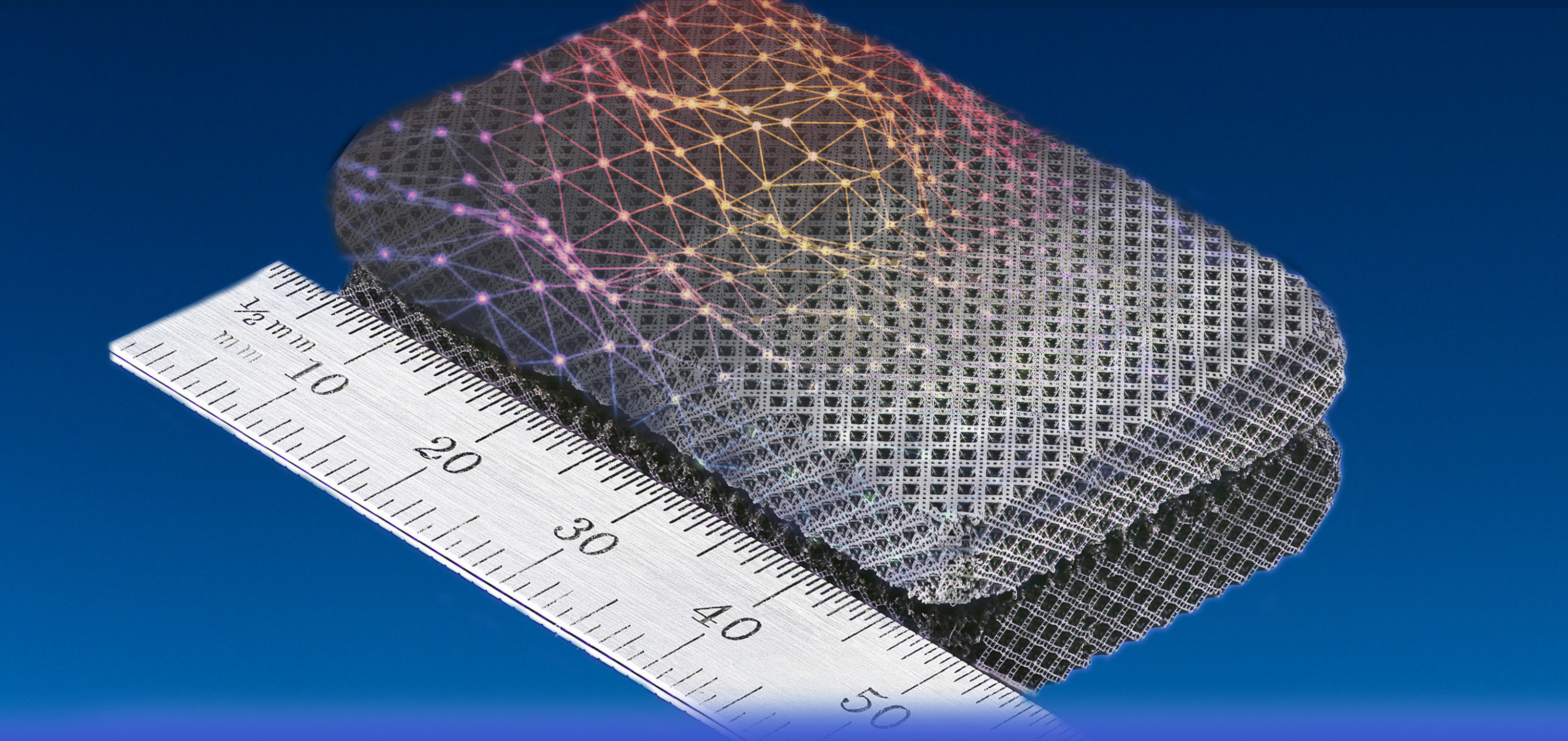

Rapid Reliability Assessment of Safety-Critical and Emerging Technologies:

Next-Generation Nondestructive Evaluation

MFORESIGHT

ALLIANCE FOR MANUFACTURING FORESIGHT

Rapid Reliability Assessment of Safety-Critical and Emerging Technologies

Next-Generation Nondestructive Evaluation

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MForesight: Alliance for Manufacturing Foresight serves as the voice of the national advanced manufacturing community, providing government, academia, and industry with information and analyses about emerging technologies, workforce training, and opportunities for public-private partnerships that strengthen U.S. competitiveness. MForesight is funded by the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST).

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Additively manufactured part featured on the cover is courtesy of Chris Spadaccini (Lawrence Livermore National Laboratories).[1]

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Executive Summary

In 1989, United Airlines Flight 232 crashed, killing 111 and injuring many more. In 2007, the I-35 Mississippi River Bridge collapsed, killing 13 and injuring 145. In 2010, the San Bruno pipeline exploded, killing 8, injuring 58, and causing immense residential property damage. In 2017, the Ohio State Fair ride failure killed one and injured seven. For each of these events, advanced rapid reliability assessment through nondestructive evaluation (NDE) could have potentially saved lives if employed in time to reveal the defects that led to catastrophic failures, but action was not taken before it was too late. Without a strategic and concerted NDE effort, these mistakes will likely be repeated. The futures of products developed in the aerospace, automotive, civil infrastructure, medical device, and many other safety-critical areas will rely on additively manufactured components, advanced composites, and complex material joining. The current state of NDE is not sufficient to safely implement these technologies in a multitude of applications. The nation must do all it can through NDE to prevent disaster from striking again.

The American Society for Nondestructive Testing (ASNT) defines NDE as “the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system.”[2] Rapid reliability assessment, enabled by NDE, is poised to enable technologies that will have tremendous impact on U.S. safety, energy, health, and national prosperity. For example, the aviation industry could replace thousands of fasteners used in airframe construction with bonding, making aircraft lighter, stronger, more efficient, and able to fly longer; however, better NDE of bonds is needed. Additive manufacturing (AM) has promised complex designs that can solve innumerable challenges, but the realization of its full potential is constrained by a lack of NDE tools to certify the safety and quality of components and systems. In addition, the future of alternative energy sources in the United States relies on new materials, structures, and processes. Finally, U.S. military readiness relies heavily on the safety and reliability of the ground, air, and sea vehicle fleet. Progressing NDE is vital to advancing these important components of the national agenda and to securing the United States’ global competitive advantage.

The challenges and emerging opportunities facing NDE cut across a spectrum of technologies and disciplines, ranging from materials science to electrical engineering and computer science. Coordination and strategic investments are needed to translate America’s scientific discoveries in next-generation NDE to technologies implemented in U.S. factories and to create new economic opportunities. MForesight: Alliance for Manufacturing Foresight convened leading U.S. industry, research, and government experts and practitioners to gather insights to identify cross-cutting prospects and challenges for next generation NDE. In alignment with MForesight’s mission of providing coordinated input from the advanced manufacturing community to inform national priorities in advanced manufacturing, this report makes **three actionable recommendations** aimed at advancing U.S. competitiveness through next-generation NDE:

- **Establish a multi-agency federal research initiative to advance NDE** capabilities to support advanced manufacturing.
- **Initiate a comprehensive NDE benchmarking program** to accelerate NDE development and implementation through novel physical and digital benchmarks.
- **Accelerate new technology implementation** through the creation of a national NDE research and user facility and an NDE workforce development working group.

Technical Recommendations

1. Establish a multi-agency federal research initiative to advance NDE capabilities for complex parts and emerging manufacturing technologies. The initiative should focus on translational research that advances NDE technologies, analysis methods, and processes for complex and safety-critical products, emerging manufacturing processes, and novel materials. Specific attention should be paid to the following NDE technology and process challenges:

- **In-process AM:** Quality and performance evaluation during AM processes is hypothesized to be critical for both anomaly detection and prevention. Evaluation can be improved through advancement of AM anomaly and material characterization, integration of NDE with feedback and control, development of tools to assess ceramic and polymer-matrix composites, and refinement of powder bed AM assessment.
- **Bonds and interfaces:** Ensuring bond strength is critical to maintaining safety and reliability but is difficult to measure. Research related to bond and interface strength assessment should focus on improving technologies to evaluate multiple bonded layers, solid state bonds, large area bonds, and diverse bonding materials; in-situ monitoring of welding; modification of bonds to improve assessment; and laser-based bond assessment.
- **Complex geometry:** Inspecting and evaluating parts with complex geometry is particularly challenging. Research should address inspection of curved interfaces, complex channels, rough surfaces, lattice structures, highly porous materials, and anisotropic materials. Representative manufacturing processes include additively manufactured parts, multi-core castings, thick composites, and ceramic-based and/or coated materials.
- **Material characterization:** NDE can be used not only to find defects, but also to measure and evaluate local material properties. Research should focus on advancing this latter capability, including evaluation of grain size and its spatial variability, residual stress, texture, microstructure variation and anomalies, dislocation density, yield stress, fracture toughness, and fatigue damage.
- **Robotic integration:** NDE is becoming increasingly automated, but robotic integration presents unique challenges. Research should focus on NDE tools that leverage automation for enhanced detection,

improved programming and path planning automation, remote and limited access inspection, and enhanced autonomy.

Research is also needed to address NDE analysis challenges and limitations, including the following:

- **Analysis and probability of detection:** Translating raw NDE data to valuable evaluation results, including quality assessment, requires sophisticated analysis methods. Research should be directed toward the application of machine intelligence, robust multi-modal analysis, and advanced data fusion to improve material characterization and advance NDE capabilities towards realizing an improved probability of detection (POD).

- **Modeling and simulation:** To transform data into actionable intelligence, data analytics must be integrated with modeling and simulation tools. Research should focus on integrating physics-based models with NDE data, relating materials models to NDE models, modeling flaws and defects, and inspection models for NDE processes.

- **Manufacturing and design integration:** NDE's power will be fully realized only when it is deeply integrated into manufacturing and design processes. Research should focus on improving mapping of data to 3D environments, integration with computer aided design (CAD), data visualization, and integration of NDE measurements and the resulting data throughout the manufacturing processes.

2. Initiate a comprehensive NDE benchmarking program to accelerate NDE development and implementation. The program should focus on the development and refinement of key physical and digital benchmarks for general defects and for defects specific to AM, bonds and interfaces, and ceramic-matrix composites, and the use of multi-modal assessment. Digital benchmarks include POD databases, digital artificial defect datasets, image databases, and multi-modal datasets. By leveraging existing national efforts, the program should ensure the creation, storage, and management of a library of relevant NDE benchmarking specimens, tools, and data. NDE data standards should also be modernized to better capture and transmit data.

3. Accelerate new technology implementation through creation of a national NDE research and user facility and an NDE workforce development working group. This facility should provide resources to accelerate the development and integration of next-generation NDE tools and methods with emerging manufacturing processes, with a specific focus on multi-modal NDE, robotic integration, and automated data processing. The working group should address (1) creation of a robust pipeline of NDT Level II and III technicians[a]; (2) integration of NDE education into engineering disciplines; (3) continuing education on recent advances in NDE tools and technologies; and (4) development of NDE experts with a foundational knowledge in multiple disciplines.

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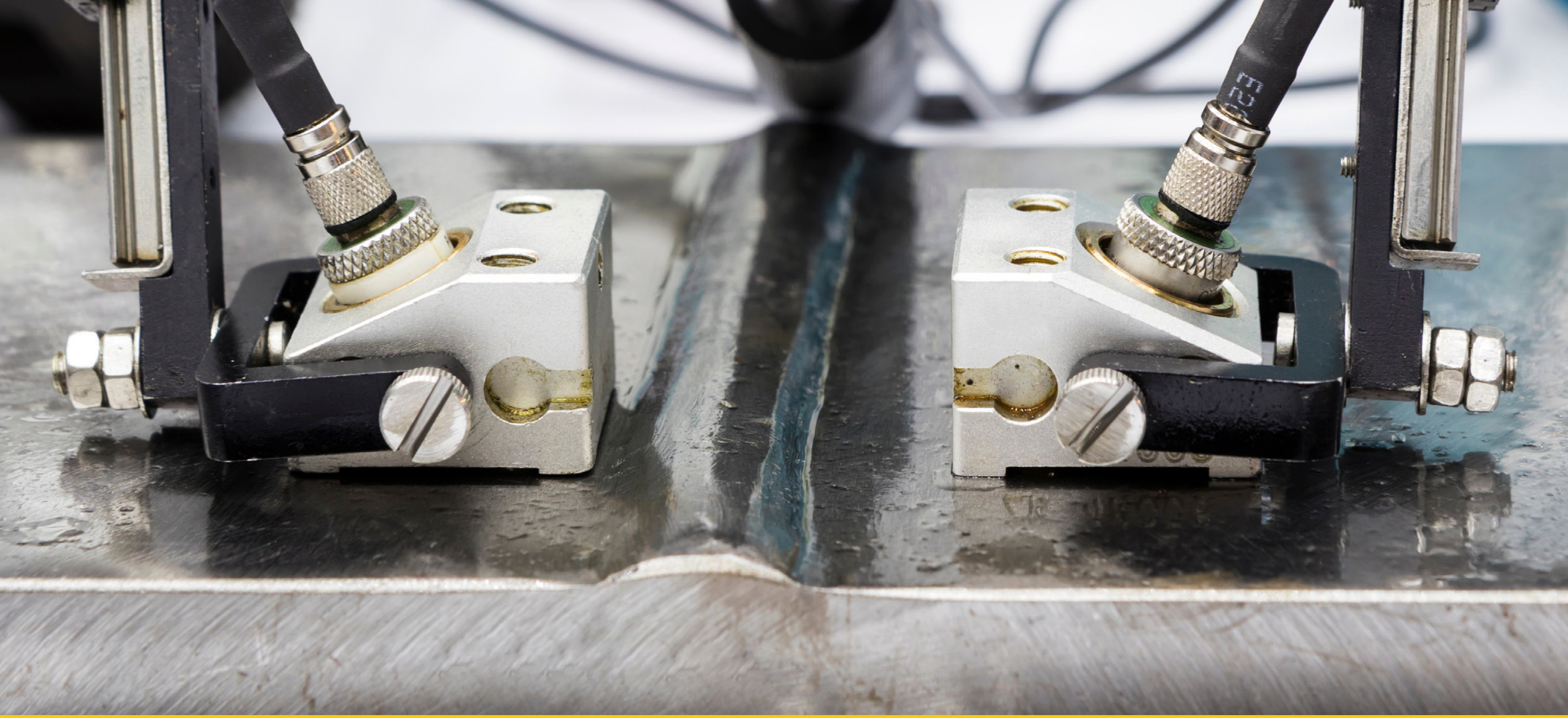
a. NDT Level II and III are certifications for nondestructive testing (NDT) experts provide by the American Society of Nondestructive Testing (ASNT).



Introduction

Rapid reliability assessment through nondestructive evaluation (NDE) is poised to enable technologies that will have tremendous impact on U.S. safety, energy, health, and national prosperity. For example, the aviation industry could replace thousands of fasteners with bonding, making aircraft lighter, stronger, more efficient, and able to fly longer; however, better NDE technology to determine bond strength is needed. Additive manufacturing (AM) has promised complex designs that can solve innumerable challenges, but the realization of its full potential is constrained by a lack of NDE tools to adequately inspect some of the complex parts and dramatically varying microstructures. Without advancements in NDE, the cost of maintaining U.S. military strength will distress budgets and reduce readiness, and the necessary growth and cost-effective maintenance of alternative energy sources will go unrealized. NDE is essential for validating new structures and materials, providing a rapid introduction of new technology into manufacturing. The next generation of NDE stands to play a critical role in Smart Manufacturing or Industry 4.0. As manufacturing moves toward full digitization, NDE can provide a critical role in closing the digital loop from final product back to design, component life assessment, and manufacturing processes; NDE is currently the weakest link in the path the full digitization.

The United States must act, or other countries will gain a lead in critical areas of advanced manufacturing. An investment in NDE capabilities to realize rapid reliability assessment is a strategic move to support the future well-being of the nation.

Nondestructive Evaluation Technologies

The American Society for Nondestructive Testing (ASNT) defines NDE as "the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system."[2] Although its goal may be straightforward, a multitude of technologies, processes, tools, and analytical methods are required to address the complexities and realize the objectives of nondestructive evaluation.

The NDE process starts long before a part is inspected or even made, with proper design for inspectability and an understanding of the requirements, capabilities, and limitations of current NDE technologies. As a part is inspected, a multitude of sensor technologies that leverage numerous sensor physics delivering various forms of energy are available. These technologies include radiographic testing, such as x-ray and computed tomography (CT) scans; electromagnetic testing, especially eddy current testing; ultrasonic testing; magnetic particle testing and magnetic flux leakage; acoustic emission testing and vibrational analysis; thermal and infrared testing; and a variety of aided visual testing, such as fluorescent liquid penetrant testing.[3,4] Many additional NDE methods and application techniques are at various stages of development, ranging from basic research to industry adoption.

Each method has unique strengths and weaknesses, and there is increased interest in using them in concert to provide the best overall assessment. These methods range from being fully automated to fully manual and are applied in-situ (in the manufacturing processes themselves), in-line (between manufacturing steps), and end-of-line (inspecting the final part or assembly). The resulting inspection data are analyzed to find anomalies and characterize defects, characterize material properties, and ensure proper assembly and joining. A host of models, artificial intelligence methods, and advanced analytics are employed to improve the probability that the process will detect and/or characterize defects and/or material properties, as well as the overall performance of the analysis. These results are then integrated into the broader manufacturing enterprise to assess service life, ensure and improve part quality, refine parts and manufacturing processes, and validate new designs and materials.

Nondestructive Evaluation in Manufacturing

NDE is critical to manufacturing, and, as noted by Boeing, "The future will continue to rely on innovation in the non-destructive inspection of our aircraft."[5] According to an EWI[b] study, when industry representatives were asked "What technical advancements would have the greatest impact on your business?," their highest ranked response was "More accurate and reliable NDE."[6] In a TMS-MForesight study, "Harnessing Materials Innovations to Support Next Generation Manufacturing Technologies," the highest ranked opportunity was "Analytics for NDE and Sensors."[7] NDE has played a role in revolutionizing manufacturing comparable to that of process innovations.[4]

The American manufacturing sector prides itself on the quality, reliability, safety, and novelty of its advanced manufactured goods. Tools that efficiently evaluate parts and processes without causing damage or affecting production are a cornerstone to delivering products with these valuable attributes. To maintain its manufactur-

b. EWI was formerly known as Edison Welding Institute (EWI) ing competitiveness, the United States must lead the way in developing and implementing accurate, reliable, and effective next-generation rapid reliability assessment tools. NDE enables manufacturers to develop and assess products with new materials, optimized designs, and reduced scrap. NDE can be employed to detect manufacturing and design issues early when introducing new products and processes, and it can be integrated into manufacturing processes to enable real-time control and feedback. **Improved NDE capability directly translates into improved design safety, quality, and value.**

NDE has essential uses in many critical emerging areas, including AM, composites, and Industry 4.0. The industrial AM market is expected to grow by more than 27% per year for the foreseeable future.[8] AM presents unique challenges, such as defects ranging from porosity to poor particle fusion, which current NDE methods cannot reliably detect and characterize in complex parts. With metal AM, challenges range from difficulty using ultrasonic probes at high temperatures during fabrication to limitations of x-ray and CT in evaluating material properties, especially in thick parts. To realize the full benefit of AM at production scale these obstacles must be overcome in material state assessment, damage detection capability, damage detection reliability, and assessment process efficiency. **Limitations in NDE's ability to detect anomalies and characterize flaws is a critical barrier to implementing higher performance designs.** Real-time NDE monitoring could allow for early detection of anomalies, enabling the build process to be stopped or altered early, conserving machine time and material costs. NDE advancements present the opportunity to expand the use of AM parts by providing enhanced qualification and certification protocols. NDE is also an essential tool for advancing AM processes and providing validation for physics-based process models.

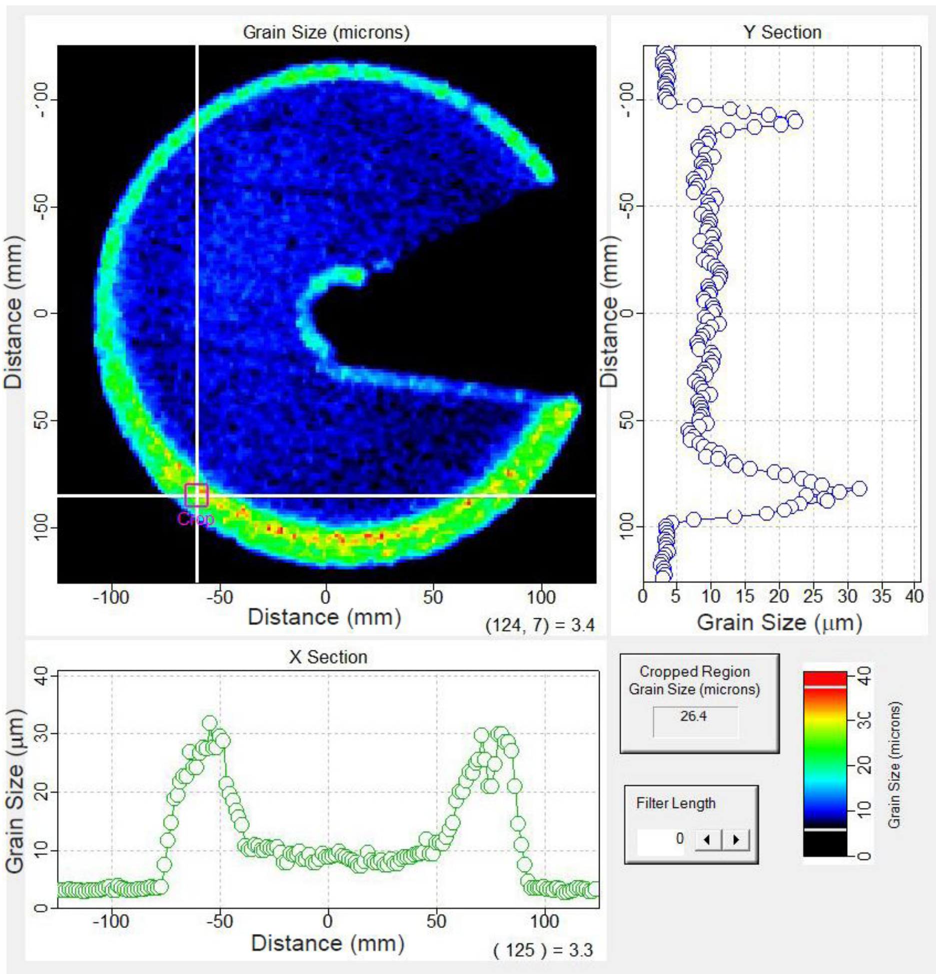
Composite materials from carbon-fiber to ceramic matrix present unique challenges and opportunities for NDE. The markets for these materials are experiencing rapid growth, with the expanding use of composites in automotive (12% CAGR[c])[9] and aerospace (11% CAGR)[10] and the ballooning ceramic-matrix composite market (13% CAGR).[11] A wide variety of defects can plague composites, including delamination, fiber fracture, interfacial cracks, porosity, moisture, wrinkles, poor curing, voids, inclusions, heat damage, and micro-cracks. The ability to identify and characterize allowable anomalies in such material is critical. Although they can address many of these challenges, existing tools cannot deliver the speed, cost, and reliability of detection and characterization required by manufacturers, especially for complex parts.

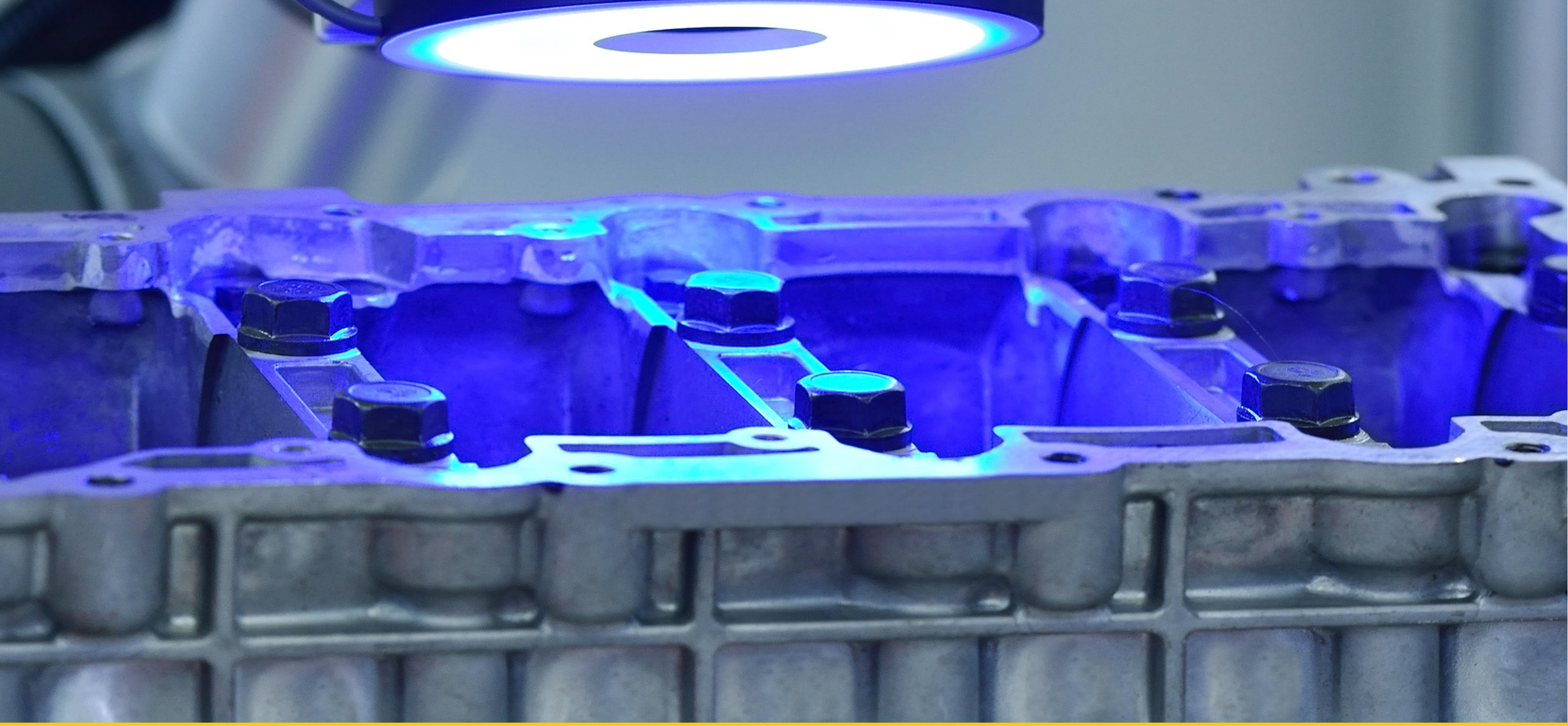
The next generation of NDE will be not only an enabling technology for additive and composites, but also a critical component of Industry 4.0. As manufacturing moves toward full digitization, rapid reliability assessment through NDE enables the essential final element to close the digital loop from final part back to the design and manufacturing processes. This advancement requires NDE not only to identify anomalies and discontinuities, but also to be a tool for material assessment, measuring mechanical properties, microstructure features, and local material changes as a function of processing steps during manufacture. For example, Figure 1 presents a mapping of microstructural grain size of a rotating engine disk that was extracted from ultrasonic inspection data.[12] Material properties are defined by more than chemistry; microstructure, such as grain structure, directly affects a range of properties, including yield strength, toughness, and fracture toughness. NDE assessment must become more automated and reliable, with improved POD, data fusion platforms that provide comprehensive 4D data[d], and more intuitive NDE processes that are ready for the

c. The compound annual growth rate (CAGR) is the average growth of the market per year and is often forecasted for the next 5-8 years.
d. 4D data often refers to data in the three spatial dimensions plus their change over time.

factory floor. NDE of the future will better connect signals, values, and images to material prognostics, finite element analysis, and design tools. The entire NDE ecosystem must be advanced to ensure that technology advancements made in the laboratory make their way to manufacturers, especially to small and medium-size firms. For this to occur, technology must be translated to industry ready tools, benchmarks must be created, manufacturing must be better integrated, and inspection technologies must become more affordable.

Figure 1: Mapping of microstructural grain size of a nickel-based superalloy rotating engine disk. Image courtesy of Paul Panetta (Applied Research Associates, Inc.).





Establish a Multi-Agency Federal Research Initiative to Advance NDE Capabilities for Complex Parts and Emerging Manufacturing Technologies.

NDE is not a single action or process. Rather, it is a combination of many sensors, processes, system integrations, models, and analysis tools that enables evaluation of parts without destroying them. Decades of research have formed a strong base of knowledge and tools, but NDE for complex parts and emerging manufacturing technologies cannot be fully realized without the development of additional capabilities through further research and advancement. These capabilities fall into two major categories:

1. Technologies and processes that enable NDE of emerging manufacturing areas, complex parts, and material properties; and

2. Analysis, modeling, and advanced sensing methods to improve the speed, accuracy, and utility of the evaluation process.

A focused research agenda is needed at the basic, applied, and especially translational research stages to address the NDE challenges and opportunities facing the nation. This section establishes the NDE research challenges most pressing to U.S. manufacturers and describes targeted research foci that provide an actionable pathway to address these challenges.

NDE Technologies and Processes

Advanced rapid reliability assessment through next-generation NDE technologies and processes will enable breakthroughs in (1) evaluation of emerging manufacturing processes, such as AM, bonds, and interfaces, (2) integration with advanced robotic systems, and (3) evaluation of properties and parts that was previously impossible, including of the highly complex geometry and the mechanical properties of the materials themselves.

In-Process Additive Manufacturing

Quality and performance evaluation during AM processes is critical for both anomaly detection and prevention. A key barrier to the broad realization of AM, especially for safety-critical parts, is a poor understanding of the anomalies present in an additively manufactured part and their effect on lifetime part performance. This understanding must evolve within the context of the part's functional requirements, so that manufacturers can determine when an anomaly becomes an unallowable defect. Detecting defects in-situ during the AM process could provide a host of benefits, including:

- Early detection of unallowable defects so that building parts can be canceled early, reducing waste;
- Real-time feedback and control of the AM process to produce higher quality parts with fewer anomalies;
- In-situ repair of defects during manufacturing;
- Better correlation of in-process data with final part condition;
- Better understanding of the microstructure of the part, especially of internal portions that are difficult to assess; and
- Enabling the creation of certifiable parts by AM processes.

AM uses many processes, materials, and raw material forms, which leads to a variety of NDE challenges that are specific to the material and/or process. With polymers, for example, the assessment of shrinkage is complicated. Post-processing, such as hot isostatic pressing, can create defects that must be better understood. Composites, including both polymer-matrix composites and ceramic-matrix composites, are a nascent AM area that is going to be particularly challenging to inspect. Manufacturers have expressed a very strong interest in advancing NDE for metal AM. Better NDE is needed throughout the process—from feedstock evaluation to assessment of powder beds to melt pool monitoring—and for the finished part.

Research into these critical areas is already under way, including with ASTM, which is working with the fabricators industry to develop E07.10 WK62181,[e] "New Guide for Standard Guide for In-Situ Monitoring of Metal Additively Manufactured Aerospace Parts." Federal agencies including the United States Air Force,

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e. See https://www.astm.org/DATABASE.CART/WORKITEMS/WK62181.htm

National Institute for Standards and Technology (NIST), Federal Aviation Administration (FAA), and National Aeronautics and Space Administration (NASA),[8] as well as the International Organization for Standardization (ISO), ASTM International, American National Standards Institute, and the America Makes Manufacturing USA Center, have held workshops and formed working groups to address the challenges of NDE for AM and have helped to inform critical research directions. The NDE and manufacturing community identified four key areas requiring a research focus:

- **Advancement of AM anomaly characterization,** including characterization of geometric and microstructural anomalies, relation of anomalies to material and part performance, and definition of allowable ranges for anomaly detectability and acceptability.

- **Integration of NDE with feedback, control, and calibration,** including real-time in-situ NDE inspection and analysis, control methods that leverage NDE data, AM machine calibration, and correlation of in-process data with final part condition.

- **Tools for assessing ceramic-and polymer-matrix composites** during AM, addressing the challenges of NDE for multi-material and non-conductive materials.

- **Development of NDE technologies for metal powder bed AM** that enable assessment and characterization of porous material and high-temperature melt pools.

Bonds and Interfaces

Bonds and interfaces include welds, adhesives, solid-state bonding, fastening, and other means to connect multiple parts and materials together. These connections are found in nearly every industrial sector. **Measurement of bond strength is critical to optimizing and lightweighting designs, as well as ensuring that bonds do not fail in operation.**

Advanced bonding combines multiple bonded layers, joins together an increasing array of diverse materials, and bonds over increasingly large areas. Multiple layers increase interference and limit the probability of detecting defects. Diverse material joining, such as metal to ceramic, limits the sensing methods that can be used because they must work for both materials. Large areas present challenges related to speed, cost, and data processing. To increase the sensitivity to defects, sources of noise, such as surface roughness, surface contamination, and surface morphology, must be reduced or eliminated. These surface attributes also have a large effect on local bond strength. Welding is an especially prevalent bonding technology, and much more can be done to monitor the welding processes so that anomalies and defects can be caught early, and weld quality can be validated deep into the part. Additional research should focus on five key areas:

- **Modifying joints to improve assessment,** such as developing contrast agents or spectroscopy markers for the joints.

- **Modeling NDE bond strength performance** as a function of surface properties, materials, microstructure, defects, layers, and connection interface. The models should relate destructive testing results to properties identified during NDE testing and should build upon existing data and models in literature.

- **Advancing technologies for multi-material and multi-layer joining**, including improved laser bond inspection and nonlinear ultrasonic assessment methods.
- **Developing rapid and robust sensing methods and analysis tools** that can be used on complex surfaces and over large areas.
- **Creating in-situ joining measurements**, especially during welding.

Complex Geometry

Highly complex geometry can hinder a sensor's ability to provide sufficient energy to penetrate a part and detect anomalies. Noise and interference from complexity may also reduce the quality of the data from these regions. Common examples of complex geometry include finding anomalies in cooling channels, analyzing parts with complex internal geometry such as lattice structures,[14,15] evaluating highly porous ceramics, and overcoming interference from structural features, such as those generated by multicore castings. Material properties, such as anisotropy, can inhibit assessment of many components, such as forged metals, processed ceramics, and additively manufactured parts. In addition, heterogeneous microstructures can distort ultrasonic beams and steer them away from their intended locations. Size alone can inhibit NDE efforts, including penetrating deep into thick sections of composites and reliably finding very small defects within very large area parts. Most current technologies quickly lose resolution at deeper penetration depths, and the methods that provide the deepest penetration are often very costly and generate enormous datasets. Figure 2 highlights the major nondestructive evaluation methods and the tradeoff between depth and resolution.

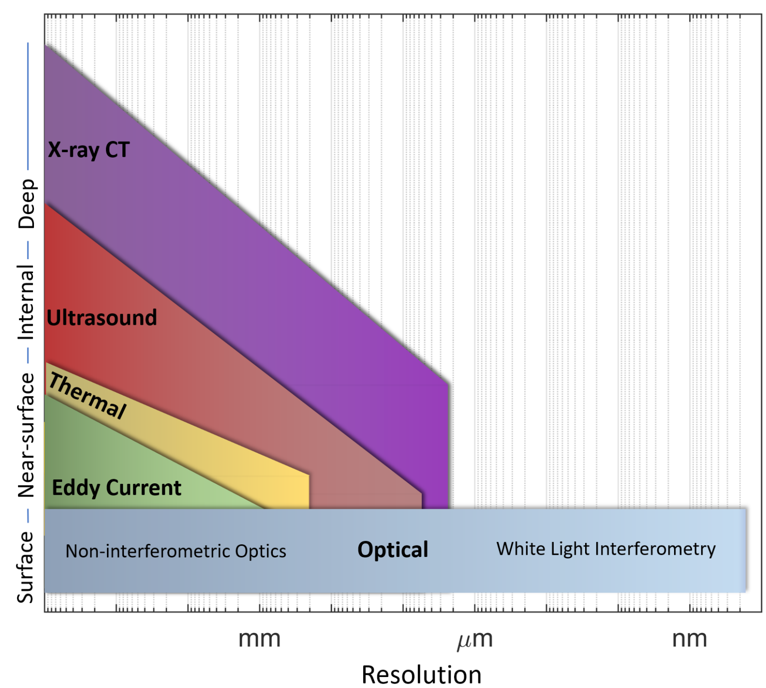


Figure 2: Tradeoff between assessment depth and resolution of major non-destructive technologies in additive manufacturing NDE. Figure adapted from image courtesy of Lucas Koester (Center for Nondestructive Evaluation, Iowa State).

Complex surfaces, including rough surfaces and highly curved interfaces, present unique obstacles to receiving and analyzing data to find defects. Complex geometry becomes more challenging as multiple materials are combined, such as with ceramic-coated metal parts. The ability to inspect complex geometry is critical to successful implementation of numerous parts across an array of applications and industries. Three key areas should receive additional research focus:

- **Tools for inspecting large areas at high resolutions**, including advancements in sensor scanning and data analysis methods.

- **Technologies that enable high-resolution and deep penetration**, including novel sensing physics, data fusion to integrate the advantages of multiple sensor physics, arrayed probes, smaller pixel pitch detectors, larger detectors, optical magnification, better beam hardening, better physical image filters, and 3D x-ray backscatter to perform one-sided volumetric scanning. High-flux radiation sources should also be advanced to increase portability, speed, and capability.

- **Sensors and analysis for complex geometry,** including curved interfaces, complex channels, rough surfaces, lattice structures, multi-core castings, highly porous materials, and anisotropic materials. Better coupling media, especially for ultrasound, should be developed, such as cryo-ultrasonic NDE.[16]

Material Characterization

Material properties are defined by more than chemistry; microstructure, such as grain structure, directly affects a range of properties, including yield strength, toughness, and fracture toughness. For some parts, such as turbine blades, even the slightest change in grain structure can lead to performance reduction, flight shutdowns, or even catastrophic outcomes. **NDE is essential for not only identifying anomalies, cracks, and voids, but also characterizing critical materials attributes throughout the part.** Examples of this characterization include the following:

- Advanced multi-phased engineered materials require an understanding of grain size distribution.

- Parts that have undergone thermal or mechanical forming or treatment must be quantitatively measured for their residual stress.

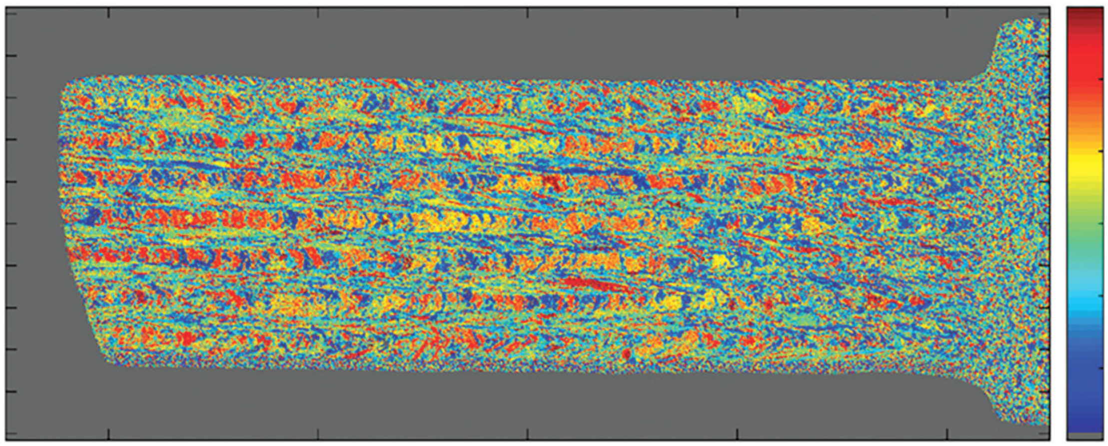
- Texture needs to be determined in metallic and ceramic materials, especially titanium and nickel-based alloys.

- A method is needed to differentiate between texture, stress, and other attributes that directly affect the same measured quality from the NDE characterization process.

- Methods are needed to detect the change in local material properties of composites as they age.

Mapping microstructural variations and anomalies is critical for qualifying parts. Dislocation density and creep void coalescence must be quantitatively measured throughout parts to determine mechanical properties and then integrated into the analysis methods that determine remaining life. Microstructural measurements should be correlated to the various local values of material properties, including yield strength and fracture toughness, to provide a very important input to a prognostic assessment of material life. Figure 3 presents an example of grain orientation mapping using surface acoustic wave velocity mapping methods.

Figure 3: Grain orientation is mapped across the entire surface of a part using surface acoustic wave velocity mapping through Spacing Resolved Acoustic Spectroscopy (SRAS). Image courtesy of C. Peter Collins (Center for Nondestructive Evaluation, Iowa State).[f]



Research could unlock the potential of NDE on material characterization in four key areas:

- **Tools to nondestructively quantify and map material microstructural properties**, such as grain structure, both on the surface and within the volume of the material. In addition to common materials, such as high-strength steels, attention should be paid to complex materials, including ceramics, composites, and multi-phased materials.
- **Tools designed to measure local material properties**, including yield strength, fracture toughness, residual stress, grain boundaries, service damage, and fatigue damage. Differentiation between stress and other confounding factors in stress evaluation (e.g., texture) should be explored.
- **Methods for assessing local material properties in non-metallic materials**, including scanning acoustic microscopy and coda wave ultrasound.
- **Multi-modal methods** that come separate physics that are sensitive to microstructure changes in different ways.

f. From Koester, Lucas, W., Hossein Taheri, Timothy A. Bigelow, Peter C. Collins, and Leonard J. Bond, "Nondestructive testing for metal parts fabricated using powder-based additive manufacturing," Materials Evaluation 76, no. 4: 514-524. Copyright © 2018 by The American Society for Nondestructive Testing Inc. Reprinted with permission.

Robotic Integration

Integration of robotics with NDE tools can improve the cost, efficacy, and speed of assessment. For example, automated scanning permits rapid coverage of large areas, reduces technician fatigue, and ensures a more repeatable evaluation process. Robotics also enables limited access and remote inspection, where it is difficult to impossible for a technician to access.

The benefits of robotic integration have not been fully realized for several reasons. Programming, especially path planning, for robotic inspection on each different part has proven to be costly and time consuming, especially for highly complex parts. Robotic inspection can improve the quality of assessment, but NDE tools must be developed or modified to take advantage of the automation. Robotic tools often have deficiencies in scalability, generalizability, sustainability, and supportability.

Finally, although much work has been done to combine full matrix capture ultrasonic inspection with robotic automation, more could be done to improve the speed and quality of the capture and data analysis.[17]
To address these challenges, the following five research areas should receive additional attention:

- **Soft robots and snake-like serial chain robots** to improve limited access inspection.
- **On-the-fly rapid automated path planning** for 3D NDE scanning. Focus should be placed on complex shapes that are not simply X-Y-Z linear motions.
- **Tailored NDE techniques that leverage automation**, including both novel methods and modifications to existing tools and techniques.
- **Intelligent autonomous NDE systems** with location tracking and NDE data integration that leverage advances in analysis algorithms for both robotics and NDE data.
- **Integration of full matrix capture with robotic automation**, continuing existing work to improve POD, speed, and robustness.

NDE Analysis, Modeling, and Advanced Detection

Analysis, modeling, and advanced detection are essential to doing more with sensor data, including improving the sensitivity of detecting defects; modeling materials and processes to improve the speed, quality, and synthesis of results; and better integrating the results with the broader manufacturing and evaluation processes. These advancements enable new and improved capabilities for rapid reliability assessment.

Improving Analysis and Probability of Detection

Extracting and interpreting NDE data from sensors is a substantial undertaking; digital datasets from the sensors are large, noisy, multi-dimensional, and often challenging for a human or computer to directly interpret. Overcoming these challenges is critical to improving the sensitivity of detecting defects, improving the speed and affordability of inspection, using NDE for real-time processes, expanding NDE into processes and parts that are difficult or impossible to evaluate nondestructively, and using NDE in emerging areas such as material property assessment.

Current research on flexible data structures has revealed a more universal way to store a multitude of NDE data types and to enhance interoperability. Large datasets slow down analysis, and current data reduction techniques cannot process some types of data in real time. Advancements in artificial intelligence, machine learning, neural nets, and a range of advanced analytical tools have been disruptive in numerous industries. Areas of importance include automatic defect recognition (ADR), where the analysis tools can directly find the anomalies, and intelligence augmentation (aka, assisted defect recognition) analysis, where software assists a technician. Ample opportunity exists to improve these advanced analytical tools and to better apply them to address current and emerging NDE challenges. Analysis tools are not yet able to handle complex inspection and evaluation situations, and current guidelines, such as Mil HDBK 1823A,[18] do not manage multi-parameter probability of detection (POD).

As the use of multiple sensor physics to tackle complex problems increases, the need for single objective functions to address multi-modal data and tools to better integrate and fuse sensor data will also increase. **A key emerging requirement for NDE is the ability to extract a wide range of local material properties from measured parameters at a high-quality level.** Federally funded programs are conducting research in these areas, including the Air Force Research Laboratory's (AFRL) "Automated Defect Detection" program. To address these critical challenges, additional focus should be placed on the following eight research areas:

- **Automated data handling,** including flexible data structures and robust data reduction and processing algorithms to improve the collection, machine readability, and size of sensor data. Tools for handling massive data streams during manufacturing should be addressed.

- **Advancements in NDE applications of machine learning, deep learning, and physics-driven learning**. This area includes developing algorithms that are specific to NDE processes, advancing analytical technique fundamentals, and applying these analytical techniques to evaluation challenges in emerging manufacturing processes.

- **Advancement of automatic and assisted defect recognition (ADR)** to reduce the human interaction and human error that are currently embedded in NDE. Continued effort should be placed on leveraging emerging data analytics techniques for ADR. Both fully autonomous ADR and human-in-the-loop ADR (i.e., intelligence augmentation) are important areas.

- **Development of methods that can better incorporate modeling and simulation data** and digital artificial defects for ADR training to rapidly validate and qualify ADR algorithms without the need for large quantities of parts with real discontinuities.

- **Algorithms for extracting local material properties from measured parameters.**
- **Tools for multi-modal sensing**, especially for sensor integration and sensor fusion. One key area is developing single objective functions for integration of multiple inspection physics.
- **Reliable multi-parameter probability of detection methods** that incorporate multiple defect types and features with multiple attributes of the assessment.
- **Assessment for data analysis**, wherein improved datasets are generated through optimized inspection processes.

Modeling and Simulation

Modeling and simulation are essential elements of NDE data analysis. Applications range from improving data fusion to connecting NDE data with material properties and finite element models for rapid determination of the best inspection and assessment approaches.

Current NDE is often limited by measurement system dynamics and noise from many sources, including the manufacturing process, the environment, the NDE process itself, and fundamental measurement noise. Simulating noise is vital to understanding the limitations of NDE and to developing optimized evaluation methods, but current noise simulation tools are inadequate. Modeling is vital for understanding how inspectable a part is; this can be used to both improve the design for inspectability and to improve the NDE process. Current models do not adequately capture the complexity of all assessments and many must be translated to industry ready code. Also needed are models of NDE sensors and sources; current models lack a full-physics approach and/or are too resource intensive. Better simulation tools are required to improve the fusion of assessment data, which along with subsequent processing, provides more usable defect metrics.

Models can be used to identify defects from the collected inspection data. Model-assisted probability of detection (MAPOD) has been investigated[19] and remains a critical path to improving POD, but focus on this area has stagnated. Current assessment models often rely on fitting or regression, when true physics-based models could provide better results. Models are also valuable for understanding the defects themselves, especially in emerging and complex manufacturing areas such as composites and AM. Modeling of defect formation informs understanding of types, orientations, sizes, shapes, and other key factors, consequently enabling more targeted inspection and more accurate analysis. These models will also assist in relating identified defects to root causes in the manufacturing process. Focus on inverse problems to derive defect characterization is needed. Creating generic inversion models will enable inversion of sensor data to provide a mapping of the defects of interest. However, this approach is quite challenging because the data are often sparse, ill posed, or non-unique. Although this area has been investigated in the past,[20, 21] modern sensors and computational tools and knowledge could greatly accelerate this effort.

NDE models, including physics-based models and simulations of the actual inspection process, are needed to understand how energy (e.g., ultrasound, thermography) interacts with complex defects. More realistic NDE models enable the study of a larger number of scenarios than is feasible using experimental specimens. For example, varying defect orientations, shapes, or other parameters could be studied through simulation alone, and the resulting inspectability could be determined. NDE inspection models and simulation tools are needed that can model the inspection of complex geometries and advanced materials. Many tools are currently `lacking in either realism or speed. Advancements in multi-core CPUs and many-core (i.e., GPU) computing are enabling physics-based NDE models to realize greater realism while running fast enough to be practical tools.

The final area where modeling will have a large impact is connecting NDE data to material properties and performance. More advanced models could provide high-fidelity understanding of flaw geometry and the effect of flaws on material performance (i.e., material prognostics). By connecting existing material and structural models to NDE physics-based models, NDE-detected microstructure can be related to material performance.[22] Finite element is ubiquitous in manufacturing design, and directly connecting current advancements in finite element tools to assessment data would improve the understanding of a part's behavior. Physics-based stress models could be connected directly to flaw characteristics extracted from NDE data with more advanced modeling.[23] These models should be designed for industry applicability, addressing the complexity of real-world parts, processes, and data.

Work has been ongoing in many of these modeling areas, with substantial efforts by AFRL, the Office of Naval Research, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and others. However, renewed attention is needed in light of modern computational and data tools, emerging manufacturing processes, and the heightened focus on obtaining local material properties and performance during NDE. Research advances in modeling are needed in seven key areas:

- **Models of noise and the inspection process** that better describe real-world assessment in both complexity and the application environment.
- **Additional full-physics models of sources and sensors** that can be applied in real-time applications.
- **Artificial intelligence–based data fusion** derived from simulations that capture real-world data.
- **Models for improving NDE data analysis**, including MAPOD and physics-based models for multi-parameter data fitting.
- **Models of defects in emerging manufacturing areas**, including AM and composites to better understand defect root cause, types, orientation, shape, and size. Linking defects back to their respective anomalous process conditions is also important.
- **Generic inversion models** to enable inversion of sensor data to provide a mapping of the defects of interest.
- **Models relating NDE data to material performance**, including flaw geometry modeling, microstructure determination, connecting finite element models to NDE data, and predicting material stress.

Manufacturing and Design Integration

The power of NDE can be fully realized only when it is deeply integrated into design and manufacturing processes. This integration includes mapping NDE data into the 3D environment from which it was obtained, integrating with manufacturing software and processes, visualizing complex NDE data, and optimizing parts and processes to improve inspectability.

It is not sufficient to identify a defect: it must be sized, oriented, and related to a specific location on the part and the ultimate stressor environment in which it will be used. This mapping between the physical 3D world, digital 3D world, and NDE data is essential to advance the state of NDE. Although substantial advances have been made in this area, tools to improve the accuracy, connect multiple data streams, easily connect to digital twins, and integrate with CAD packages are insufficient. Once the data are mapped, technicians and engineers must be able to visualize the data, but current virtual reality and as-is 3D model generation[g] tools are lacking.[24]

NDE is often performed on the final part, but a tremendous amount of valuable information can be obtained from in-process assessment. Models and tools are needed to provide direct in-process feedback from NDE data, allowing for real-time corrections. In addition, tools are needed to connect NDE data from multiple process steps to each other and to the final assessment data. Manufacturers would like to better connect NDE data to design, final use, and evaluation processes. To address these research challenges, additional focus should be placed on five essential areas:

- **Mapping of NDE data to 3D physical and digital environments**, including advances in fiducial marks, 3D registration for volumes and metrology, tools for interpolating data streams in space and time, tools to connect NDE data to digital twins, self-calibrating registration, and integration of NDE data with CAD packages.
- **NDE data visualization tools**, including augmented and virtual reality and as-is 3D model generation from assessment data. This approach aims to improve visualization for both the inspection technicians and the design teams.
- **Tools to integrate NDE data in space and time throughout the manufacturing process,** including in-situ, in-line, and end-of-line part assessment.
- **Improved integration of NDE data with design, life estimation, and assessment processes.**
- **Error accommodation and qualification**, including registration errors, data acquisition errors, and differences between as-is and model parts. Model uncertainty and the impact on the evaluation outcome should also be investigated.

g. As-is 3D model generation is the process of creating a 3D model of the actual part produced, as opposed to the ideal model that was used as the basis for the manufacturing process.

Recommendation 1: Establish a multi-agency federal research initiative to advance NDE capabilities for complex parts and emerging manufacturing technologies. The initiative should focus on translational research that advances NDE technologies, analysis methods, and processes for complex and safety-critical products, emerging manufacturing processes, and novel materials. Specific attention should be paid to the following NDE technology and process challenges:

In-process AM: Quality and performance evaluation during AM processes is hypothesized to be critical for both anomaly detection and prevention. Evaluation can be improved through advancement of AM anomaly and material characterization, integration of NDE with feedback and control, development of tools to assess ceramic and polymer-matrix composites, and refinement of powder bed AM assessment.

Bonds and interfaces: Ensuring bond strength is critical to maintaining safety and reliability but is difficult to measure. Research related to bond and interface strength assessment should focus on improving technologies to evaluate multiple bonded layers, solid state bonds, large area bonds, and diverse bonding materials; in-situ monitoring of welding; modification of bonds to improve assessment; and laser-based bond assessment.

Complex geometry: Inspecting and evaluating parts with complex geometry is particularly challenging. Research should address inspection of curved interfaces, complex channels, rough surfaces, lattice structures, highly porous materials, and anisotropic materials. Representative manufacturing processes include additively manufactured parts, multi-core castings, thick composites, and ceramic-based and/or coated materials.

Material characterization: NDE can be used not only to find defects, but also to measure and evaluate local material properties. Research should focus on advancing this latter capability, including evaluation of grain size and its spatial variability, residual stress, texture, microstructure variation and anomalies, dislocation density, yield stress, fracture toughness, and fatigue damage.

Robotic integration: NDE is becoming increasingly automated, but robotic integration presents unique challenges. Research should focus on NDE tools that leverage automation for enhanced detection, improved programming and path planning automation, remote and limited access inspection, and enhanced autonomy.

Research is also needed to address NDE analysis challenges and limitations, including the following:

Analysis and probability of detection: Translating raw NDE data to valuable evaluation results, including quality assessment, requires sophisticated analysis methods. Research should be directed toward the application of machine intelligence, robust multi-modal analysis, and advanced data fusion to improve material characterization and advance NDE capabilities towards realizing an improved probability of detection (POD).

Modeling and simulation: To transform data into actionable intelligence, data analytics must be integrated with modeling and simulation tools. Research should focus on integrating physics-based models with NDE data, relating materials models to NDE models, modeling flaws and defects, and inspection models for NDE processes.

Manufacturing and design integration: NDE's power will be fully realized only when it is deeply integrated into manufacturing and design processes. Research should focus on improving mapping of data to 3D environments, integration with computer aided design (CAD), data visualization, and integration of NDE measurements and the resulting data throughout the manufacturing processes.

Initiate a Comprehensive NDE Benchmarking Program to Accelerate NDE Development and Implementation

Benchmarking is essential to advancing NDE and rapid reliability assessment. Benchmarking has three critical uses:

1. Benchmarking enables validation of new NDE sensors, processes, and analysis methods on established metrics, ensuring that the new technology meets industry needs. This validation improves the speed, accuracy, and reliability of existing evaluation tasks, and enables new ones.

2. Benchmarking of emerging manufacturing technologies and novel materials enables development of NDE technology that addresses the inspection and performance evaluation challenges of these advances.

3. Benchmarking of NDE analysis methods, especially with the inclusion of reference datasets and specimens, enables more rapid development, validation, and deployment of novel analysis methods.

A central database of current and future NDE benchmarks that is available to U.S. researchers and manufacturers would greatly advance NDE research, development, and translation to industrial practice. It is currently prohibitively expensive for small and medium-size manufacturers to develop and produce their own benchmarks. Many federal agencies and organizations have developed NDE benchmarks across a range of areas, and efforts have been made to centralize some of these resources, but a comprehensive multi-agency, multidisciplinary initiative to address current and future benchmarks is needed. The program should focus on the development and refinement of key physical and digital benchmarks for general defects, microstructural properties, and specific scenarios such as AM, bonds and interfaces, multi-modal assessment and ceramic-matrix composites. Digital benchmarks include POD and MAPOD databases, digital artificial defect datasets, image databases, and multi-modal datasets. By integrating with existing national efforts, the program should ensure the creation, storage, and management of a library of relevant NDE benchmarking tools and data.

Physical and Digital Benchmarks

A successful NDE benchmark database will have an array of physical and digital benchmarks to address emerging challenges. Physical benchmarks should be developed for the following six essential focuses:

- **Composites:** Many defect types can be present in composites, from fiber misalignment to inclusions to layer delamination. Pore and crack simulants should be developed to test emerging NDE methods. A library of real composite defects should be generated.

- **Additive manufacturing:** AM presents challenging geometries and material microstructures. Benchmarks should address varying levels of assessment and sensitivity, as well as the array of defects that are typically found.

- **Bonds and interfaces:** Benchmarks should be used to determine not only the presence of defects, but also the quality of the bond strength. The full range of bonding types should be addressed, including adhesives, welding, and solid-state bonding.

- **Ceramics and ceramic-matrix composites:** Ceramics and ceramic-matrix composites are challenging to benchmark. Representative, repeatable, reliable reference features are needed.

- **Multi-model analysis:** NDE often requires the use of multiple sensor types on a part, but the benchmarks for assessing the quality of multi-modal assessment are lacking compared to single reference–modality assessment.

- **Technician performance and fatigue:** Because the variability in human performance can affect the quality of NDE, a reliable benchmark to assess technician errors and performance is needed. Benchmarks are also needed to compare human vs. automated processes in an objective manner, including reliability, accuracy, precision, and repeatability—in both the physical and digital domains.

Digital benchmarks and databases are also critical for advancing analysis methods, calibrating sensors, and validating new processes, tools, and technologies. Benchmarks are needed in four important areas:

- **Probability of detection database:** The likelihood that a defect will be found is probabilistic and highly dependent on the size and type of the defect, the inspection method and implementation, and many other parameters. The curves that show the POD as a function of these parameters provide an established benchmark to which novel sensors, processes, and analysis methods can be compared.

- **Digital artificial defects for automatic defect recognition:** ADR algorithms are developed and evaluated based on their ability to identify defects. An established set of artificial defects to benchmark against could allow for more rapid development and reliable evaluation of ADR tools. The variance seen in typical assessments should be included to provide a realistic environment for testing.

- **NDE image and inspection database:** Many of the NDE methods create images of the parts. A database of these images would facilitate development of advanced analysis methods. In addition, a database of images with known, well-characterized defects would enable evaluation of these analysis methods. Images of the same part derived from multiple NDE modalities would accelerate the development and validation of multi-modal NDE methods. Finally, inclusion of assessment metadata with the images would further enhance the database.

- **Known issue and parameter set for sensors:** Sensors and sources for NDE methods have noise, known phantoms, depth limitations, material limitations, ideal calibration values, and other known issues. Centralized benchmarks would help to ensure proper implementation of existing tools and rapid comparison of new technologies.

All of the benchmarks should be evaluated on their ability to meet four key criteria: cost, representativeness, repeatability, and reliability. Benchmarks will not be valuable if they are too costly to implement, do not represent the behavior of real defects found during inspection, yield different answers each time, or are at risk of not providing results.

Research should be performed to advance each of the aforementioned benchmarks. The substantial progress in some areas (e.g., composites) should be leveraged. For example, the NASA Advanced Composites Program has developed a set of physical NDE defect standards that is available to industry through the National Institute for Aviation Research. The program also generated a handbook on laminate carbon-fiber composite NDE that will be updated on an ongoing basis by the Society of Automotive Engineers. Some areas (e.g., POD databases[25]) have a long history of development, and other areas (e.g., AM) have substantial current benchmarking efforts. Image databases have been started in some areas, including a database for laminated carbon-fiber composites. Research focus should be placed especially on benchmark development in three key cross-cutting areas:

- **Model validation:** Advancing benchmarks that enable the use of models will greatly reduce the reliance on costly physical standards.

- **Controllable samples and features:** Creating methods that reliably and repeatedly generate standardized samples with controllable microstructural features is essential to establishing many of the benchmarks. Current tools cannot consistently create a variety of known realistic and representative defects. Pore and crack simulants are especially important for benchmarking.

- **Software tools for producing digital models:** NDE would benefit from tools that can produce digital models of defects and features that represent typical realistic processes and all significant contributions to noise.

The initiative should also pursue the fabrication and validation of the benchmarks. Some destructive evaluations will be necessary for validation; round robin testing can be used for “twins.” The Nuclear Regulatory Commission, in collaboration with the Pacific Northwest National Laboratory (PNNL) and the Electric Power Research Institute (EPRI), has demonstrated the utility of the round robin method for various NDE methods applied to nuclear power system elements.

Storage, Management, and Access

Once the benchmarks are created and validated, they should be stored by a centralized organization or collaboration, the physical and digital assets should be managed, and a protocol for access by U.S. industry and researchers should be created. The initiative should include the many valuable benchmarks created by federal agencies, professional organizations, and institutes, when viable with respect to national security. The initiative should leverage the ongoing work of these organizations to provide a continued source of benchmarks, research, and connection to the NDE community. These organizations include the following:
:

- National Institute of Standards and Technology (NIST)
- Department of Defense (DoD)
- Air Force Research Laboratory (AFRL), including the Materials State Awareness Branch
- Office of Naval Research (ONR)
- National Aeronautics and Space Administration (NASA), including the NASA Advanced Composites Project
- Federal Aviation Administration (FAA)
- Federal Laboratories, including the Department of Energy National Laboratories
- America Makes National Additive Manufacturing Innovation Institute
- Electric Power Research Institute (EPRI)
- U.S. Nuclear Regulatory Commission (U.S. NRC)
- Center for Nondestructive Evaluation (CNDE) at Iowa State University
- American Society for Testing and Materials (ASTM)
- American Society for Nondestructive Testing

Several existing organizations are well positioned to take the lead in storing, managing, and providing access to the benchmark library, including the following:

- **Defense Technical Information Center:** The Center's ongoing efforts to store and manage NDE benchmarks for the defense sector could be expanded to the manufacturing sector at large.
- **National Institute of Standards and Technology:** NIST facilities and expertise are well equipped to manage a benchmarking effort of any scale.
- **Manufacturing USA Centers:** These centers provide direct connections to industry in many key manufacturing technologies and industrial centers.
- **National Laboratories:** The National Laboratories have a wide array of state-of-the-art tools for testing and evaluation.

Protocols for data access should ensure the following:

Easy and affordable access to U.S.researchers and members of industry;

Protection of U.S. defense, industrial, and national competitiveness;

Methods to protect proprietary industry data; and

Mechanisms to encourage industry sharing. Advanced data management systems can provide appropriately granularized access, and data sharing can be encouraged though "data-for-access" programs.

Modernized NDE Data Standards

Reporting the results of assessment requires standards modernization to ensure interoperability, complete data, and ease of use. Standards also should address modern assessment technologies and manufacturing processes, as well as better manage errors and uncertainty. Two recommended areas of NDE data standards should receive increased focus:

- **Standardize file formats for NDE data across NDE modalities:** Different sensors provide different types of data, but a universal standard for multiple NDE modalities would facilitate data interoperability, especially when parts are inspected using multiple NDE methods. Full consideration should be given to existing standards such as DICONDE[h] (ASTM 2339 and 3169) and Hierarchical Data Format 5 (HDF5), but any standardization effort should include a trade study considering the full spectrum of emerging needs. Criteria include accessibility, vendor and end-user metadata needs, raw and processed NDE data, different NDE modalities, metadata for CAD model registration, and scalability from handheld devices to enterprise manufacturing data systems.

h. DICONDE: Digital Imaging and Communication in Nondestructive Evaluation; a universal standard for sharing NDE image data developed by ASTM.

- **Establish a standardized geometry format:** As data are reported in 3D coordinate systems, a standardized geometry format should be adopted to improve interoperability and consistency. The format should represent the geometry as a topologically organized boundary representation and should support two underlying surface representations: Non-Uniform Rational Basis Splines (NURBS) and polygon or triangle meshes. A constrained version of STEP[i] AP242 (ISO 10303) that eliminates information not related to geometry and topology and requires representation of geometry in NURBS or mesh form might satisfy these requirements.

As these standards are developed, existing resources should be leveraged including working groups such as ASTM WK62181, relevant facilities at NIST, and the range of federal agencies with interests in these standards, such as DoD, Department of Energy, National Nuclear Security Administration, AFRL, NASA, FAA, and U.S. NRC. Other organizations such as MTConnect[26] and the National Defense Industrial Association (NDIA), could prove valuable in aligning equipment and manufacturing sectors.

Recommendation 2: Initiate a comprehensive NDE benchmarking program to accelerate NDE development and implementation. The program should focus on the development and refinement of key physical and digital benchmarks for general defects and for defects specific to AM, bonds and interfaces, and ceramic-matrix composites, and the use of multi-modal assessment. Digital benchmarks include POD databases, digital artificial defect datasets, image databases, and multi-modal datasets. By leveraging existing national efforts, the program should ensure the creation, storage, and management of a library of relevant NDE benchmarking specimens, tools, and data. NDE data standards should also be modernized to better capture and transmit data.

i. STEP: Standard for the Exchange of Product Data; a common 3D file storage format.

Accelerate New Technology Implementation Through Creation of a National NDE Research and User Facility and an NDE Workforce Development Working Group

Translational research transforms basic research and promising ideas into technologies, tools, and processes that can be leveraged by U.S. manufacturers. A national NDE research and user facility could provide resources to accelerate the development and integration of next-generation NDE tools and methodologies with emerging manufacturing processes. In addition, the facility could serve as a central hub for providing rapid reliability assessment consultation and resources to small and medium-sized manufacturers and as a pipeline and resource for NDE technicians and engineers.

Because the NDE field faces an aging workforce and a minimal pipeline to replace it, a working group focused on implementing critical workforce development initiatives should be formed. The working group should address (1) creation of a robust pipeline of NDT Level II and III technicians; (2) integration of NDE education into engineering disciplines; (3) continuing education on recent advances in NDE tools and technologies; and (4) development of NDE subject matter experts with multidisciplinary expertise.

This working group should be composed of stakeholders from manufacturing, federal laboratories, academia, federal funding agencies, research organizations, standards bodies, and equipment providers. Cohesion across the NDE community at large will greatly enhance the ability to execute the working group recommendations.

NDE Research and User Facility

An NDE research and user facility would ideally meet the needs of U.S. manufacturers by fostering three essential aspects of the field:

1. Open access to physical and digital NDE resources,

2. A research and education agenda focused on industry needs, and

3. Access protocols and methods that facilitate industry collaboration.

The facility's physical and digital resources should serve as a "test range," enabling the testing, refinement, and validation of technologies and processes in realistic environments. In the physical realm, pilot-scale process loops should be created. By replicating NDE and manufacturing processes, translational research can be rapidly performed without disrupting manufacturers. This pilot-scale equipment would be especially valuable to small and medium-size manufacturers that lack the resources to develop pilot lines dedicated to research and development. At the intersection of physical and digital resources, robotic systems should be installed in the facility to accelerate the automation of NDE processes. Control schemes, sensor integration, path planning, data management, and a range of other functions can be tested on a robust robotics platform. Digital resources should include extensive image databases and cutting-edge modeling tools. As novel ADR and other analysis methods are developed, these digital resources will allow for rapid and reliable translational research and development.

The facility's research and education agenda should serve the needs of manufacturers, with a focus on capabilities that small and medium-size manufacturers cannot develop on their own. The first critical capability centers on NDE integration with robotics, focused on system integration and automation for complex applications. Another important capability is multi-modal assessment; physical testbeds provide the opportunity to perform applied research on synthesizing physical assessment, data integration, and novel analysis of multiple sensor physics. Failure analysis—the connection between assessment data and the likelihood and time to part failure—is essential to understand yet difficult to perform on a small scale. Translational research should focus on understanding this connection and providing tools for manufacturers to leverage. Model validation at scale is difficult for both academia and individual manufacturers to perform. The facility should perform research that merges process knowledge with defect models, mechanical models, defect maps, and real parts to both refine and validate emerging models. The work of existing facilities, such as the EPRI NDE Center, LLNL centers,[27] SNL, and PNNL, CNDE, EWI, NIST, and others performing applied NDE research, should be leveraged where possible, with care to avoid duplication of efforts.

The facility could serve the field by providing education and consulting services to small and medium-size manufacturers in the areas of material science, POD, MAPOD, results confidence, automation, measurement physics, and ADR. The facility could also serve as a hub for access to leading experts across academia and industry in these areas.

The facility should be both economically sustainable and accessible to small and medium-size manufacturers that lack in-house expertise or resources. It is recommended that the facility be created with federal funding and sustained with funding from the following sources:

- **Large corporate consultations for complex challenges**: A fee-for service model of consultation that leverages the facility's resources to solve complex manufacturing NDE challenges.

- **Corporate access for legal assistance and fact finding:** NDE is often the crux of major catastrophes, and the resulting investigation and lawsuits rely on NDE expertise applied to these events. A fee-for service model based around this targeted research and fact finding is feasible.

- **Vendor in-kind contributions:** Vendors and equipment manufactures could provide equipment to the facility in exchange for access to data on applied research performed on their equipment.

- **State cost sharing:** Access for small and medium-size enterprises could be provided by states that want to improve their manufacturers' competitiveness. This could be cost-shared with the manufacturer and federal sources.

Education Working Group

Challenges to developing the rapid reliability assessment workforce threaten the ability of U.S. manufacturers to inspect the next generation of parts and processes. The pipeline of young NDE technicians and engineering students with an interest in becoming NDE experts is small, leaving a large void in the workforce. Manufacturers are experiencing difficulties in developing Level II and especially Level III NDT technicians, as well as engineers with appropriate NDE skill sets for design and analysis. In addition, engineering must be connected with NDE expertise, because solving the most extreme challenges and inspecting the emerging manufacturing technologies will require expertise in both domains. NDE continues to advance and evolve, and NDE experts and technicians must keep abreast with the latest advances. Continuing education is needed to ensure that design engineers and NDE experts can use emerging analysis tools, sensors, and processes, and can apply their knowledge to emerging manufacturing methods. NDE is highly cross-cutting, ranging from sensor physics to data analysis to materials science. The expertise of NDE technicians must be similarly multidisciplinary.

Filling the pipeline of the NDE workforce requires addressing the challenges at all levels, from developing early interest to ensuring an established career path. One barrier NDE faces is a lack of knowledge of the field and an interest in it. Few U.S. university programs cover NDE. Other countries have much more robust NDE programs, for example, the UK Research Centre in NDE[28] and the large NDT focus throughout Germany. Additional focus and programs at the undergraduate level, especially community colleges, would prime the pipeline. The creation of a Professional Engineer license for NDE could help to retain Level I NDT technicians in the field.

There is an increasing intersection between many fields of engineering and NDE, especially in solving complex NDE challenges. Although valuable, the skillsets of NDT Level III technicians differ from those of engineers. Mechanical and electrical engineering are commonly tapped for NDE experts, but other fields such as artificial intelligence, data science, statistics, and signals processing are becoming increasingly important. Skillsets are needed in emerging engineering disciplines such as AM. Federal programs, ASNT, the American Society of Mechanical Engineers, and IEEE chapters and national organizations should work with local colleges and universities to increase awareness of the field and to establish opportunities to address NDE in their engineering programs. An academic minor in NDE could facilitate this effort. Iowa State University's Center for NDE serves as an example of how NDE elements can be integrated into the undergraduate curriculum through an NDE minor and a graduate certificate. The engineering programs at Purdue University, Pennsylvania State University, the University of Missouri Institute of Science and Technology, and the University of California San Diego (UCSD) offer courses dedicated to NDE, which can be used as models for other universities. Accreditation organizations, such as the Accreditation Board for Engineering and Technology, should recognize NDE as a critical component of engineering education. The federal government should consider supporting education programs in NDE at undergraduate level by scaling best practices from Iowa State University, Purdue University, UCSD, the Georgia Institute of Technology, Pennsylvania State University, and other leading NDE universities.

With continuing education, NDE experts can leverage the most recent tools and advances. Although ASNT has provided a wealth of continuing education resources, more can be done to bridge the gap between new academic knowledge and industrial practice. One recommendation is to implement a better knowledge database, where emerging advances can be cataloged and easily accessed by industry and academia. This knowledge may also serve to bridge the gap between the NDE academic community and application-driven NDE technology developers. Finally, more assistance should be provided to small and medium-size manufacturers to understand and start to implement new NDE standards and technology where applicable to their production process.

The inherently multidisciplinary nature of NDE drives the need for experts with a broad knowledge base. Additional education and training should be directed toward developing the expertise required by manufacturers in (1) multi-modal assessment so that technicians, professional engineers, and design engineers can analyze parts using multiple assessment technologies, rather than being siloed into a single area; (2) modeling; (3) algorithm development and artificial intelligence; and (4) sensor and instrument effects on measurement, including ensuring the application of best practices from measurement science. Combining NDT knowledge with broader design engineering and analysis, as well as metrology and measurement science fields, will be crucial to bridging these gaps.

Recommendation 3: Accelerate new technology implementation through creation of a national NDE research and user facility and an NDE workforce development working group. This facility should provide resources to accelerate the development and integration of next-generation NDE tools and methods with emerging manufacturing processes, with a specific focus on multi-modal NDE, robotic integration, and automated data processing. The working group should address (1) creation of a robust pipeline of NDT Level II and III technicians; (2) integration of NDE education into engineering disciplines; (3) continuing education on recent advances in NDE tools and technologies; and (4) development of NDE experts with a foundational knowledge in multiple disciplines.


A Call to Action

The importance and impact of rapid reliability assessment extends far beyond its prominence in the public's conscious. The full promise of emerging manufacturing technologies can only be realized with advanced rapid reliability assessment, enabled by NDE. If implemented, the recommendations for research, benchmarks, facilities, and education detailed in this report will have far-reaching impacts that cut across manufacturing technologies, industry sectors, and national priorities.

The United States cannot afford to fall behind other nations in rapid reliability assessment, and cannot simply import NDE expertise and leadership. Other countries are investing in applications of NDE to emerging manufacturing processes such as AM, complex composites, advanced joining, and many others. These applications are critical to advanced industries in which the United States must maintain its competitive advantage, such as aerospace, defense, medical devices, and automotive. In addition to national prosperity, other national priorities such as security, health, and energy independence rely on U.S. leadership in rapid reliability assessment through NDE. Action must be taken now.

Federal agencies, universities, national institutions and organizations, and industry must take action toward a common vision to ensure the country's leadership in NDE. The future of our safety and prosperity relies on it.

Appendix I: Workshop Agenda

November 13, 2018, Georgetown University Hotel & Conference Center

7:30	Breakfast/Check-in
8:00	Welcome and Overview: Prof. Sridhar Kota, Exec. Director, MForesight
8:10	Keynote: Dr. Gary Georgeson, The Boeing Company
8:40	Introductions, Meeting Focus
9:15	Break – proceed to Breakout Session 1
Identify Key Challenges to Non-Destructive Evaluation	
9:30	Session 1: Accelerating NDE
	Sensors and tools
	Data analysis and fusion
	Throughput, reliability, and automation
	Manufacturing integration
10:30	Break – proceed to Breakout Session 2
10:45	Session 2: NDE for Manufacturing Processes
	Additive manufacturing
	Composites
	Ceramics and metals
	Material properties
11:45	Lunch
1:00	Report Outs and Group Discussion
Develop Actionable Recommendations	
1:45	Overview of Actionable Recommendations
2:00	Sessions 3A-3D: Solutions and Recommendations
3:00	Break
3:15	Session 4: Recommendation Development
4:15	Group Discussion of Key Actionable Items
5:00	Networking Reception

Appendix II: Contributors

Workshop Participants

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** Keynote Speaker

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