices
- **Digital Twin & Predictive Maintenance**
  - Real-time simulation & optimization
  - Reduce equipment failures & downtime
- **Edge Computing**
  - Faster data processing & reduce latency

II. Industry Shifts

- **Supply Chain Restructuring**
  - Prioritizing resilience, efficiency & sustainability
- **Micro-factories**
  - Emergence of small factories
- **Workforce Transformation**
  - Workforce development, upskilling, & reskilling to address labor shortages and adapt to new technologies.

III. Emerging Technologies

- **Artificial Intelligence (AI)**
  - Process optimization,
  - Predict maintenance
  - Efficiency
- **Internet of Things (IoT)**
  - Data collection
  - Optimize supply chain
- **Additive Manufacturing**
  - Customization
  - Complex products
  - Enhanced production speed
- **Robotics and Automation**
  - Enhance product quality
  - Lower labor costs

Trends in Material Science and Engineering

Sustainability and Circular Economy

- Biodegradable & Bio based Materials
- Recyclability and Upcycling
- Carbon Capture Materials.

Advanced and Smart Materials

- Self-Healing Materials
- Metamaterials
- Shape Memory Materials

Computational Materials Science and Materials Informatics

- Generative AI for Materials Design
- Data-Driven Materials Development.

Advanced Manufacturing and Lightweighting

- Additive Manufacturing
- Lightweight Materials

Nanotechnology and 2D Materials

- Graphene and Other 2D Materials
- Quantum Dots

- **Positive Growth Projections:** The U.S. Bureau of Labor Statistics (BLS) projects that employment for materials engineers and scientist is expected to grow by 7-8% from 2023 to 2033.
- **In-Demand Technical Skills:** Additive Manufacturing, Computational Materials Science & AM/ML, Nanotechnology, Polymer and Composite Science, and Characterization & Testing.
- **Emerging Fields of Opportunity:** Sustainable & Green Materials, Energy Storage, Biomaterials, Smart Materials.

Small Business Exemplars

Technology Innovators

Machine Learning for Qualification

Senvol has been engaged in work to leverage ML to **reduce the time and cost of AM qualification.** Three key areas of this work have included:

Pre-Qualification

- Focus: Use ML to optimize the pre-qualification activities and minimize the number of builds and coupons
- Benefits: Significant savings (time and cost) leading up to allowable generation; ML approach may reduce pre-qualification activities by >75% (time and cost)
- Example program that has leveraged this approach: AFRL FlexSpecs

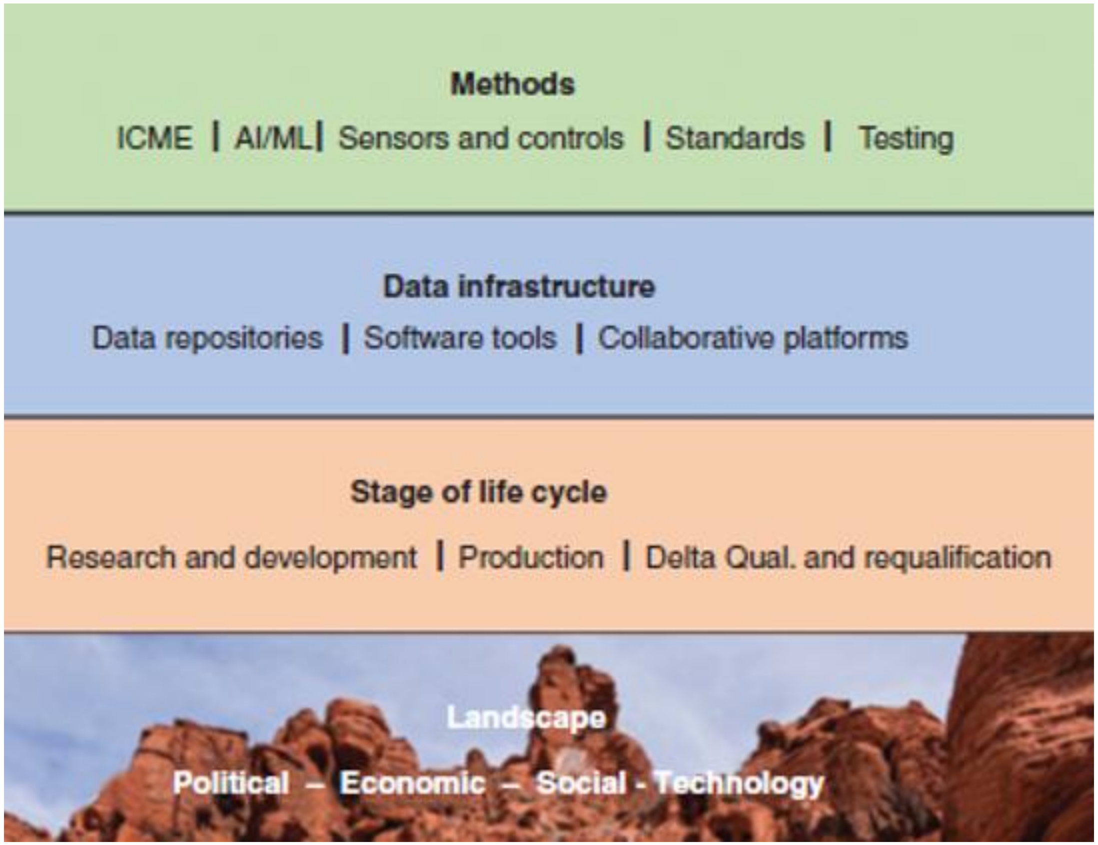
Simulated Allowables (a.k.a. "ML Allowables")

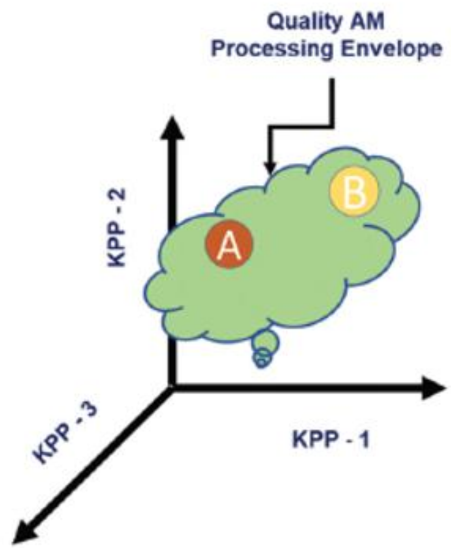
- Focus: Use ML to generate statistically-based material property predictions analogous to an allowable (e.g. B-basis)
- Benefits: Gatecheck; understand likely material allowable values *before* making the multi-year, multi-million dollar investment decision to generate actual allowables
- Example program that has leveraged this approach: Army AMMP

Equivalency

- Focus: Demonstrate a new, ML-enabled, approach to equivalency
- Benefits: Increase the chance of machines passing equivalency
- Example program that has leveraged this approach: America Makes Delta Qual

The Power of Machine Learning



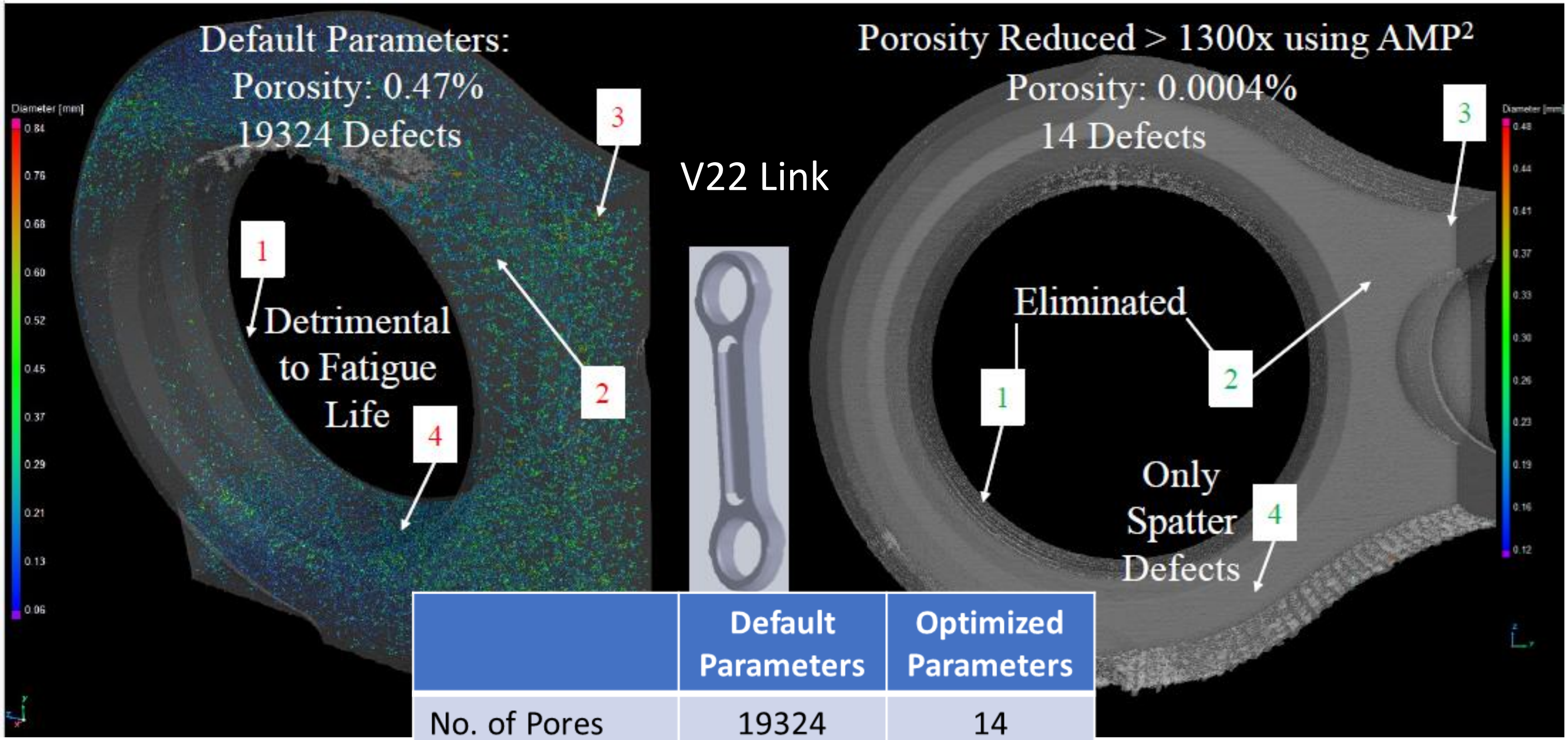


Property	A	B
Yield Strength, MPa	≥ 400	≥ 450
Elongation, %	10 to 12	≥ 8%
Fracture Toughness, MPa$\sqrt{m}$	35 to 45	≥ 30
Fatigue Strength, MPa	120	150

Sources: FRA_23 AM HDBK V24, FRA_23 AM ML Qualification

Modeling and Simulation
Reduced Porosity & Enhanced Fatigue

Applied Optimization Inc. successfully demonstrated that physics-based modeling & simulation could be used to dramatically improve part quality



	Default Parameters	Optimized Parameters
No. of Pores	19324	14
Porosity (%)	0.472	0.00034
Part Density (%)	99.5276	99.9996

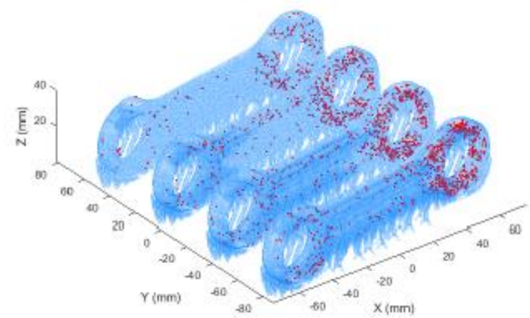
Modeling and Simulation

Reduced Porosity & Enhanced Fatigue

Physics Based

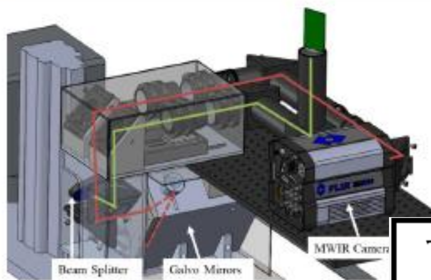
1. In-Situ Monitoring
2. Melt Pool Imaging
3. Process Control
4. Process Model
5. Process Map
6. MWIR Calibration
7. >100x Reduction in Defects
8. Defect Detection
9. Defect Correction
10. Improve Fatigue Behavior

8-9. Detect and Correct Defects

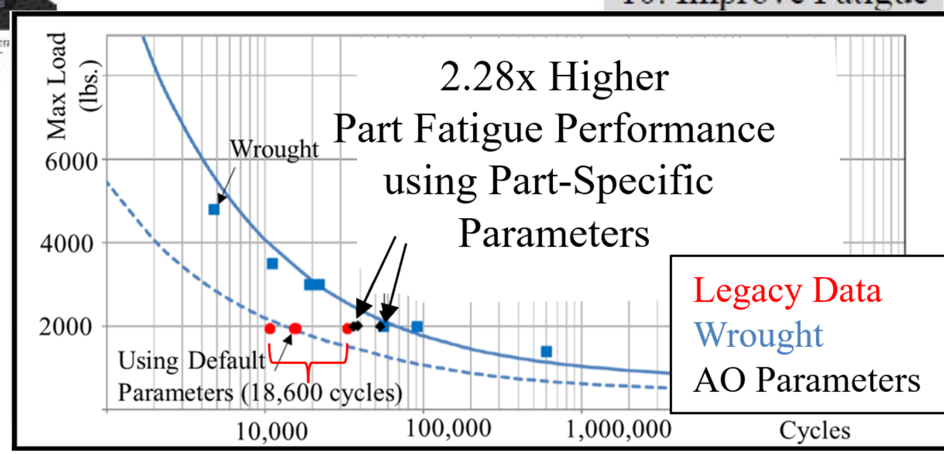


Explainable

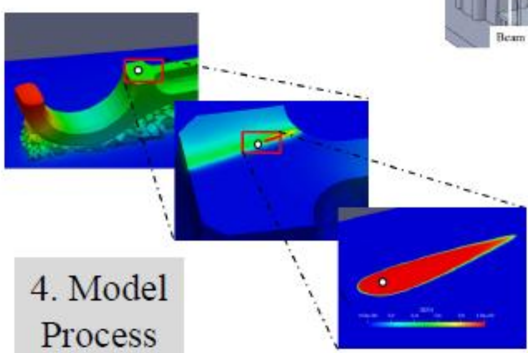
1-2. Monitor Process



10. Improve Fatigue



3. Control Process



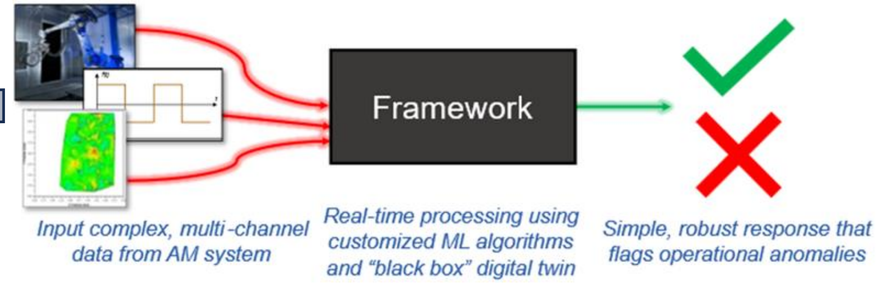
4. Model Process

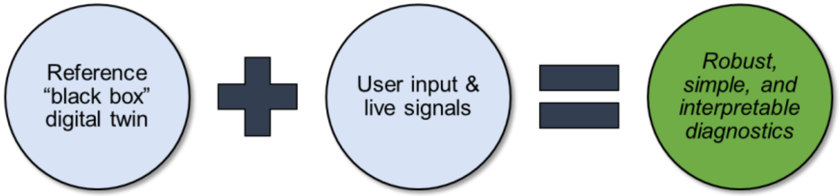
Secure Cold Spray AM for the Navy

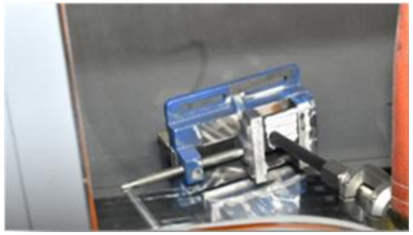
Cyber-Physical Protection & Equipment Longevity

Realtime Data + Digital Twin + Machine Learning => Flags Anomalies & Potential Defects

- **Challenge**: Distributive AM poses cyber-physical risks (IP theft, tampering, unverified parts).
- **Innovation**: ML-driven anomaly detection + low-cost, non-invasive monitoring of cold spray.
- **Impact**: Real-time assurance of part authenticity, compliance, and operational safety.







Fleet Readiness Center East (FRCE) using cold spray metallization fielded on H-1 line at the depot's detachment on board Marine Corps Air Station New River.

Confidence in operational safety when secure cold spray repairs and AM can be achieved through cross-disciplinary innovations.

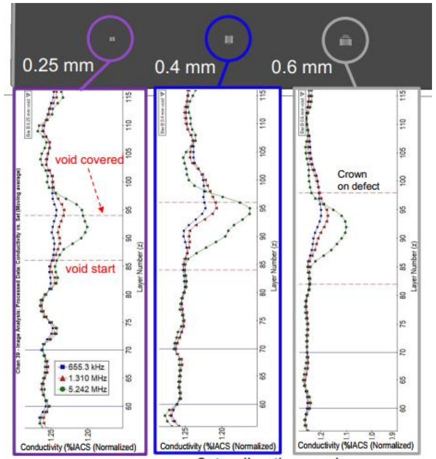
Contributed by Dr. Bryer Sousa (bsousa@tritonsys.com) & Dr. Jack Grubbs

In-Situ Eddy Current Arrays for LPBF*

JENTEK Sensors, Inc.

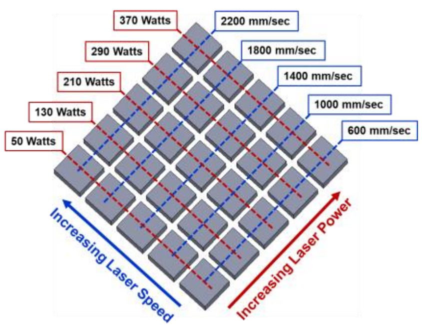
Local Defect Detection

- Less than 0.25mm voids to replace CT
- Covered defects 3-8 layers below surface
- Metallurgical and tight crack-like defects
- Z-directed filtering with Machine Learning under development

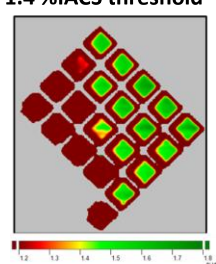


Conductivity Mapping

- Threshold good vs. bad
- Correlate with properties (e.g., porosity, hardness)
- Full 3D digital record



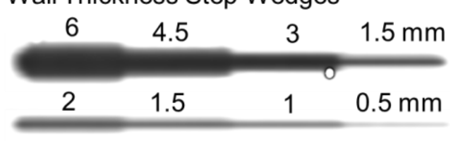
1.4 %IACS threshold

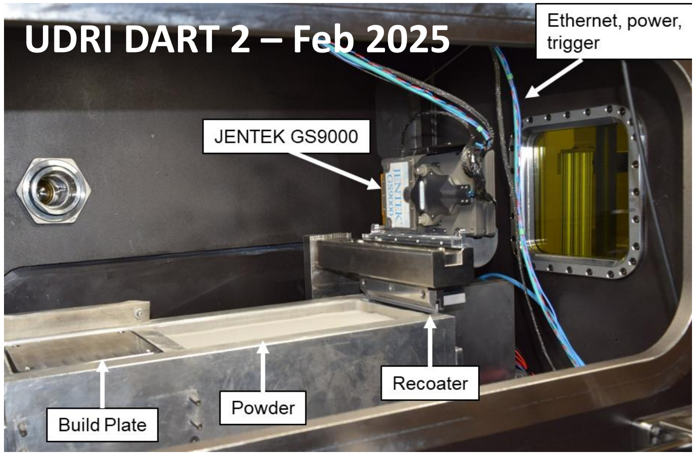


GE Concept M2 – Aug 2025

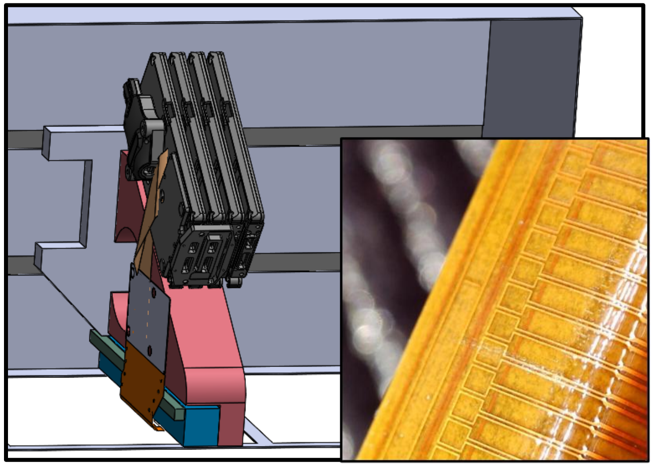
Sub-pixel geometric imaging for edges
and small features *(longer term development;*
likely requires fusion with optical or IR imaging)

Wall Thickness Step Wedges





EOS M 290 – Nov 2025

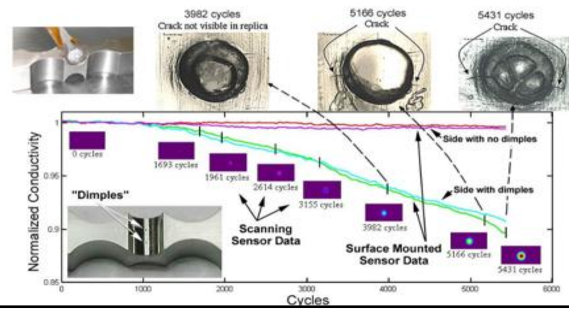


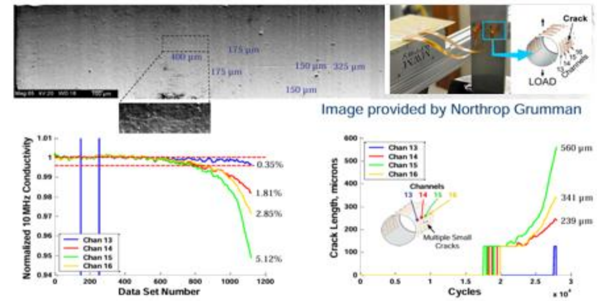
MWM®-Array

*Laser Powder Be

EDDY CURRENT ARRAY FATIGUE NDE & SHM

<table>
<tr><th>Material</th><th>Structural Health Monitoring (SHM) & Non-Destructive Evaluation (NDE)</th></tr>
<tr><td>Ti Alloy/Al Alloy

Crack Detection</td><td>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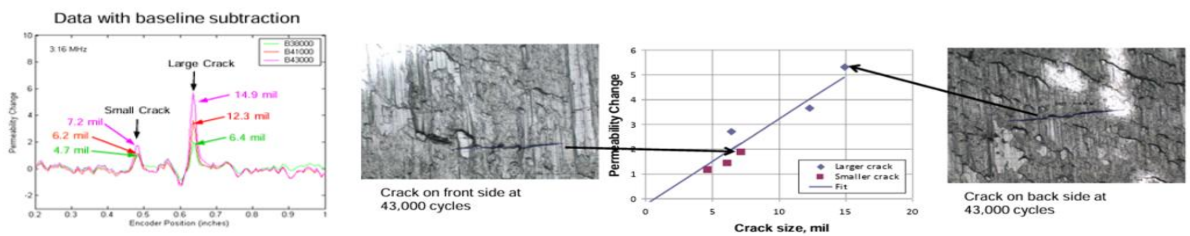
<tr><td>Steel Alloy

Crack Detection</td><td>
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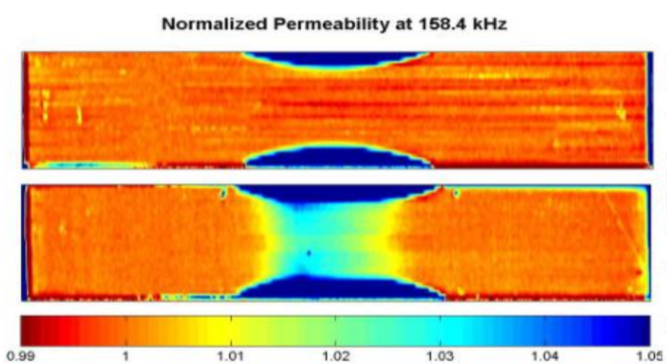
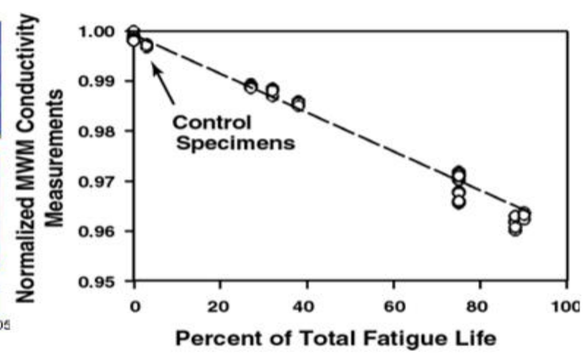
<tr><td>Stainless Steel

Pre-Crack Martensite Imaging</td><td>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Data Driven PBF-LB/M QC

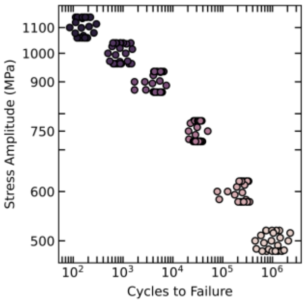
Laser Subsystem

Gass Flow Subsystem

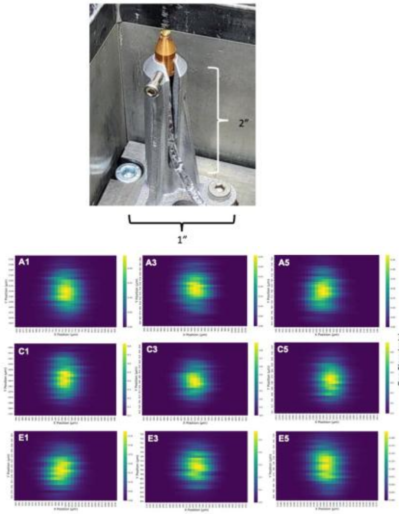
1. **Sensor Selection:** Sensors for measurement of laser and gas flow

Data Driven PBF-LB/M QC

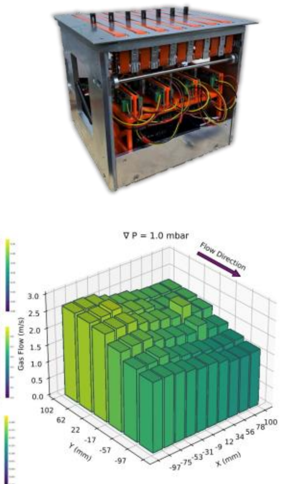
1. **Sensor Selection:** Sensors for measurement of laser and gas flow
2. **Representative Dataset:** Develop production-relevant dataset



Laser Subsystem



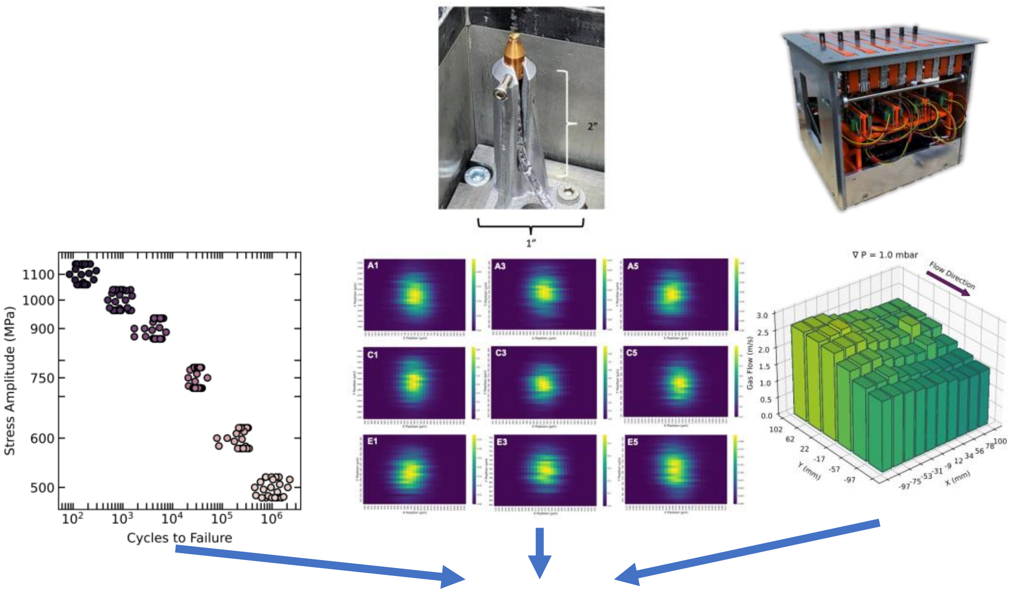
Gass Flow Subsystem



Data Driven PBF-LB/M QC

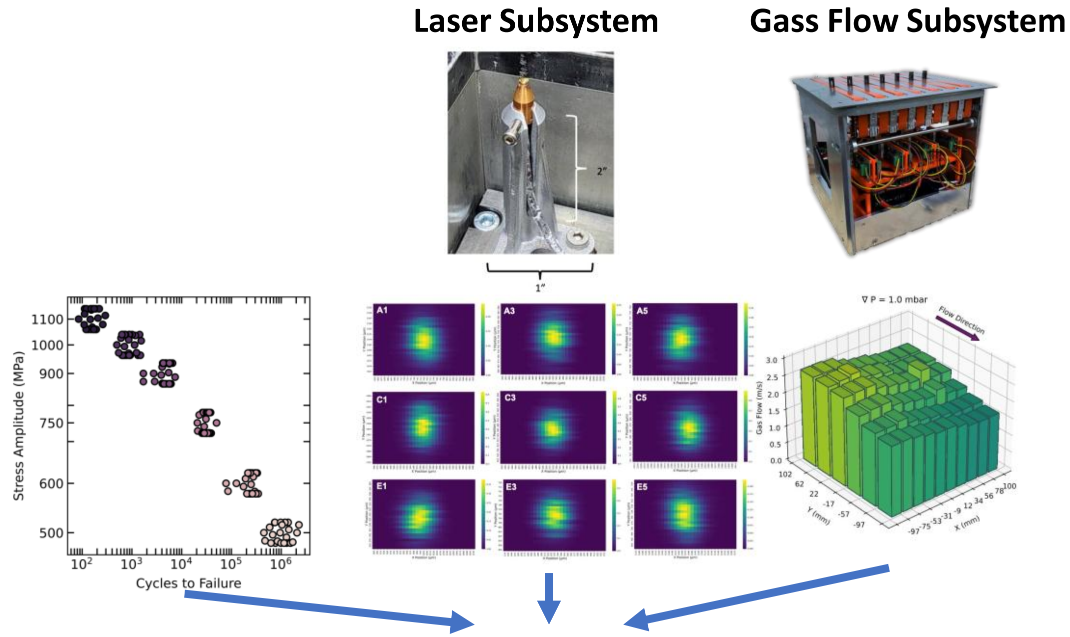
1. **Sensor Selection:** Sensors for measurement of laser and gas flow
2. **Representative Dataset:** Develop production-relevant dataset
3. **Analytics:** Predictions of mechanical properties based on subsystem performance

Laser Subsystem **Gass Flow Subsystem**

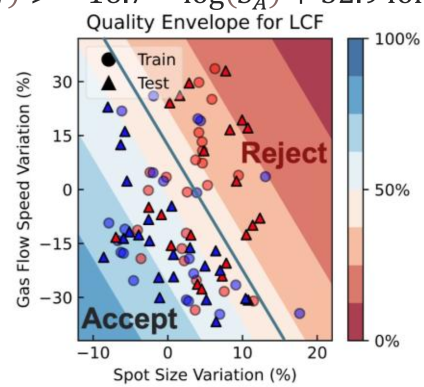


Data Driven PBF-LB/M QC

1. **Sensor Selection:** Sensors for measurement of laser and gas flow
2. **Representative Dataset:** Develop production-relevant dataset
3. **Analytics:** Predictions of mechanical properties based on subsystem performance
4. **Application:** Establish quality envelope based on requirements



$$\log(N) > -16.7 \ * \log(S_A) + 52.9 \text{ for N} < 10^4$$



https://doi.org/10.1007/s11665-025-10753-1

Knowledge Management Landscape

Applications & Platforms Computational and Modeling & Simulation ICME, CAD, CAM, FEM, PLM, Accounting, Logistics, Forecasting
Data Analytics Artificial Intelligence & Statistical (Machine Learning, Neural Networks, Genetic Algorithms, ANOVA)
Data Repositories Data Hub, Data Lake, Data Commons, Data Warehouse, Federated Database
Knowledge Management Lexicon, Thesaurus, Taxonomy, Ontology, Persistent Identifiers,
Foundational Elements WWW, FAIR, Semantic Web JASON-LD, NoSQL, RDF, XML, RESTful, OWL, MatML

Concluding Thoughts

- A Key Enabler is Knowledge Management (data, information, understanding, models & curation)
- We must adapt to Changing Global Environment Political, Economic, Social & Technological (PEST) Forces are shaping the future.

> "It is not the strongest of the species that survive, nor the most intelligent, but the one most responsive to change."
> **— Charles Darwin**

Thank You
Presentation Contributors

• Applied Optimization	Dr. Anil Chaudhary
• EWI	Dr. Alex Kitt
• JENTEK Sensors	Dr. Neil Goldfine
• SENVOL	Mr. Zach Simkin & Ms. Annie Wang
• Triton Systems	Drs. Bryer Sousa & Jack Grubbs

Questions – Comments?

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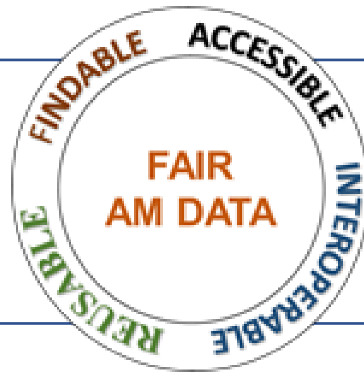
Working

Knowledge, Information, Data, Curation & Management

Generators Users	⟷	Users Generators

Science → **Innovation** ← **Engineering**

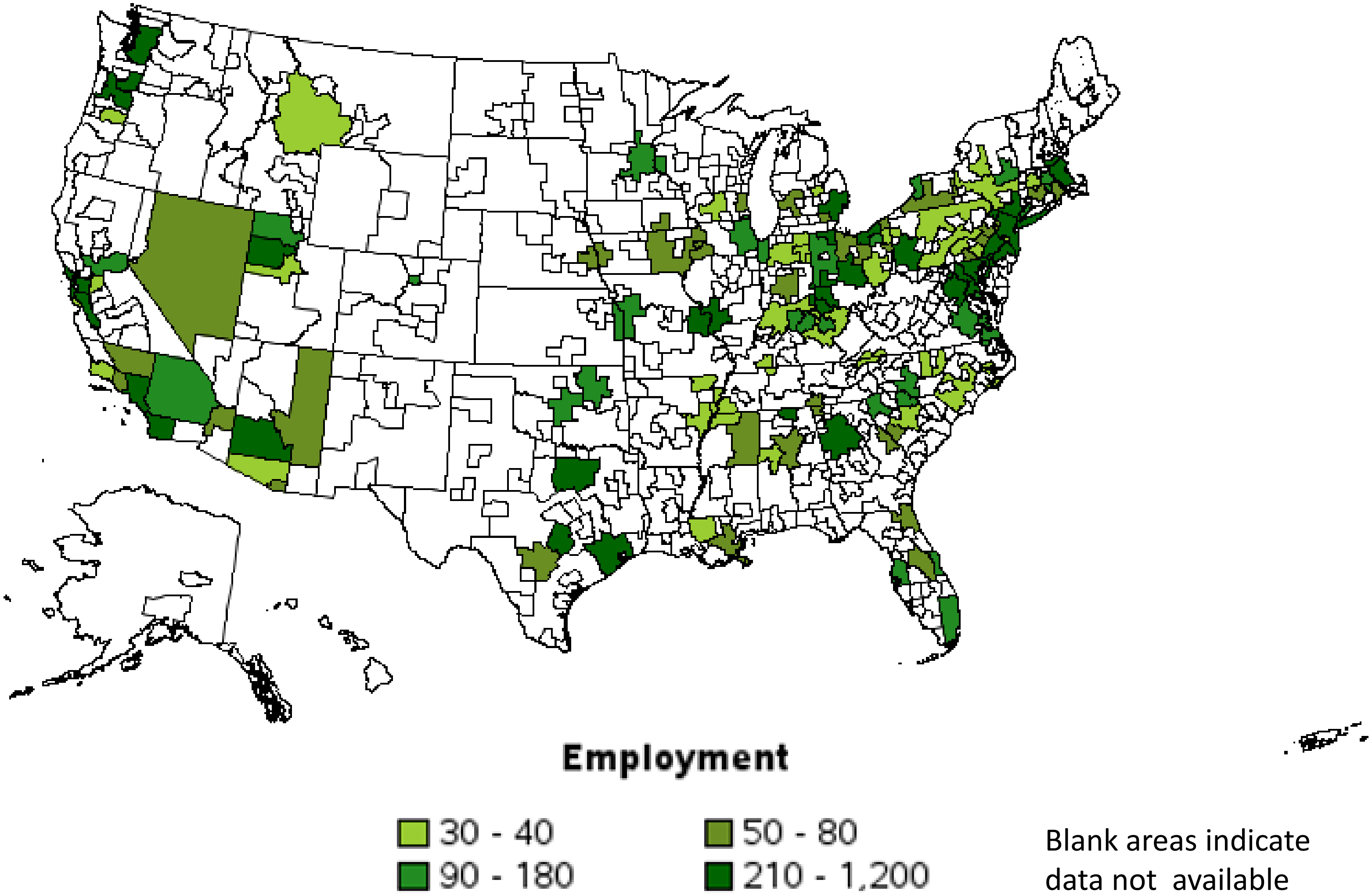
Science
Discovery
Inductive Reasoning



Engineering
Application
Deductive Reasoning

A "PEST" Problem

Employment of Materials Engineer in the US – 2023
US Bureau of Labor Statistics



Blank areas indicate data not available