NAE MEMBER-LED WORKSHOP EVENT

QUANTUM MANUFACTURING:

BRIDGING RESEARCH, INFRASTRUCTURE, AND SUPPLY CHAINS FOR SCALABLE QUANTUM SYSTEMS

DATE: MAY 7TH, 2026 | TIME: 08:00 AM - 5:30 PM

NATIONAL ACADEMY OF SCIENCES, ENGINEERING AND MEDICINE
2101 CONSTITUTION AVENUE NW, WASHINGTON, D.C. 20418.

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1. Introduction

Quantum technologies are approaching a pivotal transition from laboratory-scale scientific demonstrations to engineered systems capable of reliable deployment in computing, sensing, communications, and national security applications, on Earth and in Space. While major advances in quantum science have accelerated the performance of qubits, sensors, photonic systems, cryogenic electronics, and quantum materials, substantial engineering and manufacturing barriers continue to limit scalability, reproducibility, and commercialization. Moving from complex, heterogeneous experimental platforms to manufacturable quantum systems requires coordinated progress across design, materials, processes, packaging, system integration, infrastructure development, supply chain resilience, standards, and workforce development. These challenges are not purely scientific; they are fundamentally engineering and manufacturing problems that demand collaboration across academia, industry, government, and standards organizations.

To address these issues, this National Academy of Engineering (NAE) member-led workshop convened experts from academia, industry, government agencies, national laboratories, and standards bodies to examine the emerging landscape of quantum manufacturing and supply chain development. The workshop focused on the engineering realities associated with scaling quantum technologies from research prototypes to deployable systems, with particular attention to the trends and drivers shaping the future quantum manufacturing and supply chain ecosystem. Discussions emphasized the need to bridge the gap between scientific discovery and industrial implementation through advances in manufacturing processes, infrastructure readiness, and coordinated national strategies.

The workshop explored three interconnected domains central to long-term competitiveness in quantum technologies. First, participants examined packaging and system integration challenges in electronics and photonics, including cryogenic compatibility, interconnect density, reliability, modularity, and manufacturability of quantum devices. Second, the workshop addressed infrastructure readiness, including the availability of fabrication facilities, specialized tooling, metrology capabilities, workforce development pathways, and the transition from laboratory-scale demonstrations to scalable industrial production. Third, discussions focused on supply chain resilience and strategic dependencies associated with specialized materials, advanced components, cryogenic systems, and globally concentrated supplier networks.

Across keynote presentations and moderated panel discussions, participants identified several overarching themes driving the evolution of quantum manufacturing. These included the transition from bespoke laboratory systems to repeatable manufacturing platforms, the growing importance of resilient and secure supply chains, the need for interdisciplinary workforce development spanning materials, engineering, computer, and quantum sciences, as well as advanced manufacturing, and the increasing role of standards and interoperability in enabling scalable quantum architectures. Participants also highlighted the importance of aligning research priorities with manufacturing realities and creating stronger public–private partnerships to accelerate technology maturation.

By providing a neutral engineering-focused forum, the workshop advanced the NAE mission of applying engineering leadership to national challenges. The discussions and findings summarized in this report are intended to inform future research directions, infrastructure planning, standards development, investment strategies, and cross-sector collaboration to build a robust, globally competitive quantum manufacturing ecosystem.

2. Event Agenda

Quantum Manufacturing: Bridging Research, Infrastructure, and Supply Chains for Scalable Quantum Systems

Day and Date: Thursday, May 7, 2026

Location and Address: National Academy of Sciences, Engineering, and Medicine (NASEM), 2101 Constitution Avenue NW, Washington, D.C. 20418.

Morning Session: Setting the National Context

8:00 – 8:30 AM
Registration and Networking Breakfast

8:30 – 9:00 AM
- Welcome and Workshop Overview by Workshop Co-Chairs
    - Ajay P. Malshe (Member, NAE) and Samuel Graham
- Opening remarks by Tsu-Jae Liu (Member, NAE), President, National Academy of Engineering (NAE)

9:00 – 9:30 AM
Keynote Speaker-1
- Joseph Broz, IBM

9:30 – 10:00 AM
Keynote Speaker-2
- Joel Mozer, Emeritus Chief Scientist (1st), US Space Force

Panel 1
10:00 – 11:00 AM
Panel anchor- Samuel Graham, University of Maryland
Leads and Topic: **From Lab Prototypes to Manufacturable Quantum Systems**
- Robert Visser, Applied Materials
- Nicholas Harrigan, NVIDIA
- Vladimir Shalaev (Member, NAE), Purdue University
- Francis Patrick McCluskey, University of Maryland

Panel 2
11:05 AM – Noon
Panel anchor- Ajay P. Malshe, Purdue University
Leads and Topics: **Supply Chain Fragility, Materials, and Infrastructure**
- Nick Kamin, U.S. Space Force
- Stephan Biller (Member, NAE), Purdue University
- Michael Descour, Sandia National Laboratory
- Sauli Sinisalo, Bluefors

Noon – 1:00 PM
Networking Lunch

1:00 – 1:30 PM
Keynote Speaker-3: Sridhar Tayur (Member, NAE), Carnegie Mellon University

1:30 – 2:00 PM
Keynote Speaker-4: Vimal Kamineni, PsiQuantum

Panel 3
2:05 – 3:00 PM
Panel anchor- Ankur Srivastava, University of Maryland
Leads and Topics: Workforce, Skills, and the "Quantum Manufacturing Stack"

- Alexandra Boltasseva, Purdue University
- Jonathan Felbinger, QED-C
- Saikat Guha, University of Maryland

Panel 4
3:05 – 4:00 PM
Panel anchor- Corey Stambaugh, University of Maryland
Leads and Topics: Standards, Interoperability, and Scaling Architectures

- Jorge Arinez, General Motors
- Gretchen Campbell, University of Maryland

Panel 5
4:05 – 5:00 PM
Panel anchors: Co-chairs of the Event
Presenters and Topic: Findings, Trends & Drivers of Quantum Manufacturing

- Ajay P. Malshe, Purdue University
- Sam Graham, Jr., University of Maryland

5:00 – 5:15 PM
Closing comments:

- Alton D. Romig, Jr (Member, NAE), Executive Officer, National Academy of Engineering (NAE)

A note of thanks: Samuel Graham and Ajay P. Malshe

Note: Attendees can take bio breaks and snacks/drinks at their convenience; snacks/drinks will be available in the area.

3. Vectors for technical discussions at the event

Framework of Discussion at the event to identify Trends & Drivers for Quantum Manufacturing

Co-Chairs: Ajay "AJ" P. Malshe (Member, NAE), Purdue University, and Samuel Graham, Jr., University of Maryland.

Organizing Members:

Purdue University –	Stephan Biller (Member, NAE), Alexandra Boltasseva, and Vladimir M. Shalaev (Member, NAE)
University of Maryland –	Francis Patrick McCluskey and Ankur Srivastava

Workshop on Quantum Manufacturing:
Manufacturing and supply chain to deliver quantum systems at scale across a range of applications on Earth and in Space. In the workshop, we want to identify Trends and Drivers for Quantum Manufacturing. Top four themes for panel discussions between industries, government, and academia for quantum manufacturing and supply chain for scaling science to engineered quantum systems.

Participants and characters of the panel theme and scope:
The following themes are not only strategic but also force **cross-sector tension and collaboration**, where industry needs scale, academia pushes boundaries, and government shapes incentives and risk. Here are four high-impact panel themes that consistently surface in serious quantum manufacturing conversations:

Panel- 1. From Lab Prototypes to Manufacturable Quantum Systems

Core question: How do we transition fragile, bespoke quantum experiments into repeatable, scalable products?

Why it matters: Most quantum platforms (superconducting, trapped ions, photonics, spin systems) are still closer to lab artifacts than manufacturing systems.

Discussion angles:

- Design-for-manufacturing (DfM) in quantum hardware
- Standardization of fabrication processes (cleanroom vs. foundry models)
- Yield challenges and defect tolerance at quantum scales
- Bridging TRL gaps (Technology Readiness Levels)

Example points to explore:

- Academia optimizes performance; industry needs reproducibility
- Government funding often stops before manufacturability is proven

Panel- 2. Supply Chain Fragility, Materials, and Infrastructure

Core question: What does a resilient supply chain for quantum systems actually look like?

Why it matters: Quantum systems rely on **exotic materials, ultra-high purity components, and niche suppliers**, often single source.

Discussion angles:

- Critical materials (e.g., isotopically pure silicon, niobium, rare earths, etc.)
- Cryogenic infrastructure and specialized equipment bottlenecks
- Geographic concentration and national security implications
- Lessons from semiconductor and aerospace supply chains

Example points to explore:

- Open global collaboration vs. strategic autonomy
- Cost vs. resilience in early-stage markets

Panel- 3. Workforce, Skills, and the "Quantum Manufacturing Stack"

Core question: Who builds quantum systems, and how do we train them at scale?

Why it matters: There's a major gap between **PhD-level quantum scientists** and **technicians/operators who can run production environments**.

Discussion angles:

- Hybrid skill sets (quantum physics + microfabrication + systems engineering)
- Role of community colleges, apprenticeships, and upskilling programs
- Talent mobility between academia, startups, and large manufacturers
- Digital tools (AI, simulation, digital twins) in workforce augmentation

Example points to explore:

- Academic training pipelines vs. industry-ready skills
- Speed of workforce development vs. pace of technology evolution

Panel- 4. Standards, Interoperability, and Scaling Architectures

Core question: What standards are needed to enable a scalable quantum industry?

Why it matters: Without standards, every system is bespoke, making supply chains inefficient and slowing ecosystem growth.

Discussion angles:

- Hardware interfaces and modular architecture
- Metrology and benchmarking standards (how do we measure "quality"?)
- Software-hardware co-design and interoperability
- Role of organizations like the National Institute of Standards and Technology and international bodies

Example points to explore:

- Premature standardization vs. innovation freedom
- Competing technology stacks (superconducting vs. photonic vs. ion-based)

4. Recommendations for Quantum Manufacturing and Supply Chain

(<u>Note</u>- These recommendations are sourced through asynchronous technical feedback from Speakers and Panelists, as well as notes from the discussion during the workshop, and synthesized for coherence using human-AI collaboration.)

Quantum Manufacturing: It is the manufacturing of quantum devices and systems *at scale* for broader societal applicability (democratization). Across the workshop, participants recognized that reliability, repeatability, and reproducibility (3Rs) are key to wider applicability, as are products, productivity, and profitability (3Ps).

4.1 <u>Trends</u>

1. The Field Has Crossed from Science to Engineering- Quantum is no longer a purely research activity. IBM has sold over $1 billion in quantum products. Commercial deployments are in place across the U.S., Europe, and Asia. The community broadly agreed that 2026 marks an inflection point, the transition from "can we build one?" to "how do we build thousands, reliably?"

2. Modular Architecture is Becoming the Dominant Paradigm- Across hardware discussions, the shift away from monolithic large-chip designs toward modular, chiplet-based architectures was consistent. IBM abandoned 1,000-qubit monolithic chips in favor of smaller high-yield Heron modules assembled into larger systems. The same modularity logic applies to control electronics, I/O, cryogenic packaging, and software stacks. This mirrors trends in classical chip design (chiplets, heterogeneous integration).

3. Classical-Quantum Integration is the Near-Term Reality- No panelist expected quantum to displace classical computing. The dominant near-term model is **quantum-centric supercomputing,** with QPUs tightly coupled to HPC systems and workloads dynamically routed. NVIDIA's NV-QLink architecture and IBM's middleware strategy both reflect this. Quantum is an accelerator, not a replacement.

4. Multiple Qubit Modalities Will Coexist- No single qubit technology (superconducting, trapped ion, neutral atom, photonic, spin, topological) has emerged as the clear winner. The panel consensus was that different modalities will serve different applications, and it is too early to consolidate. This complicates supply chain standardization but preserves optionality.

5. AI is Already Reshaping the Quantum Stack- AI tools are being used across the quantum pipeline, circuit optimization, error correction decoding, algorithm discovery, digital twin development, and workforce training. The convergence of AI and quantum was treated as a current reality, not a future aspiration.

6. Geopolitical Competition is Accelerating Timelines- The U.S.- China strategic competition in quantum was a persistent undercurrent. The DeepSeek AI market shock ($1 trillion in market cap wiped in a day) was cited as a vivid warning of how rapidly strategic technology competition can destabilize assumptions. The panel treated urgency as real rather than rhetorical.

7. The Supply Chain Ecosystem is Beginning to Organize- A new wave of quantum-focused component suppliers, particularly semiconductor-grade wafer companies for quantum chips, has emerged in the last one to two years. QEDC now tracks approximately 8,500 workers at pure-play quantum companies. The ecosystem is small but structurally forming.

4.2 Drivers

1. Fault-Tolerant Quantum Computing as the North Star- IBM's 2029 Starling (first fault-tolerant system) and 2033 Blue Jay targets gave the field a concrete milestone structure. Fault tolerance drives nearly every engineering priority, coherence time, gate speed, qubit connectivity, error correction overhead, and modular scaling all flow from this goal.

2. Economic Value at Stake- Estimates of $1 trillion or more in unlockable economic value in drug discovery, materials simulation, financial optimization, logistics, and climate modeling were cited repeatedly as the justification for continued investment despite the chicken-and-egg supply chain problem. The current $4 billion in annual industry revenue is a small fraction of the projected endpoint.

3. National Security and Strategic Sovereignty- The Space Force and supply chain panelists were explicit: quantum is a strategic national asset, and the U.S. cannot afford to repeat the semiconductor mistake of offshoring critical manufacturing for short-term cost savings. DoD demand signals are shifting toward tech transfer and transition, not publications. Defense applications provide an anchor market that can sustain the ecosystem before commercial markets mature.

4. Energy Efficiency Advantage- IBM's Starling system is designed for approximately 6 megawatts, versus 60-100 megawatts for an equivalent classical supercomputer workload. This energy efficiency argument becomes increasingly compelling as data center power consumption becomes a national infrastructure constraint.

5. Democratization Imperative- The opening co-chair framed democratization, making quantum accessible broadly, as AI has become, as a core aspiration. QEDC echoed this: the $4 billion industry cannot unlock a trillion-dollar economy without making quantum accessible to enterprise users who lack in-house quantum expertise. This drives investment in interfaces, abstraction layers, and AI-assisted tools.

6. Simultaneity of Discovery and Commercialization- Unlike the laser (invented without a known application) or the transistor (supply chain was an afterthought for decades), quantum technology is being developed with manufacturing, supply chain, and commercial applications in mind from the start. This simultaneity is a structural advantage the field should deliberately preserve.

4.3 Opportunity Gaps

1. National Quantum Manufacturing Roadmap Requirement- The single most consistently cited structural gap. Unlike semiconductors (CHIPS Act) or additive manufacturing (America Makes), quantum lacks a coordinated national roadmap that aligns government, industry, and academia around shared manufacturing targets, technology-readiness milestones, and infrastructure investments. Every panelist from every session called for this.

2. Cost Per Qubit Remains 10–20x Too High- The current industry-wide fully-loaded cost is $10,000–$20,000 per qubit. The target for commercial viability is under $1,000. No clear path to close this gap at scale currently exists in the public roadmap. It requires advances in yield, miniaturization of control electronics, packaging, and cryogenic infrastructure simultaneously.

3. The Chicken-and-Egg Supply Chain Problem is Unresolved- Quantum system volumes are too low to justify supplier R&D investment; without capable suppliers, the ecosystem cannot scale. Specialized components, custom laser wavelengths for photonic and trapped-ion systems, cryogenic interconnects, and cryo-CMOS chips either do not exist commercially or are prohibitively expensive. No market mechanism currently resolves this without government intervention.

4. National Quantum Manufacturing User Facility Requirement- Sandia's MESA fab and similar national lab capabilities exist, but are not broadly accessible. The panel called for a publicly accessible **quantum manufacturing demonstration facility**, modeled on Oak Ridge's Manufacturing Demonstration Facility or the America Makes network, where startups, universities, and companies can develop and validate manufacturing processes without building their own fabs. Another option is to build through Industry-Academia collaborations, leveraging investments in the Equipment and Process Innovation and Commercialization (EPIC) Center Silicon Valley by Applied Materials, which focuses on early-stage process development and scaling to production. This gap is immediate and solvable.

5. Interconnect and Transduction Remain Unsolved- The physical interface between quantum hardware layers, particularly transduction between microwave (superconducting qubit domain) and optical frequencies (for long-distance fiber transmission), remains an open engineering problem. Current photonic quantum systems still resemble optical tables requiring manual realignment. Packaging quantum devices for signal integrity at millikelvin temperatures while managing thermal load remains an unsolved manufacturing problem.

6. Workforce Composition Challenges Across Skill Levels- The workforce gap extends beyond a simple shortage of quantum workers; it reflects a structural mismatch in how talent is being developed and deployed. A significant share of QED-C member companies reports that PhD-level staff routinely perform tasks better suited to skilled technicians, suggesting the field may be overproducing at the doctoral level while underproducing the middle layer of engineers and technicians who can translate research into manufacturable products. Scalable training pipelines for this middle layer remain limited or nascent. Need for scalable quantum workforce training identified with modular, stackable credentials, hands-on, tool-based training, industry-embedded education, and AI/digital tools as force multipliers that are currently underleveraged.

Meeting the estimated need for 150,000 new quantum manufacturing jobs by 2030 will require substantial, coordinated investment in workforce development at all levels.

7. No Common Cross-Disciplinary Language or Standards- Quantum manufacturing requires simultaneous expertise in quantum physics, cryogenic engineering, semiconductor fabrication, RF/microwave electronics, photonics, systems engineering, and supply chain management. These communities do not share a common technical language, design framework, or set of standards. Digital twins and modular abstraction layers are emerging as partial solutions, but no mature equivalent of EDA tools (Cadence, Synopsys) or semiconductor PDKs exist for quantum systems.

8. Process Integration for Non-Standard Materials- Quantum devices use materials, niobium, lithium niobate, barium scandium oxide, specialized superconductors, and isotopically purified substrates that do not fit existing semiconductor fab process flows. Material defects at scales irrelevant to classical electronics are catastrophic for qubit performance. No equivalent to silicon's mature process library exists for quantum materials, and establishing one requires long-term, coordinated investment that the market alone cannot provide.

9. Critical Material Vulnerabilities Have No Backup Plans- Helium-3 for dilution refrigerators is rare and expensive, with the most accessible natural reserves on the moon. Other quantum-critical materials face geographic and geopolitical concentration risks similar to lithium in EV batteries or rare earths in defense electronics. Unlike those industries, quantum has not yet developed quantitative supply chain resilience models or material substitution strategies. The supply chain panel's summary was direct: Quantum currently has no backup plan for material dependencies.

10. Governance, Standards, and Ethics Are Lagging- Quantum computing's implications for cryptography, national security, and potentially biology and medicine are significant. Unlike AI, where governance frameworks arrived years after deployment, quantum offers a window to establish standards, export controls, ethics frameworks, and security protocols in advance. This window is not being used effectively. Export controls in particular create an unresolved tension between open academic research (which requires international talent) and national security classification requirements. Moreover, export controls are critical to the resilience of the manufacturing supply chain, as raw materials and manufactured components will be subject to them and to geopolitical pressures. Thus, the future of manufacturing must take into account the importance and role of export control policies in scaling and securing the manufacturing supply chain.

11. Academia–Industry Translation Mechanism is Lacking- U.S. taxpayer-funded academic research generates quantum IP that is frequently commercialized abroad. The transition from university lab to manufacturable product, particularly through the TRL 3-to-5 "valley of death," lacks systematic support. Government agencies are increasingly demanding tech transfer over publications, but university incentive structures (promotion criteria, grant metrics) have not adapted. The result is an innovation pipeline that produces discoveries but struggles to convert them into domestic industrial capability.

Summary Table

Category	Count	Priority Examples
Trends	7	Modular architecture, classical-quantum integration, AI convergence
Drivers	6	Fault tolerance milestone, $1T economic value, national security
Gaps	11	No national roadmap, cost per qubit, workforce mismatch, no user facility

The clearest message across all sessions: **the science is sufficiently mature that manufacturing gaps are now the binding constraint.** The field's next decisive battles will be fought in fabs, supply chains, training programs, workforce development, and policy offices, not just in science labs.

5. Summary

Quantum technologies have entered a decisive transition from scientific exploration to engineering-scale implementation. The workshop discussions made clear that the central challenge facing the field is no longer whether quantum systems can be demonstrated in laboratories, but whether they can be manufactured, integrated, scaled, and deployed reliably at industrial levels as a part of a quantum industrial base, also addressing supply chain resiliency. This is important for a quantum industrial base on Earth and also for an emerging quantum industrial base and applications in Space. Participants consistently emphasized that quantum's future competitiveness will depend as much on advances in manufacturing, packaging, supply chains, infrastructure, workforce development, and standards as on breakthroughs in physics itself.

Several major trends emerged across the workshop. Quantum computing is increasingly converging with established semiconductor, photonics, and high-performance computing ecosystems, with modular architectures, multi-signal integration, and chiplet-based integration, and quantum-classical hybrid systems becoming the dominant development path. Multiple qubit modalities are expected to coexist for the foreseeable future, increasing both technological flexibility and supply chain complexity. Artificial intelligence (AI) is already accelerating quantum design, optimization, and workforce training, while geopolitical competition is compressing development timelines and elevating quantum technologies to the level of strategic national infrastructure and industrial base.

At the same time, the workshop identified significant engineering and manufacturing gaps that could limit scalability if not addressed through coordinated national action. Current costs per qubit (quantum bit) remain too high for widespread commercial deployment, specialized suppliers and materials remain scarce, and critical infrastructure for manufacturing and process validation is fragmented or inaccessible. Participants highlighted unresolved challenges in cryogenic packaging, interconnects, transduction, and process integration for non-standard materials, as well as the absence of mature standards, common design frameworks, and interoperable manufacturing tools. Workforce challenges extend beyond shortages of scientists to a broader need for engineers, technicians, and manufacturing specialists capable of translating research prototypes into manufacturable systems.

A recurring conclusion throughout the workshop was the urgent need for a coordinated national quantum manufacturing strategy. Participants called for stronger alignment among academia, industry, government, and standards organizations to develop shared roadmaps, establish manufacturing user facilities, strengthen domestic supply chains, and accelerate technology transfer from research laboratories to scalable industrial production. The discussions underscored that quantum manufacturing represents both a technological opportunity and a strategic imperative. Nations that successfully build resilient quantum manufacturing ecosystems will shape the future of computing, communications, sensing, energy-efficient infrastructure, and economic competitiveness for decades to come.

6. Acknowledgements

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Thank you for attending and participating!

We appreciate your participation and insights, and we look forward to continuing the conversation on advancing scalable quantum technologies together.

With appreciation,

Executive Organizing Committee