



Advanced Gas Turbine Manufacturing Technology Roadmap Executive Summary

Prepared by Energy Florida

With contributions and coordination of

**The CAPE – Consortium for Advanced Production and Engineering 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:

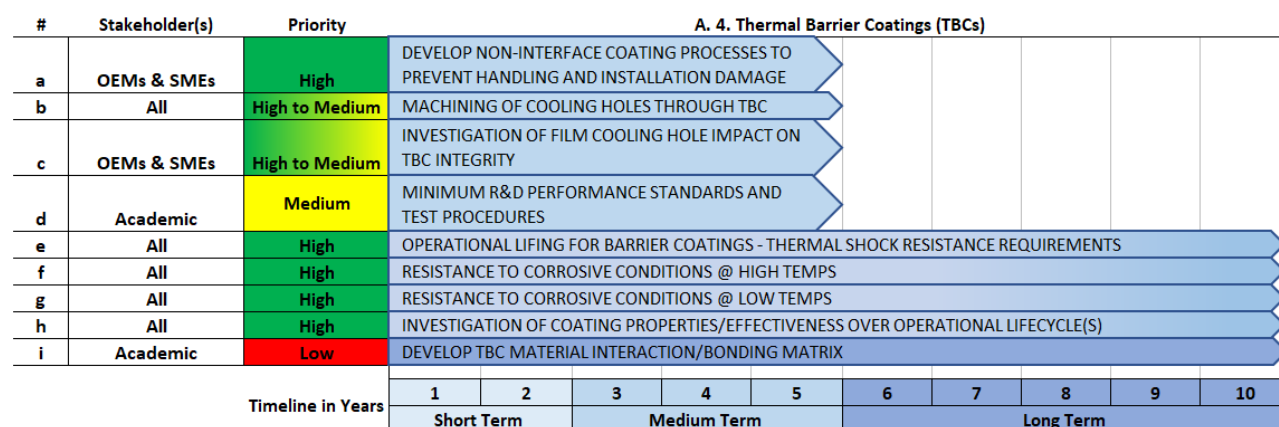
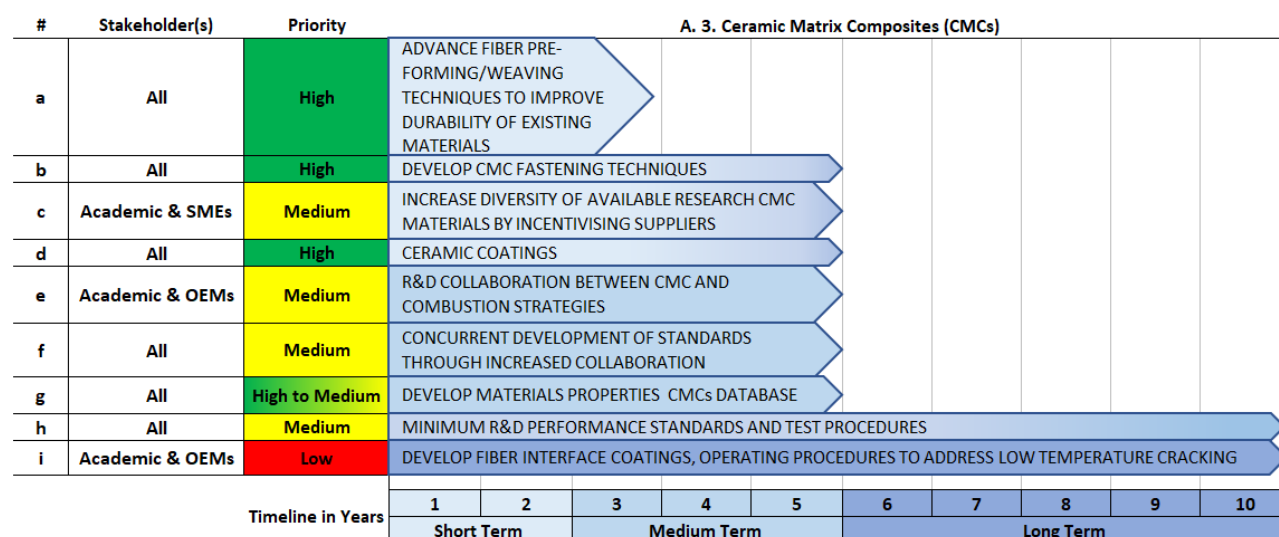
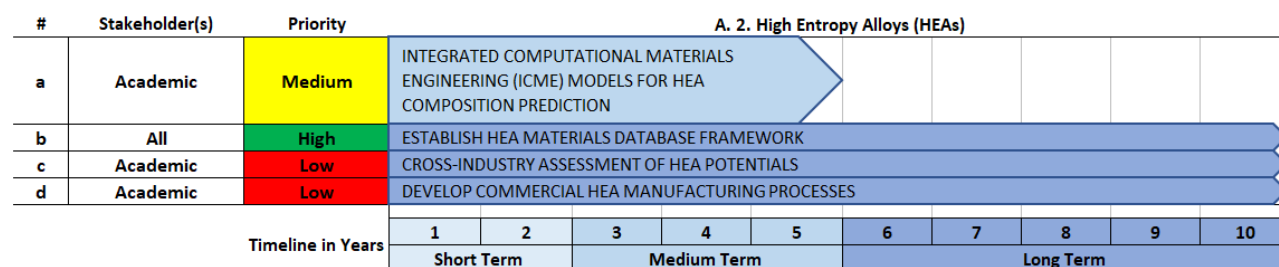
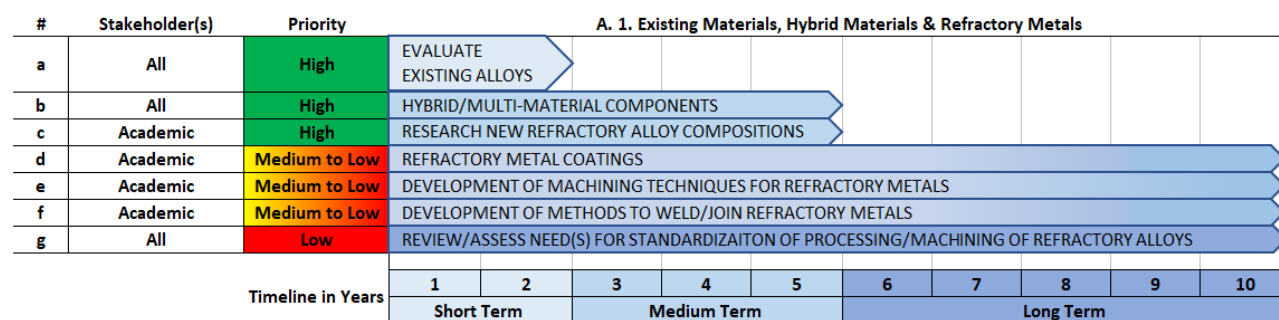
- Existing Materials, Hybrid Materials & Refractory Metals
- High Entropy Alloys
- Ceramic Matrix Composites
- Thermal Barrier Coatings

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 Lifting 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

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



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.

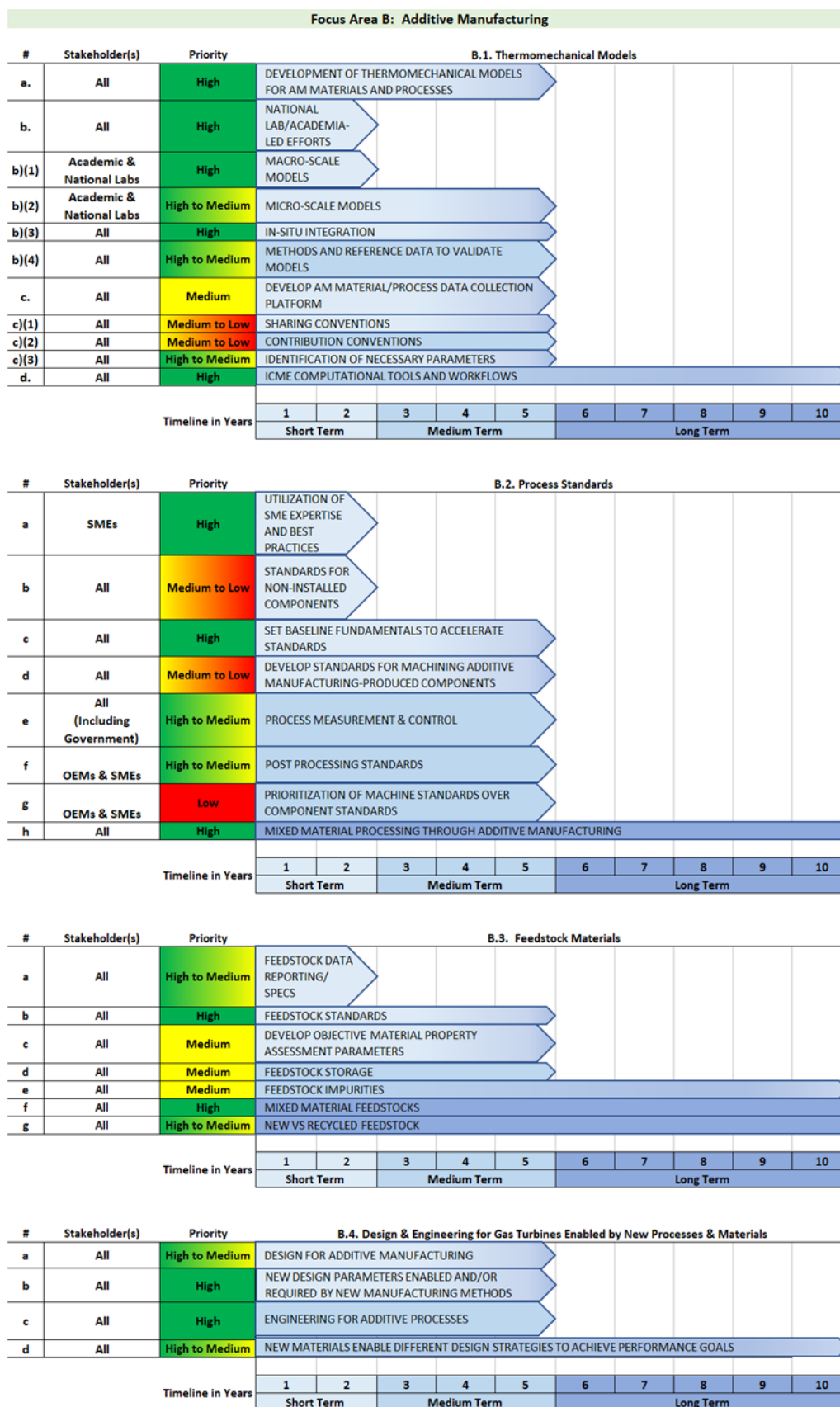
Primary subtopics included within the Additive Manufacturing that Enables New Design(s) and Engineering for Advanced Gas Turbines focus area include:

- 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

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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

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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																	
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:

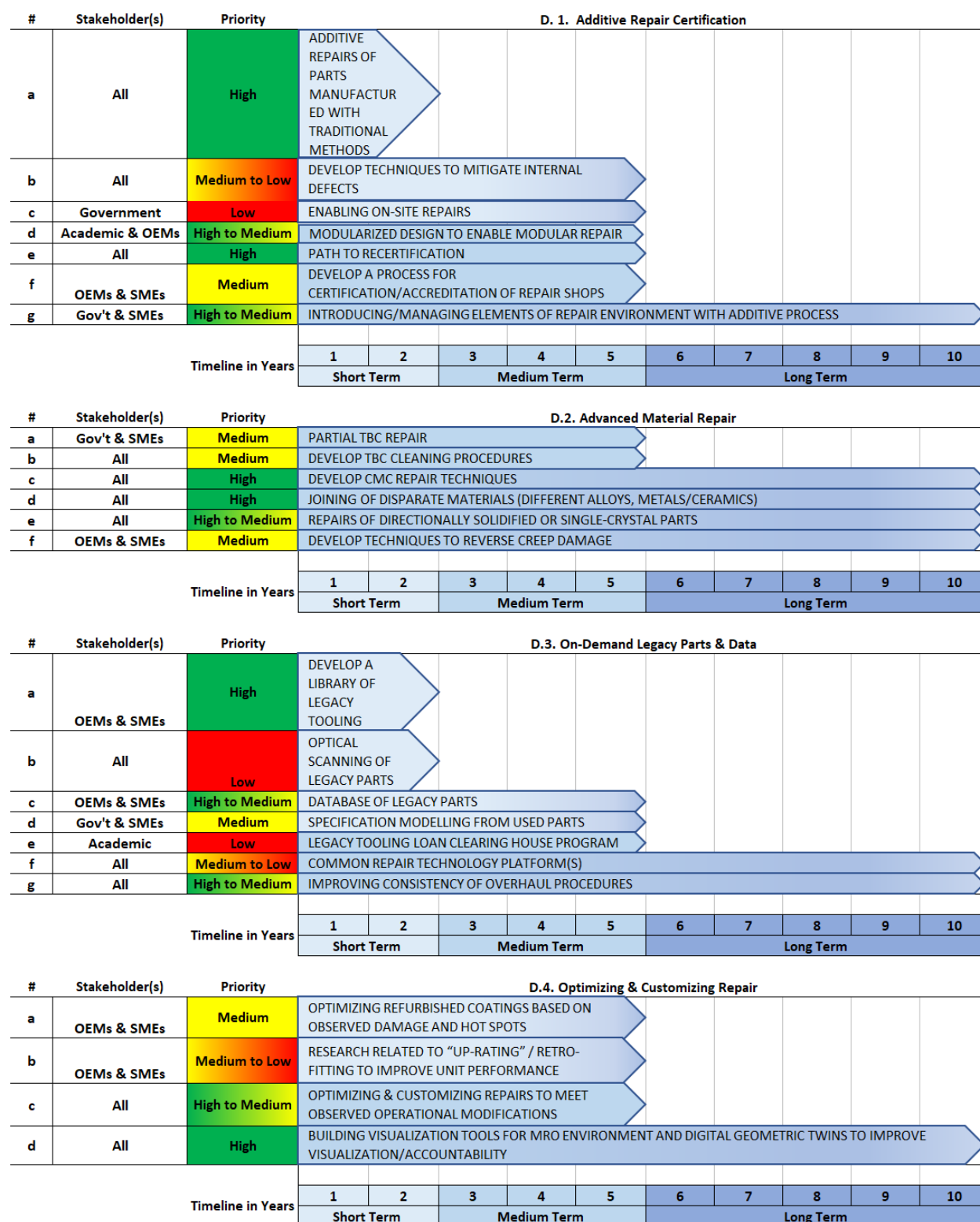
- Additive Repair & (Re-)Certification
- Advanced Material Repair Methodologies
- On-Demand Legacy Parts & Data Resources
- Optimizing & Customizing Repair

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

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Focus Area D: Maintenance Repair & Overhaul (MRO)



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

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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	FM Global	Power Systems Mfg., LLC / Ansaldo Energia
Aerojet Rocketdyne	Gas Technology Institute	Pratt & Whitney
Aerospace Industries Association	Gas Turbine Association	Pratt & Whitney Power Systems
Air Force Research Lab (AFRL)	GE Aviation	Purdue University
Alcoa	GE Global Research	Renaissance Services Inc.
American Electric Power	GE Power & Water	Rolls Royce
American Institute of Aeronautics and Astronautics (AIAA)	Georgia Tech – Inst. for Materials	Samsung Techwin
American Society of Mechanical Engineers (ASME)	Georgia Tech - Strategic Energy	Siemens Energy
Ansaldo Energia	Haynes International	Siemens Energy, Power Generation Services Division
Aspen Technologies	Honeywell International	Solar Turbines
Atlantic Precision	Impact Technologies	Southern Company
Chevron	Kelelo Engineering	Southwest Research Institute
Chromalloy	Keystone Synergistic Enterprises	Space Florida
Delta Air Lines	Longview Energy Associates	Stony Brook University
Doosan	Mainstream Engineering	Strategic Power Systems
Dresser-Rand	Mitsubishi Hitachi Power Systems Americas	Texas A&M University
Duke Energy	Napoleon Engineering Services	Turbo Machined Products
Echogen Power	National Aeronautics and Space Administration (NASA)	Turbomachinery International
Embry Riddle Aeronautical University	National Center for Defense Manufacturing and Machining	United Technologies Corporation
Energy Florida	National Energy Technology Lab	University of Central Florida
EPRI - Electric Power Research Institute	Natole Turbine Enterprise	University of Connecticut
Executive Office of the Governor of Florida/Office of Policy & Budget	NAVAIR	University of Notre Dame
Federal Aviation Administration	NIST	University of Pittsburgh
Florida Institute of Technology	North Carolina State University	University of Tennessee - Knoxville
Florida Power & Light	Oak Ridge National Laboratory	US Advanced Ceramics Association
Florida Turbine Technologies	PCC Airfoils, LLC	Vibrant NDT
	Penn State	Virginia Tech
	PennWell/Power Generation Int'l	Williams International

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