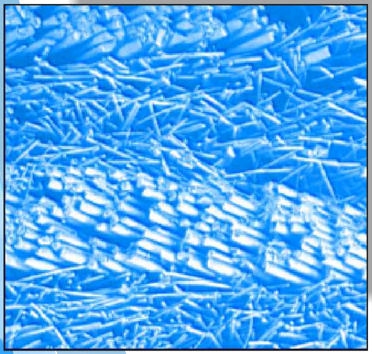
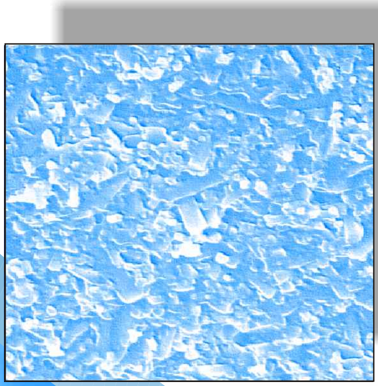
Advanced Ceramics Technology Roadmap

— Charting Our Course



Ceramic Matrix Composites

Ceramic Coating Systems



Monolithic Ceramics

Advanced Ceramics Technology Roadmap

— Charting Our Course

Priority Research, Development and Demonstration Needs to Advance Monolithic Ceramic, Ceramic Matrix Composites, and Ceramic Coating Systems

December 2000

Sponsored by
UNITED STATES ADVANCED CERAMIC ASSOCIATION
U.S. DEPARTMENT OF ENERGY

Prepared by
ENERGETICS, INCORPORATED
and
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About This Roadmap

The United States Advanced Ceramics Association and the U.S. Department of Energy co-sponsored a workshop to bring together a broad range of ceramic manufacturers and end-user companies. This roadmap, which summarizes the insights of those 40 workshop participants, sets forth the research, development and demonstrations needed for improving advanced structural ceramics. Achievement of the RD&D will significantly improve energy efficiency and productivity in many industries and help them reach their performance targets for 2020. Recognition and appreciation is extended to the workshop participants who volunteered their personal time to contribute valuable expertise and perspective.

Energetics, Incorporated organized the workshop and facilitated the workshop sessions. This roadmap was prepared by Melissa Eichner, Energetics, Incorporated and David W. Richerson of Richerson and Associates.

Cover photographs are provided courtesy of the following companies: Allied Signal, Inc.; Dow Corning, Inc.; Honeywell Advanced Composites Inc.; Kyocera Industrial Ceramics Corp.; McDermott, Inc.; Saint-Gobain Industrial Ceramics, Inc.; and Solar Turbines, Inc. The photograph on page 1 is provided courtesy of Saint-Gobain/Norton Advanced Ceramics, Inc.

Advanced Ceramics Technology Roadmap

— *Charting Our Course*

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1. Executive Summary and Introduction

Advanced ceramics are wear-resistant, corrosion-resistant, lightweight, and superior to many materials in stability in high-temperature environments. Because of this combination of properties, advanced ceramics have an especially high potential to resolve a wide number of today's material challenges in process industries, power generation, aerospace, transportation and military applications. Such applications are vital to maintaining global competitiveness, decreasing energy consumption, and minimizing pollution.

In the past three decades, breakthroughs in advanced ceramics have enabled significant new technology capabilities that are now having far-reaching impacts on the U.S. economy and society. For example, ceramic catalytic converters are responsible for reducing automobile emissions and long-life bearings are used in a wide range of applications to improve performance and reduce friction. The U.S. market value of advanced ceramics was nearly $7.5 billion in 1998, and this value is projected to grow to $11 billion by 2003[1]. More importantly, ceramics leverage much larger economic and social benefits. Catalytic converters alone enable a $38 billion pollution control business each year and have reduced air pollution by 1.5 billion tons since 1975[2]. The technological breakthroughs that make this possible are the result of sustained RD&D investment by industry and government.

Silicon Nitride Ceramic Bearings and Components

Photo DOE/ORO 2076 fig. 2.6, page 2-5 (photo credit on forward)

- RD&D began in 1972
- Reached market in 1988
- 3-10 times life of metal bearings
- 80% lower friction
- 15-20% lower energy consumption

Despite these successes, advanced ceramics are only used in a small percentage of applications that could benefit from their capabilities. Many OEMs and end-users are reluctant to try them because of concerns about reliability, higher costs compared to competing materials, insufficient design and test experience, and in some cases, inadequate properties to meet the needs of demanding applications. Today, the advanced ceramics industry is faced with an enormous opportunity as numerous sectors search for new or improved materials to resolve their technological challenges and improve competitiveness.

To realize the vast commercial potential, the advanced ceramics industry must address the needs of OEM and end-users. Specifically, RD&D is need to optimize material properties to meet the reliability requirements of specific applications, successfully demonstrate reliability through long-term end-user field tests, and gain fabrication efficiencies to allow market entry. With such continued development, the advanced ceramics market could grow significantly and leverage far more in economic benefits to end-users through maintenance reduction, energy efficiency, pollution reduction, and increased equipment life.

Advanced Structural Ceramics Have the Potential to Solve Critical Challenges in Demanding Applications

Processing and Manufacturing Industries	Power Generation, Aerospace, and Transportation	Military
▪ Extend equipment life ▪ Decrease emissions ▪ Decrease maintenance ▪ Increase energy efficiency ▪ Increase recycling, including process chemicals and water	▪ Extend equipment life ▪ Decrease emissions ▪ Increase specific power ▪ Decrease fuel use ▪ Reduce cost ▪ Reduce weight	▪ Expand capabilities of weapons and detection systems ▪ Decrease vulnerability ▪ Increase reliability ▪ Reduce cost of equipment, systems and deployment

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[1] Source: Business Communications Co., Inc.

[2] Source: Corning, Incorporated, 1999.

To respond to OEM/end-user opportunities, the U.S. Advanced Ceramics Association (USACA) has brought together the advanced ceramics industry to chart a course for the future designed to meet the diverse material needs of important U.S. sectors over the next 20 years. This roadmap is the first step in reaching consensus on priority needs and preparing a long-range RD&D plan for advanced ceramics. The ideas presented in the following pages summarize the priorities identified at an *Advanced Ceramics Technology Roadmap Workshop,* which was held September 22–23, 1999. 40 participants representing ceramic manufacturers, OEMs, research laboratories, and the government attended the workshop, which was sponsored by USACA and the Department of Energy's Office of Industrial Technologies and the Office of Power Technologies. A workshop agenda and a list of participants are presented in Appendix A and B, respectively.

A 2020 Vision for Advanced Structural Ceramics

The ceramics industry has established an ambitious vision for advanced ceramics aimed at providing maximum benefit to OEMs and end-users. In 2020, advanced ceramics will be cost-effective, preferred materials in demanding applications of industry, power generation, aerospace, transportation, military, and consumer products. Design methods, property testing standards, and property databases will be available so a team (designer, supplier, end-user) can select a ceramic that will reliably meet the application requirements and provide superior benefits compared to alternate materials (metals, polymers). Ceramics will be fabricated into complex and large shapes with minimum development time and minimum defects. NDE techniques will be able to detect small critical defects and bolster production efficiencies. End-users will have experience and confidence using ceramics. (A detailed description of the vision is presented in Appendix C.)

Vision for Advanced Structural Ceramics

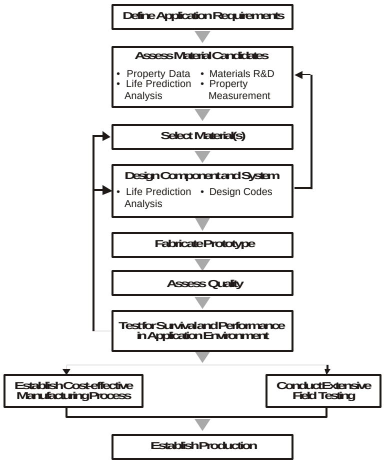
By 2020, advanced structural ceramics are cost-effective preferred materials that exceed the performance of other materials due to reliability, high-temperature capability, and other unique properties. Products are initially designed for ceramic materials, with confidence, using established standards and design tools. Automation and other advanced fabrication processes optimize cycle times and yield, ensure predictable and controllable production, and eliminate the need for post-process inspection.

RD&D Needed to Meet OEM and End-user Requirements

The RD&D required for three major classes of ceramics – monolithic ceramics, ceramic matrix composites (CMCs), and ceramic coating systems – are presented in Exhibits 1, 2 and 3, respectively These exhibits identify the priority technical challenges that must be met to satisfy OEM/end-user requirements and the RD&D needed to address these challenges. They will be used to communicate consensus research needs throughout the advanced ceramics industry so that collaborative projects may begin. In addition, they will be used to fortify support from end-use sectors that can use advanced ceramics to achieve their own visions. Successful achievement of the RD&D is expected to have significant near-term and long-term market impacts in process industries, power generation, transportation, aerospace, military, and other applications. Detailed analyses of the priority research needs for monolithic ceramics, CMCs, and ceramic coating systems, and for issues common to all three advanced structural ceramics are presented in sections 2, 3, 4, and 5, respectively. Comprehensive lists of RD&D needs from the workshop are presented in Appendices D, E, and F.

Conclusions:

CERAMIC DEVELOPMENT PROCESS



Developing a ceramic component for a specific application requires eight distinct steps that are outlined below. Improving advanced ceramics to meet the expectations of end users will require an iterative RD&D approach that considers these steps simultaneously. Reducing the development time and the number of iterations compared to competing materials is key to ceramics' commercial success.

1. Define the requirements (temperature, pressure, etc.) in a specific application or group of similar applications
2. Assess the suitability of existing ceramic-based materials and identify where improvements are needed
3. Select one or more candidate ceramic materials
4. Design a prototype component and system
5. Fabricate a prototype
6. Assess the quality of the prototype component
7. Evaluate the prototype in simulated and real environments, including long-term field testing
8. Develop and optimize a viable fabrication process for production

The R&D needs address both the near-term and long-term barriers to meeting end-user requirements. In the near-term, efforts are needed to grow the business application by application. Solving the remaining critical challenges in emerging applications and in new target applications can achieve this. Long-term efforts are needed to reach desired manufacturing efficiencies and performance profiles. Gaining fundamental understanding and developing enabling methods that can be applied to solve unique and crosscutting problems in numerous applications can achieve this.

The breakthroughs needed to realize the full benefits of advanced structural ceramics will require a significant and sustained research effort over the next two decades. This will require dedication from industry, academia, government and national labs. These efforts will build on past achievements to solve problems that currently prohibit the use of ceramics in specific applications. Although the research needed is high-risk, comparable breakthroughs have already been achieved, lending credibility to the research effort. The potential exists to revolutionize sectors throughout the economy.

RD&D is needed in the following interrelated areas:

- Materials Database **– generate data to use in material selection and improvement and to support analytical design and life prediction**
- Design and Life Prediction **– improve methods and analytical tools to allow efficient analytical component design (replace inefficient "build and break" iterative methods)**
- Non-Destructive Evaluation **– improve methods and equipment for low-cost component inspection and quality assurance**
- Fabrication Optimization **– improve the fabrication process to increase material reliability, improve manufacturing scale-up capability, and reduce costs**
- Demonstrations **– verify component viability through long-life testing and testing in the end-use environment**

EXHIBIT 1 MONOLITHIC CERAMICS RD&D PRIORITIES

RD&D Needed to Meet End-User Requirements

Priority Challenges

Improve resistance to fracture
  - Better design methods
  - Lower-stress designs
  - Increased material toughness
  - Increased material strength

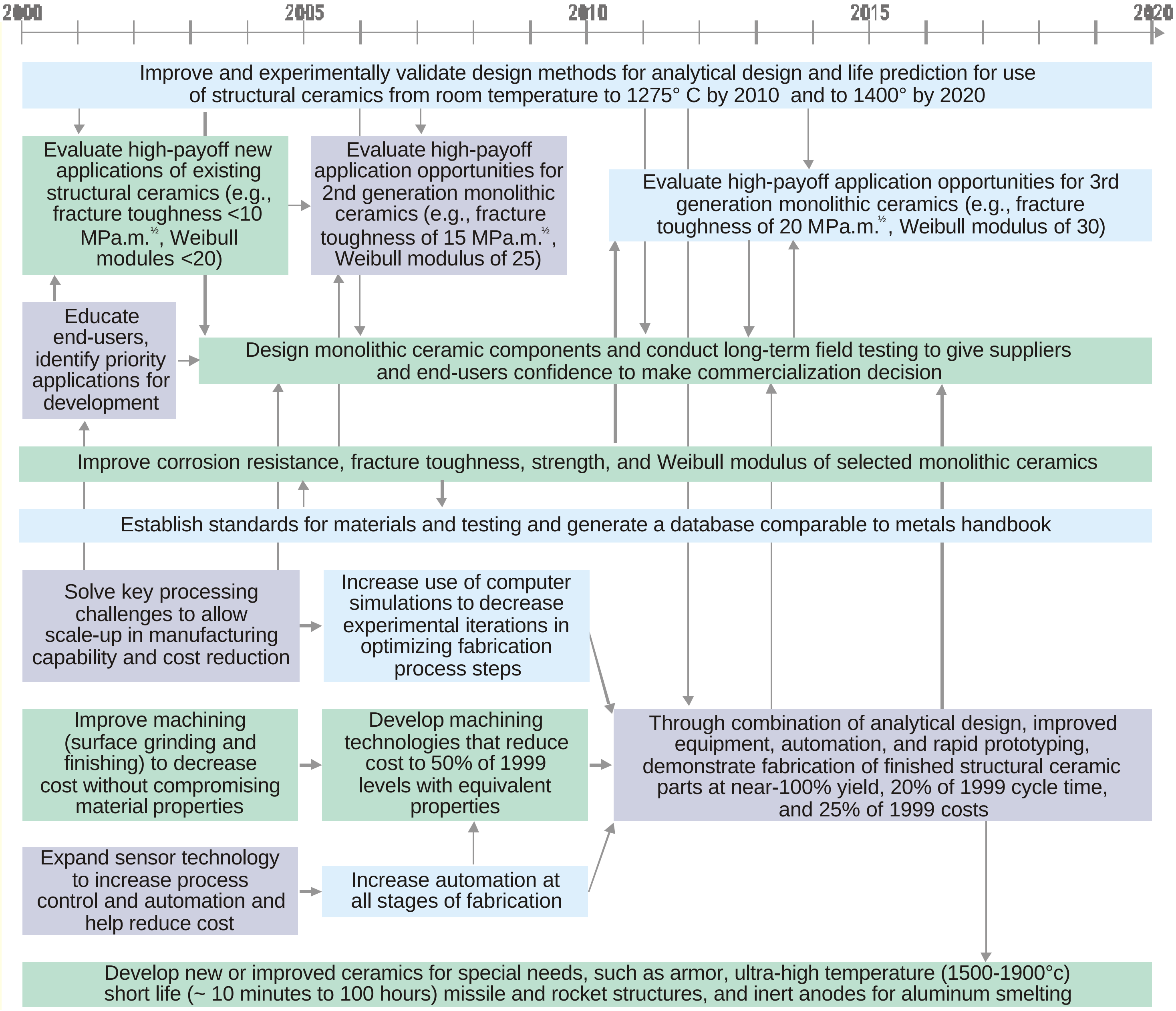
Increase reliability

Improve resistance to use environment

Long-term testing in application environment
  - Simulation tests
  - Field tests

Educate end-users

Reduce cost of manufacturing
  - Lower-cost raw materials
  - Quantity scale-up
  - Increased automation
  - Decreased final machining
  - Lower-cost quality assurance
  - Rapid prototyping



Improve and experimentally validate design methods for analytical design and life prediction for use of structural ceramics from room temperature to 1275° C by 2010 and to 1400° by 2020

Evaluate high-payoff new applications of existing structural ceramics (e.g., fracture toughness <10 MPa.m.^{½}, Weibull modules <20)

Evaluate high-payoff application opportunities for 2nd generation monolithic ceramics (e.g., fracture toughness of 15 MPa.m.^{½}, Weibull modulus of 25)

Evaluate high-payoff application opportunities for 3rd generation monolithic ceramics (e.g., fracture toughness of 20 MPa.m.^{½}, Weibull modulus of 30)

Educate end-users, identify priority applications for development

Design monolithic ceramic components and conduct long-term field testing to give suppliers and end-users confidence to make commercialization decision

Improve corrosion resistance, fracture toughness, strength, and Weibull modulus of selected monolithic ceramics

Establish standards for materials and testing and generate a database comparable to metals handbook

Solve key processing challenges to allow scale-up in manufacturing capability and cost reduction

Increase use of computer simulations to decrease experimental iterations in optimizing fabrication process steps

Improve machining (surface grinding and finishing) to decrease cost without compromising material properties

Develop machining technologies that reduce cost to 50% of 1999 levels with equivalent properties

Through combination of analytical design, improved equipment, automation, and rapid prototyping, demonstrate fabrication of finished structural ceramic parts at near-100% yield, 20% of 1999 cycle time, and 25% of 1999 costs

Expand sensor technology to increase process control and automation and help reduce cost

Increase automation at all stages of fabrication

Develop new or improved ceramics for special needs, such as armor, ultra-high temperature (1500-1900°c) short life (~ 10 minutes to 100 hours) missile and rocket structures, and inert anodes for aluminum smelting

End-Use Market Sector Payoff

Process Industries
  - Glass
  - Aluminum
  - Chemicals
  - Petroleum
  - Forest Products
  - Metalcasting
  - Steel
  - Agriculture
  - Mining and Minerals

Power Generation

Transportation

Aerospace

Military

🟩 Top Priority 🟪 High Priority 🟦 Medium Priority

Status: Monolithic ceramics are in limited use today but they could provide benefits in a wider range of applications.

RD&D Priorities:

- **Component field tests are needed to demonstrate that existing monolithic ceramics can increase component life with equivalent or better performance and reliability compared to metal alloys in use.** The advanced ceramics industry must educate end-users regarding the capability (and successes) of existing structural monolithic ceramics so they can accurately assess their value in specific component applications and understand the need for iterations of design and field-testing. Research is also needed to improve component design, fabrication, and evaluations (pre-test through post-test) at field test sites so end-users will use ceramics with confidence over the next 3 to10 years. As design methods and tools improve and as monolithic ceramics with higher strength, toughness, and corrosion resistance are developed, applications of increased severity can be addressed over the next 5 to 20 years.

- **RD&D must help reduce the cost of advanced ceramics.** Unit cost of monolithic ceramics is high because of low-volume production, high-cost diamond grinding, and high-cost inspection to assure reliability. Areas to target for cost reduction include fabrication steps (especially improved sensors, automation, and optimization of process equipment design), machining and scale-up to the level required for suppliers and end-users to make full-production commercialization decisions. Eliminating fabrication cost and scale issues are keys to commercialization success.

- **Fundamental and applied RD&D is needed to increase reliability and to meet the needs in application environments that are too severe for present materials.** RD&D is needed to understand the degradation and failure mechanisms in simulated and real application environments and to improve material properties (especially fracture toughness, oxidation/corrosion resistance, and temperature capability) to achieve the lifetime and reliability demanded by the OEMs and end-users. Extensive property testing and microstructural/ microchemical analysis will guide efforts to improve performance and generate a critical database. At this stage, most monolithic ceramic development will be linked to specific application needs, such as improved temperature stability of silicon nitride for turbines, a non-oxidizing (inert) anode for aluminum smelting, and next-generation armor.

Monolithic ceramics describes a broad category of ceramics that often include the following attributes: fabricated as a stand-alone part, rather than applied as a coating; little or no porosity; comprised of a polycrystalline microstructure without a reinforcing phase added during fabrication; and fracture at room temperature in a brittle mode

Examples of monolithic ceramics include dense forms of aluminum oxide, silicon nitride, and transformation-toughened zirconia.

Market Impact:

Near-term RD&D on monolithic ceramics will provide major benefits to process industries through promoting the use of ceramics with superior wear resistance, oxidation/corrosion resistance, and higher temperature capability to replace metals. As materials improvements are achieved, the benefits will extend to power generation, aerospace, and military sectors. As manufacturing costs decrease and reliability increases, the benefits will extend to the transportation sector as well.

EXHIBIT 2 CERAMIC MATRIX COMPOSITES RD&D PRIORITIES

RD&D Needed to Meet End-User Requirements

Priority Challenges

Improve understanding of failure modes

Increase temperature stability to 1200°-1500° C
- Higher temperature fibers and interface coatings
- Higher temperature matrix
- Environmental barrier coatings

Long-term testing in application environments

Reduce cost of precursors

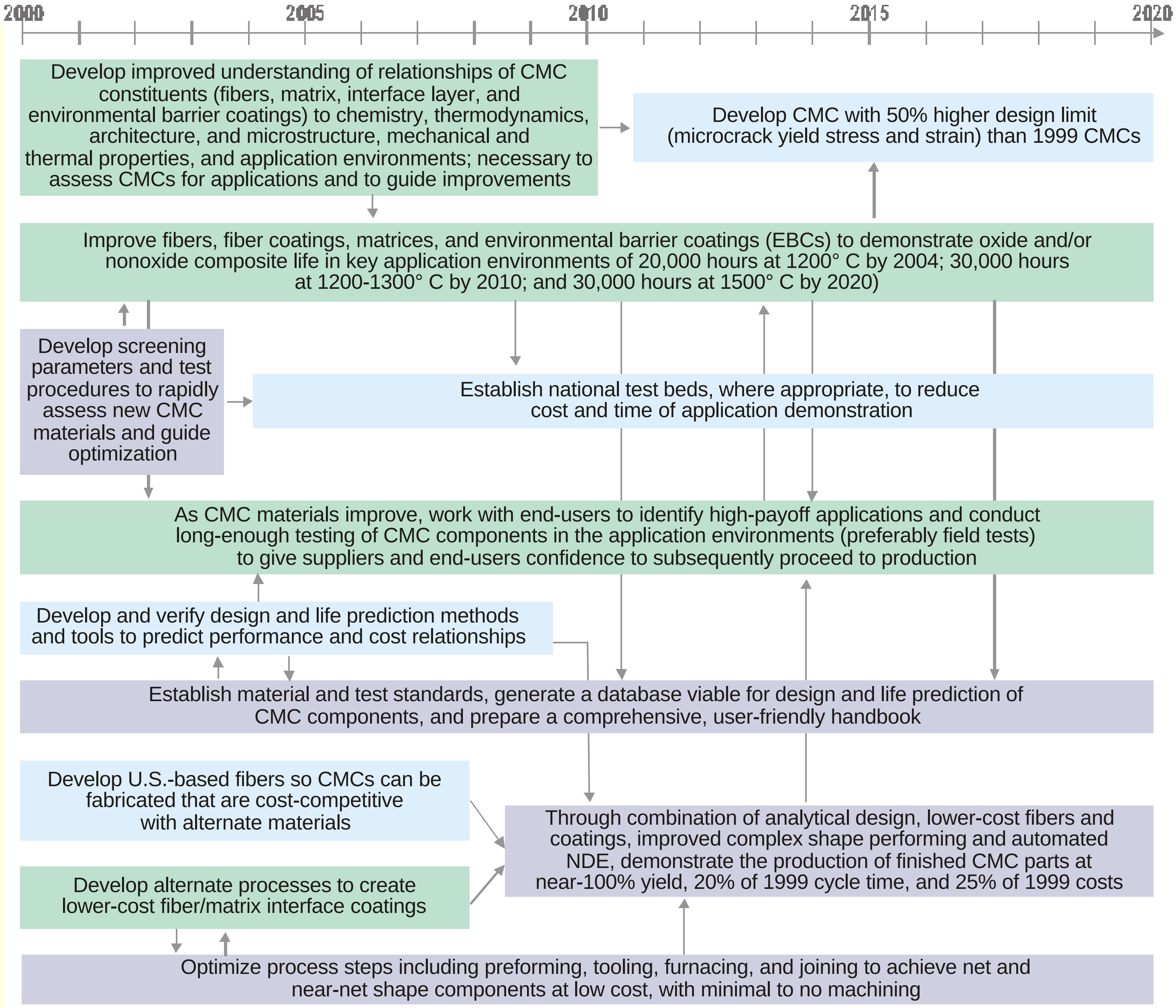
Scale-up and reduce cost of manufacturing
- Larger furnace capacity
- Automation/semi-automation
- Low-cost tooling
- Near-net shape fabrication
- Low-cost quality assurance

Improve design and life prediction
- Improve standards database
- Application-specific data
- Experimental validation of models
- Integration of design and manufacturing (concurrent design)

Improve attachment technology

Develop on-site repair methods

Educate end-users



Develop improved understanding of relationships of CMC constituents (fibers, matrix, interface layer, and environmental barrier coatings) to chemistry, thermodynamics, architecture, and microstructure, mechanical and thermal properties, and application environments; necessary to assess CMCs for applications and to guide improvements

Develop CMC with 50% higher design limit (microcrack yield stress and strain) than 1999 CMCs

Improve fibers, fiber coatings, matrices, and environmental barrier coatings (EBCs) to demonstrate oxide and/or nonoxide composite life in key application environments of 20,000 hours at 1200° C by 2004; 30,000 hours at 1200-1300° C by 2010; and 30,000 hours at 1500° C by 2020)

Develop screening parameters and test procedures to rapidly assess new CMC materials and guide optimization

Establish national test beds, where appropriate, to reduce cost and time of application demonstration

As CMC materials improve, work with end-users to identify high-payoff applications and conduct long-enough testing of CMC components in the application environments (preferably field tests) to give suppliers and end-users confidence to subsequently proceed to production

Develop and verify design and life prediction methods and tools to predict performance and cost relationships

Establish material and test standards, generate a database viable for design and life prediction of CMC components, and prepare a comprehensive, user-friendly handbook

Develop U.S.-based fibers so CMCs can be fabricated that are cost-competitive with alternate materials

Through combination of analytical design, lower-cost fibers and coatings, improved complex shape performing and automated NDE, demonstrate the production of finished CMC parts at near-100% yield, 20% of 1999 cycle time, and 25% of 1999 costs

Develop alternate processes to create lower-cost fiber/matrix interface coatings

Optimize process steps including preforming, tooling, furnacing, and joining to achieve net and near-net shape components at low cost, with minimal to no machining

🟩 Top Priority 🟪 High Priority 🟦 Medium Priority

End-Use Market Sector Payoff

Process Industries
- Glass
- Aluminum
- Chemicals
- Petroleum
- Forest Products
- Metalcasting
- Steel
- Agriculture
- Mining and Minerals

Power Generation

Transportation

Aerospace

Military

Status: CMC technology is still in an early stage of development, with many challenges that must be addressed to make CMCs available to end-users.

Ceramic Matrix Composites (CMCs) **are ceramic materials that incorporate a reinforcing phase such as whiskers or long fibers during fabrication into a ceramic matrix to create new materials with superior properties.**

Examples of CMCs include silicon carbide fibers in silicon carbide matrix, aluminum oxide fibers in aluminum oxide matrix.

RD&D Priorities:

- **RD&D is needed to understand the interactions of the composite constituents (fibers, matrix, interface coatings, surface coatings) with one another and with the application environments.** This will require iterations of composition selection, fabrication, testing, and post-test evaluation to assess performance. These material development and characterization efforts will need to be closely linked to improving design and life prediction tools and establishing standards and databases.

- **Increasing CMC lifetime is a top priority.** Research efforts will focus on progressively increasing the temperature capability, life, and ultimately the design limit (the stress to which the CMC can be exposed). These priorities will require focused RD&D on fibers, fiber coatings, matrix chemistry, and environmental barrier coatings (EBCs) as well as fabrication and testing. Establishing facilities for simulated and accelerated testing and establishing partnerships with end-users for field-testing are critical to achieving success.

- **CMC RD&D must help resolve cost issues.** Currently, CMCs are considered for only a limited number of premium applications because the costs of raw materials, fabrication, and inspection are much higher than for monolithic ceramics. Reducing costs will expand opportunities in applications that can benefit from longer life and higher reliability than metals and monolithic ceramics. Research should help reduce the cost of precursors (especially fibers), increase the scale of fabrication, achieve near-net-shape fabrication, implement process automation or semi-automation, and minimize or automate quality assurance inspections.

Market Impact:

CMC development, though high risk, could lead to high payoffs in the near-term for industrial turbines, pollution control, and process industries, and in the mid-term for military and aerospace applications, in all cases fulfilling urgent needs.

EXHIBIT 3 CERAMIC COATING SYSTEMS RD&D PRIORITIES

RD&D Needed to Meet End-User Requirements

Priority Challenges

Improve design and life prediction methods/tools

Improve coating adhesion
- Pre-coating surface treatments
- Improved interlayers
- Functional gradation

Improve understanding of failure modes and mechanisms

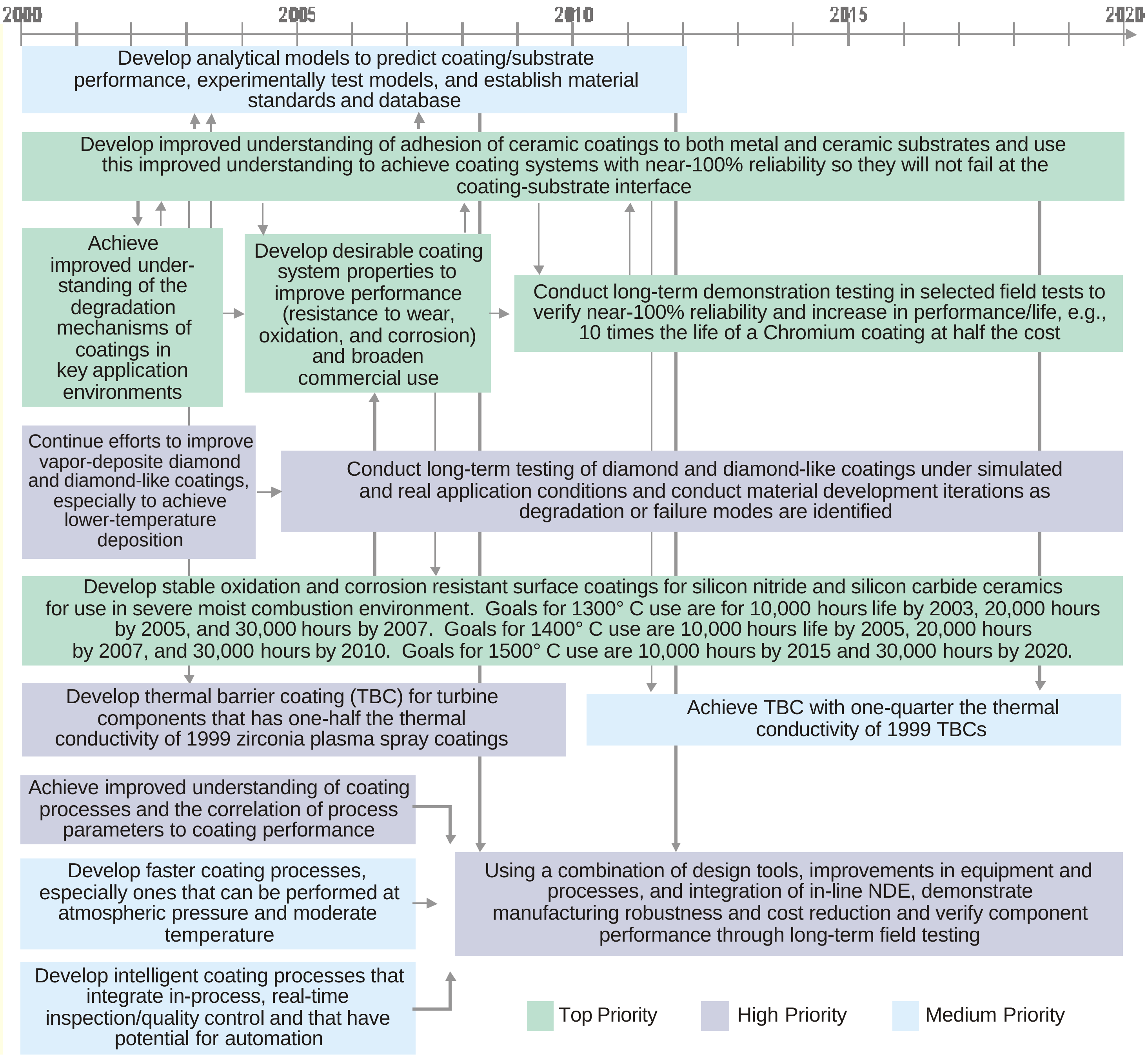
Improve coating and system properties
- Better abrasion resistance
- Better corrosion resistance
- Higher temperature capability
- Lower friction, minimal lubrication coatings
- Low thermal conductivity TBCs

Conduct long-term testing in application environments

Increase reliability, reduce cost of coating

Develop on-site repair methods

Educate end-users



Develop analytical models to predict coating/substrate performance, experimentally test models, and establish material standards and database

Develop improved understanding of adhesion of ceramic coatings to both metal and ceramic substrates and use this improved understanding to achieve coating systems with near-100% reliability so they will not fail at the coating-substrate interface

Achieve improved understanding of the degradation mechanisms of coatings in key application environments

Develop desirable coating system properties to improve performance (resistance to wear, oxidation, and corrosion) and broaden commercial use

Conduct long-term demonstration testing in selected field tests to verify near-100% reliability and increase in performance/life, e.g., 10 times the life of a Chromium coating at half the cost

Continue efforts to improve vapor-deposite diamond and diamond-like coatings, especially to achieve lower-temperature deposition

Conduct long-term testing of diamond and diamond-like coatings under simulated and real application conditions and conduct material development iterations as degradation or failure modes are identified

Develop stable oxidation and corrosion resistant surface coatings for silicon nitride and silicon carbide ceramics for use in severe moist combustion environment. Goals for 1300° C use are for 10,000 hours life by 2003, 20,000 hours by 2005, and 30,000 hours by 2007. Goals for 1400° C use are 10,000 hours life by 2005, 20,000 hours by 2007, and 30,000 hours by 2010. Goals for 1500° C use are 10,000 hours by 2015 and 30,000 hours by 2020.

Develop thermal barrier coating (TBC) for turbine components that has one-half the thermal conductivity of 1999 zirconia plasma spray coatings

Achieve TBC with one-quarter the thermal conductivity of 1999 TBCs

Achieve improved understanding of coating processes and the correlation of process parameters to coating performance

Develop faster coating processes, especially ones that can be performed at atmospheric pressure and moderate temperature

Develop intelligent coating processes that integrate in-process, real-time inspection/quality control and that have potential for automation

Using a combination of design tools, improvements in equipment and processes, and integration of in-line NDE, demonstrate manufacturing robustness and cost reduction and verify component performance through long-term field testing

🟩 Top Priority 🟪 High Priority 🟦 Medium Priority

End-Use Market Sector Payoff

Process Industries
- Glass
- Aluminum
- Chemicals
- Petroleum
- Forest Products
- Metalcasting
- Steel
- Agriculture
- Mining and Minerals

Power Generation

Transportation

Aerospace

Military

Status: Ceramic coating systems are in wide use today. Improved coating systems and coating properties would expand use in many sectors.

RD&D Priorities:

- **RD&D should focus on improving adhesion between the coating and substrate to provide longer life and higher equipment reliability, developing a better understanding of the mode and mechanisms of coating degradation in application environments; improving coating material properties to resist degradation mechanisms; and optimizing coating processes to minimize cost.** Such research will require iterations of chemical composition modifications, deposition, exposure to simulated and real application environments, and microstructure/microchemical evaluation.

Ceramic coatings are typically a thin layer of ceramic deposited on metal or ceramic to impart improved resistance to corrosion, wear, or temperature. Underlying metal substrates can carry the structural load and minimize the likelihood of catastrophic failure. Coatings deposited onto a substrate conform to the shape of the substrate, allowing complex shaped parts to be fabricated with the benefits of a ceramic at relatively low cost and without the costs associated with fabricating the whole part from a ceramic. Coatings are also used on monolithic ceramics and CMCs to obtain required performance characteristics.

- **Improved vapor-phase deposited diamond and diamond-like coatings are needed**. These coatings are relatively new technologies that have the potential to dramatically increase wear resistance and extend equipment life. RD&D should help decrease the cost of vapor-phase deposition, decrease deposition temperature so diamond (or diamond-like) coatings can be applied to lower-temperature substrates (e.g., mild steel and non-ferrous alloys), and evaluate performance and degradation mechanism in real application field tests.

Examples of coating techniques include plasma spray, flame spray, high velocity oxy-fuel deposition, and electron beam.

- **Thermal barrier coatings (TBCs) must be improved**. TBCs are used to allow engines to operate at increased temperatures, substantially increasing power per unit volume and reducing fuel consumption. RD&D and application evaluations are needed to increase the life of the TBC system to greater than 20,000 hours, increase temperature capability, and further decrease thermal conductivity to keep the underlying metal cooler.

- **Improved coatings are needed for fibers used in CMCs fabrication and for protective surfaces applied to CMCs and monolithic ceramic components (e.g., environmental barrier coatings (EBCs)).** These priority needs are addressed in the CMC and monolithic ceramic sections, respectively.

- **Specialized ceramic coating technologies are needed.** Research is needed for modified surfaces for refractories (in all of the processing industries), next-generation space shuttle surface protection, space structure coatings, functionally graded coatings, and coatings with combined optical and structural or electrical and structural functions. Coating system RD&D will also improve design and life prediction methods and tools and to develop on-site repair methods.

Market Impact:
Benefits will accrue to all market sectors with technology spinning off to products within three years and accelerating through the year 2020.

2. Monolithic Ceramics – Challenges and Needs

Monolithic describes a broad category of ceramics that is difficult to define succinctly. In this roadmap, ceramics are monolithic if they exhibit the following attributes:

- Fabricated as a stand-alone part, rather than applied as a coating
- Comprised of a polycrystalline microstructure without a reinforcing phase added during fabrication
- Fracture at room temperature in a brittle mode

Based on these criteria, two important ceramics, silicon nitride and transformation-toughened zirconium oxide, are classified as monolithic ceramics, despite the composite-like microstructures that form during their fabrication processes. Other examples of monolithic ceramics with potential for structural applications include silicon carbide, aluminum oxide, aluminum nitride, mullite, cordierite, zirconium diboride, zirconium carbide, and titanium diboride.

When end users consider a monolithic ceramic, four potential barriers are often cited: inadequate resistance to fracture, inadequate resistance to the use environment, inadequate or uncertain reliability, and cost effectiveness. Exhibit 4 lists the challenges and the priority RD&D needs to address the challenges. The challenges and RD&D needs are discussed below. Note: several key monolithic ceramic challenges are addressed in Section 5 on RD&D needs common to monolithic, composite, and coating ceramics. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 4 Priority RD&D Needs in Monolithic Ceramics to Address Key Challenges Faced by Ceramic Manufacturers and End Users

Key Challenges for Monolithic Ceramics	*Priority RD&D Needs to Address the Challenge*
Improve resistance to fracture	▪ Increased material toughness ▪ Increased material strength ▪ Better design methods/practices ▪ Lower stress designs
Improve resistance to the use environment (e.g., oxidation, corrosion)	▪ Improved material chemical stability ▪ Protective coatings ▪ Functional gradient construction ▪ Improved resistance to contact stress
Increase reliability	▪ Reduced material variability through improved fabrication process control
Reduce the cost of manufacturing	▪ Lower-cost powders/precursors ▪ Quantity scale-up ▪ Increased automation ▪ Decreased final machining ▪ Lower-cost quality assurance ▪ Rapid prototyping integrated into manufacturing

Technology Challenge: Improve Resistance to Fracture

The brittle fracture behavior of monolithic ceramic components is a major concern to end-users, especially fear of catastrophic fracture. While major advancements have been achieved, further improvement is needed to develop fracture-resistance capabilities comparable to alternative materials. For some applications, monolithic ceramics exist with adequate fracture resistance to meet end-user requirements, but end users are not aware of the material capabilities or are not willing to try them.

RD&D Priority

Increased Material Toughness. Toughness is the resistance of a material to propagation of a crack through the material. Traditional monolithic ceramics have relatively low resistance; a stress applied to the ceramic concentrates at the tip of the crack, easily driving the crack completely through to cause fracture. In contrast, a ductile metal deforms at the tip of the crack, spreading the stress over a larger volume. For example, traditional polycrystalline monolithic ceramics have fracture toughness ranging from 2 to 4 $\text{MPa.m}^{1/2}$, while ductile metals have values typically well above 40 $\text{MPa.m}^{1/2}$.

Since the 1970s, the toughness of monolithic ceramics has increased significantly, primarily through understanding the interrelationships of toughness, microstructure, and the fabrication process. Toughness values of nearly 10 $\text{MPa.m}^{1/2}$ have been achieved for special silicon nitride compositions and nearly 15 $\text{MPa.m}^{1/2}$ for some transformation-toughened zirconium oxide compositions. Even though improved toughness does not prevent brittle fracture, these ceramics are much more resistant to handling, impact, thermal shock and other application abuses that limited the use of traditional ceramics. Improved toughness significantly contributed to the successful use of silicon nitride in cutting tools, bearings, heat engines, and industrial wear-resistant parts and of transformation-toughened zirconia for wire-drawing, aluminum can manufacturing, papermaking tooling, and many other industrial wear-resistant parts.

Photo DOE/ORO 2076 fig. 2.4, page 2-3

Even with the improvements achieved, monolithic ceramics are not considered for many eligible applications. In some applications, they are still inadequate. *RD&D is needed to increase fracture toughness to help alleviate end-user reluctance and meet ever-increasing demands of new applications.* The target of 20 $\text{MPa.m}^{1/2}$ in 2020 is a difficult challenge that will require focused long-term basic RD&D.

Increased Material Strength. Strength is a measurement of the load (or stress) at which a crack starts in a ceramic, as opposed to toughness which is a measurement of the resistance of the ceramic to the extension of the crack. Both are related and together determine the fracture behavior of a material. The strength of monolithic ceramics has improved considerably. Prior to 1960, 290 MPa (20,000 psi) was considered high strength for a ceramic; now ceramics are produced with strength greater than 500 MPa. Silicon nitride materials, for example, are now available with average room

Photo DOE/ORO 2076 fig. 2.3, page 2-3

temperature strength approaching 1000 MPa and with strength at 1200°C around 700 MPa. To put these values in perspective, a 2.5-cm cross section of a 1000 MPa material can lift the weight of fifty 3000-pound automobiles.

Historically, ceramics have had a wide strength distribution. For example, an early 1970s silicon nitride had an average strength of 700 MPa, but a maximum of 900 MPa and a minimum of 400 MPa. In statistical terms, this material had a Weibull modulus below 8. The Weibull modulus for metals are typically greater than 40, so designers and end-users were suspect of ceramic reliability. At present, Weibull moduli between 15 and 20 have been achieved for silicon nitride materials, but not consistently across batches and manufactured shapes. *Continued research is needed to increase the strength especially strength, uniformity within a ceramic part and from part to part, and increase the Weibull modulus to >30 .*

Better Design Methods/Practices. For structural applications, monolithic ceramics require a different design method than metals. Because of their brittle fracture mode, ceramics require a probabilistic design method that simultaneously accounts for the stress distribution in a ceramic component and for the statistical distribution of strength-limiting defects in the ceramic microstructure. Tremendous progress has been made to establish a probabilistic design methodology. This is used for ceramic component design in gas turbine engines and other heat engine components. However, it has not been widely adopted or adapted for industrial applications. *To improve design methods, RD&D is needed to: compile a materials-allowable design manual and database handbook that can be readily used by industry comparable to metals handbooks; incorporate probabilistic design into user-friendly design software; develop a concurrent engineering and design methodology that encourages designing for manufacturability; and establish a center for advanced structural ceramics design and tool development.*

Lower Stress Designs. Historically, evaluating a ceramic for an application involved duplicating the metal part, usually without success. Ceramics designs must keep the mechanical and thermal stresses within reasonable limits. Design tools and boundary conditions data are currently inadequate to accurately predict the stress distribution. As a result, multiple iteration of design and testing are required. *RD&D are needed to improve the iterative efforts between design and testing to achieve low-stress, high-reliability ceramic component designs.* High-risk, high-payoff components would benefit from this research.

Technology Challenge: Improved Resistance to the Use Environment

Components are used in very severe environments in terms of stress, temperature, corrosion, and wear (e.g., in processing industries, power generation systems, and heat engines). Improving strength and toughness can provide resistance to stress and wear, but will not ensure resistance to corrosion and oxidation, especially at high temperature. Applications involving combustion are especially severe, particularly when ash particles and molten salts are present. Water vapor and operation pressures higher than normal atmosphere can dramatically reduce material resistance to attack.

RD&D Priority

Improved Material Chemical Stability. Stability in the use environment also is a key issue for extending equipment life and reducing maintenance in many applications. Continuing research is needed to understand the fundamentals of thermochemical stability of key monolithic ceramic materials and to develop ceramics with improved chemical stability. Testing in actual use environments is essential. For example, silicon nitride compositions developed during the 1990s survived in laboratory furnace tests for thousands of hours at temperatures up to 1400^{o} C under stress levels comparable to applications such as turbine engines. However, when these materials were tested in actual engines under pressure, flowing gases, and moist atmospheres, they exhibited much lower chemical stability and unacceptable oxidation recession rates. Existing, new, and modified chemical compositions in specific application environments will need to be considered and evaluated through iterations of synthesis, exposure in the use environment, and post-exposure testing/analysis. Also, RD&D is needed with broad applicability such as increasing the oxidation resistance of non-oxide ceramics.

Protective Coatings. Coatings on monolithic ceramics may be a viable approach to solve current problems of high temperature oxidation and contact stress, especially impact. Non-oxide ceramics have relatively low thermal expansion and most oxides have moderate-to-high thermal expansion; consequently, high stresses result at the coating interface. *Focused RD&D on protective coatings is needed to solve the problems associated with high-temperature oxidation and contact stress.* Research is needed for applying an oxide coating onto a non-oxide ceramic such as silicon nitride or silicon carbide.

Functional Gradient Ceramics. To provide environmental resistance, a monolithic ceramic could be developed with a graded composition or microstructure that provides optimum resistance to the application environment at and near the surface and optimum structural properties in the interior to resist mechanical and thermal stresses. *Research is needed to fabricate a functionally graded ceramic such as with the use of new rapid prototyping technology.*

Improved Resistance to Contact Stress. Ceramics often fail where they are attached to another material or where they contact another material during use. Sliding contact and impact both are known to cause high local stress, causing damage or failure. Many failures in structural ceramic components have been linked to contact stress and inadequate design to tolerate the contact stress or inadequate material strength and toughness. Contact stress is not often recognized as a design criterion. Instead, it is addressed after the ceramic part fails. *An integrated research approach is needed to reduce contact stress, including better analytical design tools, improved understanding of ceramic material and component limits, improved materials and design, and education of designers and end-users.*

Technology Challenge: Increase Reliability

The RD&D needs discussed above will increase the reliability of monolithic ceramics. Additional research is needed to increase the reliability of the fabrication process.

RD&D Priority

Reduced Material Variability Through Improved Fabrication Process Control. Material variability can have far reaching impact on the effectiveness of the design and fabrication process. RD&D is needed to reduce the variability of key monolithic ceramics. Improving process control in particular can decrease the variability and minimize the chance of a worse-than-average defect. RD&D is needed to refine process control capability for fabrication. Significant improvements have already been achieved for some silicon nitride materials (Weibull modulus increased from less than 10 to around 20), providing a model for improving other ceramics and for further improvement of silicon nitride ceramics.

Technology Challenge: Reduced Cost of Manufacturing

Advanced monolithic ceramics such as silicon nitride, silicon carbide, and transformation toughened zirconia have demonstrated superior performance during evaluations in severe applications, yet they were not selected because of cost.

RD&D Priority

Lower-Cost Powders/Precursors. Monolithic ceramics are typically fabricated by compacting a powder or mixture of powders and other precursors and then firing them at high temperature to consolidate the powder into a solid ceramic. Highly refined powders and precursors are typically required that are expensive until large-volume production is reached. Powder suppliers must either charge high prices or run at a loss until enough end-use applications exist for large-volume production.

Developing a U.S.-based supply of advance ceramic powders is an important materials RD&D activity. Currently, U.S. silicon nitride component suppliers are completely dependent on imported powders from Japan and Germany. U.S. companies have relatively little leverage in pricing or availability. Applications of silicon nitride such as bearings and industrial wear-resistant components are growing rapidly. GTE, Dow Chemical, and Ford Motor Company developed high-quality, chemically-derived silicon nitride powders between about 1973 and 1995, but none of these companies are suppliers today.

Large Quantity Scale-up. Scaling up production is a significant step in reducing the cost per part. Implementation of scale up involves high cost and initially a high price to the customer. End users often will not consider the ceramic process until the price-per-part is substantially reduced. *Application development support is needed to accelerate scale-up and cost reduction for high-payoff applications, such as the effort that helped silicon nitride bearings get over the final hurdle and into viable production.*

Increased Automation. Automating a fabrication process can dramatically reduce the costs from labor and increase product yield. Very little automation is integrated into fabrication of advanced structural monolithic ceramics. Ceramic parts must be inspected and measured at multiple points during the process. Automation is difficult and expensive but it can be cost effective. An example is automated manufacturing of ceramic spark plug insulators; approximately three million spark plugs are produced worldwide per day with high yield and high reliability. *RD&D focused on real production requirements is needed to develop the techniques, process equipment, and instrumentation to perform key fabrication steps (including inspection) in an automated or semi-automated mode.* The U.S. dominance in fabrication process technology has eroded in recent years and a focused research effort is needed to be competitive in the global economy.

Decreased Final Machining. Monolithic ceramics typically require diamond grinding to achieve the final shape and dimensions. Grinding operations are sometimes as expensive as all the other manufacturing steps combined. *Research is needed to improve the grinding process, equipment and tooling to decrease costs, to explore and develop alternate material removal methods; and to fabricate ceramics closer to the final dimensions (near-net-shape fabrication) and thereby minimizing the amount of ceramic that must be ground away.*

Lower-Cost Quality Assurance. Quality assurance (QA) of ceramic materials involves in-process and post-process destructive and non-destructive inspections. Many inspection steps at high cost are required to assure that a ceramic component is acceptable for a high-stress structural application. There are many ways to reduce the cost. For example, optimize the process to reduce the number of inspections required. This requires an in-depth understanding of the processing/properties/performance relationships, considerable materials and fabrication RD&D, and property/performance testing feedback. Sometimes, the inspections required can be lowered by a "go/no-go" proof test of the final component. Another way to decrease the cost of QA is to develop lower-cost QA equipment and tests. Advances in the past 10 years in computers, software, and smart sensors offer many opportunities for this approach. *Research is needed to implement strategies for decreasing the costs of QA, including developing automated or semi-automated in-line systems that can make discriminating measurements and judgements quickly and accurately.* This RD&D will need to link with RD&D in materials and processing optimization and component testing.

Rapid Prototyping Integrated into Manufacturing. Tooling and the stages of scale-up of tooling are a significant cost during the transition from prototype fabrication to large-scale manufacturing. Recent advances in rapid prototyping technologies could be used to by-pass some tooling iterations and to produce small quantities of components for end-user evaluation. This could greatly short-cut component development time and cost. *RD&D is needed to demonstrate that rapid prototyping techniques produce components equivalent to those produced by conventional processes, and to integrate rapid prototyping into production-viable processes.*

3. Ceramic Matrix Composites – Challenges and Needs

A ceramic matrix composite (CMC) is a ceramic material that incorporates a reinforcing phase during fabrication. One example of a CMC is mixing particles or whiskers of a ceramic with the matrix ceramic powder and then densifying the mixture using techniques such as sintering or hot pressing. Another example is constructing a preform of long, high-strength ceramic fibers and adding the ceramic matrix by methods such as chemical vapor deposition, sol gel or polymer infiltration, or melt infiltration.

CMCs are being developed to provide an alternative to monolithic ceramics, one with greater toughness that fractures in a non-catastrophic rather than a brittle mode. This has the potential to result in reliable components that end users can use with a level of confidence similar to the one they have for metals. Because CMCs are at a much earlier stage of development than monolithic ceramics, substantial RD&D is needed to realize their full potential, especially those reinforced with continuous fibers. The CMC materials that presently have the best chance of non-brittle failure modes are continuous fiber ceramic composites (CFCCs).

Exhibit 5 lists the key challenges for CMCs (and CFCCs) and the RD&D needed to address these challenges. The challenges and RD&D needs are addressed below. Note: several key CMC challenges are addressed in Section 5 on RD&D needs common to monolithic, composite, and coating ceramics. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 5 Priority RD&D Needs in Ceramic Matrix Composites to Address Key Challenges Faced by Ceramic Manufacturers and End Users

Key Challenges for CMCs	***Priority RD&D Needs to Address the Challenge***
Reduce the cost of precursors	▪ Scale-up/cost reduction of fiber manufacturing ▪ Lower-cost interface materials and deposition processes
Improve understanding of failure modes	▪ Basic scientific understanding of interactions between CMC constituents and application environments ▪ Micro-and macro-mechanics understanding of interactions of CMC with an applied stress or strain
Increase temperature stability to 1200-1500° C	▪ Higher-temperature fibers, matrix materials, and interface coatings ▪ Environmental barrier coatings (EBCs) ▪ Active cooling designs
Manufacturing scale-up and cost reduction	▪ Larger furnace design and construction ▪ Automation/semi-automation of preform fabrication ▪ Low-cost tooling ▪ Near-net-shape fabrication ▪ Low-cost in-process and post-process quality assurance

Technology Challenge: Reduce the Cost of Precursors

Currently, most of the precursor materials for advanced CFCCs are not in full-scale production (i.e., available only as developmental materials). Consequently, prototypes of CFCC components are expensive. Batch-to-batch variation is a problem because manufacturing controls have not been established. As the technologies evolve, the baseline is continually being replaced by "new and improved" versions, which are generally more expensive. RD&D is needed to better understand the issues and reduce the costs of precursors (i.e., fibers and interface coatings).

RD&D Priority

Scale-up/Cost Reduction of Fiber Manufacturing. Non-oxide fibers cost thousands of dollars per pound. Oxide fibers that have been in the marketplace for years sell for hundreds of dollars per pound because the production volume is still small. The price of fiber is a major barrier, especially for industrial CFCC use. *RD&D to reduce the cost of fiber fabrication and to encourage process scale-up will help break down the cost barrier and accelerate CFCC commercialization.*

Lower-Cost Interface Materials and Deposition Processes. Optimization of the interface or interphase layer between the fibers and matrix is critical to producing a viable CFCC material. Currently, the interface layer is deposited by laboratory techniques that are an expensive step in the fabrication process. *RD&D is needed to reduce the cost of existing deposition methods, develop new cost-effective methods of depositing interface layers, and explore continuous deposition methods rather than batch methods.* As with fiber research, these efforts must be closely integrated with material development, database generation, and demonstration of long-term stability in the use environment.

Technology Challenges: Improve Understanding of Failure Modes

The understanding of CFCC failure modes in several application environments has greatly improved in recent years. However, the basic scientific understanding is still inadequate to assure that CFCC component reliability will meet end-user service requirements.

RD&D Priority

Basic Scientific Understanding of Interactions Between CMC Constituents and Application Environments. The toughening mechanisms for CFCCs are different than for polymer matrix composites, so lessons learned from the many years of use of polymer matrix composites are not directly applicable to CFCCs. The major difference is that a strong bond is desired between the fibers and matrix for a polymer matrix composite, while a relatively weak bond is required for CFCCs. For most CFCCs, this weak bond has been achieved through an interface or interphase layer between the fiber and matrix. To provide long life for the overall composite, the interface layer must be thermodynamically stable so it is not degraded by contact with the matrix, fibers, and any chemical species (such as oxygen, water, alkalies) that might diffuse into the composite or enter through cracks.

At present, interface layers are very sensitive to the high-temperature application environments. *Long term RD&D is needed to understand the various degradation mechanisms of CMCs.* Studies during the past 10 years have demonstrated that fibers and matrix materials degrade in application environments, and that changes in chemistry (sometimes subtle) can greatly improve stability. Researchers are beginning to understand the mechanisms and find solutions, but further RD&D is needed.

Micro- and Macro-mechanics Understanding of Interactions of CMC with an Applied Stress or Strain. CFCCs (and other CMCs) respond to an applied stress in an application environment in two ways: at the micro-mechanics level (individual reinforcement/matrix interfaces and at crack tips) and at the macro-mechanics level (over the broad composite architecture or structure). *Before engineers can routinely use analytical design models and life prediction models, basic scientific understanding of both micro-mechanics and macro-mechanics is necessary.* Significant progress has been made in recent years, but continued RD&D is necessary.

Technology Challenge: Increase Temperature Stability to 1200-1500° C

Inadequate stability at high temperature is one of the major deficiencies of current CMCs, especially CFCC materials. This applies to both non-oxide and oxide CFCCs and to each composite constituent: fibers, matrix, interface, and surface coatings. Significant improvements have been achieved in the past 5 years. Some CFCC materials have been demonstrated to survive in severe application environments such as a gas turbine engine for about 2500 hours at temperatures in the 1100-1200° C range. However, they have exhibited significant degradation progressing from the surface inward. Environmental barrier coatings (EBCs) applied to the surface have increased the life to over 5000 hours with favorable projections to around 10,000 hours. However, the applications require lifetimes of 20,000 hours or greater. Other applications require higher temperature capability (i.e., in the range of 1200-1500° C).

RD&D Priority

Higher-Temperature Fibers, Matrix Materials, and Interface Coatings. Non-oxide composites such as those containing silicon carbide are not thermodynamically stable in air or high water-vapor atmospheres at high temperature. Efforts during the past couple years to increase the temperature capability of fiber matrix and interface materials have yielded some improvement in composite stability. Use of oxide EBCs has provided further improvements in stability and increase in life.

CFCCs based on oxide fibers and matrices also show good potential. These oxide systems are more chemically stable in high temperature and combustion environments than non-oxide ceramics. However, present oxide fibers can only be used at temperatures up to 1100° C in structural applications where significant mechanical stresses are present. The fibers are susceptible to creep deformation at high temperature. Also, the interface layers tend to interact with the fibers or matrix, and the matrix tends to change with time at these temperatures. *RD&D is needed to understand the mechanisms and limitations of both non-oxide and oxide systems and to guide development of improved high-temperature fibers, matrix materials, and interface coatings.* New materials chemistries also need to be explored. Most of the U.S. research has been on simple binary materials such as silicon carbide, aluminum oxide, or silicon nitride. In Europe, they have demonstrated some Si-N-B-O and other compositions that appear to have increased stability at high temperature.

Environmental Barrier Coatings (EBCs). Based on research in the past three years, EBCs are now required to obtain an acceptable component life for SiC-SiC CFCC materials in a gas turbine atmosphere above 1100° C, as well as for non-oxide monolithic turbine components. *On-going* *efforts on coating composition, refinement of deposition methods, and on long-term testing in realistic application environments need to be continued and extended to higher temperatures.*

Active Cooling Designs. Emphasis in CMCs has been directed at uncooled designs. However, the use temperature cannot exceed the allowable limit for the uncooled CMC. *Research is needed to build active cooling passages into the composite as a design option.* This has the potential to either increase the life of the composite by reducing the temperature to which it is exposed or to allow the composite to be used in a higher temperature application environment. Active cooling for key high temperature applications should be explored.

Technology Challenge: Manufacturing Scale-up and Cost Reduction

The high price of finished CFCC components is a major barrier to many applications. Reducing the cost of precursors, as discussed earlier, is a key step in cost reduction. Increasing the production volume and the scale of manufacturing would also substantially reduce unit costs.

RD&D Priority

Larger Furnace Design and Construction. Furnaces are required to manufacture fibers, to apply coatings to fibers, and to form the ceramic matrix. The term "larger" refers to whatever is needed to allow scale-up of manufacturing and cost reduction. For fiber manufacture and fiber coating, "larger" means equipment and techniques that can throughput an increased number of strands of fiber per unit time. Although study and RD&D are needed, this probably means establishing continuous processes. For adding matrix to fiber preforms, batch processes are necessary for some processes and continuous processes are necessary for others. *Therefore, "larger" can refer to increased furnace size for batch operations and for RD&D to design, build and test continuous furnaces needed for continuous operations.*

Automation/Semi-automation of Preform Fabrication. CFCCs are fabricated by first laying up a preform of coated fibers and then adding the matrix into the preform. Presently, preforms are usually prepared by labor-intensive hand lay-up in a laboratory or job-shop mode. Significant cost reduction and improved reproducibility are possible by integrating automation or semi-automation into preform processes. *RD&D is needed to focus on equipment and tooling design and on evaluation of the resulting CFCC materials (properties) and components (dimensions, reproducibility, and reliability) with the goal of integrating automation or semi-automation of preform fabrication.* Specific areas of RD&D that could provide large benefits include establishing continuous weaving and prepreg lines, cutting or stamping stations, tooling to reduce the time and labor of lay-up, and automated numerically-controlled filament winding.

Low-cost Tooling. CFCC parts require high-temperature tooling (such as graphite) to support the preform during lay-up and early stages of infiltration and densification of the matrix. This tooling is presently expensive and typically can only be used once. *RD&D is needed to find ways to decrease the cost of the tooling, permit multiple use of the tooling, or eliminate some of the tooling.*

Near-Net-Shape Fabrication. Expensive machining and grinding is currently required to achieve the desired dimensional tolerances and surface smoothness of CFCC (and other CMC) components. *RD&D is needed to explore ways of coming closer to the final component* *requirements during the fabrication process to minimize or eliminate post-process machining or grinding.*

Low-Cost In-process and Post-process Quality Assurance. Quality control inspections and procedures are expensive for CMCs, especially 3D engineered fiber architecture of CFCCs. The major processing defects in CFCC materials are voids or density variations due to inadequate fill of the matrix, irregular fiber distribution, delaminations between composite layers, and cracks. NDE methods such as thermal imaging, ultrasonic scanning, and x-ray radiography (especially CT) have been successful at detecting these types of defects, but are currently labor intensive and expensive. *RD&D is needed to refine NDE techniques so that they can be used in-line for continuous and rapid process control at key stages in the process and post-process.* Achieving this goal will require substantial RD&D in NDE techniques, in equipment development, and in iterations of materials inspection and property evaluation to verify reliability of the NDE equipment and techniques.

4. Ceramic Coating Systems – Challenges and Needs

Ceramic coating systems are defined as an application of ceramic to change in the surface of a substrate to

- Enhance specific desired attributes of the substrate and external environment and/or
- Provide a new function.

Coatings are applied and they may or may not be diffused.

Historically, ceramic coatings were developed to impart special properties such as hardness and corrosion resistance to the surface of metals. The metal carries the structural loads, while the ceramic coating provides wear resistance, corrosion resistance, or heat resistance. Major advances have occurred in recent years in the technology of ceramic coating deposition and in the composition of coatings. Whereas early coatings were painted on and fired, coatings are now applied by several different methods: molten particle deposition, physical vapor deposition (sputtering and e-beam), chemical vapor deposition, and reactive methods. Broader use of ceramic coatings is now possible, especially in processing industries with wear and corrosion concerns. Traditional and specialty ceramic coatings are considered a safe, reliable, and usually cost-effective way to gain the benefits of ceramics without the fear of catastrophic failure.

Ceramic coatings have been used for decades in many applications. End-users are comfortable using coated metal to carry structural loads. Consequently, there are less psychological barriers to ceramic coating use compared to monolithic ceramics or CMCs. Because of the high comfort level with traditional ceramic coatings, end users are often not aware of (or motivated to explore) new technologies or potential improvements that could substantially improve the performance and life of ceramic coatings. New and improved coating techniques such as plasma-enhanced chemical vapor deposition, physical vapor deposition, molten particle deposition techniques, and vapor deposition of diamond have widespread potential.

A new challenge for ceramic coatings has been identified in recent years: use ceramic coatings to protect non-oxide monolithic ceramics and CMCs against oxidation and corrosion. Environmental barrier coatings (EBCs) now appear to be required to achieved long life for key high-temperature applications of advanced silicon nitride based ceramics (e.g., gas turbine engines).

Examples of Ceramic Coating Systems

A high-technology ceramic coating that has become increasingly important in gas turbine engines is zirconium oxide. It is used as a thermal barrier coating and allows engines to run considerably hotter by protecting the underlying metal. This extends the component life, increases engine efficiency, and reduces fuel consumption. Continuing RD&D is needed in this area to improve adhesion, prevent attack on the underlying metal by oxygen and chemical impurities in the engine operating environment, and decrease the thermal conductivity of the coating.

One of the most promising new ceramic coating technologies is vapor deposition of diamond, the hardest and most wear-resistant material available. A thin coating of diamond on high-wear surfaces of industrial equipment could save billions of dollars per year on maintenance and replacement. Continuing RD&D is needed to learn how to deposit diamond on a broader range of substrate metals, especially on mild steel.

Exhibit 6 identifies the key coating challenges that are faced by ceramic engineers and end users. The priority RD&D needs to address each challenge are listed. Note: several key coating challenges are addressed in Section 5 on RD&D needs common to monolithic, composite, and coating ceramics. The challenges and RD&D needs are addressed below. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 6 Priority RD&D Needs in Ceramic Coating Systems to Address Key Challenges Faced by Ceramic Manufacturers and End Users

Key Challenges for Ceramic Coating Systems	*Priority RD&D Needs to Address the Challenge*
Improve coating adhesion to substrate	▪ Improved pre-coating surface treatments ▪ Improved interlayers ▪ Functional gradation
Improve understanding of failure modes and mechanisms	▪ Basic scientific understanding ▪ Micro- and macro-mechanics understanding
Improve coating and system properties	▪ Improved abrasion resistance to10 times better than chromium at half the cost ▪ Develop tribological coatings that require minimal liquid lubrication ▪ Develop low-thermal conductivity thermal barrier coatings

Technology Challenge: Improve Coating Adhesion to the Substrate

The effectiveness and life of a ceramic coating system is often limited by the strength of the coating's bond to the substrate. Improving the control of adhesion and density are essential to innovation in coating processes.

RD&D Priority

Improved Pre-coating Surface Treatments. Pre-coating surface treatments are almost always used to assure that the surface is clean and sometimes textured for improved mechanical adhesion. However, most of these treatments are chemical treatments that have not been updated for many years. Significant improvements are possible in pre-treatments and in the resulting adhesion. *RD&D is needed to systematically explore surface modification processes such as laser, ion beam etching, plasma etching, and ion implantation to determine if significant improvements in adhesion and coating performance can be achieved.*

Improved Interlayers. Some coating systems require interlayers between the substrate and the coating. In some cases, the interlayer has a coefficient of thermal expansion intermediate between the substrate and the coating; this helps to decrease thermal expansion mismatch stresses to acceptable levels. In other cases, the interlayer enhances chemical bonding at the interface or acts as a chemical barrier to decrease diffusion of substances such as oxygen that can degrade the substrate and lead to spalling of the coating. A good example of this latter situation is in the use of zirconium oxide thermal barrier coatings on metal gas turbine engine components. The coatings are porous and the zirconia crystal structure has oxygen vacancies (atom sites where an oxygen ion is missing). Oxygen from the air is able to diffuse through to the metal substrate. An interlayer material is used to form a barrier to the oxygen. Interlayers are the weak member of most coating systems. If the interlayer could be improved, the life and effectiveness of the coating and the system could be substantially improved. *RD&D is needed to increase the basic understanding of the role and mechanisms of interlayers and to develop interlayers that provide increased adhesion and coating life.*

Functional Gradation. The coating and the material to which it is applied often have dramatically different properties such as different thermal expansion coefficients and elastic modulus. This results in stresses that either crack the coating or cause cracks at or near the coating-substrate interface. Furthermore, coatings and substrates can have radically different chemistries and crystal structures and do not readily form a chemical bond. *RD&D is needed to develop functional gradation to provide a zone near the coating-substrate interface with a graded composition (i.e., between the coating and the substrate).* This provides both chemical and mechanical interlinking of the coating and substrate materials and can potentially result in a large increase in adhesion plus reduction in stresses due to thermal expansion mismatch or elastic mismatch.

Technology Challenge: Improve Understanding of Failure Modes and Mechanisms

An important step in improving the performance and life of a material or system is to thoroughly understand the modes and mechanisms of failure. For a coating system these modes and mechanisms involve interaction of the conditions imposed by the specific application environment (stress, atmosphere, temperature, etc.) with the coating system materials. To obtain a reasonable and useful understanding, RD&D must encompass both bench-scale testing and in-service component testing (such as field kits), materials development, material characterization (pre-test, in-test, and post-test observations and selected property measurements), and analytical model development.

RD&D Priority

Identification of Specific Needs. Collaborative effort is needed with end-users to identify applications where coatings either are not as reliable as desired or where increase in life could provide a major benefit.

Failure Modes and Mechanisms Understanding. Sustained RD&D is needed to better understand the thermochemical interactions of the coating, substrate, and interlayer for selected use environments. RD&D is also needed to understand the micromechanics and macromechanics interactions involving residual stress, applied stress, strain tolerance, and tribiological behavior.

Technology Challenge: Improve Coating and System Properties

This broad challenge includes new coating materials development, new and improved coating deposition process development, and improvement in existing coatings and coated components.

RD&D Priority

Improved Abrasion Resistance 10 Times Better Than Chromium at Half the Cost. One promising direction for achieving improved abrasion resistance is to continue RD&D on new materials such as vapor-deposited diamond and diamond-like coatings. These coatings have extremely high hardness and wear resistance. However, their thermal expansion coefficient and elastic modulus are very different from substrate metals and ceramics. *RD&D is needed to find ways to avoid the resulting cracking and spalling due to thermal expansion and elastic mismatch so that the coatings can be used for a wider range of substrates and applications. RD&D are also needed to find ways to apply the coatings at lower temperature onto diverse substrates.*

Develop Tribological Coatings That Require Minimal Liquid Lubrication. Many applications that involve sliding surfaces could benefit from a higher-temperature operation, but liquid lubricants can not survive high temperatures. Other applications could benefit from reducing the amount of liquid lubrication required because of design problems in delivering liquid lubricant to the sliding interface, pollution emitted by degradation or burning of the lubricant, and other factors. In general, ceramic surfaces are less reactive than metal surfaces and are less prone to adhesive wear. Also, ceramics can be polished to a high surface finish that minimizes friction. *RD&D is needed to develop improved tribological coatings that require minimal lubrication, such as with solid lubrication, where a constituent of the ceramic provides self-lubrication as the ceramic slowly wears.*

Develop Low-Thermal Conductivity Thermal Barrier Coatings. Thermal barrier coatings based on zirconium oxide ceramics are standard in aircraft gas turbine engines and are now being integrated into industrial gas turbine engines. The coating allows the engine to operate at much higher temperatures than the metals alone can survive, resulting in substantial improvement in the efficiency and specific power of the engine. Although extensive RD&D has been conducted since the 1970s, significant improvements are possible by increasing the life and reliability of the coated components, improving the adhesion and oxidation resistance, and reducing the thermal conductivity. Further reduction in thermal conductivity, especially with a goal of reaching one-fourth the thermal conductivity of current coatings, is a difficult challenge and will require continued high-priority RD&D.

5. Challenges and Needs Common to Monolithic Ceramics, Ceramic Matrix Composites, and Ceramic Coating Systems

Some challenges in the development of ceramic-based materials for advanced applications are common to monolithic ceramics, CMCs, and ceramic coatings systems. These are listed in Exhibit 7. The challenges and RD&D needs are addressed below. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 7 Challenges and Priority RD&D Needs Common to Monolithic Ceramics, CMCs, and Ceramic Coating Systems

Key Challenges Common to Advanced Ceramics	*Priority RD&D Needs to Address the Challenge*
Long-term testing and validation in application environments	▪ Viable laboratory simulation tests ▪ Long-term monitored field tests
Design and life prediction methods and tools	▪ Improved standards and databases ▪ Design manuals and database handbooks ▪ Data relevant to application needs ▪ Experimental validation of computational models ▪ Integration of design and manufacturing (concurrent design)
Improve Attachment	▪ Low-stress attachment techniques
On-site repair	▪ Patching and other repair technologies
Education and training	▪ Compilation of success stories ▪ Seminars, workshops, and presentations at trade shows and professional society meetings ▪ Improved education/training within the ceramics industry ▪ Study of market sectors to identify high-payoff opportunities; education of end-users to show how the ceramics can provide these payoffs.

Technology Challenge: Long-Term Testing and Validation in Application Environments

End-users are comfortable selecting metal components for an application based upon property data and limited trials but require additional proof for ceramic components. This proof includes extensive study and long-term test results from actual field tests. These efforts are expensive, require long-term commitment by the supplier and the end-user, and often require a couple of design iterations before the component is successful. Even if the potential payoff is very large, time and risk factors often dissuade the end-user from considering a ceramic as a solution. To foster commercialization, stakeholders must work together to achieve a level of field demonstration that ensures end-user confidence when selecting a ceramic.

RD&D Priority

Viable Laboratory Simulation Tests. *A priority RD&D need is designing, constructing, and validating laboratory test facilities that provide adequate simulation of selected application environments.* These facilities need to be integrated into application evaluation efforts, component design efforts, and materials development efforts. The following example illustrates the essential role of simulated tests. In turbine engine studies of monolithic silicon nitride and SiC/SiC CFCC materials, laboratory simulation tests that closely duplicated the application environment were necessary because property tests indicated much longer life than was demonstrated in the engine tests. Engine conditions produced an environment leading to a failure mode that had not been encountered in the laboratory. After the failure mechanism was identified by cutup and evaluation of engine hardware, a laboratory test that better simulated the engine conditions was established. This dramatically accelerated number of tests that could be conducted and the number of controlled variants that could be evaluated, which rapidly improved the life of CFCC materials**.**

Long-Term Monitored Field Tests. *Field testing is needed to identify critical failure modes and mechanisms in candidate ceramic components, guide RD&D to quickly achieve solutions, and build end-user confidence that ceramics can be reliable.* Field test demonstrations involving successful partnerships between ceramic material suppliers, OEMs, end-users, and the government have been essential to the advancement of ceramic materials into critical applications.

Technology Challenge: Design and Life Prediction Methods and Tools

End-users are comfortable designing with metals. They have handbooks filled with data generated with standardized tests and analytical models for both design and life prediction that have been verified through years of use. Similar models, databases and verified experience need to be established so end users will be comfortable designing with ceramic materials.

RD&D Priority

Improved Standards and Databases. American Society for Testing of Materials (ASTM) now has comprehensive test standards for monolithic ceramics and for some characteristics of coatings. Key tests for CMCs are being validated. Developing the database is more challenging because materials are evolving faster than a detailed database can be generated, especially for advanced materials such as silicon nitride and CFCCs. *To improve standards and databases, a systematic effort needs to continue to select key materials for property measurements and to conduct the measurements necessary for material qualification and component design.*

Design Manuals and Database Handbooks. As standards become established, databases generated, and design/life prediction models developed and experimentally verified, user-friendly design manuals and data handbooks need to be compiled. For example, the first edition of MIL Handbook 17 on CMCs needs to be completed and upgraded regularly as CMC technologies evolve. Comparable handbooks need to be prepared for monolithic ceramics and ceramic coatings. User-friendly manuals and handbooks need to be compiled for industrial design engineers.

Data Relevant to Application Needs. Physical, thermal, and mechanical property data are important for initial analytical design and long-term data on the survival of the material under the real application environments (stress, cycles, chemical, etc.) are necessary for life prediction. Property data acquisition needs to be closely linked to exposure of the ceramic materials in real and simulated application environments through a combination of test coupons and cutup of actual components. RD&D is needed to generate data to evaluate the needs in specific applications.

Experimental Validation of Computational Models. *Computational models need to be upgraded as more data are generated and evaluated and the models need to be experimentally validated.* This will foster better applied science and technology understanding that will permit more analytical design and less experimental validation in the future. As a result, end users will be able to select from available ceramics with confidence.

Integration of Design and Manufacturing (Concurrent Design). Historically, advanced ceramic designs have not been integrated with manufacturing considerations. Often a component successfully designed to work in an application was then deemed too expensive to use because of manufacturing difficulties. Manufacturing considerations need to be an integral part of the design process, and materials suppliers need to be a part of the design team. The goal is a component design that can be manufactured at a viable cost. *RD&D is needed to develop concurrent design capability that can be used to evaluate a ceramic-based material for an advanced application.* A longer-term goal is to integrate rapid prototype fabrication technologies into initial prototypes and seamlessly transition these technologies into production manufacturing.

Technology Challenge: Improve Attachment

Ceramics often fail at the point of attachment because of their brittle behavior and inability to redistribute stress away from points of contact. Ceramic coatings are often used so the component can be attached at the underlying metal. The attachment needs are an important consideration during the initial design, but the data needed to do this is inadequate.

RD&D Priority

Low-stress Attachment Techniques. Long-term research is needed to better understand attachment issues so that refined design guidelines can be developed to reduce the stress and help decision-makers select the correct ceramic-based material versus other materials. Additional RD&D is needed to improve the effectiveness of joining technologies that are necessary when components cannot be fabricated as a single piece because of cost, manufacturing considerations, or stress.

Technology Challenge: On-Site Repair

Currently, most ceramic components cannot be repaired on-site. Off-site repairs pose significant costs when components fail.

RD&D Priority

Patching and Other Repair Technologies. Research is needed to determine if on-site repair or patching is feasible and beneficial.

Technology Challenge: Education and Training

Perception of OEMs and end-users that ceramics are not reliable is a major deterrent to broader use of ceramics. Sometimes these perceptions are correct, but in most cases new advanced ceramics can reliably meet the application requirements and greatly increase component life and performance. Increased efforts on education and training are needed to break down the negative perceptions.

Priority

Compilation of Success Stories. Compile written documentation of success stories to illustrate the benefits of advanced ceramics and disseminate them to appropriate OEMs and end-users.

Seminars, Workshops, and Presentations at Trade Shows and Professional Society Meetings. Prepare articles for trade journals that update advanced ceramics capabilities and include the success stories. Provide seminars, workshops, and presentations at trade shows and society meetings. Continue to have a booth at trade shows that focuses on use of advanced materials.

Improved Education/Training within the Ceramics Industry. Establish textbooks and curriculum for a specialization and degree in advanced ceramics engineering. Upgrade the training of engineers to include up-to-date content on advanced ceramic materials to more broadly establish the understanding that advanced ceramics are an option to solving engineering challenges. Establish continuing education for engineers whose applications might benefit from ceramics.

Study of Market Sectors to Identify High-Payoff Opportunities; Education of End-users to Show How the Ceramics Can Provide these Payoffs. OEMs and end-users need more than education. They need to be part of a partnership to analyze potential solutions to their problems. Study contracts to bring the key parties together is an important first step.

Appendix A: Agenda from the Roadmapping Workshop

Creating a Technology Roadmap for Advanced Ceramics – Charting Our Course

Time	Session	Location
	Wednesday, September 22, 1999	
8:00 - 10:00	Registration and Coffee	Concorde Foyer A
10:00 - 12:00	**Plenary Session** 1. *Introduction* by Mr. David Bennett, Chairman of USACA, Dow Corning Corporation 2. *An Overview of Advanced Ceramics Markets* – keynote presentation by Dr. Thomas Abraham, Business Communication, Inc. 3. *Advanced Structural Ceramics Vision 2020* – William H. Werst, Executive Director of USACA 4. *Overview of the Facilitated Process and Instructions* – Jack Eisenhauer, Energetics, Inc.	Concorde A
12:00 – 1:00	Lunch	Atrium
1:00 - 5:00	**Breakout Sessions** ▪ Monolithic Ceramics ▪ Ceramic Composites ▪ Advanced Ceramic Coatings	Clipper Concorde A Fairfax
6:00 - 7:00	Reception	Earhart/Lindbergh
7:00 - 9:00	Dinner	Earhart/Lindbergh
	Thursday, September 23, 1999	
7:00 - 8:00	Continental Breakfast	Atrium
8:00 - 12:00	**Breakout Sessions** – *Continued*	
12:00 - 1:00	Lunch	Atrium
1:00 - 3:00	**Summary Session** Findings of Breakout Sessions and Closing Comments	Concorde A
3:00	Adjourn	

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Appendix C: Detailed Vision for 2020

In 2020, advanced structural ceramics will be a cost-effective, preferred material for industrial, military, aerospace, transportation, consumer product, and other applications. Advanced ceramic visions are presented below for materials, fabrication, design, environment, health and safety, education, and markets. These visions establish ambitious goals for advanced structural ceramics and help identify the RD&D priorities necessary to achieve them.

Materials Vision: A wide variety of ceramic materials are available with unique properties that exceed the performance of alternative materials, meet customer needs, and provide enhanced design options.

- High-purity ***raw materials*** in a wide variety of forms are available at 25 percent below 1999 costs and with ***higher yields***, approaching 100 percent.
- Better ***computational*** materials science- and knowledge-based engineering tools are available to increase prediction accuracy and accelerate development of new, low-cost, multifunctional materials.
- ***Reliability*** exceeds alternative materials.
- ***Standards*** with available underlying test methods are established for all types of advanced ceramics.
- Suppliers provide ***parts that exceed the value*** of alternative materials in terms of cost, performance, and cycle time.
- ***Product life*** is equivalent or superior to alternative materials.
- Materials have environmental resistance and foreign object damage (FOD) tolerance.
- ***Reliable attachment*** approaches are incorporated into design practices.
- ***Temperature capability*** is 400 ° to 500 °C higher than 1999 materials with equal life.
- Design and process advancements provide 100 percent ***predictability and controllability***.
- Time from concept to market is less than 6 months.
- ***Fiber interface coatings and coating processes*** increase density and adhesion and decrease costs.
- ***Composite costs*** are not more than twice that of metals in high-temperature niche applications and equivalent in cost for general applications.
- ***SiC fibers*** are one-tenth of 1999 costs for high-temperature applications and reach 3200 °F.
- Consolidation and raw material improvements double the ***weibul moduli.***

Fabrication Vision: Fabricated parts with advanced monoliths, composites, and coating systems are preferred to alternative materials due to superior cost, performance, cycle time, and yield.

- ***Finished parts*** are produced with yields approaching 100 percent (i.e., less scrap) at 25 percent of 1999 costs and 20 percent of 1999 cycle times.
- ***Prototype and small volume parts*** are routinely produced cost-effectively with a one-week turnaround.
- ***Promising Laboratory*** processes of 1999 are transitioned to full-scale manufacturing.
- ***Batch*** processing is used less as large-scale production increases.
- ***Semicontinuous and continuous*** processes are available for use as appropriate.
- ***Repair and joining*** processes are used to increase yields (i.e., in-service NDE), provide in-service maintenance, and construct large structures.
- Low-energy ***coating processes*** permit the control of density and adhesion.
- ***Part finishing*** is automated, cost-ffective, minimized to keep costs down, and eliminated whenever possible.
- ***Non-destructive evaluation techniques*** for identifying flawed parts in-process are commonplace, utilized at multiple points in the manufacturing process, and generally interactive with automated process controls.

- ***Quality assurance*** is enhanced by traceability and eliminating steps.
- ***Dimensional and surface finishing control*** eliminates defects and post-process inspection.
- Pre-forming and part consolidation are highly automated, efficient, and near-net shape.
- Coating equipment and coating process design tools are easy to use and available with low capital and operational costs.
- ***Remanufacturing*** is used to repair and refurbish parts.
- The use of ***semi-skilled labor*** reduces labor costs.
- ***Ceramic supplier base*** is strengthened and expanded by consolidation, integration, and alliances.

Design Vision: Advanced ceramics are seen as viable alternatives to traditional materials in diverse applications. Products are designed with ceramic materials from the start, not just as replacements or repairs.

- ***Design tools*** are readily available to design engineers, enabling efficient incorporation of advanced ceramics in machines and devices. The engineers, in turn, are confident in the end-use performance of these systems.
- ***Standards*** exist for commonly used advanced ceramics, and their properties are listed in design handbooks and computer-aided design tools.

Environment, Health, and Safety Vision: Advanced ceramics are viewed as energy-efficient, safe, environmentally benign, and clean and exceed environmental and energy efficiency standards.

- ***Ceramic plants*** are safe, clean, energy-efficient, and environmentally benign.
- ***Hazardous chemical*** use is reduced by 75 percent.
- ***Emissions*** from ceramic fabrication processes are reduced by 90 percent versus the 1999 average.
- ***Worker safety*** is maximized and the workplace environment is healthy and clean, indicated by no OSHA incidents.
- Parts ***operate safely*** in commercial applications.
- Ceramic parts make a significant contribution to helping industry and other consumers achieve their ***energy-efficiency*** *and* ***emissions-reductions*** goals (e.g., in turbine and internal combustion engines and in industries such as aluminium, glass, and semiconductors).
- After-market ***disassembly and recycling*** services differentiate ceramic suppliers.

Education: Advanced ceramics are widely used in part and product design due to effective education of teachers, workers, customers, designers, government, and political leaders. Everyone understands that ceramic materials improve performance, reduce energy consumption, and improve reliability of finished products.

- ***Courses*** are routinely taught in engineering materials classes such that all graduating materials and mechanical engineers are confident designing systems incorporating ceramic materials.
- Educational programs exist to ***train industry workers*** in the proper techniques for fabricating and evaluating components.
- Programs to ***educate existing engineers*** on designing with advanced ceramics are readily available in a variety of modern media, including Internet, DVD, classroom, virtual reality, and video classrooms.
- Formal training programs exist to ***educate customers***.

Markets: Advanced ceramics are the preferred material for applications requiring high-temperature resistance, corrosion resistance, wear resistance, and light weight. Marketing efforts will focus on new and/or expanded applications in the following areas:

- ***Power generation and fuel cells***
- ***Turbine engines*** (hot and wear zones)
- ***Aerospace and military*** (civilian and military structural parts and propulsion systems)
- ***Industrial process equipment*** (heat exchangers, radiant burners, furnace fans, hot fixtures)
- ***Sensors and shields*** (coatings, sleeves, and piezoelectric devices to measure process temperatures, pressures, and other critical parameters)
- ***Filtration and cleanup devices*** for harsh environments (hot gas filters, catalytic converters)
- ***Automotive applications*** including high-performance and hybrid propulsion vehicles (catalytic converters, spark plugs, sensors, wear sleeves, thermal barrier coatings, and flywheel engines/brakes)
- ***Large internal combustion engines*** (valves, followers, bearings, sleeves)
- ***Heavy equipment*** (agriculture and mining)
- ***Biomedical***
- ***Cutting tools***
- ***Structural electronics***
- ***Micromachines***
- ***Consumer-based markets***
- ***Paper***
- ***Aluminum***
- ***Mining***

Appendix D: Workshop Results – RD&D Needs for Monolithic Ceramics

A comprehensive list of RD&D needs for monolithic ceramics is presented in Exhibit 8. The RD&D areas – materials development, materials database, design and life prediction, non-destructive evaluation, fabrication optimization, and demonstration – are discussed below. Improving cost-effectiveness, while not always stated, is a need in each area.

Materials Development
The RD&D needed to improve the material properties of monolithic ceramics include efforts to: improve the understanding of material characteristics versus application failure modes; increase resistance to fracture (higher toughness, strength, resistance to impact and contact stress); increase resistance to wear and corrosion; improve tribology, develop higher temperature capabilities in application environments; and increase material reliability.

Materials Database
Adequate monolithic ceramic property data, necessary for designing ceramic components for advanced structural applications, is often unavailable. Handbooks comparable to those for metals do not exist, and often test methods and standards are deficient. RD&D is needed to establish a design database comparable to that of metals. This includes procedures for affordable data generation.

Design and Life Prediction
As computers become more powerful, they could aid in the faster, more efficient introduction of advanced materials into structural applications through the use of analytical design tools, rather than through “make and break” iterations. Design and life prediction methods and models need to be developed and verified and these user-friendly hardware and software tools made available to materials suppliers, OEMs, and end users.

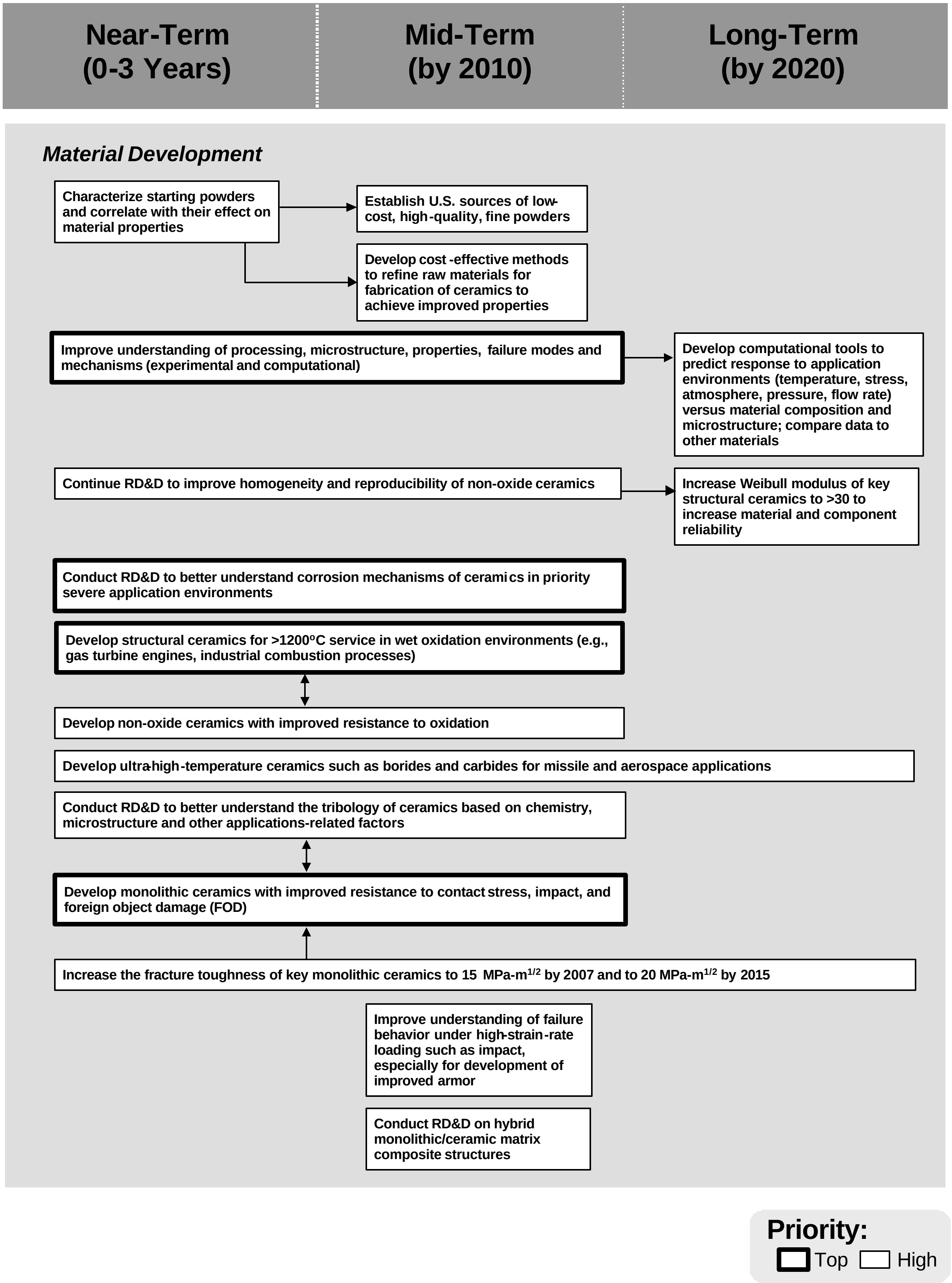
Non-destructive Evaluation
Monolithic ceramics fracture when an applied mechanical or thermal stress concentrates at a tiny defect inside the microstructure of the ceramic. For highly stressed structural applications, defects that lead to fracture can be tiny, as small as 50 micrometers (0.002 inch). Small defects are difficult to detect by non-destructive evaluation techniques, especially by low-cost techniques. Research efforts need to expand to develop cost-effective NDE techniques. The long-range goal is to establish NDE techniques that decrease inspection costs to 5 percent of the total manufacturing cost; currently, inspection costs can often be more than 20 percent. Since NDE is an integral part of the fabrication/manufacturing process, additional NDE RD&D needs are addressed in the Fabrication section below.

Fabrication Optimization
The nature and quality of the monolithic ceramic fabrication process determines key properties, material reliability, and shapes that can be produced. Thus, there is substantial overlap of fabrication research needs with needs in other areas. RD&D must continue to improve starting materials (powders and other precursors), as well as refine each step in the fabrication process. This includes incorporating sensors and other NDE tools to ensure repeatability of each process step in order to yield consistent, reliable monolithic ceramic parts. Monolithic ceramics such as silicon nitride already offer significant benefits but at a cost that is too high for many applications. RD&D will help decrease the cost of precursors, reduce the cost and/or amount of machining and NDE required, integrate rapid prototyping into manufacturing, increase automation, and scale up manufacturing operations.

Demonstrations

In general, laboratory testing does not adequately simulate real-world application environments and conditions. Field tests have dramatically demonstrated the importance of testing actual components in real application environments in order to identify in-use failure modes and mechanisms, as well as guide the RD&D addressing material and design deficiencies.

Exhibit 8 Monolithic Ceramics RD&D Needs



Near-Term (0-3 Years)

Mid-Term (by 2010)

Long-Term (by 2020)

Material Development

Characterize starting powders and correlate with their effect on material properties

Establish U.S. sources of low-cost, high-quality, fine powders

Develop cost-effective methods to refine raw materials for fabrication of ceramics to achieve improved properties

Improve understanding of processing, microstructure, properties, failure modes and mechanisms (experimental and computational)

Develop computational tools to predict response to application environments (temperature, stress, atmosphere, pressure, flow rate) versus material composition and microstructure; compare data to other materials

Continue RD&D to improve homogeneity and reproducibility of non-oxide ceramics

Increase Weibull modulus of key structural ceramics to >30 to increase material and component reliability

Conduct RD&D to better understand corrosion mechanisms of ceramics in priority severe application environments

Develop structural ceramics for >1200°C service in wet oxidation environments (e.g., gas turbine engines, industrial combustion processes)

Develop non-oxide ceramics with improved resistance to oxidation

Develop ultra-high-temperature ceramics such as borides and carbides for missile and aerospace applications

Conduct RD&D to better understand the tribology of ceramics based on chemistry, microstructure and other applications-related factors

Develop monolithic ceramics with improved resistance to contact stress, impact, and foreign object damage (FOD)

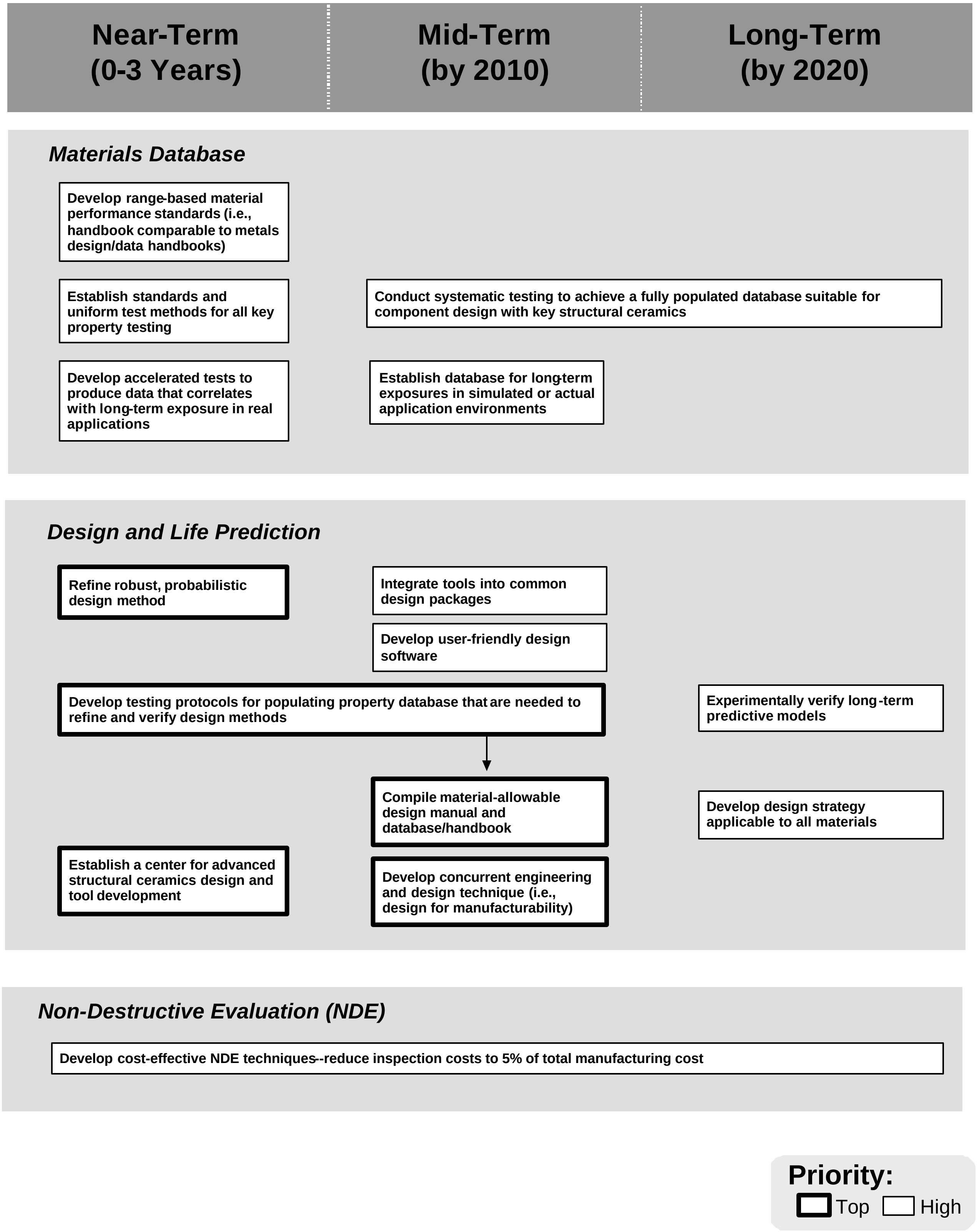
Increase the fracture toughness of key monolithic ceramics to 15 MPa-m$^{1/2}$ by 2007 and to 20 MPa-m$^{1/2}$ by 2015

Improve understanding of failure behavior under high-strain-rate loading such as impact, especially for development of improved armor

Conduct RD&D on hybrid monolithic/ceramic matrix composite structures

Priority:
Top High

Exhibit 8 Monolithic Ceramics RD&D Needs *(continued)*



Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)

Materials Database

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)
Develop range-based material performance standards (i.e., handbook comparable to metals design/data handbooks)		
Establish standards and uniform test methods for all key property testing	Conduct systematic testing to achieve a fully populated database suitable for component design with key structural ceramics	
Develop accelerated tests to produce data that correlates with long-term exposure in real applications	Establish database for long-term exposures in simulated or actual application environments	

Design and Life Prediction

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)
Refine robust, probabilistic design method	Integrate tools into common design packages Develop user-friendly design software	
Develop testing protocols for populating property database that are needed to refine and verify design methods		Experimentally verify long-term predictive models
Establish a center for advanced structural ceramics design and tool development	Compile material-allowable design manual and database/handbook Develop concurrent engineering and design technique (i.e., design for manufacturability)	Develop design strategy applicable to all materials

Non-Destructive Evaluation (NDE)

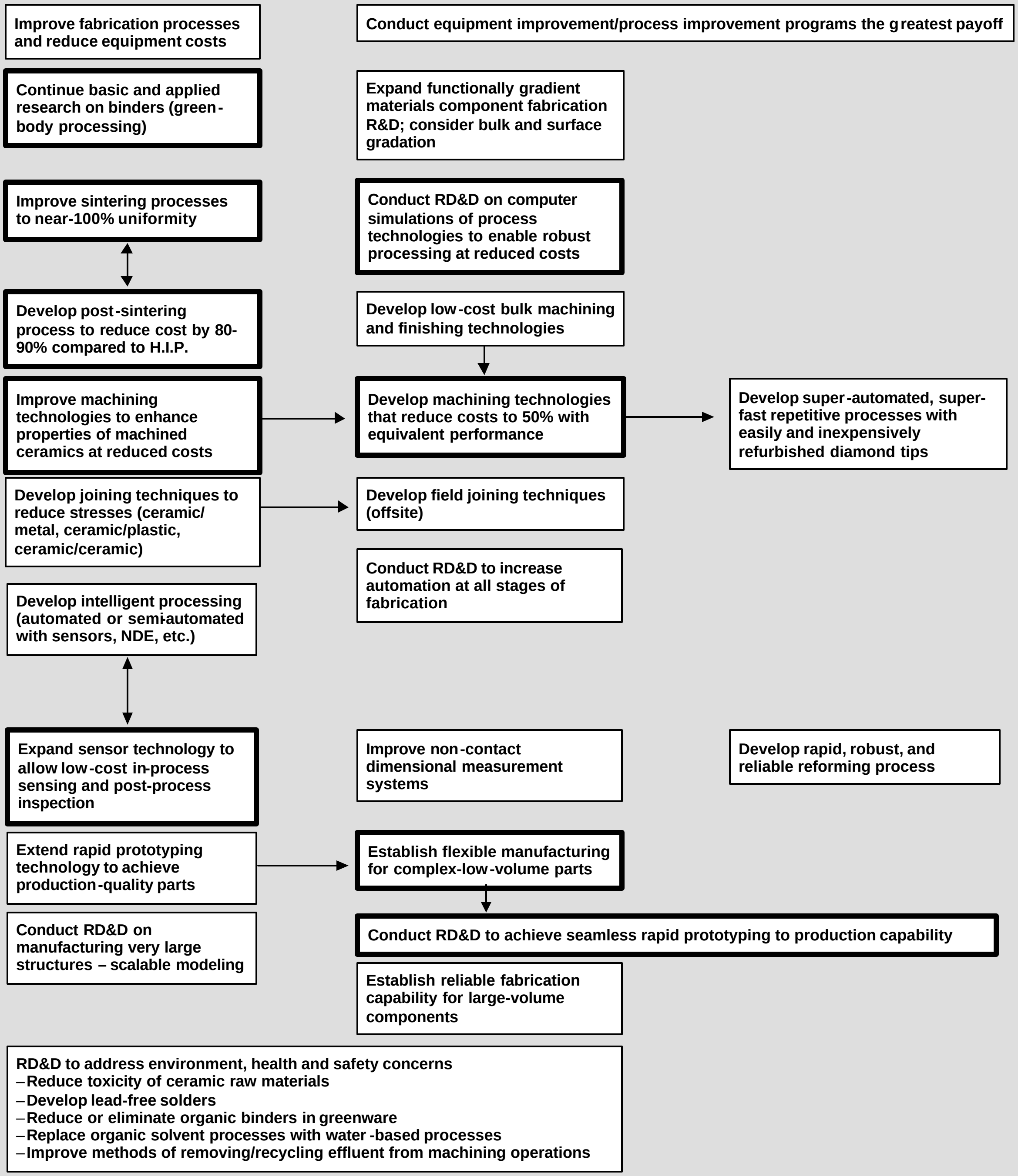
Develop cost-effective NDE techniques--reduce inspection costs to 5% of total manufacturing cost

Priority:
▣ Top ☐ High

Exhibit 8 Monolithic Ceramics RD&D Needs *(continued)*

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)

Fabrication Process Optimization



Improve fabrication processes and reduce equipment costs

Conduct equipment improvement/process improvement programs the greatest payoff

Continue basic and applied research on binders (green-body processing)

Expand functionally gradient materials component fabrication R&D; consider bulk and surface gradation

Improve sintering processes to near-100% uniformity

Conduct RD&D on computer simulations of process technologies to enable robust processing at reduced costs

Develop post-sintering process to reduce cost by 80-90% compared to H.I.P.

Develop low-cost bulk machining and finishing technologies

Improve machining technologies to enhance properties of machined ceramics at reduced costs

Develop machining technologies that reduce costs to 50% with equivalent performance

Develop super-automated, super-fast repetitive processes with easily and inexpensively refurbished diamond tips

Develop joining techniques to reduce stresses (ceramic/metal, ceramic/plastic, ceramic/ceramic)

Develop field joining techniques (offsite)

Conduct RD&D to increase automation at all stages of fabrication

Develop intelligent processing (automated or semi-automated with sensors, NDE, etc.)

Expand sensor technology to allow low-cost in-process sensing and post-process inspection

Improve non-contact dimensional measurement systems

Develop rapid, robust, and reliable reforming process

Extend rapid prototyping technology to achieve production-quality parts

Establish flexible manufacturing for complex-low-volume parts

Conduct RD&D on manufacturing very large structures – scalable modeling

Conduct RD&D to achieve seamless rapid prototyping to production capability

Establish reliable fabrication capability for large-volume components

RD&D to address environment, health and safety concerns
- Reduce toxicity of ceramic raw materials
- Develop lead-free solders
- Reduce or eliminate organic binders in greenware
- Replace organic solvent processes with water-based processes
- Improve methods of removing/recycling effluent from machining operations

Exhibit 8 Monolithic Ceramics RD&D Needs *(continued)*

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)
Demonstration		
Develop application-specific testing protocols that includes extensive field testing to bolster end-user confidence in monolithic ceramics and to encourage suppliers to fabricate enough parts to guide cost reduction efforts		

Priority:
▣ Top □ High

Appendix E: Workshop Results – RD&D Needs for Ceramic Matrix Composites

A comprehensive list of RD&D needs for CMCs is presented in Exhibit 9. The key RD&D areas – materials RD&D, materials database, design and life prediction, non-destructive evaluation, fabrication, and demonstration – are discussed below. Improving cost-effectiveness, while not always stated, is a need in each area.

Materials Development

A continuous fiber composite ceramic (CFCC) is a complex CMC material consisting of high-strength ceramic fibers in a ceramic matrix, an interface coating between the fibers and matrix, and often a ceramic coating to seal the surface of the composite from degradation. Because the technology is still in its early stages, RD&D is needed to gain a scientific understanding of the interrelationship of the fibers, matrix and coatings to each other, to properties, and to interaction with application environments, as well as to explore failure modes and mechanisms, and to improve/optimize the CMC materials. There is also a priority need to increase the high-temperature capability of CMC materials. Current CMC materials are showing resiliance at temperatures of up to 1100-1200^o C, but longer life at these and even higher temperatures is necessary for many key applications.

Materials Database

The database for CMC materials is small compared to that of metals or even monolithic ceramics. Substantial RD&D is needed to establish standardized tests and to create and analyze a database suitable for supporting material development and component design. Because CMCs are especially sensitive to application environments, property measurements must be conducted either in the application environment or a close simulation. Obtaining this data will present a major challenge.

Design and Life Prediction

Ceramic matrix composites are highly directional structures that require a special design and life prediction methodology. Existing models for polymer matrix composites provide a starting point but require substantial modification because of the different failure modes and mechanisms of CMCs. Before reliable design and life prediction models can be established, extensive CMC fabrication and testing must be conducted to gain a fundamental scientific understanding of factors such as micromechanics and macromechanics of interaction of the composite with an applied stress and thermochemical interactions with key application environments. Thus, there must be close coordination between efforts to establish models and other efforts on CMC materials development, fabrication development, database generation, and application demonstrations.

Non-Destructive Evaluation

NDE techniques are needed for in-line process control, for post-process inspection (especially to detect insipient failure and remaining life), and for rapid or in-line inspection of components in application service.

Fabrication Optimization

CFCCs are important because of their potential high reliability and ability to avoid catastrophic failures. RD&D needs include: refinement/reproducibility of the fabrication process (e.g., NDE for quality assurance); cost reduction of both starting materials (especially fibers) and each step in the fabrication process; and scale-up of key fabrication processes to a capability suitable for meeting the application needs of industry and other sectors. RD&D is needed to focus on fabrication scale-up and cost reduction as well as demonstration of the resulting CFCC components in substantial field testing.

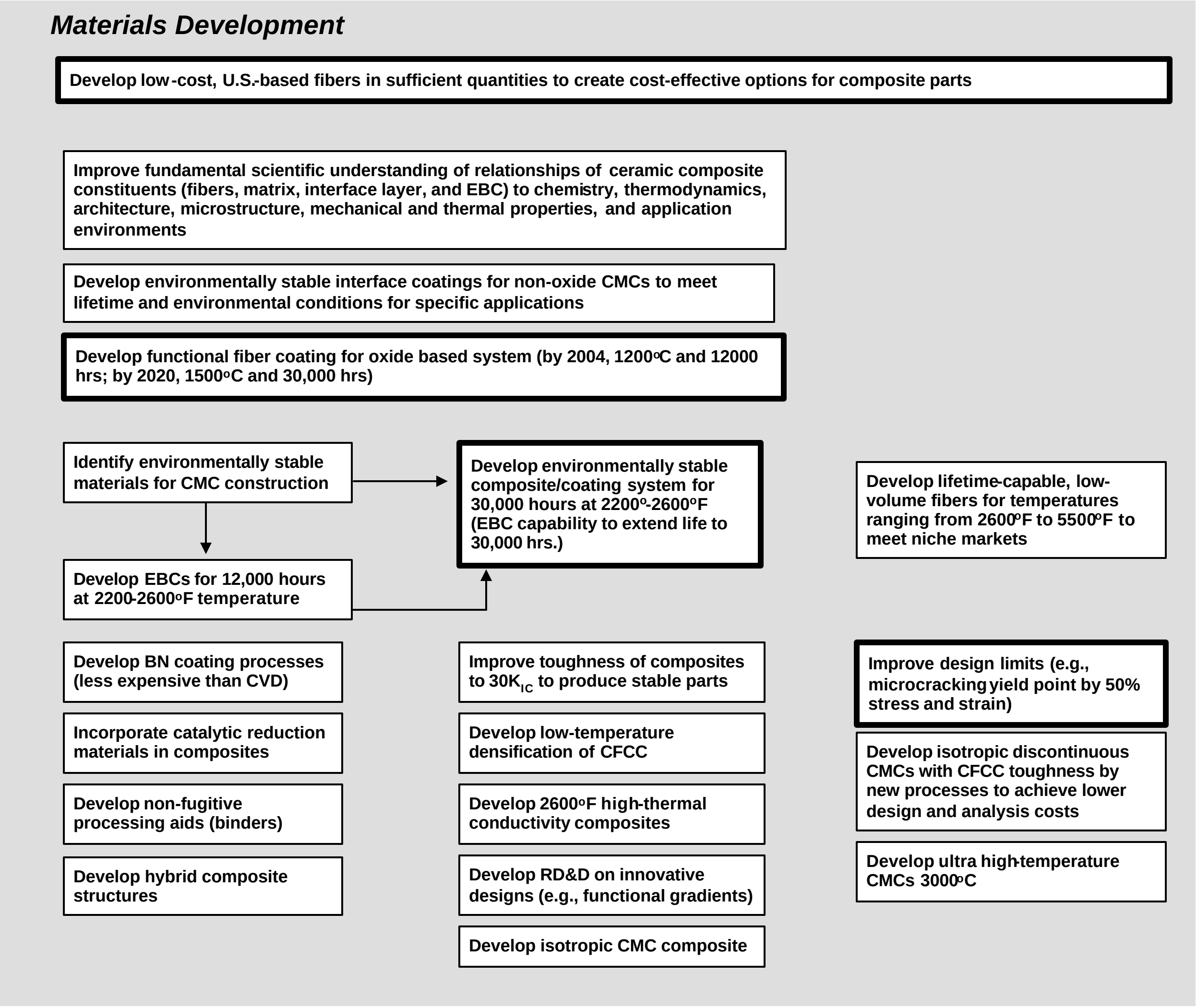
Demonstrations

Demonstration programs are important for CMCs for several reasons. First, CMCs have not existed long enough to establish an adequate success base to encourage OEMs and end users to select them for an application. Demonstration programs that subsidize design and procurement of the CMC components and their installation into equipment are often the best way to encourage OEMs or end users to consider such a new material. Second, the current prototype level of CMC fabrication capability results in high cost per part, another barrier to OEM or end user willingness to consider CMCs. Third, the early stage of technology development requires careful monitoring of prototype parts before, during and after testing, thus creating a need for special programmatic procedures and instrumentation.

Prior efforts have verified that testing CMC materials in real environments is critical. Demonstration programs conducted in actual equipment at a field test site or at a company test facility provide the best feedback on both design and material issues for CMCs. However, since most applications demand tens of thousands of hours of life, achieving lifetime data takes a long time and requires multiple test sites. An additional need is to develop laboratory simulation tests that correlate with long-term site tests, especially accelerated simulation tests.

Exhibit 9 Ceramic Matrix Composites RD&D Needs

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)



Materials Development

Develop low-cost, U.S.-based fibers in sufficient quantities to create cost-effective options for composite parts

Improve fundamental scientific understanding of relationships of ceramic composite constituents (fibers, matrix, interface layer, and EBC) to chemistry, thermodynamics, architecture, microstructure, mechanical and thermal properties, and application environments

Develop environmentally stable interface coatings for non-oxide CMCs to meet lifetime and environmental conditions for specific applications

Develop functional fiber coating for oxide based system (by 2004, 1200°C and 12000 hrs; by 2020, 1500°C and 30,000 hrs)

Identify environmentally stable materials for CMC construction

Develop EBCs for 12,000 hours at 2200-2600°F temperature

Develop environmentally stable composite/coating system for 30,000 hours at 2200°-2600°F (EBC capability to extend life to 30,000 hrs.)

Develop lifetime-capable, low-volume fibers for temperatures ranging from 2600°F to 5500°F to meet niche markets

Develop BN coating processes (less expensive than CVD)

Incorporate catalytic reduction materials in composites

Develop non-fugitive processing aids (binders)

Develop hybrid composite structures

Improve toughness of composites to $30K_{IC}$ to produce stable parts

Develop low-temperature densification of CFCC

Develop 2600°F high-thermal conductivity composites

Develop RD&D on innovative designs (e.g., functional gradients)

Develop isotropic CMC composite

Improve design limits (e.g., microcracking yield point by 50% stress and strain)

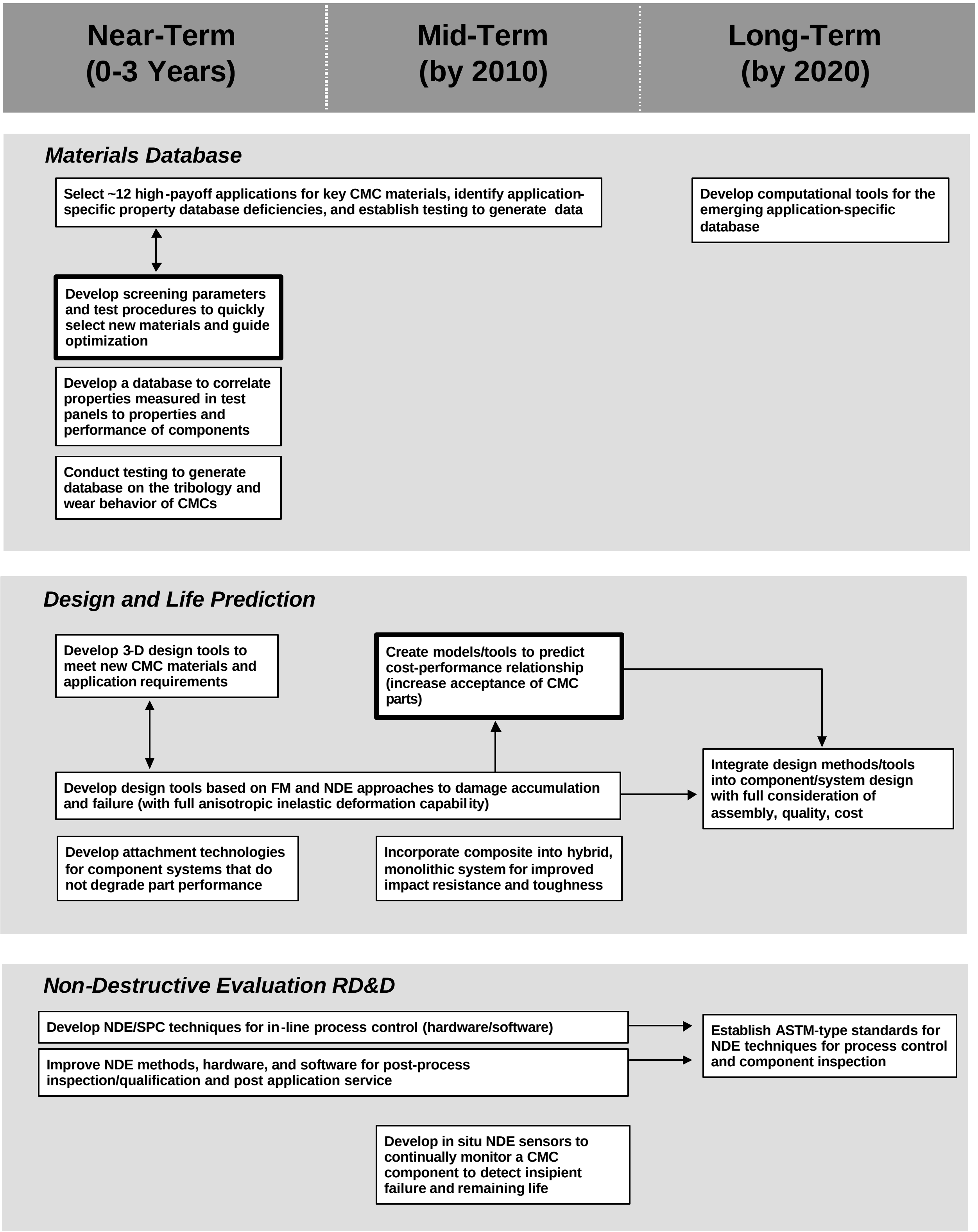
Develop isotropic discontinuous CMCs with CFCC toughness by new processes to achieve lower design and analysis costs

Develop ultra high-temperature CMCs 3000°C

Priority:

▣ Top ☐ High

Exhibit 9 Ceramic Matrix Composites RD&D Needs *(continued)*



Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)

Materials Database

Select ~12 high-payoff applications for key CMC materials, identify application-specific property database deficiencies, and establish testing to generate data

Develop screening parameters and test procedures to quickly select new materials and guide optimization

Develop a database to correlate properties measured in test panels to properties and performance of components

Conduct testing to generate database on the tribology and wear behavior of CMCs

Develop computational tools for the emerging application-specific database

Design and Life Prediction

Develop 3-D design tools to meet new CMC materials and application requirements

Create models/tools to predict cost-performance relationship (increase acceptance of CMC parts)

Develop design tools based on FM and NDE approaches to damage accumulation and failure (with full anisotropic inelastic deformation capability)

Integrate design methods/tools into component/system design with full consideration of assembly, quality, cost

Develop attachment technologies for component systems that do not degrade part performance

Incorporate composite into hybrid, monolithic system for improved impact resistance and toughness

Non-Destructive Evaluation RD&D

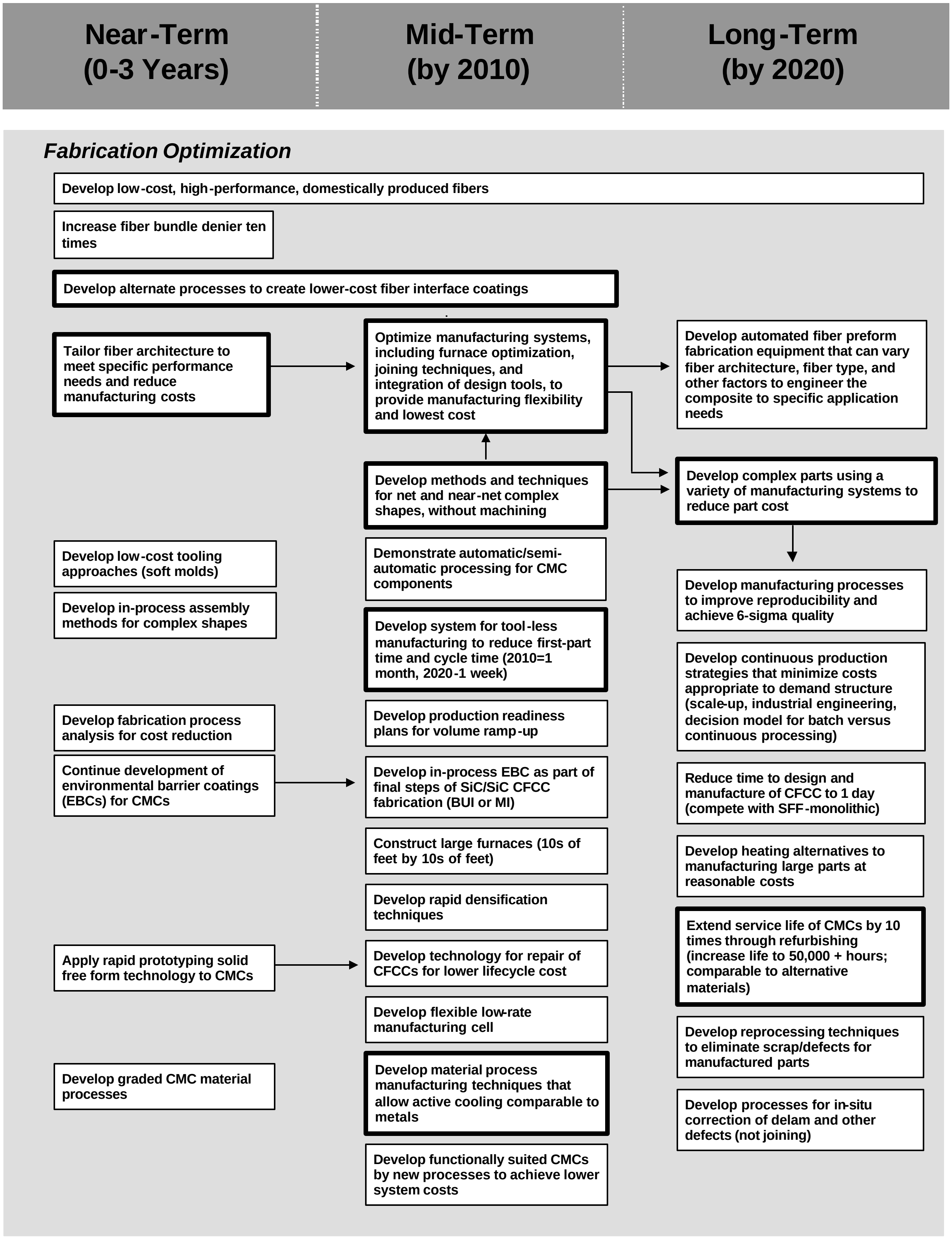
Develop NDE/SPC techniques for in-line process control (hardware/software)

Improve NDE methods, hardware, and software for post-process inspection/qualification and post application service

Establish ASTM-type standards for NDE techniques for process control and component inspection

Develop in situ NDE sensors to continually monitor a CMC component to detect insipient failure and remaining life

Exhibit 9. Ceramic Matrix Composites RD&D Needs *(continued)*



Near-Term (0-3 Years) | **Mid-Term (by 2010)** | **Long-Term (by 2020)**

Fabrication Optimization

Develop low-cost, high-performance, domestically produced fibers

Increase fiber bundle denier ten times

Develop alternate processes to create lower-cost fiber interface coatings

Near-Term (0-3 Years)

- Tailor fiber architecture to meet specific performance needs and reduce manufacturing costs
- Develop low-cost tooling approaches (soft molds)
- Develop in-process assembly methods for complex shapes
- Develop fabrication process analysis for cost reduction
- Continue development of environmental barrier coatings (EBCs) for CMCs
- Apply rapid prototyping solid free form technology to CMCs
- Develop graded CMC material processes

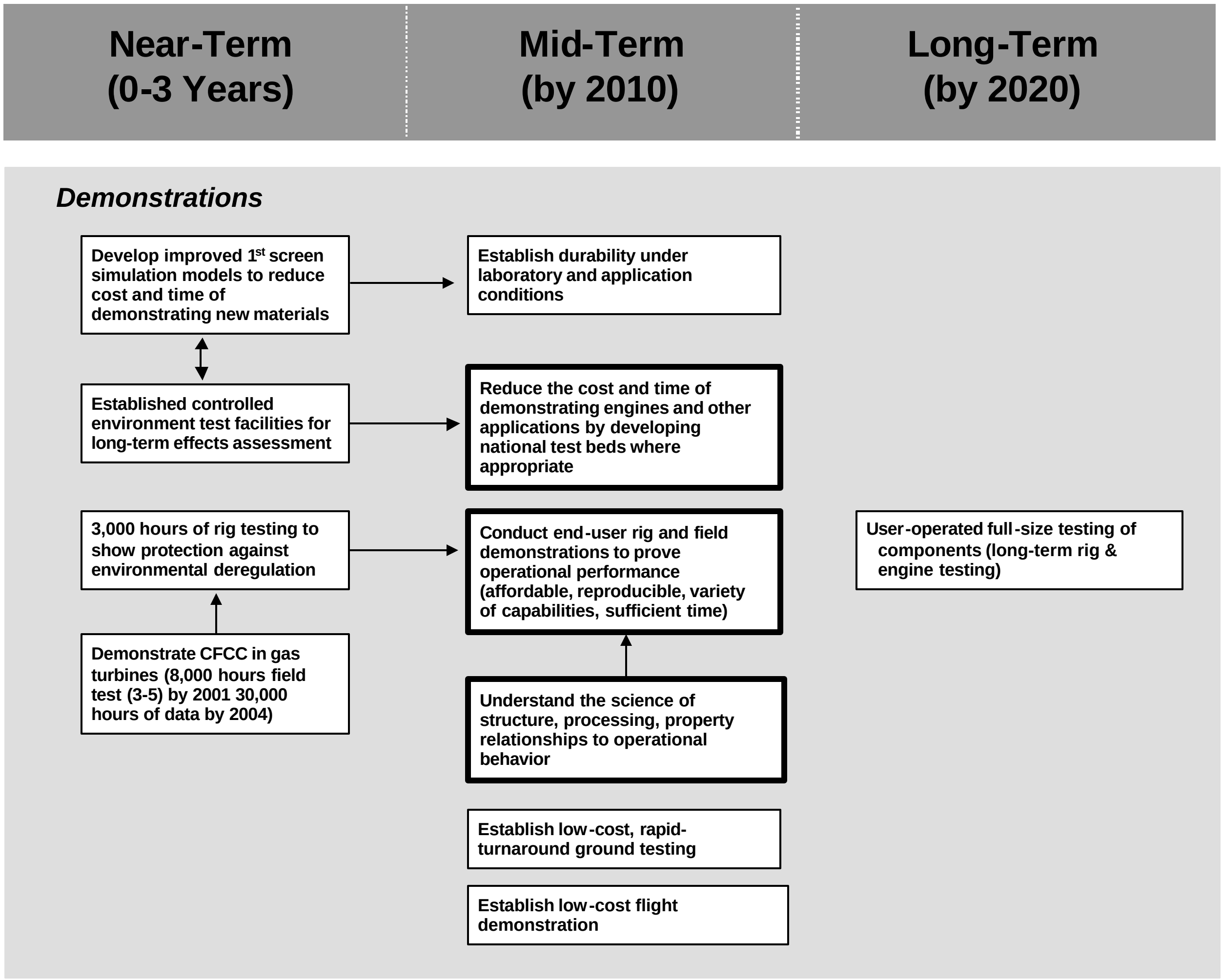
Mid-Term (by 2010)

- Optimize manufacturing systems, including furnace optimization, joining techniques, and integration of design tools, to provide manufacturing flexibility and lowest cost
- Develop methods and techniques for net and near-net complex shapes, without machining
- Demonstrate automatic/semi-automatic processing for CMC components
- Develop system for tool-less manufacturing to reduce first-part time and cycle time (2010=1 month, 2020-1 week)
- Develop production readiness plans for volume ramp-up
- Develop in-process EBC as part of final steps of SiC/SiC CFCC fabrication (BUI or MI)
- Construct large furnaces (10s of feet by 10s of feet)
- Develop rapid densification techniques
- Develop technology for repair of CFCCs for lower lifecycle cost
- Develop flexible low-rate manufacturing cell
- Develop material process manufacturing techniques that allow active cooling comparable to metals
- Develop functionally suited CMCs by new processes to achieve lower system costs

Long-Term (by 2020)

- Develop automated fiber preform fabrication equipment that can vary fiber architecture, fiber type, and other factors to engineer the composite to specific application needs
- Develop complex parts using a variety of manufacturing systems to reduce part cost
- Develop manufacturing processes to improve reproducibility and achieve 6-sigma quality
- Develop continuous production strategies that minimize costs appropriate to demand structure (scale-up, industrial engineering, decision model for batch versus continuous processing)
- Reduce time to design and manufacture of CFCC to 1 day (compete with SFF-monolithic)
- Develop heating alternatives to manufacturing large parts at reasonable costs
- Extend service life of CMCs by 10 times through refurbishing (increase life to 50,000 + hours; comparable to alternative materials)
- Develop reprocessing techniques to eliminate scrap/defects for manufactured parts
- Develop processes for in-situ correction of delam and other defects (not joining)

Exhibit 9 Ceramic Matrix Composites RD&D Needs *(continued)*



Near-Term (0-3 Years)

Mid-Term (by 2010)

Long-Term (by 2020)

Demonstrations

Near-Term:

- Develop improved 1st screen simulation models to reduce cost and time of demonstrating new materials
- Established controlled environment test facilities for long-term effects assessment
- 3,000 hours of rig testing to show protection against environmental deregulation
- Demonstrate CFCC in gas turbines (8,000 hours field test (3-5) by 2001 30,000 hours of data by 2004)

Mid-Term:

- Establish durability under laboratory and application conditions
- Reduce the cost and time of demonstrating engines and other applications by developing national test beds where appropriate
- Conduct end-user rig and field demonstrations to prove operational performance (affordable, reproducible, variety of capabilities, sufficient time)
- Understand the science of structure, processing, property relationships to operational behavior
- Establish low-cost, rapid-turnaround ground testing
- Establish low-cost flight demonstration

Long-Term:

- User-operated full-size testing of components (long-term rig & engine testing)

Appendix F: Workshop Results – RD&D Needs for Ceramic Coating Systems

A comprehensive list of RD&D needs for ceramic coating systems is presented in Exhibit 10. The key RD&D areas – materials development, materials database, design and life prediction, non-destructive evaluation, fabrication optimization, and demonstration – are discussed below. Improving cost-effectiveness, while not always stated, is also a need in each area.

Materials Development

The priority RD&D needs for materials include improving scientific understanding of coating attributes versus coating performance in applications, increasing coating adhesion, developing ceramic coating systems with superior abrasion resistance and tribology characteristics, developing coating systems with improved corrosion resistance and temperature capability, and increasing the high-temperature capability and reducing the thermal conductivity of thermal barrier coatings.

Coating Systems Database

In order to choose whether to use a coating, monolithic ceramic, or CMC, an OEM or end user needs a suitable database to consult. RD&D is needed to establish a coating systems database. RD&D is also needed to develop standard test methods for coatings that provide information on application performance in applications as well as help to establish a basic scientific understanding of composition/processing/properties/ performance relationships. The ultimate goal is to develop an accessible database that can be readily and easily used for material selection and component design.

Design and Life Prediction

Considerable research has been conducted in recent years to develop analytical design and life prediction methods for monolithic ceramics and CMCs, yet little has been done for ceramic coatings. As the use of thermal barrier, environmental barrier, and wear-resistant coatings expands to meet increasingly severe application conditions or to extend component life in existing applications, efforts to establish better design and life prediction capabilities must be stepped up. Specifically, models based on first principles and measurable properties need to be developed that correlate with performance.

Non-Destructive Evaluation

Quality assurance of coatings presents a variety of challenges, including strength and reliability of adhesion, uniformity of thickness, microstructure features such as porosity and grain size, and the general properties of the coating. Given the advances that have occurred in recent years in instrumentation and NDE, NDE should be able to be integrated into the coating process to continuously monitor these issues and ensure consistent coating quality.

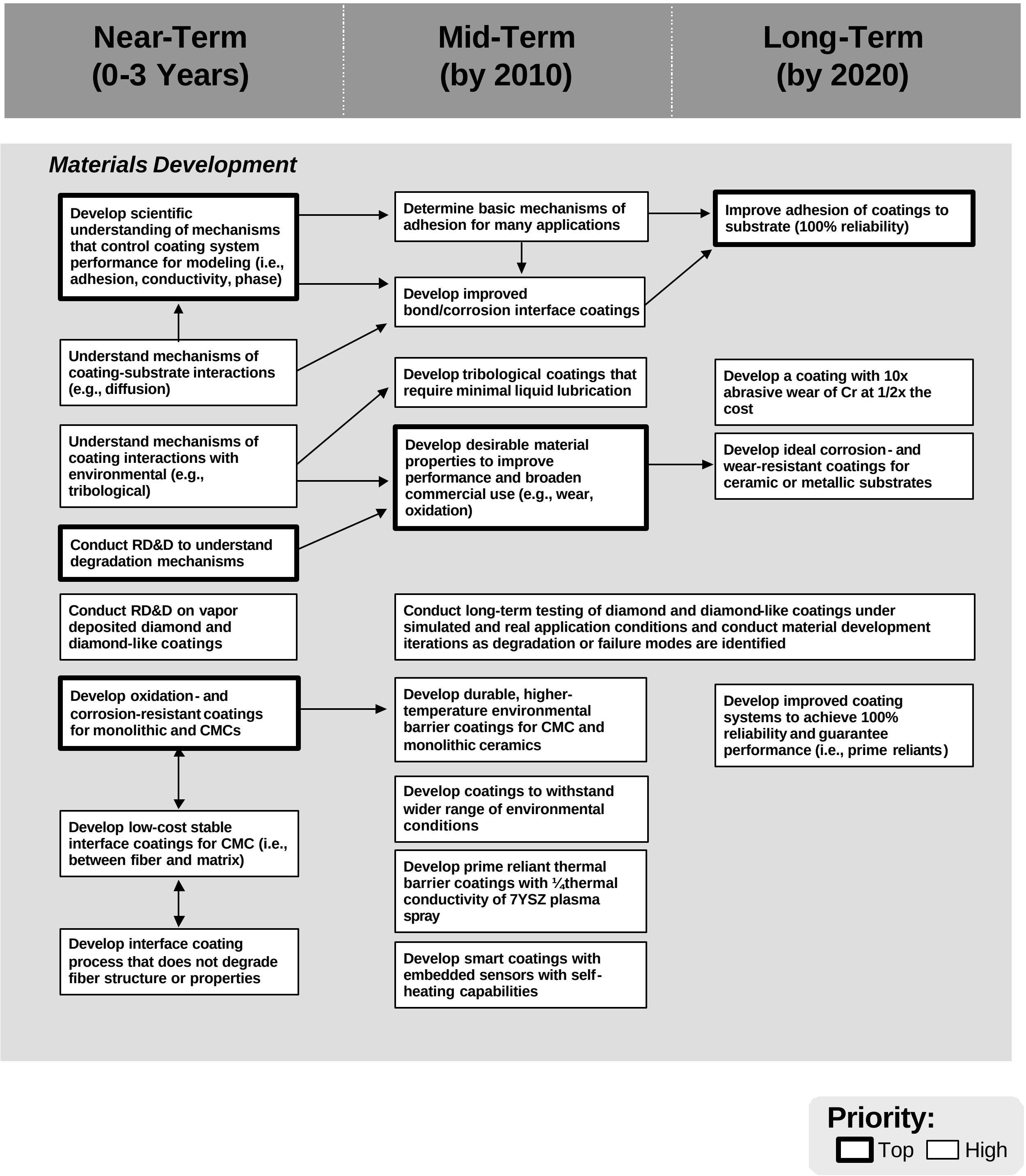
Fabrication Optimization

RD&D is needed to improve coating system fabrication. The goals are to increase coating quality and reproducibility, and integrate modeling and on-line NDE into the fabrication process, while ultimately decreasing cost by 40 to75 percent (depending on the specific coating process). Achieving these goals will require improvements in precursor materials, in each step of the fabrication process, and in equipment design/function.

Demonstrations

Although end users are usually more willing to try a ceramic-coated metal than a monolithic ceramic or a CMC, they are still hesitant to do a trial evaluation. As with other ceramic-based materials, a successful trial usually requires several iterations of design, material, or both. An effective approach is an *insertion program* -- a partnership among the supplier, the component designer (often an OEM), the end user, and the government (as a catalyst). Such a program is a logical outcome of successful RD&D efforts in coating materials development, design, and fabrication. The outcome of an insertion demonstration program is multifold: working relationships are developed among the supplier, OEM, and end user; end users gain confidence that the ceramic will be reliable and beneficial; and suppliers accumulate enough fabrication experience during field testing to initiate a viable, cost-effective manufacturing process.

Exhibit 10 Coating Systems RD&D Needs



Near-Term (0-3 Years)

Mid-Term (by 2010)

Long-Term (by 2020)

Materials Development

Develop scientific understanding of mechanisms that control coating system performance for modeling (i.e., adhesion, conductivity, phase)

Determine basic mechanisms of adhesion for many applications

Improve adhesion of coatings to substrate (100% reliability)

Develop improved bond/corrosion interface coatings

Understand mechanisms of coating-substrate interactions (e.g., diffusion)

Develop tribological coatings that require minimal liquid lubrication

Develop a coating with 10x abrasive wear of Cr at 1/2x the cost

Understand mechanisms of coating interactions with environmental (e.g., tribological)

Develop desirable material properties to improve performance and broaden commercial use (e.g., wear, oxidation)

Develop ideal corrosion- and wear-resistant coatings for ceramic or metallic substrates

Conduct RD&D to understand degradation mechanisms

Conduct RD&D on vapor deposited diamond and diamond-like coatings

Conduct long-term testing of diamond and diamond-like coatings under simulated and real application conditions and conduct material development iterations as degradation or failure modes are identified

Develop oxidation- and corrosion-resistant coatings for monolithic and CMCs

Develop durable, higher-temperature environmental barrier coatings for CMC and monolithic ceramics

Develop improved coating systems to achieve 100% reliability and guarantee performance (i.e., prime reliants)

Develop low-cost stable interface coatings for CMC (i.e., between fiber and matrix)

Develop coatings to withstand wider range of environmental conditions

Develop prime reliant thermal barrier coatings with ¼ thermal conductivity of 7YSZ plasma spray

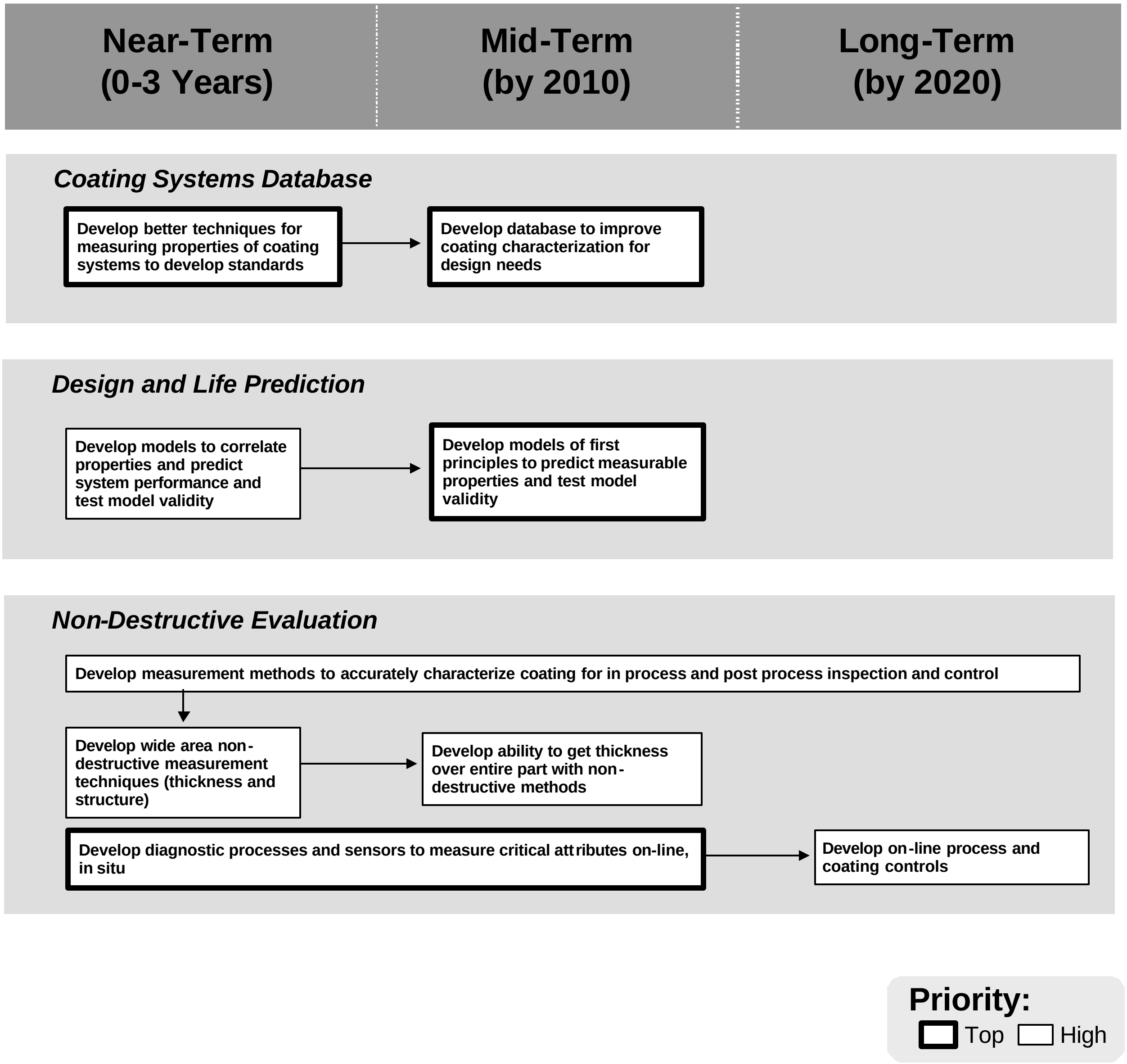
Develop interface coating process that does not degrade fiber structure or properties

Develop smart coatings with embedded sensors with self-heating capabilities

Priority:

Top High

Exhibit 10 Coating Systems RD&D Needs *(continued)*



Near-Term (0-3 Years) | **Mid-Term (by 2010)** | **Long-Term (by 2020)**

Coating Systems Database

Develop better techniques for measuring properties of coating systems to develop standards → Develop database to improve coating characterization for design needs

Design and Life Prediction

Develop models to correlate properties and predict system performance and test model validity → Develop models of first principles to predict measurable properties and test model validity

Non-Destructive Evaluation

Develop measurement methods to accurately characterize coating for in process and post process inspection and control

Develop wide area non-destructive measurement techniques (thickness and structure) → Develop ability to get thickness over entire part with non-destructive methods

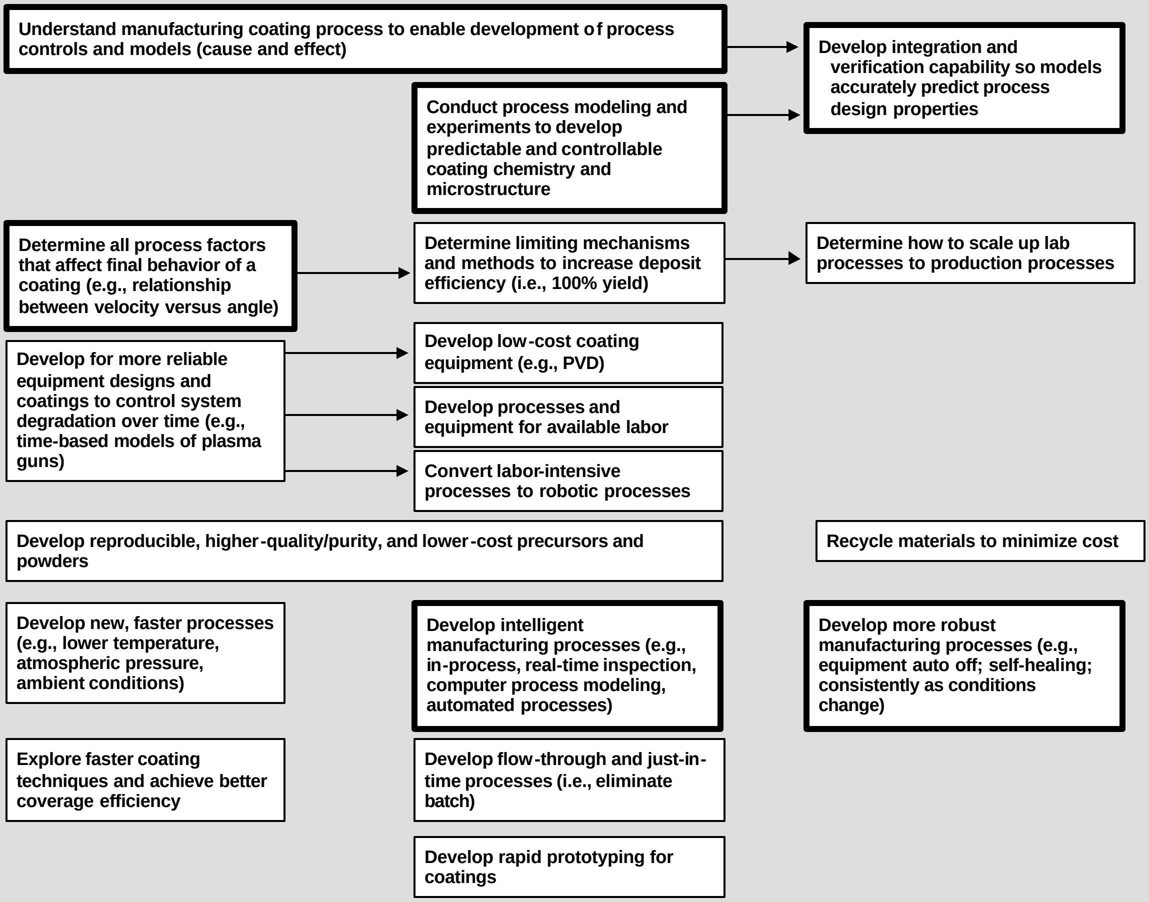
Develop diagnostic processes and sensors to measure critical attributes on-line, in situ → Develop on-line process and coating controls

Priority:
▭ Top ▭ High

Exhibit 10 Coating Systems RD&D Needs *(continued)*

Near-Term (0-3 Years)	Mid-Term (by 2010)	Long-Term (by 2020)

Fabrication Process



Understand manufacturing coating process to enable development of process controls and models (cause and effect)

Develop integration and verification capability so models accurately predict process design properties

Conduct process modeling and experiments to develop predictable and controllable coating chemistry and microstructure

Determine all process factors that affect final behavior of a coating (e.g., relationship between velocity versus angle)

Determine limiting mechanisms and methods to increase deposit efficiency (i.e., 100% yield)

Determine how to scale up lab processes to production processes

Develop for more reliable equipment designs and coatings to control system degradation over time (e.g., time-based models of plasma guns)

Develop low-cost coating equipment (e.g., PVD)

Develop processes and equipment for available labor

Convert labor-intensive processes to robotic processes

Develop reproducible, higher-quality/purity, and lower-cost precursors and powders

Recycle materials to minimize cost

Develop new, faster processes (e.g., lower temperature, atmospheric pressure, ambient conditions)

Develop intelligent manufacturing processes (e.g., in-process, real-time inspection, computer process modeling, automated processes)

Develop more robust manufacturing processes (e.g., equipment auto off; self-healing; consistently as conditions change)

Explore faster coating techniques and achieve better coverage efficiency

Develop flow-through and just-in-time processes (i.e., eliminate batch)

Develop rapid prototyping for coatings

Demonstrations

Develop insertion programs to test coated parts in various applications (non-proprietary, low-level, few parts)

Priority:
▣ Top ☐ High