Advanced Gas Turbine Manufacturing Technology Roadmap

Executive Summary

Prepared by Energy Florida

With contributions and coordination of

The CAPE – **C**onsortium for **A**dvanced **P**roduction and **E**ngineering of Gas Turbines and Rotating Machinery

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Advanced Gas Turbine Manufacturing Technology Roadmap

Executive Summary

Scope & Objectives of the Advanced Gas Turbine Manufacturing Technology Roadmap

In 2013, the Gas Turbine Association published a highly detailed and comprehensive study on the requirements to keep the US gas turbine industry competitive on the national and global market considering recent investments in this technology by other nations. Several end-state technology goals and timelines were suggested by this report, which Energy Florida is adopting and extending to gas turbines other than large natural gas-fired combined cycle turbines. The end-state technology goals are as follows:

1. **Achieve 67% efficiency for combined-cycle natural gas fired generation systems within 15 years**
2. **Achieve a 10% relative efficiency improvement(s) for smaller-scale, distributed generation and/or load-following power generation turbines and gen-sets within 15 years**
3. **Achieve 10% overall efficiency improvement in gas turbine engines for aviation propulsion within 15 years**
4. **Enable and support accelerated adaptation and adoption of new technologies, materials and processes by the gas turbine manufacturing sector and the service and repair community**
5. **Cut time-to-market and development costs for Gas Turbine technologies**

This roadmap developed by Energy Florida and the CAPE identifies practical approaches, collaborative efforts and research projects to realize these end-state technology goals. To this end, the Consortium for Advanced Production & Engineering of Gas Turbines (CAPE) roadmap outlines the necessary steps for developing new industrial materials, manufacturing processes, inspection and data protocols, maintenance repair and overhaul activities, and workforce development and safety issues to advance the next generation of gas turbine and rotating machinery manufacturing technologies here in the United States. The CAPE roadmap makes recommendations for the adoption and implementation of collaborative, pre-competitive industry practices cross-cutting between the various gas turbine industry sectors, as well as between the power generation and aviation gas turbine industry, in order accelerate gas turbine technology development and commercialization and increase the global competitiveness of the US gas turbine industry.

Roadmap Process & Methodology

Being industry-led, Energy Florida and the CAPE have actively and continuously conducted industry interviews and one-on-one industry discussions with its partners, as well as a series of technical working groups comprised of technical experts drawn from leading industry and academic stakeholders active in the advanced turbine design, engineering, manufacturing and maintenance industry. This allows our consortium to have unique insights into industry demands, requirements and challenges, ongoing projects and efforts and available opportunities for partnerships. This industry information is utilized to open communication between the various industry partners by providing networking expertise and through the hosting of industry workshops to further the open exchange and discussion among all industry branches and partners.

The networking efforts coordinated by Energy Florida aim to match various industry partners for collaborative projects, as well as matching these partners with potential funding opportunities, whose pursuit is assisted by the Gas Turbine Technology Network.

On behalf of the CAPE consortium, the consortium's leadership conducts regular briefings in Washington, DC to promote industry objectives of the entire gas turbine industry and to act in an advisory role to federal and state policymakers. In addition, our consortium has worked very closely with the relevant industry associations: the Gas Turbine Association and the Aerospace Industries Association, which represent the industrial gas turbine manufacturers and aviation gas turbine engine manufacturers respectively, as well as many of their key suppliers, customers, and small and medium enterprises associated with the gas turbine and aviation propulsion industry. We have also worked with key relevant technical societies, including the American Society for Mechanical Engineers (ASME) and the American Institute for Aeronautics and Astronautics (AIAA), both of whom have been key partners in conducting outreach and convening stakeholders in support of this effort.

Through the development and maintenance of consortia such as the CAPE, long-lasting pre-competitive collaborative industry partnerships are formed, subsets of which are organized and coordinated to pursue specific industry goals, such as the implementation and realization of small-scale technical demonstration projects, which offer immediate returns for the partners, as well as the pursuit of larger scale funding.

Focus Area Analysis - Industry Priorities

The CAPE team has conducted extensive interviews with gas turbine industry partners and completed wide spread market research to identify technical areas of interest for the acceleration of gas turbine technology advancement. From the resulting list of initially over 100 technology areas, this industry input has led to the selection of the following technology areas as being identified to have the highest impact on technology advancement. The presented list of topics represents technology areas, in which collaborative, precompetitive technology development efforts are possible due to the high cross-cutting impact on the entire gas turbine industry.

These topics are organized into five technical focus areas which are outlined below:

Focus Area A: Materials for Hostile Environments & Extreme Conditions (MHEEC)

Focus Area B: Additive Manufacturing that Enables New Design(s) and Engineering for Advanced Gas Turbines

Focus Area C: Non-destructive Evaluation (NDE) & Digital Thread

Focus Area D: Maintenance Repair and Overhaul (MRO)

Focus Area E: Workforce Development & Safety

Executive Summary Graphics: Technical Focus Area Recommendations

In this executive summary, each focus area is represented by a summary graphic highlighting the list of technical topics presented in the roadmap under each respective focus area. These graphics provide a high-level overview of the main findings and recommendations in each focus area, including color-coded priorities, timelines and information regarding the constituencies within the gas turbine industry (Original Equipment Manufacturers, Small and Medium Enterprises, Academia, Government & National Labs or All) that are impacted or engaged within each individual recommendation.

A. Materials for Hostile Environments & Extreme Conditions (MHEEC)

The recommendations contained within the Advanced Gas Turbine Manufacturing Technology Roadmap Focus Area on Materials for Hostile Environments & Extreme Conditions (MHEEC) outline the necessary steps for developing new industrial materials, testing standards and certification parameters that will the introduction of new materials into the manufacturing of gas turbines and rotating machinery.

Primary subtopics included within the Materials for Hostile Environments & Extreme Conditions (MHEEC) focus area include:

- Existing Materials, Hybrid Materials & Refractory Metals
- High Entropy Alloys
- Ceramic Matrix Composites
- Thermal Barrier Coatings

Priority recommendations within the Materials for Hostile Environments & Extreme Conditions (MHEEC) focus area include but are not limited to:

- Evaluate Existing Alloys (for use with additive manufacturing or other new processing methods)
  - High gamma-prime, ODS & shape memory alloys
- Develop Hybrid/Multi-Material Components
- Ceramic Matrix Composites (CMCs):
  - Attachment Techniques, Coating/Durability improvements, Repairability
- Operational Lifing Analysis for Barrier Coatings
- Materials Properties Databases for Next-Generation or New Materials
  - Existing Alloys (for AM applications), 2700 deg F CMCs, High Entropy Alloys

Focus Area A: Materials for Hostile Environments & Extreme Conditions (MHEEC)

#	Stakeholder(s)	Priority	A. 1. Existing Materials, Hybrid Materials & Refractory Metals
a	All	High	EVALUATE EXISTING ALLOYS
b	All	High	HYBRID/MULTI-MATERIAL COMPONENTS
c	Academic	High	RESEARCH NEW REFRACTORY ALLOY COMPOSITIONS
d	Academic	Medium to Low	REFRACTORY METAL COATINGS
e	Academic	Medium to Low	DEVELOPMENT OF MACHINING TECHNIQUES FOR REFRACTORY METALS
f	Academic	Medium to Low	DEVELOPMENT OF METHODS TO WELD/JOIN REFRACTORY METALS
g	All	Low	REVIEW/ASSESS NEED(S) FOR STANDARDIZAITON OF PROCESSING/MACHINING OF REFRACTORY ALLOYS

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	A. 2. High Entropy Alloys (HEAs)
a	Academic	Medium	INTEGRATED COMPUTATIONAL MATERIALS ENGINEERING (ICME) MODELS FOR HEA COMPOSITION PREDICTION
b	All	High	ESTABLISH HEA MATERIALS DATABASE FRAMEWORK
c	Academic	Low	CROSS-INDUSTRY ASSESSMENT OF HEA POTENTIALS
d	Academic	Low	DEVELOP COMMERCIAL HEA MANUFACTURING PROCESSES

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	A. 3. Ceramic Matrix Composites (CMCs)
a	All	High	ADVANCE FIBER PRE-FORMING/WEAVING TECHNIQUES TO IMPROVE DURABILITY OF EXISTING MATERIALS
b	All	High	DEVELOP CMC FASTENING TECHNIQUES
c	Academic & SMEs	Medium	INCREASE DIVERSITY OF AVAILABLE RESEARCH CMC MATERIALS BY INCENTIVISING SUPPLIERS
d	All	High	CERAMIC COATINGS
e	Academic & OEMs	Medium	R&D COLLABORATION BETWEEN CMC AND COMBUSTION STRATEGIES
f	All	Medium	CONCURRENT DEVELOPMENT OF STANDARDS THROUGH INCREASED COLLABORATION
g	All	High to Medium	DEVELOP MATERIALS PROPERTIES CMCs DATABASE
h	All	Medium	MINIMUM R&D PERFORMANCE STANDARDS AND TEST PROCEDURES
i	Academic & OEMs	Low	DEVELOP FIBER INTERFACE COATINGS, OPERATING PROCEDURES TO ADDRESS LOW TEMPERATURE CRACKING

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	A. 4. Thermal Barrier Coatings (TBCs)
a	OEMs & SMEs	High	DEVELOP NON-INTERFACE COATING PROCESSES TO PREVENT HANDLING AND INSTALLATION DAMAGE
b	All	High to Medium	MACHINING OF COOLING HOLES THROUGH TBC
c	OEMs & SMEs	High to Medium	INVESTIGATION OF FILM COOLING HOLE IMPACT ON TBC INTEGRITY
d	Academic	Medium	MINIMUM R&D PERFORMANCE STANDARDS AND TEST PROCEDURES
e	All	High	OPERATIONAL LIFING FOR BARRIER COATINGS - THERMAL SHOCK RESISTANCE REQUIREMENTS
f	All	High	RESISTANCE TO CORROSIVE CONDITIONS @ HIGH TEMPS
g	All	High	RESISTANCE TO CORROSIVE CONDITIONS @ LOW TEMPS
h	All	High	INVESTIGATION OF COATING PROPERTIES/EFFECTIVENESS OVER OPERATIONAL LIFECYCLE(S)
i	Academic	Low	DEVELOP TBC MATERIAL INTERACTION/BONDING MATRIX

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

B. Additive Manufacturing that Enables New Design(s) and Engineering for Advanced Gas Turbines

The recommendations contained within the Advanced Gas Turbine Manufacturing Technology Roadmap Focus Area on Additive Manufacturing outline the necessary pre-competitive steps for developing and characterizing new industrial materials, testing standards and certification parameters enabling the introduction of new additive manufacturing processes, materials and concepts into the design, engineering and manufacturing of gas turbines and rotating machinery.

Primary subtopics included within the Additive Manufacturing that Enables New Design(s) and Engineering for Advanced Gas Turbines focus area include:

- Thermo-mechanical models
- Process Standards
- Feedstock materials
- Design & Engineering for Gas Turbines Enabled by New Processes & Materials

Priority recommendations within the Additive Manufacturing focus area include but are not limited to:

- Development, Verification and Validation of Thermomechanical Models for Additive Manufacturing Processes
    - Industry-wide pre-competitive efforts on developing baseline models, in-situ integration and verification and validation procedures
- Set Baseline Fundamentals to Accelerate Standards for Additive Manufacturing Processes
- Utilization of SME Expertise and Best Practices
- Development of Feedstock Standards
    - Feedstock Data Reporting & Specifications
- Mixed Material Feedstock Development
- Engineering for Additive Processes

Focus Area B: Additive Manufacturing

#	Stakeholder(s)	Priority	B.1. Thermomechanical Models
a.	All	High	DEVELOPMENT OF THERMOMECHANICAL MODELS FOR AM MATERIALS AND PROCESSES
b.	All	High	NATIONAL LAB/ACADEMIA-LED EFFORTS
b)(1)	Academic & National Labs	High	MACRO-SCALE MODELS
b)(2)	Academic & National Labs	High to Medium	MICRO-SCALE MODELS
b)(3)	All	High	IN-SITU INTEGRATION
b)(4)	All	High to Medium	METHODS AND REFERENCE DATA TO VALIDATE MODELS
c.	All	Medium	DEVELOP AM MATERIAL/PROCESS DATA COLLECTION PLATFORM
c)(1)	All	Medium to Low	SHARING CONVENTIONS
c)(2)	All	Medium to Low	CONTRIBUTION CONVENTIONS
c)(3)	All	High to Medium	IDENTIFICATION OF NECESSARY PARAMETERS
d.	All	High	ICME COMPUTATIONAL TOOLS AND WORKFLOWS

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	B.2. Process Standards
a	SMEs	High	UTILIZATION OF SME EXPERTISE AND BEST PRACTICES
b	All	Medium to Low	STANDARDS FOR NON-INSTALLED COMPONENTS
c	All	High	SET BASELINE FUNDAMENTALS TO ACCELERATE STANDARDS
d	All	Medium to Low	DEVELOP STANDARDS FOR MACHINING ADDITIVE MANUFACTURING-PRODUCED COMPONENTS
e	All (Including Government)	High to Medium	PROCESS MEASUREMENT & CONTROL
f	OEMs & SMEs	High to Medium	POST PROCESSING STANDARDS
g	OEMs & SMEs	Low	PRIORITIZATION OF MACHINE STANDARDS OVER COMPONENT STANDARDS
h	All	High	MIXED MATERIAL PROCESSING THROUGH ADDITIVE MANUFACTURING

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	B.3. Feedstock Materials
a	All	High to Medium	FEEDSTOCK DATA REPORTING/ SPECS
b	All	High	FEEDSTOCK STANDARDS
c	All	Medium	DEVELOP OBJECTIVE MATERIAL PROPERTY ASSESSMENT PARAMETERS
d	All	Medium	FEEDSTOCK STORAGE
e	All	Medium	FEEDSTOCK IMPURITIES
f	All	High	MIXED MATERIAL FEEDSTOCKS
g	All	High to Medium	NEW VS RECYCLED FEEDSTOCK

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	B.4. Design & Engineering for Gas Turbines Enabled by New Processes & Materials
a	All	High to Medium	DESIGN FOR ADDITIVE MANUFACTURING
b	All	High	NEW DESIGN PARAMETERS ENABLED AND/OR REQUIRED BY NEW MANUFACTURING METHODS
c	All	High	ENGINEERING FOR ADDITIVE PROCESSES
d	All	High to Medium	NEW MATERIALS ENABLE DIFFERENT DESIGN STRATEGIES TO ACHIEVE PERFORMANCE GOALS

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

C. Non-Destructive Evaluation (NDE) & Digital Thread

The recommendations contained within the Advanced Gas Turbine Manufacturing Technology Roadmap Focus Area on Non-Destructive Evaluation (NDE) & Digital Thread outline the necessary pre-competitive steps for developing and characterizing new inspection techniques and related technologies, testing standards and data management protocols and strategies enabling the introduction of new manufacturing processes, materials and concepts into the design, engineering and manufacturing of gas turbines and rotating machinery.

Primary subtopics included within the Non-Destructive Evaluation (NDE) & Digital Thread focus area include:

- Non-Destructive Evaluation (NDE)
- Digital Thread
- Digital Twins

Priority recommendations within the NDE & Digital Thread focus area include but are not limited to:

- Physical Reference Standards for Validation and Calibration of NDE Equipment
- Real-Time Sensors in Areas Critical for Process Management and Control
- Non-Destructive Evaluation Methods for Ceramic Matrix Composites
- Cybersecurity for Digital Thread
- Data Integration & Commonality Enabling Digital Threads
- Elements of Digital Twins Enabling Re-Certification

Focus Area C: Non-Destructive Evaluation (NDE) & Digital Thread

#	Stakeholder(s)	Priority	C. 1. Non-Destructive Evaluation
a	All	High	NDE METHODS FOR CMCs
b	All	High	PHYSICAL REFERENCE STANDARDS
c	All	Medium	NDE METHOD TO EVALUATE THERMAL BARRIER COATINGS (TBC) WITHOUT STRIPPING BLADE
d	All	High to Medium	NDE METHODS FOR AM
e	All	High	REAL-TIME SENSORS IN AREAS CRITICAL TO PROCESS MONITORING AND CONTROL
f	All	High	HIGH THROUGHPUT METHODS FOR SCREENING CANDIDATE MATERIALS
g	Academic & OEMs	High to Medium	DEVELOP OBJECTIVE TBC QUALITY PARAMETERS
h	All	Medium	DATABASE OF PROCESS PARAMETERS AND EXISTING CONTROLS FOR NDE
i	Academic & OEMs	Medium to Low	NDE FOR COMPLEX GEOMETRIES ENABLED BY AM-PRODUCED CASTING MOLDS
j	Academic & OEMs	Medium	DEVELOP EMBEDDED SENSORS TO MONITOR TBC DEGRADATION

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	C.2. Digital Thread
a	All	High	CYBERSECURITY
b	OEMs & SMEs	High to Medium	DATA INTEGRATION & COMMONALITY
c	All	Medium	BIG DATA STORAGE/ANALYSIS
d	All(IGT*)	High to Medium	ACCESSIBILITY/RIGHT-TO-ACCESS; For IGT*
e	Academic & OEMs	High to Medium	BIG DATA QUALITY

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	C.3. Digital Twins
a	All	High	ELEMENTS OF "DIGITAL TWINS" ENABLING RE-CERTIFICATION
b	OEMs & SMEs	High to Medium	THIRD-PARTY CLEARINGHOUSE FOR OPERATIONAL BEST PRACTICES
c	OEMs & SMEs	High to Medium	COMMON CONVENTIONS FOR MAINTENANCE, REPAIR AND OPERATIONAL INFORMATION
d	All	High to Medium	DIGITAL TWINS FOR OPERATION & PERFORMANCE
e	All	High to Medium	SUPPLY CHAIN INTEGRATION IN DIGITAL THREAD

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

D. Maintenance Repair and Overhaul / Life Cycle Management

The recommendations contained within the Advanced Gas Turbine Manufacturing Technology Roadmap Focus Area on Maintenance Repair and Overhaul / Life Cycle Management outline the necessary pre-competitive steps for developing and characterizing new industrial materials, testing standards and certification parameters enabling the introduction of new processes, materials and concepts into the maintenance, repair and overhaul of gas turbines and rotating machinery.

Primary subtopics included within the Maintenance Repair and Overhaul / Life Cycle Management focus area include:

- Additive Repair & (Re-)Certification
- Advanced Material Repair Methodologies
- On-Demand Legacy Parts & Data Resources
- Optimizing & Customizing Repair

Priority recommendations within the Maintenance, Repair and Overhaul (MRO) focus area include but are not limited to:

- Additive Repairs of Parts Manufactured with Traditional Methods
- Pathway to Certification of Additive Manufacturing-produced Parts for Aviation and IGT Repairs
- Develop Repair Techniques for Ceramic Matrix Composite materials
- Develop/Improve Techniques for Joining of Disparate Materials
- Establish a Cross-Industry Digital Library of Legacy Tooling
- Improving Consistency of Overhaul Procedures
- Building Visualization Tools and Digital Geometric Twins for the MRO Environment

Focus Area D: Maintenance Repair & Overhaul (MRO)

D. 1. Additive Repair Certification

#	Stakeholder(s)	Priority	D. 1. Additive Repair Certification	Timeline
a	All	High	ADDITIVE REPAIRS OF PARTS MANUFACTURED WITH TRADITIONAL METHODS	Years 1–2 (Short Term)
b	All	Medium to Low	DEVELOP TECHNIQUES TO MITIGATE INTERNAL DEFECTS	Years 1–5
c	Government	Low	ENABLING ON-SITE REPAIRS	Years 1–5
d	Academic & OEMs	High to Medium	MODULARIZED DESIGN TO ENABLE MODULAR REPAIR	Years 1–5
e	All	High	PATH TO RECERTIFICATION	Years 1–5
f	OEMs & SMEs	Medium	DEVELOP A PROCESS FOR CERTIFICATION/ACCREDITATION OF REPAIR SHOPS	Years 1–5
g	Gov't & SMEs	High to Medium	INTRODUCING/MANAGING ELEMENTS OF REPAIR ENVIRONMENT WITH ADDITIVE PROCESS	Years 1–10

Timeline in Years: 1 2 (Short Term) | 3 4 5 (Medium Term) | 6 7 8 9 10 (Long Term)

D.2. Advanced Material Repair

#	Stakeholder(s)	Priority	D.2. Advanced Material Repair	Timeline
a	Gov't & SMEs	Medium	PARTIAL TBC REPAIR	Years 1–5
b	All	Medium	DEVELOP TBC CLEANING PROCEDURES	Years 1–5
c	All	High	DEVELOP CMC REPAIR TECHNIQUES	Years 1–10
d	All	High	JOINING OF DISPARATE MATERIALS (DIFFERENT ALLOYS, METALS/CERAMICS)	Years 1–10
e	All	High to Medium	REPAIRS OF DIRECTIONALLY SOLIDIFIED OR SINGLE-CRYSTAL PARTS	Years 1–10
f	OEMs & SMEs	Medium	DEVELOP TECHNIQUES TO REVERSE CREEP DAMAGE	Years 1–10

Timeline in Years: 1 2 (Short Term) | 3 4 5 (Medium Term) | 6 7 8 9 10 (Long Term)

D.3. On-Demand Legacy Parts & Data

#	Stakeholder(s)	Priority	D.3. On-Demand Legacy Parts & Data	Timeline
a	OEMs & SMEs	High	DEVELOP A LIBRARY OF LEGACY TOOLING	Years 1–2 (Short Term)
b	All	Low	OPTICAL SCANNING OF LEGACY PARTS	Years 1–2 (Short Term)
c	OEMs & SMEs	High to Medium	DATABASE OF LEGACY PARTS	Years 1–5
d	Gov't & SMEs	Medium	SPECIFICATION MODELLING FROM USED PARTS	Years 1–5
e	Academic	Low	LEGACY TOOLING LOAN CLEARING HOUSE PROGRAM	Years 1–5
f	All	Medium to Low	COMMON REPAIR TECHNOLOGY PLATFORM(S)	Years 1–10
g	All	High to Medium	IMPROVING CONSISTENCY OF OVERHAUL PROCEDURES	Years 1–10

Timeline in Years: 1 2 (Short Term) | 3 4 5 (Medium Term) | 6 7 8 9 10 (Long Term)

D.4. Optimizing & Customizing Repair

#	Stakeholder(s)	Priority	D.4. Optimizing & Customizing Repair	Timeline
a	OEMs & SMEs	Medium	OPTIMIZING REFURBISHED COATINGS BASED ON OBSERVED DAMAGE AND HOT SPOTS	Years 1–5
b	OEMs & SMEs	Medium to Low	RESEARCH RELATED TO "UP-RATING" / RETRO-FITTING TO IMPROVE UNIT PERFORMANCE	Years 1–5
c	All	High to Medium	OPTIMIZING & CUSTOMIZING REPAIRS TO MEET OBSERVED OPERATIONAL MODIFICATIONS	Years 1–5
d	All	High	BUILDING VISUALIZATION TOOLS FOR MRO ENVIRONMENT AND DIGITAL GEOMETRIC TWINS TO IMPROVE VISUALIZATION/ACCOUNTABILITY	Years 1–10

Timeline in Years: 1 2 (Short Term) | 3 4 5 (Medium Term) | 6 7 8 9 10 (Long Term)

E. Workforce & Safety

The recommendations contained within the Advanced Gas Turbine Manufacturing Technology Roadmap Focus Area on Workforce & Safety outline important elements to be considered in developing effective workforce recruitment, training and retention programs on behalf of the gas turbine industry, as well as highlight relevant workplace safety and environmental health issues that are important to the turbine manufacturing and repair community. Addressing these workforce development and health and safety issues will help enable the safe and effective introduction of new processes, materials and concepts into the manufacturing, operation, maintenance and repair of gas turbines and rotating machinery.

Primary subtopics included within the Workforce & Safety focus area include:

- Workforce Pipeline
- Workforce Training
- Workforce Retention
- Safety

Priority recommendations within the Workforce & Safety focus area include but are not limited to:

- Security Clearances
- Cybersecurity Training & Resources
- Additive Manufacturing Operations Training (for Skilled Technicians)
- Additive Manufacturing-Specific OSHA Training
- Increasing Academia's awareness of and engagement in gas turbine industry priorities
- Develop Clear Career Pathways for Members of the Technical Workforce
- Capture Institutional Knowledge

Focus Area E: Workforce & Safety

#	Stakeholder(s)	Priority	E.1. Workforce Pipeline
a	OEMs & SMEs & Government	High	SECURITY CLEARANCES
b	All	High to Medium	INCREASED PROMOTION OF APPRENTICESHIPS/VOCATIONAL SCHOOLING
c	All	High to Medium	FELLOWSHIP PATHWAY
d	All	High to Medium	FOREIGN TALENT
e	All	High	INCREASE ACADEMIA'S AWARENESS OF INDUSTRY REQUIREMENTS

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	E.2. Workforce Training
a	All	High	CYBERSECURITY TRAINING
b	All	High	ADDITIVE MANUFACTURING OPERATIONS TRAINING
c	Academic	High to Medium	MATERIALS-RELATED DATA SCIENCE AND INFORMATICS APPROACHES
d	Academic	Medium	INCREASE ABET GUIDELINE FOR HANDS-ON TRAINING
e	All	Medium	PRODUCT CHAIN TRAINING
f	Academic	High to Medium	ACADEMIC TRAINING TO DESIGN FOR ADDITIVE MANUFACTURING
g	All	High to Medium	TECHNOLOGY CURRENCY TRAINING (CONTINUING EDUCATION)
h	All	High	CAPTURING INSTITUTIONAL KNOWLEDGE
i	All	High to Medium	STRATEGIES FOR DEALING WITH DEMOGRAPHIC DIVIDE

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	E.3. Workforce Retention
a	All	High	DEVELOP CLEAR CAREER PATHWAYS FOR MEMBERS OF TECHNICAL WORKFORCE
b	OEMs & SMEs	Medium	WORK-LIFE BALANCE: CONSIDER VOLUNTARY MAX WORKHOUR GUIDELINES
c	OEMs & SMEs	Medium	WORK-LIFE BALANCE: IMPROVEMENT OF FLEX-HOUR SYSTEMS
e	All	High to Medium	NURTURE SUPPORT STRUCTURES, NETWORKS & RESOURCES FOR CAREER DEVELOPMENT

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

#	Stakeholder(s)	Priority	E.4. Safety
a	All	High	ADDITIVE MANUFACTURING-SPECIFIC OSHA TRAINING (AM POWDER SAFETY/EXPLOSION/INHALATION MITIGATION)
b	SMEs	Medium	ENABLE US SPRAY COATING BY ADDRESSING OSHA REGULATORY CONCERNS
c	Government	Medium	REVIEW OF MSDS SHEETS FOR POWDERS VS. SOLID MATERIALS
d	Government	High to Medium	ON-SITE REPAIR - ADDITIVE MFG SAFETY IN UNCONTROLLED ENVIRONMENTS
e	Academic to All	Medium	INADVERTENT AM POWDER OXIDATION (MULTI-MATERIAL AM)
f	All	Medium to Low	NON-DESTRUCTIVE EVALUATION RADIATION SAFETY REGULATIONS

Timeline in Years	1	2	3	4	5	6	7	8	9	10
	Short Term		Medium Term			Long Term				

Conclusion & Next Steps

Despite the high degree of competitive interests and strict confidentiality regulations of gas turbine technology, numerous high priority, industry-wide issues have been identified, that must be addressed to accelerate technology development and ensure the continuing competitiveness of the US gas turbine industry. Through extensive dialogue with industry representatives, priorities for such pre-competitive collaborations in the fields of materials, additive manufacturing, non-destructive evaluation, digital thread, maintenance, repair & overhaul, and workforce & safety have been identified and outlined. The CAPE team will continue to work to disseminate information regarding the specific technology priorities and timelines contained in this roadmap to industry leaders, policy and association leadership and relevant program directors in federal and state governments across the country and provide this information and resources to its stakeholder community. The CAPE and its partners look forward to continuing to be a key part of the conversation in advancing the development of these technologies, and catalyzing cross-industry and cross-disciplinary collaboration to enable and accelerate the next generation of gas turbine technologies for power generation and propulsion applications.

Consortium for Advanced Production and Engineering of Gas Turbines and Rotating Machinery (CAPE) Advanced Gas Turbine Manufacturing Technology Roadmap Stakeholders & Contributors

Advanced Magnet Lab

Aerojet Rocketdyne

Aerospace Industries Association

Air Force Research Lab (AFRL)

Alcoa

American Electric Power

American Institute of Aeronautics and Astronautics (AIAA)

American Society of Mechanical Engineers (ASME)

Ansaldo Energia

Aspen Technologies

Atlantic Precision

Chevron

Chromalloy

Delta Air Lines

Doosan

Dresser-Rand

Duke Energy

Echogen Power

Embry Riddle Aeronautical University

Energy Florida

EPRI - Electric Power Research Institute

Executive Office of the Governor of Florida/Office of Policy & Budget

Federal Aviation Administration

Florida Institute of Technology

Florida Power & Light

Florida Turbine Technologies

FM Global

Gas Technology Institute

Gas Turbine Association

GE Aviation

GE Global Research

GE Power & Water

Georgia Tech – Inst. for Materials

Georgia Tech - Strategic Energy

Haynes International

Honeywell International

Impact Technologies

Kelelo Engineering

Keystone Synergistic Enterprises

Longview Energy Associates

Mainstream Engineering

Mitsubishi Hitachi Power Systems Americas

Napoleon Engineering Services

National Aeronautics and Space Administration (NASA)

National Center for Defense Manufacturing and Machining

National Energy Technology Lab

Natole Turbine Enterprise

NAVAIR

NIST

North Carolina State University

Oak Ridge National Laboratory

PCC Airfoils, LLC

Penn State

PennWell/Power Generation Int'l

Power Systems Mfg., LLC / Ansaldo Energia

Pratt & Whitney

Pratt & Whitney Power Systems

Purdue University

Renaissance Services Inc.

Rolls Royce

Samsung Techwin

Siemens Energy

Siemens Energy, Power Generation Services Division

Solar Turbines

Southern Company

Southwest Research Institute

Space Florida

Stony Brook University

Strategic Power Systems

Texas A&M University

Turbo Machined Products

Turbomachinery International

United Technologies Corporation

University of Central Florida

University of Connecticut

University of Notre Dame

University of Pittsburgh

University of Tennessee - Knoxville

US Advanced Ceramics Association

Vibrant NDT

Virginia Tech

Williams International

For questions or further information regarding the CAPE consortium or additional details on the Advanced Gas Turbine Manufacturing Technology Roadmap, please visit:

https://EnergyFlorida.org

or contact the Energy Florida/CAPE team at:

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CAPE

Consortium for Advanced Production and Engineering of Gas Turbines

