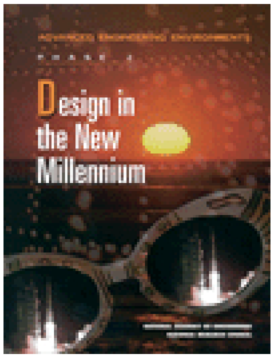

Design in the New Millennium: Advanced Engineering Environments: Phase 2

Committee on Advanced Engineering Environments, Aeronautics and Space Engineering Board, National Academy of Engineering, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Design in the New Millennium

ADVANCED ENGINEERING ENVIRONMENTS

PHASE 2

Committee on Advanced Engineering Environments

Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

National Academy of Engineering

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Preface

Advanced engineering environments (AEEs) combine advanced, networked computer systems with advanced modeling and simulation technologies. When more fully developed, AEEs will enable teams of researchers, technologists, designers, manufacturers, suppliers, customers, and other users scattered across a continent or the globe to develop new products and carry out new missions with unprecedented effectiveness. Business as usual, however, will not achieve this vision. Government, industry, and academic organizations need to make the organizational and process changes that will enable their staffs to use current and future AEE technologies and systems.

The Committee on Advanced Engineering Environments of the National Research Council and National Academy of Engineering has completed a two-part study of AEEs. *Advanced Engineering Environments,* the Phase 1 report issued in 1999, identified steps the federal government, industry, and academia could take in the near term to enhance the development of AEE technologies and systems with broad application in the U.S. engineering enterprise. *Design in the New Millennium,* the Phase 2 report, focuses on the long-term potential of AEE technologies and systems. Appendices A through C of this report include a complete copy of the statements of task and the findings and recommendations resulting from both phases of the study.

In both the Phase 1 and Phase 2 reports, the committee urges "the government" to take action. The committee was not chartered to determine which federal agency should take the lead in developing AEEs. Currently, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration, the National Science Foundation, the U.S. Department of Defense, the U.S. Department of Energy, and the National Institutes of Health are involved in AEE research and development. The executive branch (e.g., the Office of Management and Budget) should determine which agency should take the lead in carrying out recommendations for government action.

This study was sponsored by NASA and conducted by a committee appointed by the National Research Council and National Academy of Engineering (see Appendix D). The Statement of Task directed the committee to pay particular attention to NASA and the aerospace industry. In most cases, however, the committee determined that issues relevant to NASA and the aerospace industry were also relevant to other organizations involved in the development or use of AEE technologies or systems. Therefore, although some recommendations specifically call for action by NASA, the report was written with a broad audience in mind.

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the National Research Council in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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Jaron Lanier, Advanced Network and Services, Inc.
Robert Naka, NAE, CERA, Inc.
Henry Pohl, National Aeronautics and Space Administration (retired)

While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the National Research Council.

The committee also wishes to thank others who supported this study, especially those who took the time to participate in committee meetings (see Appendix E).

Robert E. Deemer, chair
Advanced Engineering Environments Committee

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Executive Summary

America is changing. Many of the most noticeable changes in day-to-day life are associated with the advancing capabilities of computer systems, the growing variety of tasks they can accomplish, and the accelerating rate of change. This report addresses the development of advanced engineering environments (AEEs) over the next 15 years.[1] Inherent in this charge is the assumption that the future of computer applications and technology is foreseeable on a 15-year time scale. Experience has shown, however, that reality usually defies predictions. In some cases, predictions turn out to be overly optimistic, as with past expectations about the future of artificial intelligence or intelligent highways. In other cases, predictions have been greatly exceeded. For example, in 1989 supercomputers cost between $1 million and $20 million, and the best commercially available machines, such as the Cray Y-MP, could perform about 1 billion (giga) floating-point operations per second (i.e., 1 gflop) using 8 interconnected central processing units.

In 1989 a National Research Council report predicted that in the following 10 years general-purpose supercomputers would demonstrate 100 billion gflops using from 32 to 256 interconnected central processing units (NRC, 1989). By November 1999, the most capable supercomputer in the world could perform 2,400 gflops using 9,632 linked processors, and commercially available machines, such as the Cray SV1, could be configured to provide up to 1,000 gflops. The National Research Council report also predicted that the cooling requirements for a supercomputer the size of a suitcase would be so great that there would be an instant meltdown if the cooling system failed. Today, the special-purpose computer processing unit in the PlayStation® 2 video game console is capable of 6.2 gflops, yet it is the size of a typical video game and has no cooling system because it consumes just 15 watts of power.

The National Research Council and National Academy of Engineering identified many barriers to the widespread use of AEEs in the Phase 1 report of the Committee on Advanced Engineering Environments (NRC, 1999). Key barriers included incompatibility of software and hardware; information management systems incapable of dealing effectively with vast amounts of data; the lack of definable metrics to justify expenditures on AEEs; and the need to integrate AEE education and training into academic programs. In this Phase 2 report, the committee describes long-term approaches that industry, government, and academia could use to achieve the AEE vision.

Large companies (such as Boeing and DaimlerChrysler) and small companies (such as Concepts, ETI, a designer and manufacturer of turbomachinery) have demonstrated the costs and benefits of pioneering the use of AEE technologies and systems. Initial costs can be high, but AEEs can initiate a rising tide of improvements in terms of shorter development times, reduced development costs, and improved product performance. Continued improvements in the engineering enterprise will depend partly on continued growth in the capabilities of computational and communications systems. Improvements in interactive communication technologies will create many new opportunities for engineering collaborations via distributed networking, telecommunications, multiuser computer software, and interactive virtual reality. Interdisciplinary collaborations will be especially important for implementing comprehensive processes that can integrate the design of mechanical systems with the design of electrical systems and software. Successful collaborations, however, will require first overcoming incompatibilities between emerging technologies and the existing technological infrastructure and organizational cultures.

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[1] AEEs are defined in this report as particular implementations of computational and communications systems that create integrated virtual and/or distributed environments linking researchers, technologists, designers, manufacturers, suppliers, and customers.

BASIC APPROACH

The Phase 1 report provided initial guidance on the general approaches and roles for industry, government, and academia in pursuing more advanced and capable AEEs. The additional information collected for the Phase 2 report confirmed that the recommended approach would provide a solid foundation for achieving long-term goals. Key steps in this top-level process include the following:

- forming a national partnership of government, industry, and academia to take advantage of the current historic opportunity to develop AEEs
- forming government-industry-academia AEE partnerships by individual agencies, such as the National Aeronautics and Space Administration (NASA), as an interim step for addressing agency-specific goals while a national partnership is being formed
- overcoming major barriers related to the integration of systems, tools, and data; information management; cultural, economic, and management issues; and education and training
- facilitating the transfer of new capabilities to commercially available products by developing application-specific tools required by government through contracts with industry whenever practical
- focusing the government's AEE research and development on key objectives, such as (1) modeling key physical processes, (2) improving generic AEE methodologies and automated tools, (3) developing testbeds that simulate user environments, (4) developing accurate performance metrics, and (5) other areas where market-based incentives are not motivating adequate industry-sponsored research
- providing government incentives for (1) industry to adopt AEE technologies in government procurements, (2) academia to adopt AEE technologies in major government-sponsored research programs, and (3) industry and academia to collaborate in modernizing educational curricula to prepare students for an AEE work environment

National Partnership

Government agencies involved in research and development of AEE technologies should be more aggressive in forming a national partnership with industry and academia to develop AEEs that offer seamless, end-to-end engineering design capabilities encompassing the entire life cycle of products and missions (see Table ES-1). The federal government is spending more than a billion dollars each year on research for advanced computing technologies, and industry is investing even more. As a result, most of the computational and communications technologies needed to create AEEs will probably be developed, even if the needs of AEEs are not directly considered. Building new AEEs that take advantage of these new technologies, however, will be impeded if AEE requirements are not considered during technology development. For example, small adjustments in some future Internet-related technologies and applications (which are discussed below) might make a big difference in their ability to support interoperable AEEs. Areas of particular interest include latency, quality of service (i.e., the ability to guarantee users that they will have the communications bandwidth necessary to conduct AEE operations at a given time), and security (i.e., the ability to provide authorized users with easy access to data and systems, while protecting competition-sensitive data from unauthorized disclosure or alteration). For example, widespread use of AEEs would involve simultaneously providing many users with reliable, low-latency, high-bandwidth service. A national partnership that includes developers of AEEs and Internet-related technologies and applications should be formed to develop (1) open architectures and functional specifications for AEEs, (2) plans for transferring the results of government research and development to the commercial software industry and software users, and (3) approaches for resolving information management and organizational issues.

An AEE is not just a technology system. The purpose of AEEs is to improve the efficiency with which large, distributed teams design and implement large, complex systems. To achieve this goal, the national partnership will have to address psychosocial issues related to human-machine

TABLE ES-1 High-Level Steps in the Design and Development of Products and Processes[a]

1. Mission requirements analysis/product system strategy
2. Product specification
3. Concept development
4. Preliminary product and process design
5. Refinement and verification of detailed product and process designs
6. System prototype development
7. Preparation for production
8. Production, testing, certification, and delivery
9. Operation, support, decommissioning, and disposal

[a] *Product* refers to hardware, such as a space station, a service, or something more conceptual, such as a mission. *Process* refers to the means by which a product is manufactured and supported. *Development* refers to the refinement of products and processes to correct problems.

interfaces and the manner in which work is carried out by the people who use AEE technologies and systems.

NASA's Role

NASA is developing AEE-related technologies and has facilities in several different regions of the United States. NASA also has a wide-ranging mission, which includes encouraging "the most effective utilization of the scientific and engineering resources of the United States, with close cooperation among all interested agencies" (National Aeronautics and Space Act of 1958, Public Law 85-568, as amended). Furthermore, many NASA programs challenge the limits of human ingenuity and involve leading engineering universities and corporations. Thus, NASA would benefit from increased use of AEEs, and it is well positioned to form a government-industry-academia partnership for NASA missions as an interim step (while a national partnership is being formed). However, the conditions necessary for significant, widespread adoption of AEEs in the agency do not yet exist. Sustained leadership, high-level organizational commitment, adequate funding, and a cohesive plan that includes all NASA centers is necessary to accelerate the adoption of AEEs within NASA.

NASA should not create a broad-based AEE research program to develop comprehensive AEE systems. Instead, NASA should advocate and facilitate greater use of AEE technologies by contractors involved in NASA programs, capitalize more on commercial technologies, fund research and development to satisfy NASA's specialized needs, quantify and advertise the benefits of AEEs in different applications, and support advances in the state of the art in focused areas that industry's market-driven research and development are not addressing. NASA should also ensure that its systems are compatible with the AEE technologies and systems used by its research and development partners in industry, academia, and other government agencies. In particular, NASA should investigate how NASA-funded research related to AEEs and the Next Generation Internet can enhance the ability of Internet-related technologies and applications to meet AEE objectives.

Education and Training

Creating and maintaining an AEE-qualified workforce will require changes in education and training. AEEs could enable students to learn in virtual environments, foster the development of critical thinking skills, and, perhaps, improve educational efficiency so much that AEE-related education could be integrated into curricula without requiring the elimination of existing courses. AEEs could also be used to integrate schools of engineering with schools of liberal arts and sciences. Because the capabilities of AEEs are not limited to traditional engineering tasks, access to AEEs should not be limited to engineering students.

Just as individual corporations will require a champion to implement AEEs, engineering schools will need influential champions to integrate AEEs into the university environment and sustain support for AEEs and related interdisciplinary programs. Champions will be especially important if individual academic departments do not embrace AEEs. At many universities, strong internal leadership, combined with external pressure from accrediting organizations and industrial engineering organizations, will be necessary to encourage faculty to use AEEs and modify undergraduate and graduate curricula accordingly. In a broader context, the federal government can facilitate change by funding long-term interdisciplinary research associated with AEEs and, with industry, by including academia in a national partnership for fostering the development of AEE technologies and systems.

INTERNET-RELATED TECHNOLOGIES AND APPLICATIONS

Internet-related technologies and applications include software and hardware that provide the basic capabilities of the Internet to (1) transfer large amounts of data quickly and reliably among interconnected public and private networks and (2) enable shared, distributed applications and objects (such as e-mail, Web browsers, Internet-based videoconference systems, and simulations) that enhance the functionality of the Internet to the general public, including the science and engineering communities. Internet-related technologies and applications may be associated with (1) the current Internet, (2) the Internet of the future (in whatever form it takes), or (3) current or future private networks, which may be established to provide a guaranteed level of quality of service or to test advanced technologies. The committee recommends that AEEs be designed in a way that is compatible with and takes advantage of Internet-related technologies and applications. However, AEEs are in a distinct class because they are intended for a special purpose and have a small market compared to the Internet as a whole. Thus, the development of Internet-related technologies and applications will proceed without reference to the needs of AEEs unless special efforts are made to integrate them.

Advanced Internet technologies are one of the keys to developing AEEs that can overcome critical technical, cultural, management, and educational barriers. One of the most difficult long-term barriers concerns integration of software tools for design and development across (1) disparate operating systems, distribution networks, and programming languages and (2) different governmental and corporate cultures. Overcoming this barrier in the next 15 years will require general solutions to the problems of interoperability (i.e., the ability of various systems to work together in a meaningful and coherent fashion) and composability (i.e., the ability to build systems using components designed for other systems). The committee believes that the current move toward the Internet as a universal medium will make it easier to solve these complex problems. Accordingly, the government's AEE research and development programs should greatly increase their emphasis on technologies, open standards, industry-wide consortia, and other processes that have contributed to the success of the Internet. AEEs should benefit as much as possible from Internet-related technologies and applications being developed by other research programs, such as the Internet-2, the Next Generation Internet, the very high performance Backbone Network Service, and the Information Technology Research Initiative.

New telecommunications and collaborative capabilities of future Internet-related technologies and applications will enable users in the same or separate locations to engage in interdependent, cooperative activities using a common computer-based environment. The nature and extent of these collaborations will depend, in part, on the extent to which AEE developers have been able to integrate their technologies with the Internet. Just as important, however, will be bringing mission-oriented communities together with the computer and social science communities to address cultural barriers. Interdisciplinary studies are necessary to develop AEEs that enable workers with various work styles to form effective teams and to accommodate the psychological and temporal dimensions of synchronous, distributed, collaborative activities, especially if they involve personnel in multiple time zones and organizations with different cultures and business goals. Coordinating the development of AEEs with the development of Internet-related technologies and applications, such as tele-immersion capabilities, would increase the likelihood that solutions to cultural barriers will be incorporated into the technologies that underlie the future Internet. This coordination could also lead to AEEs with a feel similar to the future Internet, thereby reducing the need for specialized equipment and training.

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Prologue
A Future Perfect

This report calls on government, industry, and academia to make major changes to current organizational cultures and practices to achieve a long-term vision that goes far beyond what current capabilities allow. True to that spirit, the committee offers the following fictionalized account to encourage the type of radical thinking needed to take full advantage of technological advances. The committee hopes that this vignette of a "perfect" future will inspire others to think in revolutionary ways and create visions of their own.

A bright blue flame of rocket exhaust shot out of the back of the engine, which sailed noiselessly through space on its way to the outer planets. But Kyle, standing three meters away resting his chin on his fist, knew the engine would be going nowhere unless they could eliminate oscillations in the combustion chamber.

"I'm going to take off the cooling jacket," he called out to the room as he reached for the floating holographic display panel on his right and touched a translucent orange button. The cover disappeared from the life-sized, holographic engine floating in the middle of the room. Without looking at his instruments, Kyle could see that the flow wasn't as steady as it should be.

"Let's take it one layer deeper and look inside the combustor." Another touch on the floating panel split the engine in half, revealing red fuel rushing into the combustion chamber forward of the exhaust nozzle. The fuel ignited to blue in the combustion chamber and shot out the nozzle into the vacuum of holographic interplanetary space. But Kyle knew something wasn't right.

With the touch of another button, small yellow arrows, highlighting small fuel concentrations that formed droplets just past the fuel injectors, popped up inside the combustion chamber. That wasn't the problem. The droplet formation was normal, but the sweeping red ribbon-like waves bouncing from one combustion chamber wall to the other were not. The acoustic waves meant there was a resonance coming from somewhere. The waves grew in intensity until reaching a crescendo as they entered the rocket nozzle. Worst of all, at the peak intensity the hologram motion froze and the simulation automatically reset, meaning a real-life rocket would have just exploded. The engine looked like it was bleeding, and Kyle couldn't figure out how to stop it.

"I think we should call Rachel in," suggested Jeff, a structural engineer with a soft Texas drawl. Startled, Kyle looked to his left. Jeff was a little late, and Kyle hadn't expected him to be standing over his shoulder. Jeff's image shimmered slightly as he moved closer to the engine because he was actually standing in an identical lab 1,500 kilometers away.

Kyle muttered to himself and clenched his jaw. He was the lead thermodynamics engineer on duty, and this problem was a showstopper. Rachel's specialty was combustion dynamics, and Kyle knew if anyone could solve the problem, she was the one. "Make the call."

~ ~ ~

As the sun dropped towards the horizon, it threw a blanket of gold across the lazy blue-green ocean. Rachel burrowed her toes into the sand, concentrating on the grains rubbing against her skin. She wanted to make sure she was awake, that this perfect sunset was real. A fantastic end to an incredible day.

"Mom, you're being paged," Amber called from under an umbrella by a grove of palm trees where she and her father had been sampling drinks in coconut shells. Amber had finished her drink and was moving her arms in slow circles in the air. Wearing her mother's teleimmersion sunglasses, the young girl's odd ballet was really movements in a gaming environment with friends scattered around the planet.

Rachel took one last look at the sunset, turned, and headed up the beach.

"Looks like they're having a little trouble," her husband, Conner, said.

"It shouldn't take but a few minutes, and I am on call," she replied.

"Come on Amber," Conner said getting up from his chair, "let's go for a swim." Amber passed the glasses to her mother and headed toward the water.

"I'll join you soon," Rachel added with a smile. She settled into the beach chair and put the glasses on. A transparent heads-up display overlaid the sunset as the voice of her computer-generated digital assistant announced "Retinal identity verified. Welcome, Rachel. I understand you have been paged. Kyle seems to be having some trouble in the shop. I'll connect you now."

"Thank you, Rhett." The display immediately became opaque and blocked out the beach and her family in the surf.

Almost instantly she was sitting virtually in the Immersed Technology Design Facility, or ITDF in official jargon. But for the people who thought of it as a second home, it was simply the "Design Shop," or even just the "Shop." Rachel saw the holographic rendering of the interstellar engine hovering in mid-flight at one end of the room next to Kyle and Jeff.

"Okay, I'm here," Rachel called out. Kyle turned around and saw a standardized image of Rachel. Because she was using a portable unit, the system projected a constructed image based on stored data instead of a real-time image of the beach setting.

"Thanks for getting here so quickly," Kyle said. "As you can see we have a little problem." A swarm of red waves still poured out of the engine.

"The waves represent acoustic wave fronts," Rhett informed her.

"So where are the acoustic waves coming from?" she asked.

"I haven't been able to figure that out yet," Kyle answered. He was not surprised by the question. Although he could not hear Rhett's comments to Rachel, he knew that the digital assistant would inform her of the basic setup.

"Let's see if we can walk through this together and see what's happening." Using controls activated by eye motion, Rachel moved her viewpoint closer to the engine. Although she never left her beach chair, Kyle and Jeff saw her image walk across the room. To get a sense of what the system was doing, Rachel watched the engine run for a minute. Kyle stepped up next to her.

"We've been looking at it for a while now with this same display, but I can't determine the origin of the waves," he said quietly.

"I think I see something," Rachel said, as she moved a little closer. "Set the controls to 75 percent flow rate, and adjust the gimbal angle by, say, five degrees."

"Will do," Kyle replied, as he walked to his floating control panel and started entering data.

Rachel couldn't help marveling that she was vacationing in paradise with her family and, at the same time, helping to design a rocket engine a continent away. Thanks to the flawless integration of models and simulations, incredible advances in interactive and communications technologies, and a cultural revolution, the relationship between engineers and their work had changed drastically. Here they were, designing the entire engine at one time, Rachel thought. No longer were subsystems designed separately, to be integrated later. System problems, such as this one, showed up immediately. Design and testing had become one with advanced physics-based simulation capabilities.

In the beginning there were a lot of challenges. Working in an immersed environment was intense, and people tended to burn out after about four hours. Maintaining a high level of performance day after day, week after week, seemed impossible. But in the end they worked it out with the help of an unlikely acquaintance. One of the design engineers had a cousin who worked a rotating schedule on oil rigs in the Gulf of Mexico. After a lot of argument, senior management decided to try something similar, and it had worked far better than anyone expected. The designers had been organized into two teams. Each team worked for three weeks and then had two weeks off. Workdays included four hours of integrated design and four hours of individual work in their own offices. Some hours were devoted to debriefings and brainstorming to improve the integrated design sessions. The change had required a colossal shift in workplace thinking, but no one could argue with the results. Time to completion was down and quality was up.

Rachel was grateful for the change. She was spending more time with her family and had a new sense of excitement about her work. She was now on her two-week break, taking the vacation that had been postponed several times because of the rough work schedules under the old system.

"Okay, I'm ready," Kyle said. Rachel snapped back to attention. Her display turned blue with red lines streaking past as she directed her avatar to walk directly into the holographic combustion chamber. Ignoring the red acoustic waves, she moved forward until she saw the yellow arrows marking the fuel droplets forming just after the fuel was atomized by the fuel injectors. The injectors acted like an industrial-scale perfume sprayer, but with a punch. In this case, the droplets were highly flammable rocket fuel that ignited almost immediately in the combustion chamber.

"Kyle, could you please slow the flow rate." The fuel flow rate slowed so that she could see where the fuel droplets formed. "Wait a minute!" The whole design shop heard a loud pop when Rachel snapped her fingers on the beach. "I think I have it, Kyle!"

"Where?" Kyle passed through part of her holographic projection as he ran into the display.

"Right here. See how the droplets form all at once as they come out of the fuel injector? See the same pattern that forms at equal intervals?" Before Kyle could answer she said, "Rhett, what is the time difference between individual droplet formation within a single set of droplets?"

"The simulations indicate that 95.6 percent of the droplets form within 0.01 milliseconds of each other. And the time interval between droplet sets is a constant 0.12 milliseconds," Rhett replied.

"That has to be it. See the droplet formation here, Kyle?" She pointed into the fuel stream. "It has a constant formation rate."

"Oh, that's it," Kyle sighed. "I should have thought of it. That's well within the structural resonance range."

With new energy, Kyle turned around. "Jeff, please compare the frequency of the mechanical resonance in the combustion chamber with the frequency of the droplet set formation rate."

Jeff keyed a few buttons on his design panel. "They're within half a Hertz of each other."

"That's it, then!" Rachel said.

"What's it?" Jeff asked, not understanding the consequences of the data he had pulled up.

"The fuel droplet formation rate corresponds exactly to one of the combustion chamber's acoustic resonance frequencies," Kyle answered. "When the fuel droplets vaporize and burn all at once, the periodic forces from the resulting pressure waves interact with the mechanical properties of the combustion chamber. That unstable burning process increases the peak pressure of the waves until the chamber ruptures and the engine explodes."

"So all we need to do is shift the resonance frequency of the combustion chamber," Rachel concluded.

"I'll take care of that," Jeff said, as he touched his display screen a few times. "You two are a couple of smart designers."

As he finished speaking the red acoustic wave markers disappeared. The combustion instability was gone. Everyone in the room applauded. Images and voices of people who had been monitoring the design work from other labs filled the room. Rachel had almost forgotten about the other design and manufacturing groups that were linked into the shop and had been monitoring their progress remotely. One of the newcomers, a manufacturing engineer, called out to Jeff, "What changes did you make?"

Jeff raised his voice above the excited noise. "First, I had the atomization model change the hole distribution pattern with the manufacturing tolerances in the fuel injectors to randomize the droplet formation. Then I adjusted the dimensions of the chamber slightly based on the chamber acoustic model to shift the chamber resonance frequency. But when I adjusted the chamber size, the structural model indicated I had to change the weave on the composite fiber structure to compensate for some stress points the model picked up."

"Well, according to the manufacturing stress models," the manufacturing engineer said, "that composite change makes the combustion chamber stronger. We can get rid of some supporting struts, which also simplifies the assembly process. Good job!"

A moment later several team members jumped as an office cubicle, complete with pictures of the family and a coffee cup pencil holder, appeared at the back of the room. The cost engineer sitting at his desk was flushed.

"Jeff! That's fantastic!" he yelled. "I just got the update from manufacturing. Because of the reduced support structure, we can save 2 percent on engine manufacturing costs."

The whole room applauded again. Kyle cut in, "Hey, Jeff. Kudos to you and Rachel."

"You're welcome. Call any time," Rachel smiled even though they couldn't see her facial expressions. "But right now the waves are calling. I'll see you next week." The engine they had almost finished would be finalized in three weeks after a total development time of five weeks. The preliminary parts would be available even sooner. The rest of the spacecraft was being developed simultaneously in other immersed design shops, and the mission was expected to take off, literally, just nine months later. The schedule from initial concept to launch was 14 months.

Rachel sat for a moment longer observing the excitement in the room. Everyone was smiling and people were trying to slap each other's holograms on the back and give translucent high fives. It was a good feeling to turn a design problem into a design improvement.

"Disconnect please, Rhett," Rachel said. With a satisfied smile she headed down to join her family for a sunset swim.

1

Introduction

As interactive communication technologies improve, more people will collaborate on projects via distributed networking, telecommunications, multiuser computer software, and interactive virtual reality. These collaborations face many barriers to success, such as incompatibilities between emerging technologies and the existing technology infrastructure and organizational cultures.

In the Phase 1 report, the Committee on Advanced Engineering Environments (AEEs) identified many barriers to the widespread use of AEEs, including incompatibility of software and hardware; information management systems incapable of dealing effectively with vast amounts of data; the lack of definable metrics to justify expenditures on AEEs; and the need to integrate AEE education and training into academic programs (NRC, 1999).[1] In this Phase 2 report, the committee focuses on long-term issues and approaches that industry, government, and academia could use to achieve the AEE vision.

DEFINING AN ADVANCED ENGINEERING ENVIRONMENT

As defined in the Phase 1 report, AEEs are specific implementations of computational and communications systems that create integrated virtual and/or distributed environments[2] linking researchers, technologists, designers, manufacturers, supplies, customers, and other users involved in mission-oriented, leading-edge engineering teams in industry, government, and academia. AEEs should be designed to accomplish two key objectives:

- Enable complex new systems, products, and missions.
- Greatly reduce product development cycle time and costs.

In addition, the implementation process should achieve the following objectives:

- Lower technical, cultural, and educational barriers.
- Apply AEEs broadly across U.S. government, industry, and academia.

Vision

The committee anticipates that AEEs will create environments that enable organizations to introduce innovations and manage complexity with unprecedented effectiveness in terms of time, cost, and labor throughout the life cycle of products and missions. AEEs may be perceived simply as conglomerations of hardware and software, but they cannot be used to their full potential unless they are immersed in compatible organizational environments. AEE developers, therefore, must consider cultural factors, and the first step in implementing an AEE should be to identify organizational and process problems.

Many organizations are already implementing AEE technologies as they are developed and validated. As more AEE technologies become available for integration, they are beginning to take on the characteristics of an AEE system. An ideal AEE system would encompass the entire mission or product life cycle, from the initial analysis of mission requirements to system disposal at end of life. Throughout the process, the AEE would constantly seek to optimize reliability, performance, and cost. These activities would take place in a seamless blend of interdisciplinary work functions

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[1] A complete list of the barriers identified in the Phase 1 report appears in Appendix B of this report (see Table B-1). The Phase 1 report is also available on line at *http://books.nap.edu/html/adv_eng_env/*

[2] A *virtual environment* is defined as "an appropriately programmed computer that generates or synthesizes virtual worlds with which the operator can interact" (NRC 1995). A *distributed environment* is a nonvirtual, collaborative computing system.

through flawlessly integrated data sets and tools that would not require burdensome software development. For example, the AEE described in the prologue allows engineers to look inside the engine they are designing and to visualize with ease the internal characteristics of a full-scale, integrated system using a simulation of the actual operating environment. In this engineering environment, physically separated members of the design team all view the same events. Even for relatively simple problems, the AEE approach described would be of great benefit because complex engineering systems often fail, not because of exotic, poorly understood problems, but because of simple flaws that could not be identified in isolation from the operation of the full systems. The prologue shows how even complex problems could be solved. In that scenario, a perfectly fine injector in terms of basic operation contributes to a catastrophic failure mode when combined with a rocket chamber and nozzle, both of which are perfectly satisfactory units in isolation from each other. AEE systems that could eliminate such failures would represent an immense step forward in engineering practice.

An ideal AEE would also accommodate diverse user groups and facilitate their collaboration by helping to eliminate cultural barriers between groups from different parts of an organization, different organizations, or different areas of the world. The system would be marked by innovative solutions to difficult problems and functional flexibility that could rapidly reorient and restructure itself at little or no extra cost. Finally, the ideal AEE would be amenable to hardware and software upgrades in a transparent way. Table 1-1 lists the major components of an AEE and the most important characteristics for fulfilling the committee's AEE vision.

TABLE 1-1 AEE System Components and Characteristics

Computation, Modeling, and Software
- multidisciplinary analysis and optimization
- interoperability of tools, data, and models
- system analysis and synthesis
- collaborative distributed systems
- software structures that can be easily reconfigured
- deterministic and nondeterministic simulation methods

Human-Centered Computing
- adaptive human-machine interfaces
- networked virtual environments
- immersive systems
- telepresence
- intelligence augmentation[a]

Hardware and Networks
- ultrafast computing systems
- large high-speed storage devices
- high-speed and intelligent networks

[a] *Intelligence augmentation* is the ability of computer systems to enhance human performance in terms of decision making, problem solving, and other task-critical capabilities. Intelligence augmentation includes monitoring and storing important data, creating filtered information, and suggesting alternative courses of action based on the situation and task at hand.

Although developing a "perfect" AEE and integrating it with existing systems might seem far-fetched, the committee believes that independent advances in AEE technologies and the resolution of cultural issues will help achieve a comprehensive AEE system that incorporates the legacy systems currently used. With strong leadership and sustained commitment to innovation, organizations can establish the cultural and technological base necessary to take full advantage of AEE technologies and systems, now and at every stage of development.

Internet-Related Technologies and Applications

One theme of this report is the importance of coordinating the development of AEE technologies and systems with the development of Internet-related technologies and applications. These technologies and applications include software and hardware that provide the basic capabilities of the Internet to (1) transfer large amounts of data quickly and reliably among interconnected public and private networks and (2) enable shared, distributed applications and objects (such as e-mail, Web browsers, Internet-based videoconference systems, and simulations) that enhance the functionality of the Internet to the general public, including the science and engineering communities. Internet-related technologies and applications may be associated with (1) the current Internet, (2) the Internet of the future (in whatever form it takes), or (3) current or future private networks, which may be established to provide a guaranteed level of quality of service or to test advanced technologies. Unlike Internet-related technologies and applications, AEEs are intended for a special purpose and have a small market compared to the Internet as a whole. Thus, the development of Internet-related technologies and applications will proceed without regard to the needs of AEEs unless special efforts are made to integrate them.

STUDY OVERVIEW AND REPORT ORGANIZATION

The Statement of Task for this study (see Appendix A) required that the committee conduct a two-phase assessment of existing and planned methods, architectures, tools, and capabilities associated with the development of AEE technologies and systems and their transition into practice by the current and future workforce. The Phase 1 report, issued in June 1999, focused on AEE requirements and alternatives for meeting those requirements, barriers to the implementation of AEEs, and near-term steps that would further the development of AEE technologies and systems with broad application in industry, government, and academia. A complete list of the findings, recommendations, and barriers identified in the Phase 1 report appear in Appendix B of this report.

Expanding on the results of Phase 1, this Phase 2 report focuses on the feasibility of developing AEE technologies and systems over the long term (the next 5 to 15 years). Chapter 2 examines current product and mission design practices and goals for the future. Chapter 3 identifies AEE technologies that are available but underutilized, describes how AEE capabilities would improve specific aspects of the design process, describes future expectations based on the current state of AEE research and development, and identifies high-priority efforts that would improve the 15-year outlook. Chapter 4 expands on the barriers identified in the Phase 1 report and recommends ways to overcome them. Chapter 5 describes a general approach for making long-term improvements in AEE capabilities and corresponding roles of industry, government, and academia. Appendix C lists all of the findings and recommendations in this report.

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NRC. 1999. Advanced Engineering Environments: Achieving the Vision (Phase 1). Committee on Advanced Engineering Environments. Washington, D.C.: National Academy Press. Available on line at: *http://books.nap.edu/html/adv_eng_env/* April 5, 2000.

2

"As Is" to "Future Perfect"

This chapter describes current practices in product and process design and compares them to three visions of the future: the 2015 vision of the Integrated Manufacturing Technology Roadmapping (IMTR) Initiative, the 2015 vision of the Intelligent Synthesis Environment (ISE) Initiative of the National Aeronautics and Space Administration (NASA),[1] and the committee's view of a "future perfect" world with an extremely advanced product and process design system. The two 15-year visions define long-term goals used in current AEE research and development; the future perfect vision describes an idealized scenario against which current capabilities and the 15-year visions can be compared. This chapter also includes examples of AEE success stories. Cultural and educational factors, including issues related to teaming and collaboration in distributed environments, are discussed in more detail in Chapter 4.

PRODUCT DESIGN PRACTICES TODAY

Figure 2-1 depicts generic, high-level steps in product and process design and development. The first step is a *requirements analysis* for a mission or a *system strategy* for a product. For example, before analyzing a proposed mission or system, the Aerospace Corporation defines both the scope of the task and the resolution of the analysis. This defines the largest whole that will be analyzed and the smallest pieces that will be used in describing or examining the larger whole. The following scale (from small to large) is used to define both the scope and the resolution (Aerospace Corporation, 1999):

- part
- component
- subsystem
- segment
- system
- system of systems
- mission architecture
- policy architecture

The second step is the development of a *product specification.* This step involves stating the strategic intent of the product, determining what the customer wants and is willing to pay for, and developing a preliminary high-level specification for the product or mission that is consistent with environmental and other regulatory requirements.

The third step is the *development of a concept* for the product and its processes, including preliminary subjective and objective targets; brainstorming on alternatives and comparing their expected characteristics to the targets for cost, schedule, performance, etc.; and selecting a concept for further design. Depending on the nature and complexity of the product, this step can be very lengthy and may result in multiple concepts that must be refined and evaluated in subsequent steps.

In general, the line between the concept phase and step four, *preliminary product and process design,* is not clearly defined. At some point, when one or more design concepts have been selected for refinement, a larger design team with additional specialized expertise is gathered to develop preliminary designs of the product and processes. The general purpose of this step is to enable more accurate projections of the design's ability to meet the targets set in earlier stages. In this iterative process, the concept can be adjusted, the design evaluated (either by calculation or physical experiment), the results compared to expectations, and further adjustments made. During this step, high-level system trade-offs will probably be necessary for products of even moderate complexity. A trade-off analysis of performance versus cost, for example, is almost always conducted. Depending on the outcome of these evaluations, it may be necessary to go back to

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[1] The ISE Initiative and several other AEE research and development efforts are described in the Phase 1 report (NRC, 1999).

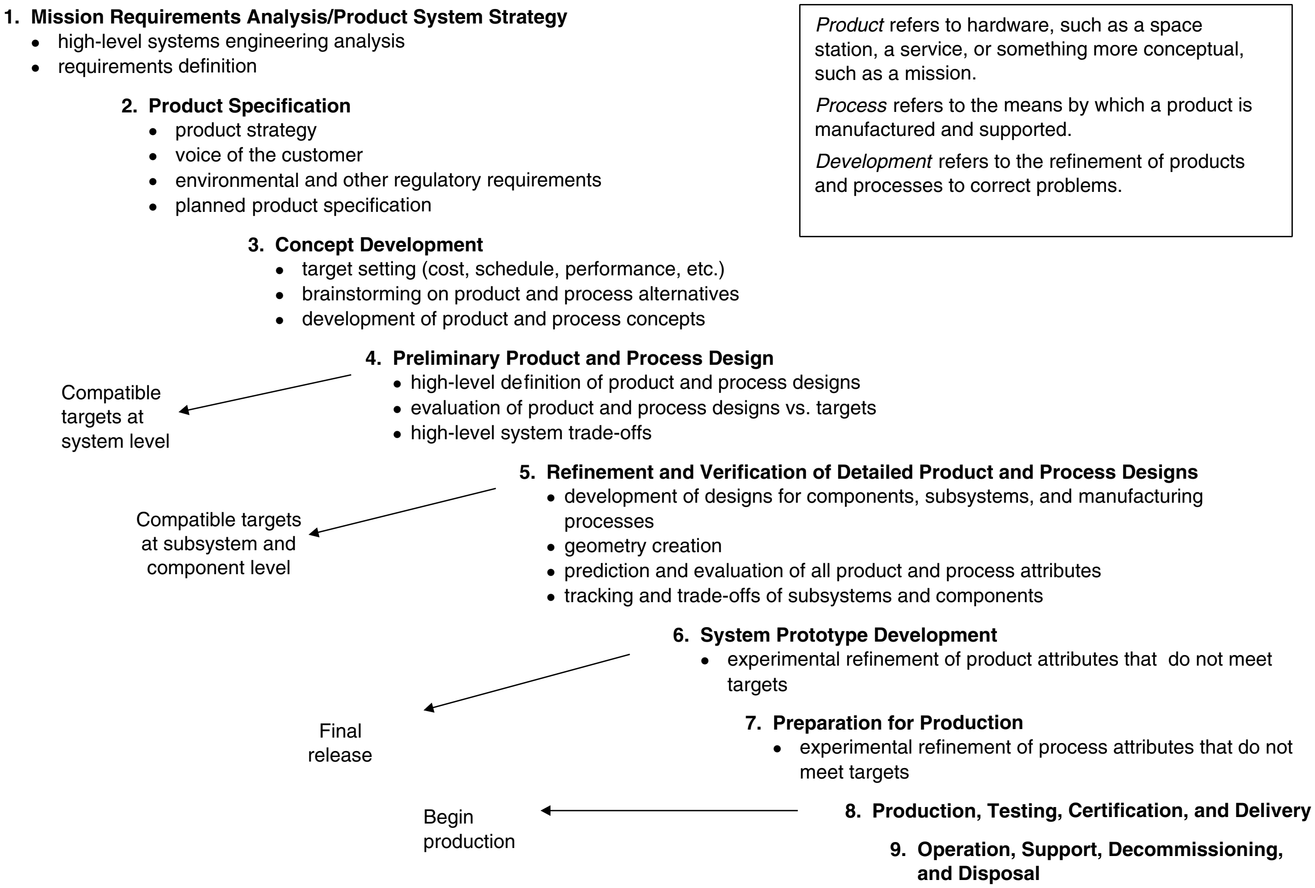

FIGURE 2-1 Steps in the design and development of products and processes.

the concept level or even to the product specification level if the design iterations do not result in performance that meets the customer's need.

The fifth step is *refinement and verification of detailed product and process designs*. Once again, the dividing line between this step and the preceding step is often hard to establish. In step five, only small changes are made to the design as it proceeds to production. The detailed design typically places a heavy emphasis on definition of product geometry (i.e., physical dimensions of component parts), and a great deal of effort is spent on evaluating the evolving design against design goals. The intense competition in today's marketplace often results in aggressive goals, and new designs frequently cannot meet all of them simultaneously. Therefore, this phase also includes a lot of performance tracking and trade-offs.

The sixth step involves creation of *prototypes* to test or refine product attributes. For a physical product, developers may initially test prototypes of subsystems, such as aircraft wings or engines, for attributes that can be evaluated without the rest of the product being present. Final product performance is validated using prototypes that are equivalent in all respects to the production model of a fully integrated product, such as an entire automobile or a complete computer program. For a service, prototype testing may take the form of trial runs with potential customers or simulated customers.

The seventh step in the design process is *preparation for production*. For products produced in small quantities, this step refines and validates the attributes of manufacturing processes. For mass-produced products, this step could entail building and testing prototypes of high-risk elements of the manufacturing process first, then building and testing subsets of the manufacturing line at various supplier locations. The final phase of this step involves assembling the entire production facility and running hundreds of trials to gain confidence that process uniformity will be achieved. For a service, this step could take the form of limited operational trials.

The final steps are *production, testing, certification, and delivery* and *operation, support, decommissioning, and disposal* of the product. These steps vary tremendously for different products. Some products require little or no certification (prior to sale) or customer support (after sale). Others, however, require extensive testing and certification, as well as manufacturer support until the end of the product's useful life.

TYPICAL PRACTICES TODAY

The first column in Table 2-1 reproduces the steps described above. The second column describes how these steps are typically carried out today, based primarily on interviews conducted for the needs-analysis portion of the Phase 1 report (NRC, 1999).

Currently, mission requirements analysis is based primarily on traditional systems-engineering methods (i.e., a top-down decomposition approach). Product specification typically estimates future performance requirements based on the performance of existing products, the projected capabilities of competitors' products, and customer expectations. This step, which may include customer interviews, focus groups, and product demonstrations using mockups or prototypes to gain feedback from potential customers, generally results in written documents, such as a mission needs statement, system attributes document, or initial product specification.

As currently practiced, concept development is often accomplished by a small advanced design/configuration team, which may be fairly loose and unstructured. Setting targets for complex systems is generally only accurate from the bottom up (i.e., system synthesis), rather than from the top down. In complex systems, the assumption of top-down target cascading using simplified models can actually be misleading because it constrains the design to trade-off regions that ultimately cannot meet targets for performance, manufacturing, and/or operational support. The concept development process tends to be driven by heuristics, first-order analytical tools, rules of thumb, and existing data based on benchmarks as a means of evaluating alternatives. The process may use structured brainstorming sessions (facilitated brainstorming), but developing feasible alternatives is usually left to experienced practitioners.

Existing processes for preliminary product and process design generally rely on heuristics and benchmark data because the design may be too coarse to be accurately evaluated by other means. Therefore, most new designs tend to be derivatives of previous designs with manageable risk. In the early design stages, therefore, a substantial range of design detail is available. Although a large amount of information is available for parts and subsystems reused from previous applications, usually only a concept or coarse design is available for new parts. This discrepancy results in the so-called "mixed phase" design problem, which makes evaluating performance difficult for users who are not skilled in combining different levels of definition. Current design practices use very different methods of evaluating product and process attributes against targets. Based on an informal survey conducted by the committee, only about 20 percent of attributes are evaluated analytically at this stage. Evaluations of the remaining 80 percent rely heavily on physical prototypes at the component and system levels.

The detailed design of physical products focuses on the definition of physical dimensions and specifications. For new parts, most detailed design is performed one line and one feature at a time.[2] More emphasis should be placed on (1) integrating tools for computer-aided design (CAD) and computer-aided manufacturing (CAM) (e.g., by providing common definitions of features and design intent), (2) using parametric design capabilities, (3) and reusing geometric design data from similar parts. As the design definition proceeds, all elements of the design reach a common level of detail, and about one-third of the attributes of physical products can be evaluated analytically. Physical prototypes, however, are still commonly used to refine and verify designs and processes. If trade-offs are required, they are usually done separately from the ongoing design process.

Current processes for creating prototypes and preparing for production typically involve a significant amount of experimental work using representative hardware. The committee estimates that more than half of product attributes and manufacturing processes require some form of hardware-based refinement.

Production processes typically rely heavily on automated statistical process control,[3] while operation, support, decommissioning, and disposal depend more on manual operations.

The bottom row of Table 2-1 describes educational factors related to AEEs. Typical practices today emphasize fundamental core courses; system-level education is limited primarily to undergraduate capstone courses, which teach "as is" design synthesis processes. Education continues to take place mostly in the traditional classroom setting.

AEE SUCCESS STORIES

Although early attempts to deploy AEE technologies often resulted in poor returns on investment in the short term, innovators remained confident that AEE technologies would pay off in the long term. Lessons learned from early mistakes, along with more realistic expectations, have led to

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[2] Features, which describe the purpose of each element of a solid part's geometry, can be important to manufacturing engineers. For example, a shaft might include a square-edged circumferential groove. If the groove is described as a snap ring groove—and if there is agreement on what that term means—then a manufacturing engineer would know that maintaining perpendicularity of the groove's sides to the long axis of the shaft is important.

[3] Statistical process control uses average and standard deviations of key dimensions as measures of process capability.

TABLE 2-1 Current and Future Practices for the Development of Products and Processes

Steps in the Design and Development of Products and Processes	Typical Today	2015 Vision: Integrated Manufacturing Technology Roadmapping Initiative	15-Year Vision: NASA's Intelligent Synthesis Environment Initiative	Future Perfect	Possible Today
1. Mission Requirements Analysis/Product System Strategy • high-level systems engineering analysis • requirements definition	• traditional systems engineering methods		• life-cycle simulation of mission requirements	• real-time or faster than real-time life-cycle simulations of mission requirements	• integrated systems and quality engineering methods
2. Product Specification • product strategy • voice of the customer • environmental and other regulatory requirements • planned product specification	• competitive comparisons • projections of future products • interviews and focus groups of customers and others • demonstrations • output is written documentation	• mass customization • strategic decision models • links to external and internal data • market assessment totals • risk management tools	• reliable specifications even for first-of-a-kind products • much faster responses to requests for proposals	• reliable "batch of one" methods for unique products • ability to write in preferences and requests • product created on demand	• more effective use of the Internet to determine customer demographics and preferences • virtual prototypes
3. Concept Development • target setting • brainstorming on product and process alternatives • development of product and process concepts	• iterative, largely manual, bottom-up, nonoptimized • benchmarks • rules of thumb • innovation relies on experienced practitioners	• integrated, predictive life-cycle cost and profitability models • optimization of shared resources	• complete life-cycle optimizations, trading performance, cost, risk, and schedule	**Steps 3, 4, and 5 combined** • expert system generates alternatives • optimized, top-down concept development process • automatic analytical evaluation of all product and process attributes (including risk and uncertainty) • single-pass product and process design and concurrent evaluation with multifunction optimization and automatic cascade to next lower level of design • automated generation of details about component and subsystem design and manufacturing details from high-level descriptions and desired attributes • single data source • full automation of subsystem and component tracking and trade-offs • no late trade-offs	• more systematic use of available performance data
4. Preliminary Product and Process Design • high-level definition of product and process designs • evaluation of product and process designs vs. targets • high-level system trade-offs	• iterative, largely manual, largely bottom-up, heuristic • derivations of existing designs • progressive definition • coarse definition, mostly manual from scratch • unequal levels of definition for new and reused parts • 20% of product and process attributes evaluated analytically using simplified models • reliance on physical prototypes	• rapid iteration of product and process design • object-oriented models scalable from macro to micro levels • single interoperable data set • automated process model creation • analytical evaluation of all attributes, including cost and producibility • multifunctional optimization	• some degree of iteration implied, but guided by optimization capability • analytical evaluation of all attributes, 200 to 300 times faster than current methods • integrated; single data source		• semiautomated refinement of proposed concept • reuse of one-half to three-quarters of generic designs with embedded rules, features, parametrics • analytical evaluation of about one-quarter of product and process attributes • data and model sharing • limited multifunction optimization • virtual manufacturing

5. Refinement and Verification of Detailed Product and Process Designs • development of designs for components, subsystems, and manufacturing processes • geometry creation • prediction and evaluation of all product and process attributes • tracking and trade-offs of subsystems and components	• detailed process and product definition mostly manual and from scratch • limited reuse of design geometries for new parts • analytical evaluation of one-third of product and process attributes using detailed models • some model sharing • reliance on physical prototypes • attribute prediction and evaluation partially automated, but not integrated with design evolution	• design advisors • distributed, collaborative processes • physical prototypes essentially eliminated • immersive evaluation environment	• immersive design environment • distributed, collaborative processes • minimal, "surgical" testing • immersive evaluation environment • no late trade-offs and no errors		• reuse of more than half of generic designs • analytical evaluation of one-third to one-half of detailed product and process attributes • tracking and trade-offs of subsystems and components managed by system tracking software
6. System Prototype Development • experimental refinement of product attributes that do not meet targets	• analytical evaluation required for more than half of all product attributes		• rework eliminated	• no experiments required	• less than one-quarter of all product attributes require experimental refinement
7. Preparation for Production • experimental refinement of process attributes that do not meet targets	• analytical evaluation of required for more than half of all process attributes		• rework eliminated	• no experiments required	• less than one-quarter of all process attributes require experimental refinement
8. Production, Testing, Certification, and Delivery	• on-line statistical process control	• products with 100% quality—getting it right the first time		• virtual design and manufacturing process with zero defects • only minor facility reconfigurations required for single product runs	• off-line robust design • lean, agile manufacturing • design for manufacturing: fewer parts, more compatibility, and easier assembly processes
9. Operation, Support, Decommissioning, and Disposal	• sequential, historically based modeling approach • a lot of manual operations	• consideration of remanufacturing in design • autonomous systems • accurate predictions of operating costs	• autonomous systems • accurate predictions of operating costs	• self-disassembly • self-disposal • self-healing	• simulation models based on operational processes • improved automation of support activities • design for easy repair • design for disassembly • design for reuse and remanufacture

continued

TABLE 2-1 Continued

Steps in the Design and Development of Products and Processes	Typical Today	2015 Vision: Integrated Manufacturing Technology Roadmapping Initiative	15-Year Vision: NASA's Intelligent Synthesis Environment Initiative	Future Perfect	Possible Today
Education and Training	• strong fundamental core courses • single capstone design course • courses taught in traditional classrooms • some video and Web-based courses	• just-in-time training via intelligent tutoring and advisory systems • training support using enterprise and product and process models • focused training tuned to new opportunities and the best match with different employee skills and working styles	• learning centers at each of NASA's Collaborative Engineering Environment facilities • university use of collaborative, distributed-learning consortia • practical experience of new engineers increased by one-half • technological obsolescence of workforce virtually eliminated	• AEE technologies and systems replicated at the university and used for maintaining a strong fundamental core course structure, with simultaneous links to the math and science departments and virtual links to industry and government laboratories • team teaching in engineering, math, science, management, and the humanities • personal learning experience emphasized—anytime, anywhere via an advanced Internet with high bandwidth • just-in-time training and tutoring • virtual interns	• integrated curriculum within a single discipline • design and system engineering courses starting with the freshman year • just-in-time training via computer networks

Sources: Adapted, in part, from: IMTR, 1999; NASA, 1999a; NASA, 1999b.

NOTE: The contents of the typical today and possible today columns are based primarily on (1) information collected from industry and government representatives during both phases of the study and (2) the experience of committee members.

greater benefits and increased satisfaction with each new generation of AEE technologies. Some early AEE risk takers were financially sound industry leaders; others faced a crisis of survival. The following case studies describe early efforts to implement AEE technologies:

- The Boeing Company's use of AEE tools in the development of the Boeing 777
- Electric Boat Corporation's (EB's) use of AEE tools in the development of nuclear submarines
- DaimlerChrysler's use of digital design and simulation in the development and launch of the Dodge Intrepid
- Concept ETI's use of personal computer (PC)-based AEE software in component design

The Boeing Company

In 1989, at the start of the 777 commercial airplane program, Boeing decided to use a CAD system (CATIA™)[4] with the primary goal of improving product quality. In addition, the company selected a formal, disciplined team approach to improve the design and manufacturing process. Specific goals were established for product quality and the new design process.

The results showed that product quality for the 777 was significantly improved over previous new designs. Boeing was also able to eliminate the full-scale mockup traditionally required for the spatial integration of structures and systems. Five months had to be added to the 777 program schedule, however, because the new system required new computer hardware, computer infrastructure, and personnel training. The associated costs offset the savings from more efficient processes, but the benefits of the new processes would continue to reduce costs in subsequent programs.

Based on lessons learned from the 777 program, Boeing and Dassualt Systèmes, the provider of CATIA, improved the design process and CATIA. When the improvements were incorporated into the 737 next-generation derivative airplane program during the 1993–1997 design phase, they resulted in further improvements in product quality, higher rates of airplane production (up to 24 airplanes per month), service reliability consistent with expectations, a shorter program schedule, and lower costs.

In the Joint Strike Fighter (JSF) Program, which is in the concept demonstration phase, further improvements have been made to both design and manufacturing processes. Boeing has reported that tooling costs for its JSF X-32 concept demonstration aircraft were less than half of the tooling costs for the YF-22 (the concept demonstrator for the F-22). Boeing also estimates that assembly of the X-32 aircraft required almost 50 percent fewer labor hours than comparable aircraft and that overall fabrication and assembly costs for the X-32 aircraft are 30 to 40 percent lower than initial projections (Tibeau, 1999).

Boeing's experience illustrates the ongoing return on investment that AEEs can provide by increasing the competitiveness of future programs that were not envisioned when the initial investments were made. However, because Boeing has also made many other changes in its operations since 1989, it is difficult to validate the extent to which one area, such as AEEs, has contributed to overall improvements.

Electric Boat Corporation

EB, a business unit of the General Dynamics Corporation, is one of two submarine manufacturers in the United States. As the production of Los Angeles Class nuclear-powered attack submarines (SSNs) was being completed in the mid-1990s, EB and the Newport News Shipbuilding Company (the other manufacturer) jointly designed the Seawolf Class submarine. EB then built and delivered two Seawolf-class SSNs, and a third is under construction. In addition, EB designed a new class of SSNs (the Virginia class), which are being built through a teaming arrangement between EB and Newport News.

EB has two major facilities: a shipyard at Groton, Connecticut, and a fabrication and outfitting facility at Quonset Point, Rhode Island. Hull frames and cylindrical hull segments are manufactured at Quonset Point and then shipped to Groton for final assembly and launch. The Quonset Point facility was built in the 1970s as a completely new facility and, from the beginning, has used unconventional shipbuilding techniques. Because most of the personnel at Quonset Point had no prior shipbuilding experience, management was able to adopt new methods without having to overcome a traditional shipbuilding culture among the workforce.

As the rate of submarine construction declined sharply in the 1980s, EB was faced with the possibility of going out of business unless the cost of new submarines could be reduced. Driven by necessity, EB management became very open to new ideas for improving products and processes. A champion with vision and strong leadership skills was critical to this process. He enlisted the strong support of the workforce for implementing the new processes and received strong corporate support that remained firm even when unexpected problems occurred. Another key element in EB's success in implementing AEE technologies for the Virginia class was its preliminary survey of recognized industry leaders. For example, Boeing, Chrysler, and others were consulted before EB decided to "single-up" on CATIA as its principal electronic design tool.

The process of bending pipes, which is an important step in the submarine manufacturing process, exemplifies some

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[4] CATIA originated as an acronym for Computer-Aided Three-Dimensional Interactive Application. The committee did not evaluate and does not endorse any commercial products mentioned in this report.

of the changes EB has introduced. Nuclear submarines contain vast quantities of piping for fluids and gases (e.g., seawater, fresh water, diesel oil, hydraulic oil, air, and oxygen). EB can move design data from CATIA to pipe-bending, plate cutting, and weld preparation machines with little or no human interaction. In addition, a rule-based feedback loop from the manufacturing facility to the design system warns designers if they specify a pipe configuration that available machines are unable to produce.

EB has selectively applied AEEs to the processes with the largest potential return. Ten years ago, EB built full-scale wooden mockups for all new submarine designs. In some cases, several rework cycles with the mockups were needed before the designs were judged to be satisfactory by EB and Navy technical managers. EB now relies almost entirely on electronic product and process simulations. For example, simulations are used to investigate moving parts for interference or operability problems. The physical mockup of the propulsion plant for the Virginia class SSN required an average of less than 10 percent rework. Based on this experience, the Virginia class will probably be the last SSN that EB designs with physical mockups.

Another major contributor to EB's success with the Virginia class SSNs was the integration of key manufacturing resources into "design-build" teams. Each team had two coleaders, one from the technical community and one from manufacturing, to ensure that all products would be optimized from a manufacturing perspective in the design phase.

EB has also used AEE technologies to expand the use of its modular manufacturing process. The Virginia class SSNs will be approximately 95 percent modular. Each module consists of a large platform on which the ship's systems, components, and other elements are assembled. The modules are then inserted into preassembled hull sections. The modules within a given section are then connected to each other and shipped to the waterfront, where the hull sections are joined to form a complete submarine. Systems can be manufactured, assembled, and, in many cases, tested in an open factory environment, greatly reducing the number of tasks that must be performed in the tight physical confines of an assembled submarine hull. As a result, submarines are being built in less time and at lower costs.

EB decided against full implementation of integrated product data management, which would provide a single data set for all products and processes, because the savings would be small compared to the cost of implementation for a company like EB that manufactures complex products in small quantities.

EB has clear metrics for measuring the efficiency of its shipbuilding operations. It carefully tracks labor and material costs, design changes, numbers of design documents, and deficiencies. If a manufacturing unit manager at EB claims that near-term investments in new processes and tools will reduce future costs, that manager is expected to reduce his or her budget in future years by the amount of the projected savings. Managers' abilities to achieve projected savings are an important factor in annual performance evaluations.

Based on their experience with AEEs to date, EB managers interviewed by the committee believe that efforts to improve the efficiency of design and engineering processes should focus on organizational issues, as well as tools and processes. In addition, although EB relies heavily on software and parts produced by outside vendors, the company sometimes creates software and parts even if software design or parts manufacturing services are available from outside sources. EB reported that generating software internally (with EB staff and dedicated contractors) ensures that tools are optimized for EB processes and that EB has instant access to the developers when problems arise or modifications are needed. EB also reported that manufacturing submarine parts in house often leads to improved designs because the fabricators, assemblers, installers, and testers—who understand how their components are used and have a vested interest in improving the quality and reducing the cost of the total system—often suggest ways to redesign parts to improve performance or reduce manufacturing costs. Other large organizations, such as NASA, that make similar make-or-buy decisions should have a clear understanding of the benefits and consequences of the alternatives (i.e., either designing and manufacturing software and equipment internally or procuring them from outside vendors) to ensure that each decision is in the organization's best long-term interests.

DaimlerChrysler

The Chrysler Corporation (now DaimlerChrysler) pioneered the use of digital design and simulation to reduce the development time and cost of new automobile programs. DaimlerChrysler's goal in using AEE technologies was to improve its competitiveness and increase its market share and profitability. DaimlerChrysler developed the Dodge Intrepid using a nontraditional approach, planning, designing, building, and testing the new vehicle in a purely digital design and engineering (CAD/CAE [computer-aided engineering]) environment. This approach eliminated the need for most physical mockups. All information surrounding the design of the car (e.g., schematics, specifications, documentation, and test results) was electronically generated, manipulated, and stored, thereby eliminating difficult-to-manage paper documentation.

Program costs through production of the first vehicle, which typically range from $1 to $2.5 billion for new car designs, were approximately $2.1 billion for the Intrepid and three other cars off the same platform and new family of V6 engines. Total development costs were reduced by $80 million net, including the expense of installing the infrastructure needed to shift the design, development, and test process to a new, advanced environment. The product design, build, and test cycle, which typically lasts 40 to 44 months, took approximately 31 months for the Intrepid. These results, combined with reportedly high levels of owner satisfaction, indicate that this application of AEE technologies was successful. Also, the validated digital designs and simulations produced for the Intrepid are reducing the cost and development time for updates to the Intrepid and new models based on similar digital platforms.

Concepts ETI, Inc.

Concepts ETI, Inc., a small company in Vermont with 50 employees, designs and manufactures pumps, compressors, and other turbomachinery. Concepts ETI has demonstrated that powerful AEE technologies incorporated into a desktop PC can notably improve design and manufacturing processes and product quality. Concepts ETI, which has specialized expertise in the limited range of products that it manufactures, had previously developed its products in a partially standardized setting. Although the designs are sophisticated, the products are much less complex then the rockets, aircraft, and ships in which they are installed. All of these factors contributed to the company's success in using AEE technologies.

Concepts ETI captures its engineering design knowledge in a tool set that creates a concurrent engineering design process with seamless connectivity between different software design tools. These tools combine profiles of internal fluid or gas velocity for a proposed pump or compressor design with computational fluid dynamic models and finite element analyses of structures on one PC. Product lifetime, size, weight, and cost are assessed using real-time design interactions.

Concepts ETI adopted AEE design practices to cut costs, reduce design cycle time, and improve its competitiveness. These goals have been achieved. In the last 20 years, Concepts ETI has reduced the cost of designing a typical product from $600,000 to $150,000, even though its products have doubled in mechanical design complexity and the complexity of the design and analysis process has increased by five orders of magnitude. Building on the success of its analytical tools and processes, Concepts ETI now markets software for engineering design, analysis, and testing. In addition, the company has established graduate education and professional development programs through which students can earn credit hours towards graduate engineering degrees at the University of Vermont.

VISIONS OF THE FUTURE

15-Year Visions

The purpose of NASA's Intelligent Synthesis Environment (ISE) Initiative is to develop AEE technologies and systems. The ISE initiative is focused on integrating widely distributed science, technology, and engineering teams and enabling the rapid creation of innovative, affordable products for science and engineering applications. Additional information on the initiative is available on line (NASA, 2000).

The Next Generation Manufacturing Project, completed in 1997, was sponsored by several federal agencies and conducted jointly by representatives of industry associations, government agencies, and academic institutions. This project studied long-term trends in U.S. manufacturing in light of global changes and recommended ways to overcome competitive challenges. One of the recommendations was that technology road maps be created to guide future developments. The IMTR initiative, described below, was established to accomplish this.

The third and fourth columns in Table 2-1 depict the IMTR 2015 vision and the 15-year vision of NASA's ISE initiative, respectively. Neither vision was organized according to the steps listed in the first column of Table 2-1, so the committee took the liberty of reorganizing them for the purposes of comparison.

The IMTR vision anticipates a rigorous and capable product specification stage, with broad access to product and customer data. The plan also calls for objective tools to assess market needs, market characteristics, and product capability, as well as analytical models to improve strategic decision making and risk management. The rigor in these key elements flows down through the other design steps, emphasizing accurate predictions of all product attributes at every stage of the design without the testing of physical properties until product and process designs are refined (step 5). The IMTR vision also anticipates optimization capabilities for trading off product attributes starting fairly early in the process. Therefore, the trade space is defined early in the process (in terms of minimum and maximum acceptable values for each product attribute). The optimization capability reduces or eliminates iterative steps as the design progresses. It also improves tools and other engineering resources that are used by more than one program, further increasing capabilities in the early stages of the process.

The ISE's 2015 vision is even more ambitious. It foresees the ability to conduct first-of-a-kind missions routinely with high levels of confidence, even for missions for which little or no experience or experimental data are available to predict system capability. The ISE vision includes the evaluation and optimization of attributes across the complete life cycle at all stages of design refinement and product trade-offs with minimum design iteration. Like the IMTR vision, the ISE vision includes minimal "surgical" testing of attributes. Almost all evaluations would be done virtually, not physically, with immersed environments operated by geographically and temporally distributed collaborative teams. Rework and late trade-offs would be eliminated. Because the ISE vision must also support missions, such as deep-space probes, where human supervisory control will not be practical, the ISE vision emphasizes autonomous system capability for some functions, such as self-directed exploration and fault repair.

Many other public and private organizations are also involved in the development of AEE technologies and systems. For example, the U.S. Department of Energy is sponsoring the Accelerated Strategic Computing Initiative to develop computational-based methods of ensuring the safety, reliability, and performance of the U.S. nuclear weapons stockpile in the absence of nuclear testing and with a greatly reduced weapons manufacturing infrastructure (Sandia National Laboratories, 2000). In addition, the Defense Modeling and Simulation Office sponsors 10 separate initiatives for increasing the efficiency and interoperability of modeling and simulation within the U.S. Department of Defense (DMSO, 2000). Separate elements of federal departments are also conducting their own AEE programs, such as the U.S. Army's Simulation and Modeling for Acquisition, Requirements and Training (SMART) Program. The intent of this program is to use advanced modeling and simulation technology to improve the performance of future systems while reducing costs, development time, logistics requirements, and training requirements (U.S. Army, 2000).

The committee did not attempt to evaluate the interrelationships among all ongoing AEE technology development programs, or even to compile a comprehensive program list. In some cases, however, the committee noted that steps have been taken to improve interagency coordination, such as the recent decision by NASA and the U.S. Army to link the ISE initiative and the SMART program. Also, the ISE and IMTR visions seem to be generally consistent with expectations for related programs with which the committee became familiar.

Future Perfect

Column 5 in Table 2-1 defines a "future perfect," which combines and expands on the 15-year visions. The capabilities described are perhaps even more aggressive than those implied in the prologue. The mission-requirements process envisioned for the future perfect uses, at a minimum, real-time simulation of all aspects of product and mission performance that account for and describe the effects of uncertainty and risk on product attributes and prospects for mission success. This vision also emphasizes first-of-a-kind or batch-of-one product customization and includes the capability for customers to design their own products using the system's automated optimization capabilities. Indeed, in this vision the steps of concept development, preliminary design, and detailed design are collapsed into a single step. Inherent in this merging of design and development steps is the integration of product design with the development of manufacturing methods (i.e., an extension of existing design for manufacturing and assembly methods). An expert system generates design alternatives, which are then optimized in a single pass while cascading requirements down through system and component levels. This capability would be error-free and eliminate the need for iteration, physical prototypes, experimental refinement, or rework. Although this vision will certainly not become a reality in the next 15 years, it does serve as a useful reference point for judging improvements beyond the 15-year visions.

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3

Expected Future

This chapter extends the process paradigm in Chapter 2 to predict how the mission/product design process will look in 7 and 15 years. The chapter discusses underutilized elements of available AEE technologies by examining the gaps between typical current practices and what is possible with current technology. Major areas of improvement are identified by examining technical advancements that would enhance progress toward realizing AEE capabilities. Based on current efforts to advance AEE technologies and processes, expectations for the next 7 and 15 years are described and compared to the IMTR and ISE 15-year visions. The chapter closes with findings and recommendations for improving the 15-year outlook.

UNDERUTILIZED AEE ELEMENTS

The gap between practices that are typical today and practices that take full advantage of currently available AEE capabilities is substantial. Some of these gaps can be identified by comparing the second column with the last column of Table 2-1. More robust mission requirements could be established if quality engineering methods were integrated with traditional systems engineering methods. Using virtual prototypes (i.e., computer models and simulations) instead of physical prototypes for development testing is another capability that could benefit many industries, as some architectural firms have shown. But this practice is not widespread. Systematic methods of comparing performance data of alternative designs could also be used more.

Several factors have contributed to the underutilization of AEE technologies. First, finding and accessing analytical data for many products and processes is difficult, and some attributes can only be compared heuristically. Second, institutional program inertia and the natural desire to create new designs rather than extend someone else's old design (even though the latter is almost always the result in any case), have also impeded the use of new AEE technologies.

Based on information collected for this report and the experience of individual committee members, the committee estimates that one-half to three-quarters of new parts could reuse previous designs and still meet product and process requirements. Reuse reduces the need for new product geometries and increases the use of previously determined features, parametrics, and embedded rules. At the preliminary design level, the committee estimates that about one-quarter of product and process attributes could be evaluated analytically; this number could increase to one-half during detailed design, depending on the attribute being evaluated. Analytical evaluations would greatly reduce the percentage of attributes requiring experimental refinement through prototypes. The fraction of manufacturing processes that require experimental refinement could also be reduced, from about one-half to about one-quarter.

Simulations of manufacturing processes could be greatly improved by using accurate, scalable human figure representations (virtual humans), which can be created by products such as Jack™ from Engineering Animation or ERGO™ from Deneb Robotics. Virtual humans can be scaled by gender, age, and size to evaluate the ability of people with given strength and joint-angle constraints to perform proposed tasks. For example, EB used ERGO extensively to verify electronically the human factors aspect of the Virginia class SSN. This, in turn, significantly reduced the number of downstream design changes that had traditionally been necessary in the manufacturing, testing, and operational phases.

Taking full advantage of today's AEE capabilities will require commensurate changes in organizational culture and educational practices. For example, available methods could better integrate the curricula in a given discipline (e.g., fluid mechanics and thermodynamics) and enable the teaching of system-level engineering beginning in the freshman year of undergraduate studies. Also, the committee observed that most organizations do not use distributed collaborative work teams, and very few organizations that do use them have extended their use beyond the preliminary design stage. Using AEE technologies to facilitate effective teamwork would constitute a significant step forward in organizational culture.

Finding 3-1. Industry, government, and academia can significantly improve their engineering practices by using available AEE technologies.

MAJOR AREAS OF IMPROVEMENT

Table 3-1 links improvements in AEE capabilities to steps in the product and process design and development process. The process steps listed on the left side of the table are the same as the ones described in Table 2-1. Improvement areas and methods of improving AEE capabilities are listed across the top of the table. These areas are described here briefly and in some detail below. Table 3-1 is based on information collected by the committee during both phases of the study.

Design paradigm refers to the trend away from regarding parts as the central theme of design and toward regarding assembly and, ultimately, function as the starting point for design and the focal point for all design attributes. *Attribute evaluation* is the means of predicting design characteristics and performance. *Hybrid evaluation* refers to the typical process of using a combination of physics-based and empirical models to make analytical predictions. *Physics-based evaluation* refers to analytical modeling based on first principles, which is possible in areas that are so well understood that empirical data are not needed during the design and development of new products and processes. This capability will have to be expanded to a wide range of disciplines and applications to achieve the first-of-a-kind design capability desired by NASA and others. With *statistical/stochastic evaluation,* all aspects of uncertainty and variability can be incorporated into performance predictions. In this context, *statistical* implies that the elements of uncertainty and their probabilistic distributions are known, whereas *stochastic* implies that little or no information is available about the variables involved or their behavior.

The two methods associated with visualization of product and process designs are *scientific visualization* and the developing field of *networked virtual environments.* Methods associated with *guidance for designing products and processes* progress from *heuristics* (including rules of thumb) to *multifunctional optimization* (MFO) and *expert systems* as means of advising the designer.

The entries (H [high], M [medium], and L [low]) at the intersections of the rows and columns in Table 3-1 show the importance of each improvement to each process step. For example, achieving a true physics-based analytical capability would greatly improve (H) the prediction of product attributes throughout the overall process and, thereby, move the product design process from the typical today state toward a future perfect state. Improved heuristics would have a highly beneficial impact (H) on target setting for new concepts, a moderate impact (M) on the development of new concepts and high-level system trade-offs, and a minor effect (L) on trade-offs at the component level.

EXPECTATIONS FOR THE FUTURE

The following sections summarize the committee's expectations for product and process improvements over the next 7 and 15 years. These projections are based on interviews by committee members with key providers and practitioners of the methods listed and the assumption that ongoing research and development efforts continue as planned, with no significant reductions or additions. Predicting the future, however, is always risky. In some cases, predictions turn out to be overly optimistic, as with past expectations about the future of artificial intelligence or intelligent highways. In other cases, predictions have been greatly exceeded (see Box 3-1). Thus, the committee considers these expectations informative, but also speculative.

In the following discussion, analytical methods of predicting attributes are referred to as either *general-purpose* or *special-purpose* methods. General-purpose methods are applicable to a broad variety of problems and/or problems with a broad user base. Examples include kinematics, material processing (e.g., machining, forging, or casting), electrical circuit analysis, and finite element methods of calculating strength and stress. The committee anticipates strong demand and support for improvements in general-purpose methods. Special-purpose methods, such as combustion analyses and predictions of total life-cycle costs, have either a narrow user base or require significant customization to meet each user's needs. Improvements in special-purpose methods will probably require targeted investments by affected companies or user groups.

Conceptually, projects can be grouped into *less complex projects* (i.e., the development of evolutionary or relatively simple products or missions) and *highly complex projects* (i.e., the development of new, complex, or highly interactive products or missions). Less complex projects include changes to the design of a well characterized motor or pump that would not depart from the fundamental operating principles of existing designs, even if the redesign significantly alters the product's geometry, electrical characteristics, or performance. *Relatively simple* implies that the product is probably either (1) a component or subsystem or (2) a system whose internal and external interfaces are relatively simple and can be well defined. By contrast, highly complex projects include the development of automobiles, whose system interactions are very difficult to define, and first-of-a-kind design of an undersea robot or autonomous spacecraft. Highly complex projects also include systems of systems, such as the Federal Aviation Administration's National Airspace System, which involves interactions of advanced

TABLE 3-1 Improvement Areas and Methods of Designing and Developing Products and Processes

Improvement Areas:	Design Paradigm	Attribute Evaluation			Visualization of Product and Process Designs		Guidance for Integrated Design of Products and Processes			Collaborative Support
Steps in the design and development of products and processes **Methods:**	Parts-to-Function Paradigm	Hybrid Evaluation	Physics-Based Evaluation	Statistical/ Stochastic Evaluation	Scientific Visualization	Networked Virtual Environment	Heuristics	MFO	Expert Systems	
1. Mission Requirements Analysis/ Product System Strategy										
• high-level systems engineering analysis			M	M		M				
• requirements definition										
2. Product Specification			H							
• product strategy										
• voice of the customer										
• environmental and other regulatory requirements										
• planned product specification				M		M				
3. Concept Development										
• target setting							H	H		
• brainstorming on alternatives					M	H			H	H
• development of product and process concepts	H	M		M			M	H		H
4. Preliminary Product and Process Design										
• high-level definition of product and process designs	H				M	H				H
• evaluation of product and process designs vs. targets		H	H	H		M			M	
• high-level system trade-offs		M		M			M	H	H	M
5. Refinement and Verification of Detailed Product and Process Designs										
• development of designs for components, subsystems, and manufacturing processes	H									
• geometry creation	H					M				
• prediction and evaluation of all product and process attributes		H	H	H					M	
• tracking and trade-offs of subsystems and components				M			L	H	H	M
6. System Prototype Development										
• experimental refinement of product attributes that do not meet targets	H	H	H	H						
7. Prepare for Production										
• experimental refinement of process attributes that do not meet requirements	H	H	H	H						
8. Production, Testing, Certification, and Delivery										
9. Operation, Support, Decommissioning, and Disposal		M								H

NOTE: Entries indicate importance (high [H], medium [M], or low[L]) of improvement areas in moving process elements from the "typical today" state toward the "future perfect" state.

BOX 3-1
Unpredictable Acceleration of Computing Technology

In 1989, supercomputers cost from $1 to $20 million, and the best commercially available machines, such as the Cray Y-MP, could perform about 1 billion (giga) floating-point operations per second (i.e., 1 gflop) using 8 interconnected central processing units. A National Research Council report published in 1989 predicted that in 1999 commercially available supercomputers would demonstrate 100 gflops using from 32 to 256 interconnected central processing units (NRC, 1989).

Improvements in general-purpose supercomputers have exceeded these predictions. By November 1999, the 50 most capable supercomputers in the world, which were built by six different manufacturers, could all perform more than 200 gflops. The top 15 could perform more than 500 gflops, and the most capable machine (the Department of Energy's *ASCI Red* supercomputer, manufactured by Intel), could perform 2,400 gflops using 9,632 linked processors (TOP500, 1999). Commercially available machines, such as the Cray SV1, can be configured to provide up to 1,000 gflops (Cray, 2000a).

The 1989 report also described the technical difficulty of reducing the size of supercomputers. The Cray X-MP supercomputer, which was introduced in 1982 with a capability of 0.5 gflops, occupied about 100 square feet—and was much smaller than earlier generations of supercomputers (Cray, 2000a, 2000b). The 1989 report predicted that supercomputers smaller than the Cray X-MP might be developed, but cooling would be a "fantastic problem." A "suitcase-sized supercomputer may dissipate a couple thousand watts of power," and there "would be an instant meltdown in case of a cooling malfunction" (NRC, 1989). Today, the most capable supercomputers are still massive devices with large cooling requirements. At the lower end, however, children's toys that feature impressive capabilities come in small packages with no special cooling requirements. Unlike general-purpose supercomputers, the special-purpose PlayStation® 2 video game console conducts single precision computations. Nonetheless, the PlayStation 2 is capable of 6.2 gflops, takes up just 0.25 square feet, consumes 15 watts of power, and sells for about $300 (Sony, 1999).

technologies for air traffic control with advanced technologies for aircraft.

Product Technologies

This section describes 7-year and 15-year expectations for product technologies related to design paradigms, attribute evaluations, design/process visualizations, guidance for designing products and processes, collaboration support, and education and training.

Design Paradigm

Seven-Year Expectations. The committee predicts that approximately half of CAD work will be done on Web-based systems communicating through open standards. Exchange of parts will be reliable up through "dumb" solids (which contain no information about features, parametrics, or design intent). It will be possible to design 75 to 90 percent of simple parts from generic, reusable design templates (wizards). For these parts, the traditional laying of lines or creation of geometry from scratch on CAD systems will be eliminated. For example, rather than creating the geometry of a structural rib one feature at a time, the user will specify a minimum set of unique dimensions, and a generic template will automatically create the rest of the product specification. Design tables will be used for part regeneration, and design templates for processing. Automated part creation from functional descriptions will be emerging, but only for simple, common parts and assemblies. Graphical interfaces will replace dialogue boxes. Haptic feedback will be used to display the results of analyses to experienced users for some tasks, such as evaluating fit and assembly processes.

Fifteen-Year Expectations. Monolithic CAD systems will no longer exist. Data exchange will be reliable, even for "featured" solids, which include information on function and design intent. Function-based design will be common for simple parts and will be emerging for complex parts and assemblies. Some forms of unique parts will be created using functional descriptions. Geometry optimization will be common at the part level. Concept design with detailed, automatically generated models of complex systems will be possible. Rules-based algorithms embedded in the design generator will ensure that the specified part is satisfactory for all design conditions (e.g., thermal pressure and impact loading). This will reduce the difficulty of analysis when parts are at different levels of design definition (the mixed-phase design problem). Virtual reality interfaces will be common for aspects of functional design, and they will be integrated with real-time analysis of functions, at least for general-purpose methods.

Attribute Evaluation

Seven-Year Expectations. The speed of general-purpose methods will be 10 to 30 times faster than today, significantly automated, and easier to use. Evaluations will be more accurate and provide high levels of product definition. These methods will be at least half Web-based, with reliable data exchange and interoperability of related analytical streams. Most verification testing will have been eliminated for these methods. Back-end analyses, such as processing and assembly, will benefit from industry's emphasis on rapid service to the consumer. Special-purpose methods will advance unevenly, depending on the efforts of individual companies or user groups. The utility of design analyses with a low level of detail definition will show limited progress. Improvements in physics-based analyses will also be limited for most attributes. Dynamic analysis methods are likely to show the most progress.

Fifteen-Year Expectations. The growth of rules-based automated methods of designing parts based on functional descriptions will lead to highly automated general-purpose design methods for most applications. These methods will account for product and process variabilities, including manufacturing variability, and will provide better predictions of performance than prototype testing. Special-purpose methods will have advanced similarly, especially in areas of special interest to individual companies or user groups that have been active in supporting the development of advanced design methods. Mixed-phase analysis will be automated, enabling seamless integration of highly detailed parts with concept-level parts, and general-purpose methods will be as useful for concept development as for detailed design. Also, some of today's special-purpose methods, such as vibration or impact analysis, may be so easy to perform 15 years hence that they will be considered general-purpose methods.

Design/Process Visualization

Seven-Year Expectations. Multimodal systems will have graphics that operate at more than 300 million polygons per second, with some spatial audio interfaces[1] and haptic interfaces (on tool handles). Computer-generated agents will be available to guide human designers, but the agents will not operate autonomously. Computers will be 200 times faster than today.

Fifteen-Year Expectations. Graphic systems will have high speed and quality (one billion polygons per second, 60 frames per second, images indistinguishable from reality). Interfaces with full spatial-audio effects, full-hand haptics, and olfactory displays will also be available. With computer-generated autonomy, agents will do much of the design, guided by high-level specifications. Computers will be 30,000 times faster than today.

Guidance for Designing Products and Processes

Seven-Year Expectations. Easing constraints will be a tempting and popular alternative to true optimization analysis. MFO (multifunctional optimization) will be incorporated into general-purpose methods, including analyses of control, stress, vibration, and assembly, but will not be widely used for linking different general-purpose methods. MFO will not be incorporated into special-purpose methods, cost, weight, or complex material processing. Enterprise resource management will have moderate optimization capability but will not include life-cycle cost. Recursive design will be the dominant method, with faster iterations and more heuristic guidance than today. Expert systems will be used with general-purpose methods of raising the performance of less skilled users to a predictable, consistent level, but they will not replace experienced designers or engineers when creativity is required. Expert systems will play a role in moving from geometry-based to function-based design but will be confined to repetitive design tasks. Heuristics will be extensively used in conjunction with general-purpose methods and will provide substantial benefits in the concept development stage of design.

Fifteen-Year Expectations. MFO will be available across the more common general-purpose methods. For example, producibility may be combined with stress and control performance. Special-purpose methods will be included in MFO for selected situations. Enterprise resource management will be highly developed, with moderate life-cycle cost capability. Heuristics will be so well integrated with design and MFO packages that heuristic methods will be virtually indistinguishable from rigorous optimization. Nonrecursive design will be possible for less complex projects and general-purpose methods, but recursive design with design guidance will still be required for more complex problems and special-purpose methods. With expert systems, unique parts and simple assemblies will be created automatically based on functional descriptions.

Collaboration Support

Seven-Year Expectations. Video walls and smart meeting rooms will be widely available. Grid-like networking infrastructures connecting designated user groups with secure high bandwidth will enable routine exchanges of large data files and group interactions. Shareable distributed sets of extant data, objects, and tools will be readily available. Event

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[1] When using headphones, spatial-audio interfaces make sounds appear to come from particular points in space outside the listener's head. With ordinary stereo headphones, sound generally appears to originate somewhere on a line between the listener's ears. Spatial-audio effects increase the sense of being immersed in a virtual environment, especially when sounds are generated at more than one location in virtual space.

capture will be commonly used to provide access to knowledge bases with group memories. A large selection of interoperable tools and techniques will be available for education and training of individuals involved in new collaborations or projects.

Fifteen-Year Expectations. Immersive telepresence and roomless meetings will become practical. Large-scale collaborations with broad scopes will be available through ubiquitous networking technologies, not just specially equipped user locations. Heterogeneous interoperability will enable the transparent sharing of data, objects, and tools among collaborators. Event guidance and smart capture to facilitate collaborations will create an accessible knowledge base and group memory. Automatically adaptive, reconfigurable tools will be available for teaching individuals involved in new collaborations and projects.

Education and Training

Seven-Year Expectations. A large number of Web-based degree programs will be available. Some AEE links will be established with NASA and industry. Design and system engineering courses will start in the freshman year and will be partially integrated into the curriculum.

Fifteen-Year Expectations. Fundamental courses will be linked with AEEs. Team teaching in engineering, mathematics, and science will be common. Case studies of projects using AEEs will be used as examples. Cross-disciplinary design and system-engineering courses will be fully integrated into the curriculum.

Processes

Seven-Year Expectations

For less complex projects, the concept development and preliminary design phases will collapse into a single process step, especially for general-purpose attributes. The time required for these steps will be reduced by as much as one-half. The most difficult aspect of achieving this goal will be improving the accuracy of predictive methods of refining detailed designs. Improvements can be expected in selected areas with the development of heuristics, physics-based analysis, and expert systems to support early design.

For complex projects, preliminary design and detailed design will still be distinct tasks. The level of available design detail will vary at different points in the design process. Therefore, the accuracy of performance predictions will also vary. For less complex projects and general-purpose methods, predictions will be very accurate during the later design phases and manufacturing. This increase in accuracy will almost completely eliminate the need for experimental refinement and physical prototypes (but only for less complex projects and general-purpose methods). The time for steps 5 through 7 of the design and development process (detailed design through preparation for production) will decrease by as much as a third.

Highly complex projects will benefit from part reusability and limited, function-based geometry creation. Special-purpose methods could achieve many of the same improvements as general-purpose methods if the demand and corresponding investments are sufficient. However, process steps are unlikely to collapse into a single step, as they will for less complex projects.

Semiautonomous, computerized, digital design advisers will be created for specific purposes. Limitations will include insufficient physics-based analysis capabilities, a limited ability to break down complex systems, and difficulties in dealing with nonlinear and subjective phenomena. Reductions in total process time will be limited to about 20 percent, with similar reductions in cost. Although physical prototypes will still be necessary for highly complex projects and special-purpose methods, the speed of iteration and improved visualization should reduce their number by at least 20 to 30 percent, with similar reductions in the amount of rework associated with experimental refinement during prototype development and preparation for production (steps 6 and 7).

Also during the next seven years, improved collaboration processes will enable work in all design process stages to be distributed more broadly across teams and organizations. However, participation in a distributed design collaboration will still depend heavily on physical location, and effective anywhere-to-anywhere collaboration will continue to be a future goal. Improved capabilities for sharing data, objects, and tools will be evident throughout distributed work on less complex projects, particularly projects that rely on general-purpose methods for which open standards will have emerged. Improvements in the distribution and sharing of digital designs will mean that human efforts to integrate and synthesize work outputs will occur largely at the system and subsystem levels of design. At the part and component level, integration and synthesis will be mostly automated.

Fifteen-Year Expectations

For less complex projects and general-purpose methods, steps 3, 4, and 5 (concept development, preliminary design, and detailed design) will be collapsed into a single process, which will be one-quarter to one-half as long as today's processes. This reduction will be attributable to a combination of computerized design advisers, rapid iterations of design and analysis, physics-based analyses, MFO, and advanced visualization, all of which will reduce the number of design iterations, although the process will still be recursive for all but the simplest products. Experienced staff will be required to manage the design flow for all but the most repetitive designs because the selection of appropriate methods from available tools will have to be tailored to the individual problem. Many mundane functions, such as geometric design, specification of tolerances, assessment of processing feasibility, and prediction of general-purpose attributes, will be completely automated. Physical tests will be unnecessary to validate product attributes and processes, except where special-purpose methods are needed. Physical testing of special-purpose prototypes will only be needed when special-purpose methods are not as capable as general-purpose methods.

For general-purpose methods applied to highly complex projects, it will be possible to collapse steps 3 and 4 (concept development and preliminary design) into a single step for all but truly unique products. Tools will be augmented with function-based design and concept design methodologies that include detailed part definitions to make this collapse possible. Little or no hardware evaluation will be necessary during concept development or preliminary design. In step 5 (detailed design), evolving design maturity will produce changes in the design that will require redefinition, reevaluation, and trade-offs. These changes will probably not be automated for new or complex systems. Augmentation of experienced personnel with computerized advisors will reduce the time and improve the accuracy of detailed design. For prototype development and preparation for production (steps 6 and 7), physical tests will be limited to the evaluation and refinement of system interactions and will, therefore, be reduced by at least half.

For special-purpose methods applied to highly complex projects, progress will depend entirely on the degree to which special-purpose methods have been developed. Concept development and preliminary design (steps 3 and 4) will probably be partially combined, depending on the maturity of the special-purpose methods. In the absence of highly developed special-purpose methods, the ability to conduct concept design with detailed parts and the assistance of computerized advisors will be critical to increasing the speed and accuracy of the early design stages. Depending on the maturity of special-purpose methods, perhaps one-third of prototypes used during preliminary design will be eliminated, with a similar reduction in testing during experimental refinement of prototypes and production methods in steps 6 and 7. These reductions will be less pronounced for projects that require nonphysics-based analyses and for projects with complex system interactions for which decomposition techniques are not available.

Advances in computer systems are likely to be so great that users will not be limited by the capabilities of computing hardware. Voice interfaces will be common, and distributed computers and wireless interfaces will be embedded in a wide variety of products. Immersive environments will be commonly available for entertainment and work. The demand for skilled technicians to manage AEE systems will increase, and the educational system will adjust curricula to meet this need.

Finally, constraints on the physical location of personnel engaged in complex collaborations will have been largely eliminated for nearly all stages of the design process (with manufacturing likely to be the most notable exception). Further improvements in the sharing of standards-based and heterogeneous data, objects, and tools will facilitate distributed work on all types of projects, whether they rely on general-purpose or special-purpose methods. For all less complex projects, and for some highly complex projects, moreover, human work in integration and synthesis of information will be confined to the system and metasystem levels of design. All lower levels of integration and synthesis will be handled by autonomous AEE technologies.

COMPARISON OF EXPECTATIONS TO THE 15-YEAR VISIONS

This section compares the committee's expectations for future technologies and processes (described above) to the 15-year visions defined by the ISE and IMTR initiatives (summarized in Table 2-1). Based on current and projected efforts by industry and government, the committee does not believe that all elements of the 15-year visions are likely to be achieved. Because of political pressure to constrain discretionary spending by the federal government, obtaining support for major new initiatives is very difficult. As a result, advancing the state of the art of AEE technologies and systems rapidly enough to achieve the 15-year visions of the IMTR or ISE initiatives is highly unlikely. For example, physics-based, first-principles analyses will not be able to predict the reliability and performance of first-of-a-kind products and missions with enough certainty or accuracy to preclude testing. Shortcomings will also persist in modeling interactions in highly complex systems.

Life-cycle optimization will be limited to general-purpose and selected special-purpose methods and will not accurately predict cost or risk. Enterprise resource management will predict comprehensive life-cycle costs with limited accuracy.

The committee believes that attribute prediction will be almost completely analytical for general-purpose and selected special-purpose methods, but physical testing will still be required to refine some attributes, especially for complex system interactions and first-of-a-kind missions or products.

The time needed to complete some steps of the design process will be reduced by more than the factor of 200 predicted in the ISE 2015 vision. However, the time to complete the overall design and manufacturing cycle will not reflect a similar reduction because some process elements will have made less progress. For complex, first-of-a-kind missions, cycle times will be reduced by a factor of 10 at the most, and actual gains are likely to be somewhat less.

In 15 years, the interchange of geometry and geometry-related data will be seamless, but the same cannot be expected for generalized product data. For example, a truly integrated approach to system and mission design must include electrical systems and software. Most AEE activities, however, seem to be focused on structural design issues, with relatively little effort devoted to electrical system design or software development. Software engineering is particularly important because mechanical design methods are very different from software engineering methods. Also, software-intensive systems, such as avionics, account for an increasing percentage of the total cost of complex systems, especially in the aerospace sector. Validating the performance and reliability of complex software is difficult, expensive, and time consuming (NRC, 1999). As a result, validation often misses software problems that subsequently cause product or mission delays, accidents, or failures.

The committee believes that the entertainment industry may prove to be an important source of advanced technologies in areas such as immersive environments, which are likely to become widely available as part of entertainment systems (NRC, 1997). Large corporate and government entities may then adopt these systems for many of their own applications.

RECOMMENDATIONS FOR IMPROVING THE 15-YEAR OUTLOOK

The following recommendations will enhance the ability of research and development by government, industry, and academia to achieve the 15-year visions described in Table 2-1.

Finding 3-2. Government agencies (such as NASA) acting alone will not be able to achieve the 15-year visions of the Integrated Manufacturing Technology Roadmapping Initiative or NASA's Intelligent Synthesis Environment (ISE) Initiative. Similarly, actions such as linking the Army's Simulation and Modeling for Acquisition, Requirements, and Training (SMART) Program with the ISE initiative, although a step in the right direction, are unlikely to achieve these visions unless the partnerships are expanded to include other government, industry, and university programs with additional resources.

Recommendation 3-1. Until additional funding is made available to invigorate the recommended national partnership for AEEs, government agencies should make the most efficient use of the limited resources now available for the development of AEE technologies and systems by focusing their efforts on the types of missions and products that can benefit most from AEEs and on functional areas that are lagging behind the rapid advances being made in other areas, such as the speed, size, and cost of computer hardware. Research and development should be focused on the following areas:

- comprehensive processes for project design and development that integrate the design of mechanical systems with electrical system design and software development
- general-purpose methods of analyzing cost and determining the effects of risk and uncertainty to reduce the need for project-specific cost and risk analysis tools
- physics-based analysis of mission-specific phenomena if first-of-a-kind missions are a high priority

Recommendation 3-2. The federal government should carefully assess how the limited resources available for AEE research and development (such as the Intelligent Synthesis Environment Initiative) are allocated between the development of (1) general-purpose research with broad application (to improve engineering processes throughout the United States), and (2) engineering processes of particular relevance to agency missions (including activities by industry and academia). The guidelines in Recommendations 9 through 12 of *Advanced Engineering Environments—Achieving the Vision* (the Phase 1 report), which call for action by NASA and other federal agencies, remain relevant.[2]

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[2] See Appendix B of this report, which lists the recommendations from the Phase 1 report.

4

Overcoming Barriers

In the Phase 1 report, the committee identified a number of barriers that will slow or limit the implementation of AEE systems. In this chapter, the committee discusses ways to overcome long-term barriers in five key areas:

- integration of tools, systems, data, and people
- knowledge management
- organizational culture
- education and training
- management and economics

Efforts to overcome technical barriers to integration and knowledge management should be redirected to take full advantage of technologies and applications being developed for the Internet of the future. Overcoming cultural inertia in the engineering enterprise and inciting a revolution in design, business, and educational methodologies will be difficult. Currently, however, many organizations either ignore AEEs altogether or have delegated internal responsibility for AEEs to technology researchers and developers who do not have the authority or resources to influence the overall organization. As a result, not enough action has been taken to address important barriers to the implementation of AEEs, especially in the areas of organizational culture, education and training, and management and economics.

Like AEEs, U.S. railroads in the early 1800s had to overcome problems associated with technological, economic, and cultural barriers (see Box 4-1). Nevertheless, railroad executives persisted through decades of moderate economic success to bring revolutionary change to the country. The commitment to a vision of a connected continent—much more than incremental advances in technology—was the key to success.

INTEGRATION OF TOOLS, SYSTEMS, DATA, AND PEOPLE

Interoperability and Composability

One of the most daunting, long-term barriers to establishing AEEs is the integration and portability of software tools for design and development across (1) disparate operating systems, distribution networks, and programming languages and (2) governmental and corporate cultures. From the technological perspective, crossing this barrier will not be as easy as selecting a standard rail gauge. AEEs of the future will require general solutions to interoperability (i.e., the ability of various systems to work together in a meaningful and coherent fashion) and composability (i.e., the ability to build new systems using components designed for existing systems) (NRC, 1997b).

The current state of practice is typified by a proliferation of nonuniform software tools written by engineers working in isolation to solve discipline-specific problems, by tools that are monolithic rather than modularized in structure, and by special-purpose tools created by individual organizations for their own use.

For some companies, limiting access to critical, proprietary software is an important factor in creating and maintaining a competitive advantage. Many software programs also use proprietary file formats for processing and storing data, which inhibits data exchange. Consequently, a product or process designed with one software tool may be very difficult to work on using another tool. In some cases, old data are ignored because they cannot be accessed by new software tools. Interoperability problems are exacerbated by software vendors who do not consider interoperability to be

BOX 4-1
Legacy Systems: Spaceships, Steam Engines, and Chariots

In 1829, Horatio Allen chose 5 feet as the track gauge, or distance between the tracks, for the new South Carolina Railroad. When completed in 1833, the railroad extended from Charleston to Hamburg, South Carolina, making it the longest rail line in the world and twice as long as any other American railroad. To build this revolutionary railroad, more than 1,300 laborers had to cut through swamps and forest, and construction costs were 38 percent over budget. Rework during the first 10 years of operation increased the cost to 3.3 times the original estimate, largely because of unexpected problems with new technologies in railroad design (Derrick, 1930). The South Carolina Railroad survived, but it achieved only modest economic success because of engineering and cultural problems (Vance, 1995).

To succeed economically, the South Carolina Railroad Company had to ship goods outside the state. These shipments were greatly hampered by the local government in Augusta, Georgia, which was near the end of the rail line. The South Carolina Railroad was not able to join its rail lines with railroads in Georgia because of lobbying by Augusta cargo handlers who moved cargo between the separate rail lines. This cultural barrier drove prices up and reduced revenue for the rail line (Vance, 1995).

Integrating rail lines was also inhibited by differences in track gauges, which were often chosen to foster economic protectionism. For instance, North Carolina refused to use the 5-foot southern gauge chosen by Horatio Allen, even though the southern gauge was used by railroads in Virginia to the north and South Carolina to the south. Instead, North Carolina used the incompatible “standard gauge” (of 4 feet, 8.5 inches) to insulate its rail lines from competition from railroads in neighboring states (Vance, 1995).

After the Civil War, the southern gauge was used throughout the South, and the standard gauge was dominant in the North. In 1886, the southern railroad companies held a convention in Atlanta, Georgia, to address concerns about competition from northern railroads. Motivated by the need to improve their competitiveness, the southern railroad operators, “in a display of amazing technical courage and confidence … decided that more than 13,000 miles of southern gauge line would be shifted to standard gauge in a four-month period, with the actual narrowing of lines taking place on no more than two days, May 31 and June 1, 1886” (Vance, 1995).

The legacy of rail gauges, which extends much farther back in history, has had wide-ranging effects. In the 1970s, during the preliminary design phase for the Space Shuttle solid rocket boosters, Utah-based rocket manufacturer Thiokol Propulsion chose to move rocket booster sections from Utah to the Kennedy Space Center by rail. When evaluating the railroads, representatives from Thiokol Propulsion carefully checked tunnel and sidetrack clearances from Utah to Florida to ensure that the booster sections would pass safely. These clearances were one of the factors that determined the booster diameter of 12 feet, 2 inches (NASA, 1988; Shupe, 2000).

Clearance for railroad tunnels (see Figure 4-1) and switch-track sidings are determined by railroad car width and the standard gauge (of 4 feet, 8.5 inches), which U.S. railroads still use today (Harris, 1998). The standard gauge was based on the British railway gauge of the same measure established in the early 1800s. The British gauge was apparently determined by the track width of horse drawn carts, which were built to a standard width so that the wheels of each cart would fit neatly into the ruts formed by other carts. Archaeologists have found ruts worn into ancient Roman roads by centuries of carts passing over them. These ruts measure 1.44 meters (4 feet, 8.7 inches) wide, only 0.2 inches different from the standard railroad gauge used today in the United States (Margary, 1973; Von Hagen, 1967). These measurements, which suggest that the design of the U.S. Space Shuttle is based partly on the track width of ancient carts and Roman chariots, show the lasting influence of legacy systems.

in their best interest. The same is true of the lack of standards for software interfaces, files, and even basic data definitions. Software vendors’ experience has shown them that proprietary solutions make money; they have no other experience.

The proliferation of individual tools is not a problem, per se. Allowing (or even encouraging) experts to update old tools and create new ones is often necessary to advance the state of the art in individual disciplines. However, without interoperability, innovation is slowed and advances in tools may be counterproductive.

Overcoming the tool and data interoperability barrier in the next 15 years will require major research into software composability and interoperability, as well as significant cultural and educational changes. Composability would facilitate the development of AEE systems with more robust, reusable components and flexible structures that can evolve

FIGURE 4-1 The lasting effect of legacy systems: a modern train passing through a surviving section of an ancient Roman aqueduct. Source: Von Hagen, 1967.

as technologies, users, and their organizations evolve. Reusable software modules would eliminate the need for each organization to develop the same tools. By packaging software for easy reuse, composability would also diminish the problems of monolithic software tools and systems.

Increasing the use of "open-source" guidelines (i.e., each software program's source code would be openly available via the Internet, with changes coordinated through on-line source-code control systems) is a promising approach for developing and implementing composable software (Raymond, 1999). To address proprietary concerns associated with competition-sensitive design and development software, open-source guidelines could be used for infrastructure software that supports interoperability and composability functions, while limiting access to competition-sensitive functions. The concept behind open-source code is that many people and organizations will continually examine and improve the code, increasing its reliability. Also, many engineers prefer open-source technology because they believe that they can correct problems more readily than with proprietary source codes that are owned and managed by individual corporations.

The committee believes that the current trend toward using the Internet as a universal medium should be expanded to search for general, Internet-based solutions to complex tool interoperability issues. Current ad hoc interoperability mechanisms tend to be governed either by the sharing of data files formatted in proprietary formats or by government mandates regarding the use of languages (such as Ada) and architectures (such as High Level Architecture). Government mandates may improve interoperability within a niche market controlled by the government, but they can also result in policies that isolate that market from the larger software community and unnecessarily hinder the use of more efficient software (NRC, 1997a). Converting data between different proprietary file formats is problematic, at best, but history provides little hope for establishing a universal standard; the diversity of software vendors, applications, languages, operating systems, and architectures, and the rate at which all of these factors change, is simply too great for any single standard to address. Therefore, basic research on interoperability should be supported in the flow of open Internet computing, open standards, industry-wide consortia, and other processes that have served the Internet so well. The same technological advances that would enable disparate tools and applications to interact would also overcome disparities between different versions of the same software tool.

New telecommunications and collaborative capabilities of future Internet technologies and applications will enable users in the same or separate locations to engage in interdependent, cooperative activities using a common computer-based environment. The nature and extent of these collaborations will depend, in part, on the extent to which AEE developers have been able to integrate their technologies with the Internet. The new, federally funded Information Technology Research Initiative (which grew out of the proposed research initiative, Information Technology for the Twenty-First Century) will create opportunities for information technology research related to AEEs that would be compatible with the Internet of the future.

The federal government's budget for fiscal year 2000 provides $236 million for the new Information Technology Research Initiative divided among five agencies, as shown in Figure 4-2 (NCO, 1999). The National Science Foundation (NSF) is the lead agency for this initiative, which is focused on long-term, fundamental research on information technology. The initiative is also intended to develop advanced computing technologies to meet the needs of science, engineering, and the nation as a whole and to evaluate the economic and social impact of the information revolution (for additional information, see CRA, 2000).

Finding 4-1. Interoperability and composability problems are a major barrier to realizing the AEE vision. The understanding of and technology base for developing interoperable and composable software architectures need to be improved.

Recommendation 4-1. The federal government should support basic research on the interoperability and composability

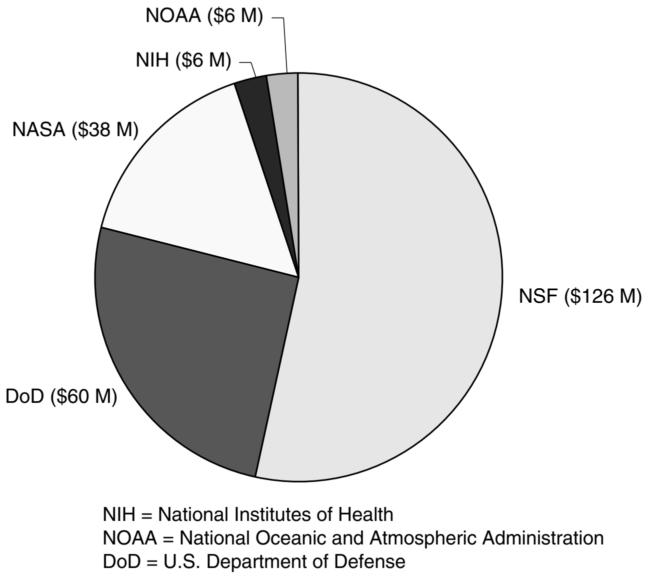

FIGURE 4-2 Fiscal year 2000 funding for the Information Technology Research Initiative. Source: NCO, 1999.

of component software architectures in the context of open Internet computing to increase software reliability and encourage the widespread use of promising solutions. Efforts to resolve interoperability and composability problems should investigate approaches, such as open-source guidelines, for bringing together software designed for diverse applications (e.g., mechanical, electrical, software, and biomedical systems).

Recommendation 4-2. Government, industry, and academia should seek consensus on interoperability standards.

Legacy Systems

Legacy systems are difficult to integrate with advanced tools that support AEE capabilities. Moving from today's monolithic codes to open-source, interoperable, and composable tool sets that will work on the Internet of tomorrow will require in-depth knowledge of the legacy systems that are retained. These tools must either be rewritten in accordance with composability and interoperability requirements for AEE systems or encapsulated in an interoperable software "shell." The latter option is illustrated by the growth of middleware, programs that act as intermediaries between sets of incompatible software tools.

Multiple Hardware Platforms

Integrating the multiple hardware platforms (computers, hardware, databases, and operating systems) on which AEEs rely is a major software challenge. For example, many different operating systems are currently in use: the Macintosh operating system, Windows operating systems (Windows NT, 2000, 1998, 1995, …), Unix and its cousins (Irix, Solaris, HPUX, Linux,…), and Java and its extensions. Assuming that the transition to Internet computing (i.e., writing application programs in Java so they work on the Internet) continues and that basic research in interoperability and composability proceeds, fewer choices for operating systems are likely to be available in 15 years. Java was invented as a proprietary code but is becoming more like an open-source code. Three proprietary versions of Java are now available, and Sun Microsystems is trying to establish a Java standards organization under the auspices of the European Computer Manufacturers Association. The committee believes that, in the future, an open-source successor to Java is likely to be dominant, becoming the primary interface with the underlying operating systems embedded in the hardware of individual users. The underlying operating systems will be much simpler than current operating systems and will probably have achieved prominence by acclamation and adoption, rather than by government mandate or corporate control.

Finding 4-2. Engineering tools and systems have been developed on a variety of incompatible operating systems and with a variety of programming languages. This situation is changing as more advanced tools and systems are being developed for Internet deployment.

Organizational Interoperability

This section addresses technical issues associated with organizational interoperability. The cultural barriers associated with organizational interoperability are discussed in the section on "Organizational Culture" later in this chapter.

AEEs should facilitate interoperability not just among different tools, but also among different organizations. For example, a significant fraction of the products of large manufacturing companies, such as the automotive and aerospace industries, is supplied by manufacturers of components and subassemblies. In 1999, The Boeing Company, with $58 billion in sales, had 29,000 suppliers worldwide, who represented about 50 percent of Boeing's total product cost. As the global economy continues to evolve, market forces will continue to exert pressure on product availability, quality, and cost. Prime manufacturers striving to meet market demands will be analyzing and streamlining their total production systems. Industry penetration of digital CAD, CAE, and CAM tools, which began some 15 years ago, will continue to expand. Business systems are also becoming more responsive to corporate requirements for higher speed and better accuracy.

Changes experienced by prime manufacturers are being felt throughout the supply chains of various industries. Because some 50 percent of product cost is represented in the supplier base, pressure will continue for improvements in quality, cost, and speed at the supplier level. Boeing recently announced a plan to rate suppliers on their ability to produce and deliver quality components and subassemblies on schedule. In addition, Boeing suppliers must show plans for continuing improvements in cost and quality. Boeing also plans to reduce the overall number of suppliers.

The automotive industry has taken similar actions. In many cases, suppliers are being required to work only from digital data sets. For major components and subassemblies, suppliers are often required to provide a digital model and operational simulation to the prime manufacturer. In the near future, this information will be a requirement for suppliers who bid on new products or wish to maintain their current positions in the supplier base. As the capabilities of CAE, CAD, and CAM tools and Web-based delivery capability increase, the industrial supplier base will need to keep pace with their customers' requirements to remain in business.

Prime manufacturers will continue to focus on product innovation, quality, speed, and cost. The science of enterprise modeling and management will improve and include the supply chain because of its significant contribution to the product and the well-being of the corporation. AEEs will provide connectivity throughout the market development, design, manufacture, and support processes of manufacturing industries and their customers.

KNOWLEDGE MANAGEMENT AND SECURITY

The current exponential growth in the rate at which new information is becoming available is likely to continue during the 15-year window examined in this report. To handle this flood of data, technologies are being developed to extract, manipulate, integrate, and display information culled from huge amounts of heterogeneous data. The capability of the Internet to display visual information is rapidly improving, as are the speed and reliability of data communication technologies. Industry is energetically tackling the challenges of accessing and displaying available data. Security systems for controlling access to data will also be necessary. AEEs must provide effective knowledge management in this constantly changing environment.

Quantity of Information

The scientific and engineering communities continue to generate data (empirical and analytical) in increasing quantities. The productivity of data-generating systems has long exceeded the capacity of communications systems used for dissemination and display. The World Wide Web (created, in part, to address the problem of access to a growing body of knowledge) seemed to provide the answer to the inability of printed media to keep pace with the volume of new knowledge. Unfortunately, the World Wide Web still depends largely on text to communicate knowledge. Large quantities of images are also used on the World Wide Web, but only recently has a reasonable level of standardization for coloration of images become accepted. Much work remains to be done on image-attribute associations, animations, video, and audio delivered via the Web.

Two key questions must be answered to resolve the fundamental problem posed by the information explosion:

- How can someone intelligently and quickly locate necessary information?
- How can someone comprehend the amount of information generated in even a simple search?

The first question is in the process of being answered, at least in part, by the development of search engines with higher levels of intelligence. Engines will soon be available that can accept the typically fuzzy ways in which humans articulate their queries. In addition, new types of engines will greatly improve the ability to search intranets within organizations, as well as the Internet and other large data repositories. For example, industry is developing a high-speed parallel search engine that can deliver integrated results from variously formatted sources (Restivo, 2000). Organizations could use these search engines to locate applicable parts, subsystems, and software modules from old products for reuse on new products and otherwise facilitate the exchange of information among organizational elements that may have little knowledge of each other's operations, capabilities, or products. In addition, new software is being constructed to extract and manipulate meaningful information from huge data collections without complicating the human-computer interface. In fact, data mining is now the focus of at least one journal, *Data Mining and Knowledge Discovery* (Kluwer, 2000) and international conferences (e.g., the Sixth International Conference on Knowledge Discovery and Data Mining; for additional information, see ACM, 2000). Thus, without any investment by NASA or the aerospace industry, search engine and data extraction technology will continue to evolve rapidly. At most, the aerospace engineering community will have to ensure that the scope of search engine capabilities meets the community's needs.

Visualization of scientific or engineering data is making an important contribution to the problem of data understanding. This nascent field is exploring new methods of representing data, investigating interactions among data sets, and displaying data with the goal of enabling knowledgeable experts to comprehend and manipulate large quantities of data effectively.

Rapid advances in data visualization are already being made in some applications. For example, a four-dimensional, interactive model has been developed that incorporates diverse geospatial and other types of data into a virtual earth through which users can interactively move in space and time. Users can also inject data, which are visually fused with existing data to simulate current and future states and comparisons between states (Gordon, 2000).

The most likely means of improving existing capabilities for data visualization is within the framework of multimodal display and interaction. This work will extend the term visualization to include characterization of nonvisual displays and interaction modes (e.g., audio and haptic representations, displays, and interactions).

In the long term, the government could enhance the management of large amounts of information by conducting basic research in several areas, including multidimensional data visualization (i.e., visualization of data that contains more than four dimensions) and multisensory display and interaction. These areas are too risky to attract large investments by industry, but successful research could lead to new applications that greatly improve human capabilities for comprehending large, complex data sets.

Recommendation 4-3. Research and development by the federal government on the visualization of engineering and scientific data should focus on long-term goals that go beyond those of ongoing research and development by industry.

Data Communications

Communicating large amounts of engineering data quickly and reliably requires hardware and software infrastructures that today are neither uniform or ubiquitous. Meeting the data communication needs of an engineering team is difficult, especially if the team is dispersed geographically and organizationally. The AEE vision requires that data be accessible, in quantity, from any location and that interaction with that data be instantaneous in human terms. This presupposes that all engineers have desktop access to high-bandwidth, low-latency networks.

Data transmission rates for user interfaces and throughput limits on the total system for the current Internet impede the exchange of large amounts of data or detailed images. However, industry and government are investing billions of dollars in high-capacity data transmission technologies and systems, and transmission rates will increase greatly in the next few years. For example, the bandwidth available for transmitting data through a fiber-optic cable is growing at a Moore's Law rate,[1] as is the amount of data that can be transmitted using a given amount of bandwidth. Thus, the total amount of data that can be transmitted via a fiber-optic cable is doubling every nine months. Assuming that AEE requirements will not be significantly larger than the commercial applications that will drive the deployment of the Internet of the future and other new data transmission systems, data transmission will not be a significant constraint on the deployment of future AEEs.

Improving latency may be more challenging. A latency of less than about 100 milliseconds is required to create a three-dimensional, networked virtual world without losing the illusion of presence. Speed-of-light limitations impose a latency of at least 8.25 milliseconds per time zone, which is then increased by latency in the responsiveness of sensors, processors, transmission equipment, displays, and systems (Singhal and Zyda, 1999).

The need for increased Internet capacity is illustrated by the rate of growth of Internet users and hosts. As of February 2000, there were about 275 million Internet users worldwide, about half of them in the United States (Nua Ltd., 2000). Also as of February 2000, more than 72 million host computers were connected to the Internet, and the annual rate of growth was 63 percent. At that rate, 100 million hosts will be on line by the last quarter of 2000, and 1 billion hosts will be on line by 2005. About 60 percent of hosts are in the United States (NGI, 2000).

The availability of low-latency, high-bandwidth networks will be increased by information technology research and development programs, such as the Internet-2, the Next Generation Internet (NGI), and the very high performance Backbone Network Service (vBNS). The purpose of Internet-2 is to develop and deploy advanced, network-based applications and network services to enable a new generation of Internet services and applications. Started in October 1996 by 34 U.S. research universities, Internet-2 is now a collaborative research effort being carried out by a consortium of more than 170 universities and coordinated by the University Corporation for Advanced Internet Development. Internet-2 is also supported by partnerships with telecommunications, networking, and computer companies (for additional information, see Internet-2, 2000a).

Several federal agencies, including the U.S. Department of Defense, the U.S. Department of Energy, NASA, and the National Institutes of Health, are supporting the NGI program to develop advanced networking technologies and applications. System capabilities will be demonstrated on testbeds that are 100 to 1,000 times faster than the current Internet. The NGI program involves many of the same technologies as Internet-2 and funds some Internet-2 activities, but NGI is focused more on the needs of the sponsoring agencies (for additional information, see Internet-2, 2000b).

The vBNS is being developed by the NSF in cooperation with MCI*WorldCom* to provide high-bandwidth networking for research applications and to develop technology and applications for the Internet of the future. The vBNS provides high-speed interconnections among the NSF supercomputing centers and more than 100 universities and other research organizations, but it is not being used for general Internet traffic. The vBNS offers high data throughput (more than 490 megabits per second) and low latency (an average of less than 100 milliseconds coast to coast). Ongoing

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[1] In the 1970s, Gordon Moore, cofounder of Intel, predicted that the number of transistors on a microprocessor would double every 18 months. This prediction, called Moore's Law, has been amazingly accurate.

developments have significantly increased system capability since the project began in 1995, and current program goals include transmission speeds of more than 2.2 gigabits per second (for additional information, see vBNS, 2000).

Finding 4-3. Advanced Internet technologies and applications are likely to provide the universal, high-bandwidth, low-latency communications network necessary to meet most communications needs for AEEs.

Recommendation 4-4. Research, development, and engineering organizations in government, industry, and academia should ensure that technical staff and students have access to advanced data communications networks as those systems become available.

Data Security and Access

An ideal computer security system would protect organizations from unauthorized use or modification of data or systems while providing easy access to authorized users. Both qualities are important for AEEs, which often involve the sharing of sensitive data among distributed engineering teams. Compromised security could reduce productivity (e.g., if access to AEEs is disrupted by denial-of-service attacks), result in defective products (e.g., if corrupted data is used for product development), or harm a company's competitive position or national security (e.g., if proprietary or classified information is compromised).

Many organizations, such as NASA and large aerospace companies, are attractive targets for computer hackers. Security measures, such as firewalls, intrusion detection systems, data encryption, decoupling of computer systems used for different functions, and security education can be used to limit access by unauthorized users, detect intruders who gain access, minimize problems caused by authorized users (inadvertently or by design), and respond appropriately.

Designing and implementing security systems for complex systems can be challenging, especially if multiple organizations are involved. As the number of points at which security can be compromised increases, administration and oversight of the security system becomes more difficult.

Security measures also create significant barriers to data access by authorized users. For example, the data systems that NASA uses in mission operations are not directly interconnected with data systems used in engineering design, even in the same NASA center.

A central aspect of the committee's vision for AEEs is ubiquitous access of the entire engineering team to relevant data, and a sophisticated system for managing access control is essential. To limit the potential for compromising sensitive data or altering data without authorization, individuals should only have access to information necessary for their jobs. Access controls must not be too rigorous or cumbersome, however, because the entire engineering process can be disrupted if data are not available or if significant delays or complex processes are involved in accessing data. Thus, no matter how well conceived an AEE might be, successful implementation will require resolving critical data security problems in a way that balances the need for robust security with ease of use for the engineer. Specific approaches for enhancing the security of distributed computing networks are described in a recent report, *Trust in Cyberspace* (NRC, 1999).

ORGANIZATIONAL CULTURE

Successful AEEs cannot be burdensomely complex; they must improve productivity by simplifying processes and reducing worker stress. Potential barriers associated with organizational culture and human behavior include the following:

- resistance to change because of fear of the unknown, aversion to risk, and hesitancy to criticize past practices or those who established and maintained them
- organizational cultures that impede innovation and participatory design through excessive oversight and the lack of effective reward systems
- differences in how individuals work efficiently
- disruptions caused by new technologies that do not work as expected
- discipline-specific jargon that impedes communication or leads to miscommunication
- difficulties associated with creating and maintaining collaboration within teams and across an organization or group of organizations
- simulator sickness,[2] information overload, and other shortcomings of human-machine interface technologies, which are not maturing fast enough to counteract the effects of increasing complexity in projects, processes, tools, and systems
- difficulties in applying lessons learned from other organizations or projects to the task at hand

Overcoming these barriers will require social and behavioral changes because of (1) the increasing scale and scope of collaborative activities within and across institutions, (2) the increasing complexity and informational density of advanced engineering projects, and (3) the increasing interdependencies among engineers and other team members and between them and their computer-embedded work processes.

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[2] In one project, as people moved through a virtual building using a simulator, 30 percent of the subjects had to stop because of nausea, eye strain, and dizziness caused by the mismatch between what their eyes saw and what their bodies felt. Overall, the subject loss rate is about 20 percent. Keeping rooms cool, scheduling lots of breaks, using fans to circulate air, and keeping initial sessions brief can alleviate these effects (Goldberg, 1999).

Historically, as this committee's Phase 1 report underscores, not enough attention has been paid to the psychological, behavioral, and social aspects of the user environment for advanced engineering. AEEs, however, are expected to intensify the interrelationships between the social and technical dimensions of tasks, making it especially important to overcome the kinds of cultural barriers listed above. The committee identified four steps for overcoming these barriers:

- Create, maintain, and dynamically reconfigure collaborations.
- Cope effectively with complexity.
- Institute participatory design.
- Establish a culture of innovation.

Create, Maintain, and Dynamically Reconfigure Collaborations

The increase in collaborative activities is being driven by economic and competitive pressures that are unlikely to diminish. The design team for a very complex project may be so large that it becomes uneconomical or impractical for an individual company to increase its workforce enough to staff the team using only its own employees. For example, Sun Microsystems in the "Silicon Valley" south of San Francisco, California, cannot hire enough qualified people locally to support major new projects. As a result, it breaks up design tasks for complex chips so that remote teams can collaborate in the design of a single chip. Separating chip development into discrete tasks that can be easily integrated at the end of the project is technically very difficult. The use of remote teams can also create organizational and management problems because of extremely limited personal contacts or personal relationships among teams members. Videoconferences and teleconferences can be used to supplement face-to-face meetings, but video and audio technologies cannot yet effectively substitute for face-to-face meetings. Exchanging written summaries of meeting outcomes after remote meetings is essential, especially when participants speak different languages. The written summaries help identify misunderstandings so they can be resolved quickly.

In distributed environments that depend on more—and more diverse—collaborations to accomplish their missions, the emergence of new norms and rules of interaction must support team-building, as well as communications and task coordination in both synchronous and asynchronous activities. The dynamics of engineering teams can increase the pace of change, as each member of the team strives to contribute as much as possible to project success. Also, by working with experts in other disciplines, each person develops a better feel for how her or his work fits in with work in other disciplines. AEEs should improve interactions, for example, by improving the sense of place and point of view in virtual reality environments, by speeding some classes of asynchronous events to yield near real-time experience, by improving the representations of locations and actions of humans and other active objects, and by adjudicating efforts by multiple parties to manipulate the same object simultaneously. AEEs will have to provide a range of options between today's avatars[3] and full holographic representations.

In addition, advances in interoperability should make it easier for groups with different tools to work in collaborative distributed teams. The greatest incentive to working in these teams, however, may be offered by AEEs that can provide experiences that go "beyond being there" (Dewan, 1999). In other words, when distributed networked technologies are used simply as a less expensive alternative to face-to-face meetings, they are likely to be viewed as inferior interaction media. However, when they enable interactions that could not be carried out in real environments (e.g., interactions with very small objects, very numerous objects, very distant or otherwise inaccessible objects, or observations of phenomena at normally inaccessible scales), AEEs will become the only—or at least the only desirable—way of carrying out highly advanced projects or missions.

Cope Effectively with Complexity

AEEs will be able to accommodate complex tasks and tools, along with complex information about the status of ongoing actions and outcomes generated by both people and computers. AEEs should enable users to cope with these complexities using interfaces and presentations that can be easily understood and managed. This will require improved representation techniques, including better visualization of engineering and scientific data (as discussed earlier) and better methods of giving users a sense of their place in the environment, the place of other actors and activities, and the status of ongoing processes. The goal is to make it easy for team members to develop and maintain general situational awareness while providing them with task-specific information.

AEEs should also support users by actively informing them of ongoing events. For instance, AEEs should offer intelligent dynamic help to users (coaching or expert advisor systems). They should also incorporate "smarter" knowledge repositories that will improve the retrieval of relevant information, help users formulate options, or guide their next steps.

As illustrated in the vignette in the prologue, innovative scheduling can also help reduce the intensity and stress associated with complex multiperson tasks. Synchronous, distributed, collaborative tasks in existing environments often heighten stress, but they may also encourage innovation, partly because they bring "tacit" knowledge to the surface and partly because they create opportunistic synergies from "loose ties" (Granovetter, 1978). Having all members of a

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[3] In a virtual reality environment, avatars are representations of either human participants or computer-generated actors.

team in the same location (physically or in a virtual environment) enables them to participate in multiple, simultaneous conversations and move from one conversation to another, as needed. If a team leader is present to coordinate the action, productivity is greatly enhanced compared to one-on-one conversations (or point-to-point communications). Future research should explore methods of achieving the same benefits using asynchronous collaborations.

Institute Participatory Design

Constructing the kinds of distributed collaborative work environments envisioned as AEEs will require participatory design and development. That is, very close cooperation between engineering design team members and information and computer scientists will be necessary to generate the tools, models, data sets, interfaces, communications media, and application systems incorporated in AEEs. No other approach would bring together the varied types of expertise that AEEs must embody. Participatory methods that engage users throughout the design process have the added benefit of making users much more knowledgeable about the technologies that support their tasks and, therefore, much more effective at troubleshooting when breakdowns occur.

Participatory design methods, however, will face most of the same problems as other types of multidisciplinary collaborative projects. The work of designing AEEs will never be finished because continued technical advances will stimulate continued transfer of new technologies to AEEs. But even now, workers could begin to learn about participatory design techniques in relation to the digital technologies that support today's engineering environments.

Establish a Culture of Innovation

As suggested above, AEEs will be characterized by continuing technological change. At the same time, the successful implementation of AEEs will require dramatic changes in the social order of many organizations. Aversion to risk and resistance to change are well-known barriers to the implementation of new processes. Risks associated with greater dependency on new technologies can be alleviated in at least two ways. First, AEEs should incorporate high levels of redundancy in critical technologies (both hardware and software). Second, the ability to conduct multiple iterations of solutions very rapidly or try out great numbers of design options should encourage bold exploration and increase confidence in the ultimate decisions, while still reducing cycle time. In addition, enlightened management can reinforce a culture of innovation by establishing policies and practices that reward innovation on the part of teams and individuals. In the long term, however, working in an environment with world-class technologies and teams of innovative colleagues from diverse disciplines may be considered an important reward in itself.

Conclusions

Highly capable AEEs will lead to a drastic reduction in the use of physical models and prototypes in favor of digital objects (e.g., simulations, scientific representations, avatars, and virtual objects). But little is known about the roles that physical artifacts play in supporting collaborative design processes. Research suggests that artifacts are bearers of shared "tacit" understanding, but not enough is known about these aspects of physical artifacts to replicate them virtually. Therefore, further research is needed.

AEEs will enable rapidly reconfigurable teams, with members moving fluidly from project to project as their special skills are needed. Individuals may have the opportunity to work on concurrent project teams with different schedules and varying task demands. Not all individuals will thrive in this kind of environment; some are likely to prefer working alone in a concentrated way over long periods on single projects. Not much is known about how to prepare people for a transition to the new work structures that AEEs will enable. As discussed below, changes in the educational system should be designed, in part, to provide preparatory experiences. In addition, AEE technologies themselves should be designed to support the rapid and intuitive acquisition of situational awareness for people transitioning between tasks, teams, and projects. Moreover, AEEs should be designed to support heterogeneous work styles (as well as heterogeneous data, models, tools, and languages). This may require tradeoffs between individual worker satisfaction and the efficiency of the total enterprise because, in some cases, work processes that maximize individual productivity will not optimize overall productivity.

AEEs are expected to overcome geographic barriers to shared, distributed work, but temporal constraints will probably be much harder to overcome. In fact, even current synchronous collaborative environments can create satisfying, yet very intense work experiences that are difficult to sustain over long periods of time. Thus, even though AEEs may reduce cycle time and improve productivity, they are unlikely to be perceived by workers as a step forward unless they also improve the workplace atmosphere, for example, by reducing stress and time pressures and helping to build social relationships. Therefore, new research is needed to address the psychological and temporal dimensions of engineering design work in synchronous and asynchronous distributed collaborative activities.

Recommendation 4-5. The government and academia should conduct research to improve understanding of the following topics:

- the role of physical artifacts in supporting collaborative design processes and how that role can be fulfilled when physical artifacts are replaced by simulations, virtual objects, avatars, and other nonphysical artifacts

- methods for designing AEE systems that accommodate workers with a variety of work styles and improve the new work environment (e.g., by improving situational awareness for workers transitioning between tasks, teams, and projects)
- the psychological and temporal dimensions of engineering design work in synchronous, distributed collaborative activities, especially if team members are located in multiple time zones and work for organizations with different cultures and business goals

EDUCATION AND TRAINING

"Economic development is a prerequisite for growth and opportunity, research is a prerequisite for development, and education is the foundation of research" (Moniz, 2000). Barriers associated with education and training generally fall into two categories: (1) undergraduate and graduate education and (2) continuing education and training to sustain and improve the skills of engineers and scientists throughout their careers.

Undergraduate and Graduate Education

Four forms of scholarship are recognized in today's educational environment: education, discovery, integration, and application (Boyer, 1990). Undergraduate education primarily focuses on the scholarship of education, while graduate education focuses on the scholarship of discovery. The scholarship of integration and application are largely undeveloped in the academic community. With the development of AEEs, these important forms of scholarship could be developed by combining research opportunities and professional development at the undergraduate and graduate levels.

Current engineering programs typically require that undergraduate engineers take only one course in introductory programming. However, as nearly all forms of engineering increase their reliance on computer-based methodologies, courses on computer programming and methods will become increasingly important. In addition, designing systems with a high degree of composability and interoperability will require that engineers both understand the importance of these features and include computer scientists with this expertise on tool and model development teams.

Interdepartmental cooperation is essential for universities to address these challenges, but university engineering and computer science departments have historically operated independently. Even the accreditation boards have been separate: the Accreditation Board for Engineering and Technology for engineering and the Computing Sciences Accreditation Board for computer science.

Every demand for additional course work places additional pressure on already overcrowded engineering curricula. Unless the efficiency of the educational process is improved, each new course requirement results in the removal or compression of other essential courses. Degrading the core curriculum, however, would jeopardize the ability of students to learn the basic principles behind the increasingly sophisticated engineering tools and software models at their disposal. Furthermore, meeting all of the needs of industry and government will require improvements in both computer science programs and traditional engineering programs. Many of the barriers described in this chapter will be especially difficult to overcome as long as the current shortage of information technology workers persists.

Fortunately, changes in the educational process are already under way. In the past decade, undergraduate engineering programs have increasingly emphasized design, manufacturing, communication, and teamwork. In addition, the Computing Sciences Accreditation Board has agreed to integrate its accreditation commission into the Accreditation Board for Engineering and Technology (CSAB, 2000). Under pressure from industry and academia, the accreditation process, which is governed by the accreditation boards and professional societies, is focusing more on educational outcomes (i.e., preparation for professional practice) than credit hours (seat time). Under the new approach, educational institutions and programs have redefined their missions and objectives in terms of their ability to meet the needs of constituencies with an emphasis on outcomes. For example, students are generally required to complete a capstone design project or other culminating experience that incorporates the knowledge and skills acquired in earlier course work; engineering standards; and real-world constraints, such as economics, the environment, sustainability, manufacturability, ethics, worker health and safety, and social issues. AEEs would directly improve the ability of students to complete complex capstone projects.

Other positive developments in the educational process include the following:

- Professional societies, such as the American Institute of Aeronautics and Astronautics, the Society of Automotive Engineers, and the American Society of Mechanical Engineers, are providing opportunities for student teams to compete in design-build-test competitions involving, for example, solar cars, remotely controlled aircraft, and human-powered vehicles.
- NASA is providing opportunities for student teams to compete for the chance to conduct experiments on board the KC-135 microgravity research aircraft.
- The Industry, University, and Government Roundtable for Enhancing Engineering Education is exploring options for reforming the educational process so that engineering graduates can meet the challenges of future business environments and professional standards. The roundtable is also concerned with improving knowledge management, enhancing the engineering profession, and improving continuing education (IUGREEE, 2000).

- The NSF's Engineering Education and Centers Division is improving engineering research and education by sponsoring eight engineering education coalitions, which involve approximately 55 universities. These coalitions are investigating issues such as multidisciplinary pedagogical models and integrated approaches to undergraduate engineering and manufacturing education (NSF, 2000b). The NSF has also established engineering research centers at 33 universities to create educational environments that integrate engineering and research for undergraduate and graduate students. The centers focus on next-generation advances in complex engineered systems and expose students to industrial practices (NSF, 2000a).

Although the advent of AEEs will increase educational requirements and the use of advanced tools could obscure students' awareness of basic principles, AEEs could also enhance the educational process by teaching students in virtual environments. For example, currently available training technologies enable students to interact within a three-dimensional, virtual reality to explore basic concepts, such as the forces created by electrical charges, as well as complex problems, such as the impact of orbital mechanics on the field of view of instruments on an orbiting platform. By providing opportunities to combine professional development with research more effectively, AEEs could stimulate interest in graduate engineering education by increasing its perceived value and relevance to industry.

Despite the progress that has already been made, however, much more needs to be done to incorporate AEE technologies into undergraduate and graduate curricula. Based on the experience of committee members, the committee believes that the following barriers remain at many universities:

- a university culture that rarely fosters or rewards interdisciplinary academic careers
- insufficient appreciation by faculty of the benefits of emerging AEE techniques and tools, which are too often perceived as producing little more than interesting graphics
- limited time and resources for faculty to develop interdisciplinary programs[4]
- the view by government and industry that academia is a minor player in implementing AEEs in the engineering enterprise
- a lack of proven methods for preparing students and working engineers for the new work structures and processes that AEEs will enable

Overcoming these barriers will require investments of time, effort, and money. In addition, demonstrations of new methods will be necessary to convince a skeptical university audience that AEEs can (1) help students develop critical thinking skills and (2) improve educational efficiency so much that AEE-related education can be integrated into curricula without having to eliminate existing courses.

AEEs could also be used to integrate schools of engineering with the liberal arts and sciences. Just as the functionality of AEEs is not limited to traditional engineering tasks, access to AEEs should not be limited to engineering students. Synergies can arise when different communities come together in a constructive way (NRC, 1997b).

Just as individual corporations will require a champion to implement AEEs (see Recommendation 8 from the Phase 1 report, which is reprinted in Appendix B of this report), individual engineering schools will need an influential AEE champion to make AEEs an important part of the university environment and sustain support for AEEs and related interdisciplinary programs. A champion will be especially important at schools where individual departments do not embrace AEEs. At many universities, strong internal leadership, along with external pressure from accrediting organizations and industrial engineering organizations, will be needed to encourage faculty to accept AEEs, support the scholarship of integration, and modify undergraduate and graduate curricula accordingly.

In a broader context, funding for long-term research will be necessary to support interdisciplinary research associated with AEEs. Because publishing research results is a sign of academic competence, journals dedicated to interdisciplinary research must be available to publish research results. The federal government can facilitate change by funding research and, with industry, by including academia in a national partnership for fostering AEEs (see Recommendations 1, 2, and 12 in Appendix B). The involvement of the federal government will be essential for supporting long-term research whose expected benefits are likely to (1) be realized beyond the investment horizons of industry; (2) be so generic that the benefits cannot be contained and applied in a way that gives the sponsoring company a proprietary, competitive advantage; or (3) be of such high risk that it is impossible to make a solid financial justification for conducting the research.

Continuing Education and Training

Continuing education and training does not lead to an undergraduate or graduate degree and may be conducted at government or industry sites, specialized training facilities, or universities. Continuing education and training is needed for teaching newly hired workers to use their employers' engineering and design systems and to refresh the skills of existing staff, especially when systems are updated.

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[4] This barrier is especially acute because rapid advances in AEE technologies require that courses be constantly updated.

Learning to Use AEEs

To make the most effective use of new AEE technologies and systems, the training and education program for the existing labor force and future workers must be upgraded. Special efforts will be needed to prevent engineering skills and knowledge from atrophying in the presence of AEEs that automatically perform increasingly sophisticated engineering tasks. Just as overreliance on complex engineering tools and software models can prevent students from developing a fundamental understanding of important engineering and scientific principles, overreliance on AEE systems and technologies may prevent design teams from developing a fundamental understanding of their products and missions. As a result, teams could unwittingly use tools on tasks for which they have not been validated. For example, several years ago a manufacturer of large, complex products tried to use analytical models to reduce the need for destructive testing. When test engineers attempted to qualify the models, however, the analytical results repeatedly failed to match actual test results. As costs and frustrations increased, the testing manager asked the modelers to predict what would happen if a simple component, such as a pipe with a square cross section, were bent in half. The model had to be revised several times before it accurately predicted how the walls of the pipe would deform during the bending process. Starting with that success, the models were refined with increasingly complex test articles until they could accurately predict the performance of the entire product. The same models could then be used to predict the performance of new products, as long as the models were updated to handle new structural components. This example illustrates the importance of educating the engineering workforce to understand the capabilities and limitations of their AEE technologies and systems. Continuing education and training will be crucial to prevent existing knowledge from degrading or becoming outdated as experienced personnel leave and new tools are adopted.

AEEs designed for complex engineering applications will generally have sophisticated simulation and modeling capabilities and, as a result, will be technically capable of functioning as sophisticated, automated training devices for new users. However, education and training requirements should be explicitly addressed during the development of AEEs to ensure that adequate training features are included in the final product.

Using AEEs to Learn

For most AEEs, training and education will be a secondary function used to train new users. Training simulators, however, use AEE technologies and systems to teach users some other activity, such as flying an aircraft. Training simulators provide many benefits. For example, advanced training simulators benefit the U.S. Air Force in the following ways:

- reducing the use of aircraft, which are expensive to operate and are reaching end of life faster than they are being replaced
- eliminating unrealistic restraints, such as minimum altitudes, that are imposed on real-world training because of safety concerns
- reducing costs
- increasing training opportunities
- reducing air crew deployments for training[5]

AEEs will be used to create increasingly sophisticated training environments that combine real and virtual environments for individual and group training locally and in distributed training environments. In fact, the Air Force has already used transportable simulators to conduct distributed mission training exercises with pilots at several remote sites. Trainee evaluations indicate that simulator training is more effective than real-world aircraft training in some ways, but less effective in others. In general, simulators were judged to be less effective for tasks involving visual fidelity but more effective for tasks involving decision making and complex team interactions (e.g., encounters involving several aircraft on each side). Why? Primarily because Air Force combat pilots rarely have the opportunity to train with large numbers of aircraft in the real world. Distributed mission training also seems to be especially effective for intensive training (because it provides many training exercises in a few days), for enabling pilots to fly with and against disparate aircraft, and for breaking down organizational barriers (by making it easy for pilots in different squadrons to train together) (Andrews, 1999).

Findings and Recommendations

Finding 4-4. Research funding, interdepartmental cooperation, and organizational support for interdisciplinary programs has traditionally been difficult to obtain from the government or academia, largely because funding agencies have usually set narrow limits on the types of projects they are willing to support.

Recommendation 4-6. Accrediting organizations, industrial organizations, and professional societies should continue to advocate greater use of AEE technologies and systems in the academic environment at both the undergraduate and graduate levels.

Recommendation 4-7. Universities should appoint AEE champions to provide strong, long-term leadership for

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[5] Eighty percent of Air Force pilots are leaving the service when their obligated service is completed, largely because of lifestyle hardships associated with deployments (Andrews, 1999).

implementing AEE technologies and systems; establish the innovative, interdisciplinary educational programs and faculty needed to take full advantage of the capabilities of AEEs; increase the emphasis in undergraduate and graduate education on the scholarship of integration and application; and develop curricula with a stronger foundation in software development, including component software architecture, composability, and interoperability.

Recommendation 4-8. Initial and continuing education should include strategies for (1) maintaining scientific and engineering understanding of processes and tasks that will be done automatically by AEE technologies and (2) training people for the transition from conventional working environments and processes to the pace and structure of working as members of multiple, concurrent, rapidly reconfigurable teams.

Recommendation 4-9. AEE research and development should consider training and education requirements for undergraduate, graduate, and continuing education. The lessons learned from the development of advanced training simulators that incorporate AEE technologies and systems should be used to improve the training and educational capabilities of AEEs focused on other applications, including university education.

MANAGEMENT AND ECONOMICS

The new and different types of work teams that may be necessary for effective implementation of AEEs will, in some cases, highlight shortcomings in organizational structure, leadership, and management. AEEs will also accelerate design and engineering processes and reduce cycle times. Done properly, this will reduce costs and improve competitiveness. Done poorly, however, AEEs may simply speed the way to failure. Correcting organizational and process problems is a prerequisite for—not a result of—the successful implementation of AEEs. AEEs will not eliminate the need for leading, motivating, and inspiring employees, who will still be the most important part of the enterprise. This section describes economic considerations and management solutions for implementing AEEs, particularly with regard to start-up costs, uncertainties, and metrics.

Economic Considerations

Some commercial organizations are turning to AEE technologies to reduce costs and cycle times, increase customer satisfaction, and improve competitiveness. Government organizations are turning to AEE technologies to meet the needs of some challenging and costly missions. The importance of AEEs, however, goes far beyond the immediate goals of reducing the costs and schedules of current projects. The committee believes that the long-term viability of many companies will increasingly depend on their willingness and ability to embrace an AEE vision that looks beyond short-term gains. In fact, the expense and trouble of making the cultural and technological changes to implement AEE technologies often cannot be justified economically in the short term.

The economic risks of implementing AEEs are often high, but the committee believes that the risk of not implementing AEEs is increasing. In many applications, AEE technologies are already reducing costs, increasing customer satisfaction, and enabling new missions. Organizations that rely on traditional methods may be confronted by mission and product challenges they cannot meet, while AEE-enhanced competitors may be able to move forward. The committee believes that the increasing benefits of AEE technologies will ultimately promote their widespread use despite current barriers.

The growth of electronic commerce illustrates the importance of adapting to new methods. Electronic commerce is expanding every day to support the rapid, accurate transfer of funds among business, industry, government, and financial institutions. The growth of electronic commerce on the Internet is expected to continue as more consumers look to their PCs to purchase goods and services, although the profitability of many Internet-based businesses remains uncertain. For example, Amazon.com has been very successful in terms of market share, but it has yet to earn a profit.

All forms of electronic commerce are expected to continue to grow rapidly over the next decade, aided by technologies that ensure the security of transactions. These advances will reduce reliance on paper records and enable contracts to be negotiated, executed, and administered almost entirely in the virtual realm. The federal government has already established regional centers for electronic commerce to help small and midsize companies make the transition to electronic commerce.

Start-up Costs

The following start-up costs are associated with AEE technologies and systems:

- acquiring software licenses and hardware
- translating legacy data
- implementing effective product data management
- training for start-up and proficiency maintenance
- validating simulation models and analyses
- updating or replacing software and hardware
- overcoming hardware and software incompatibilities throughout the enterprise
- establishing and verifying metrics

These costs can be extraordinarily high, and the cost-time curve for projects developed with AEEs are usually very

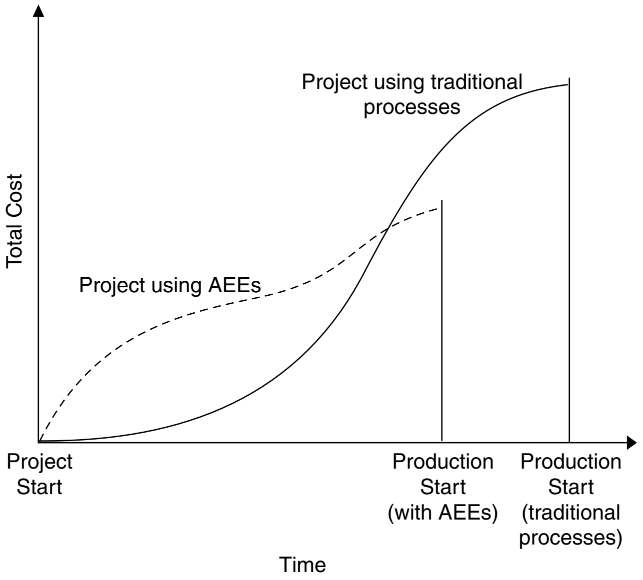

FIGURE 4-3 Comparison of notional cost-time curves for projects using traditional processes and AEEs.

different from traditionally managed projects (see Figure 4-3). High start-up costs increase economic risk because the project may fail or the AEE infrastructure may turn out to be poorly suited to the project, potentially leaving the company with an expensive white elephant. Despite the expectation of long-term benefits, high start-up costs can also be a significant barrier to the approval of AEE projects, especially for companies with limited capital, government agencies with declining budgets, or organizations using AEEs for the first time.

Uncertainties

Uncertainties about the impact of AEEs on costs and benefits over the life of a project also increase risk. Early attempts by industry or government organizations to implement AEE technologies have had limited success in the short term. The economic uncertainties and concerns of some AEE pioneers can be summarized as follows:

- poor near-term returns, although economic returns have been much better in the long term as technologies mature and expertise in their use grows
- high cost uncertainties associated with overcoming cultural barriers, gaining acceptance across the enterprise, and maintaining AEE systems in a rapidly evolving technological environment
- lack of experience with nontraditional cost-time curves for new product development and acquisition
- difficulty in separating the impact of AEEs from other efforts to lower costs, reduce cycle time, etc.
- uncertainty about the amount and timing of returns on investment, financially and in terms of improved quality, customer satisfaction, or mission effectiveness, for different products and processes
- difficulty of certifying that AEE simulations can reliably replace physical validation tests, especially for complex new projects and one-of-a-kind missions
- difficulty of identifying and analyzing low-frequency events that may be caused by cost-saving modifications to existing products and processes[6]

Metrics

Uncertainties about the costs and benefits of using AEEs will persist until a set of metrics is available to quantify improvements. Precise measurements using traditional metrics, such as those listed in Table 4-1, require well-defined data collected over long periods under carefully controlled conditions for similar programs or functions with and without AEEs. This type of data is rarely available. Most products and processes experience many changes over time, and many variables are at work when AEE technologies are being implemented. Isolating the effects of individual factors on cost or quality is usually impossible, especially if the benefits fall under different functions or time frames. For example, if the use of AEEs results in new designs that are more tolerant of variations in the manufacturing process, the primary benefits would not be in reduced engineering costs or even in lower production costs, but in higher quality and lower product returns. Managers need a comprehensive set of accurate, short-term, cost-justified metrics for predicting the effects of implementing AEEs.

Metrics related to risk are important because risk reduction is the focus of many technology development and demonstration programs and because perceived risk is a key parameter in management decision making. Different stakeholders may have different perceptions of the specific or overall risks associated with a particular product or mission, and risk estimates are not precise. Rather, levels of risk are estimates that are best characterized by probability distributions.

Affordability, in terms of a cost-to-benefits ratio, is another important metric, because AEEs will affect both the costs and performance of products and missions. To be comprehensive, affordability metrics should capture as many of the costs and benefits as possible, including intangible benefits, such as employee morale and customer goodwill. Although these factors are hard to pin down, they can be tracked through staff turnover rates, repeat customer business, and other indicators.

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[6] For example, reducing quality assurance checks might initially improve productivity, but fewer checks might also increase the occurrence of low-frequency events that require extensive rework, which would offset productivity gains.

TABLE 4-1 Traditional Metrics

- time to profitability (commercial organizations)
- return on investment
- return on expectations[a]
- mission value to cost ratio (government organizations)
- development and production cycle times
- total life-cycle costs
- cost of development, validation testing, production, and operations, including capital facilities, material, and labor
- number of physical prototypes and physical tests
- quality
- cost of quality

[a] *Return on expectations* compares the results of a research, development, or operational project to initial expectations, in terms of project goals and metrics. Return on expectations is especially appropriate for government and academic projects that cannot be suitably evaluated using profit-driven parameters, such as return on investment.

One approach for evaluating the effect of AEEs would be to establish project tracers in a large project. As described in the success stories in Chapter 2, Concepts ETI, Inc., has been able to measure the impact of AEEs on cost and time to market for a relatively narrow range of products (i.e., pumps, compressors, and other types of turbomachinery). The techniques used by Concepts ETI are not yet suited for tracking the impact of AEEs on large projects. However, the managers of a large project could take advantage of the lessons learned by Concepts ETI by designating specific project tasks that reflect the progress and level of success of the overall mission or product.

Project tracers should relate to established, semistandardized products or processes for which improvements can be measured in traditional terms. Project tracers should be limited in scope; rather than encompassing the entire project, they should provide a statistical sampling across the large project. For example, an automobile manufacturer might monitor the number of engineering change orders, manufacturing labor hours, and defect rate for left-front body fenders as an indication of how AEEs are affecting the design and development for other large sheet metal parts. Project tracers would have to be carefully selected to build confidence among managers and other decision makers that the tracers accurately indicate the effect of AEEs on the overall project.

Management and Economic Solutions

Problems associated with economic uncertainties, high start-up costs, the lack of accurate metrics, and other economic and management barriers noted in the Phase 1 report (see Table B-1 in this report) add to risk. Setbacks and failures may occur as managerial, cultural, technological approaches to the implementation of AEEs evolve. Costs are likely to increase in the near term, and the return on investment may seem questionable. Nevertheless, although the economic risks of employing AEEs are high, the risk of continuing to rely on traditional methods is even higher. Organizations that do not move forward are likely to remain on the sidelines as others reap the rewards of an effective AEE culture and technology base. As described in the success stories in Chapter 2, AEE pioneers are achieving increasingly ambitious goals, reducing costs, increasing customer satisfaction, and enabling new missions. As demonstrated by Concepts ETI, even small design and manufacturing companies can take advantage of AEE technologies, if they have sufficient technological expertise. AEE technologies that can be easily adapted to a variety of applications would facilitate the use of AEEs by other small companies with less technological expertise.

Advanced technologies can help organizations overcome economic and management barriers. As discussed above, Internet-based AEE technologies, systems based on open architectures, and other technological advances can improve the interoperability and composability of software, as well as strengthen engineering education programs. These changes will produce a more capable information technology workforce and improve the interoperability of tools used by prime manufacturers and their suppliers. AEE technologies will also improve data transmission among users of tools created by different organizations, increase information security, and lower cultural barriers. Nevertheless, approaches for implementing AEEs that are limited to technological changes will not succeed. Management priorities must be realigned to accomplish the following tasks:

- Fund sustained, interdisciplinary research and development, which are critical to the future of AEEs.
- Nurture collaborative approaches to complex problems.
- Reduce the amount of specialized training required to operate engineering systems and make that training readily available.
- Reward workers for participating in both short-term and long-term collaborations.
- Efficiently implement complex teaming arrangements.
- Quickly assess complex problems and produce easily understandable information, instead of overloading workers and managers with enigmatic data.
- Balance users' needs for easy access and high security.
- Maintain corporate knowledge of products and processes regardless of staff turnover, which is especially high in the information technology workforce.

Creating a work environment that accomplishes these tasks will require (1) innovative management to ensure that complex AEE systems are applied in an orderly way; (2) a flexible management approach that rewards team collaboration and is willing to accept risks to reach important long-term goals; and (3) a strong organizational commitment that includes buy-in by key managers. Commitment is essential to sustain changes long enough to work through start-up problems and assess long-term benefits. Strong leadership is needed to maintain momentum and focus, especially for electronically linked project teams that span continents, time zones, and diverse cultures or corporate philosophies. Striking an appropriate balance between the tight management control possible with traditional teams and the freedom associated with loosely regulated cooperative efforts (such as development of the Internet or the Linux operating system) may be difficult. However, balance is essential for realizing the benefits of the dynamic interactions that AEEs enable. At the same time, management must retain enough focus to achieve the goals of specific products or missions.

Finding 4-5. The costs of implementing AEEs may not be justifiable in the short term. However, pioneers in the use of AEE technologies are realizing economic benefits. As AEE technologies become more common and sophisticated, the long-term viability of most commercial design and manufacturing companies and other complex, technical enterprises will increasingly depend on their ability to implement AEE technologies and systems of increasing sophistication.

Recommendation 4-10. Because of the technical and social complexities involved in applying AEEs, efforts to implement them should include the following:

- processes for taking advantage of the lessons learned by AEE pioneers, especially with regard to the reduction of implementation costs, uncertainties, and risks
- realistic goals for the economic payoffs of implementing AEEs, especially the time needed to realize a positive return on investment
- innovative and determined management that is willing to accept risks; appoint a "champion" with broad, interdisciplinary authority; persevere despite temporary setbacks; and accept uncertainty in assessments of the cost and benefit of implementing AEE technologies
- Web-based AEE technologies with open architectures and improved interoperability and composability to reduce implementation costs

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5

General Approaches and Roles

This chapter describes the general approaches and roles that industry, government, and academia should take in pursuing more advanced and capable AEEs. The recommendations in the Phase 1 report (which are reprinted in Appendix B of this report) provided initial guidance in this area. The additional information collected for this report confirmed that the originally recommended approach would provide a solid foundation for achieving long-term goals.

Finding 5-1. The Phase 2 study reaffirmed the approach described in the Phase 1 report for developing AEE technologies and systems. That approach includes the following key steps:

- forming a national partnership of government, industry, and academia to take advantage of the current historic opportunity to develop AEEs
- forming government-industry-academia AEE partnerships by individual agencies, such as NASA, as an interim step for addressing agency-specific goals while a national partnership is being formed
- overcoming major barriers related to the integration of systems, tools, and data; information management; cultural, economic, and management issues; and education and training[1]
- facilitating the transfer of new capabilities to commercially available products by developing application-specific tools required by government through contracts with industry whenever practical
- focusing the government's AEE research and development on key objectives, such as (1) modeling key physical processes, (2) improving generic AEE methodologies and automated tools, (3) developing testbeds that simulate user environments, (4) developing accurate performance metrics, and (5) other areas where market-based incentives are not motivating adequate industry-sponsored research
- providing government incentives for (1) industry to adopt AEE technologies in government procurements, (2) academia to adopt AEE technologies in major government-sponsored research programs, and (3) industry and academia to collaborate in modernizing educational curricula to prepare students for an AEE work environment

Although some companies have successfully implemented AEE technologies, these efforts are still in the early stages of achieving the 15-year visions described by the IMTR and ISE initiatives. Examples of a positive industrial management approach include Boeing's development of the 777 and subsequent aircraft development projects, the "reinvention" of the submarine design and manufacturing process by EB (Electric Boat Corporation), and other success stories described in Chapter 2. These examples indicate that AEEs can succeed if organizational management makes a major commitment to initiate the process and see it through despite high initial costs and other implementation problems. Leadership should be provided by an authoritative champion, but the champion should not be a "lone ranger." Especially at large organizations, a strong support team should be established at management levels above and below the champion to provide multiple layers of leadership, support, and commitment.

Special care should be taken when AEE technologies and systems are developed by one organization for use by another. End users must be involved in product and system development to ensure that the product will meet their needs. Users, however, tend to have a low tolerance for new products that do not work well: they often become frustrated, give up on the product, and are reluctant to try it again in the future even after it has been updated to correct earlier shortcomings. Overcoming this problem will be difficult.

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[1] See Chapter 4 and Table B-1.

Teaming processes and organizational roles are changing. Historically, prime manufacturers selected vendors based on competitive bids for providing precisely defined components or systems. Increasingly, especially in the electronics industry, prime manufacturers are partnering with outside organizations to obtain engineering, design, and manufacturing services. For example, Sun Microsystems often selects a manufacturer for new products before the product is designed. For maximum value, Sun management has learned that product design, development, and testing tasks must be carefully allocated between their own company and product manufacturers. The selection process is intended to choose a manufacturer whose engineering skill set complements Sun's own skill set. The ability to merge work cultures and capabilities with potential manufacturers was not a consideration even 10 years ago.

Finding 5-2. Most government, industry, and academic organizations have yet to take advantage of AEE technologies because of technical, cultural, management, and economic problems, some real and others perceived, even though available technologies can tremendously improve products and processes. The advantages of using AEEs cannot be realized with business-as-usual approaches because of the high start-up costs and fundamental technological and cultural changes necessary to implement AEEs.

Recommendation 5-1. Federal agencies involved in AEE research and development should be more aggressive in forming a national partnership with industry and academia to develop AEEs that offer seamless, end-to-end engineering design capabilities that encompass the entire life cycles of products and missions.

Recommendation 5-2. To deploy AEEs successfully, organizations should identify and resolve organizational issues in addition to improving processes and tools. Each organization should also assign a strong leader or "champion" supported by the following:

- a knowledgeable team familiar with lessons learned from similar organizations that have implemented AEE technologies
- a plan for deploying AEEs that is tailored to the stated objectives and the barriers that must be overcome
- realization by all levels of the organization that both technical *and* nontechnical changes are needed in the near term and/or the long term for future success (or, perhaps, survival)
- long-term commitment by senior executives to the deployment of AEEs despite the costs of setting up new systems and processes and the risks of short-term setbacks
- willingness of the workforce to accept new methods

The technologies for developing AEEs are available, and their performance is improving rapidly. High-bandwidth technologies will enable the Internet of the future to provide much higher data transmission rates than current systems. The committee is convinced that the telecommunications and collaborative capabilities of the hardware and software technologies being developed for the Internet of the future offer the best hope for addressing interoperability issues. Industry, government, and academia each have a role in advancing these technologies.

Finding 5-3. Advanced Internet technologies and applications (including operating systems, software architectures, and hardware) are one of the keys to developing AEEs that (1) overcome critical technical issues, such as those associated with interoperability and information management, and (2) facilitate the use of AEEs by small companies.

Recommendation 5-3. The government's AEE research and development programs should focus much more on approaches to AEEs that will be compatible with the Internet of the future and information technologies being developed by other programs, such as Internet-2, Next Generation Internet, very high performance Backbone Network Service, and Information Technology Research Initiative.

NASA, which is just beginning to implement AEEs across the agency, should strive to make its systems compatible with the AEE technologies and systems used by its research and development partners in industry and academia. Like other federal agencies, NASA could accelerate the adoption of AEEs within the agency and throughout the nation by advocating greater use of AEE technologies by contractors involved in agency programs, capitalizing on commercial technologies, funding research and development to satisfy the agency's specialized needs, and supporting advances in the state of the art in focused areas that industry's near-term, market-driven research and development are not addressing. For example, PCs, the Internet, and CAD tools, as we know them today, would not exist except for extensive government research programs.

Finding 5-4. NASA could greatly benefit from increased use of AEEs. However, the conditions necessary for significant, widespread adoption of AEEs do not yet exist in the agency.

Recommendation 5-4. Successful implementation of AEEs by NASA will require sustained leadership and commitment, adequate funding, and a cohesive plan that includes all NASA centers, as outlined in Recommendations 4, 10, 11, 12, and 13 of the Phase 1 report:

- NASA should not create a broad-based AEE research program to develop comprehensive AEE systems.

Instead, NASA should provide for research and advocacy in areas that AEE research and development sponsored by other organizations do not adequately address, especially areas related to the needs of NASA and the rest of the aerospace industry.

- NASA should capitalize on industrial advances in AEE technologies. In particular, NASA should investigate how NASA-funded research related to AEEs and the Next Generation Internet can enhance the ability of Internet-related technologies and applications to meet AEE objectives.
- NASA should form a government-industry-academia partnership for AEEs to help advocate and implement AEEs in the agency and the nation.

Industry and government have traditionally viewed universities as research laboratories and as sources of workers with discipline-specific educations (baccalaureate degrees) and independent research experience (advanced degrees). Universities have less often been viewed as developers of new methodologies, applied technologies, testbeds, or integrated systems, especially for complex products or missions. Integrating AEEs with undergraduate and graduate engineering and computer science programs would greatly alter the way students are taught, but it would also produce graduates with a new perspective on engineering design and development processes. When AEE-trained students enter the workforce, they could be a catalyst for changing the culture in industry and government. Change is not guaranteed, however, because organizational cultures are usually defined by the attitudes of experienced workers who may prefer the comfortable familiarity of traditional design and development processes.

Government has traditionally supported university research in individual disciplines, although multidisciplinary research projects have become more common in recent years. Many universities are heavily involved in technological advances associated with AEEs (e.g., computing frameworks, multidisciplinary design optimization, and robust design). Universities should accept the importance of working with industry as partners in the scholarship of integration and application, and the government should ensure that universities are appropriately involved in the national AEE partnership.

Recommendation 5-5. The federal government should continue to support educational advances related to AEEs in the following ways:

- Continue to support the development and implementation of new educational methods through programs such as the National Science Foundation's engineering education coalitions and engineering research centers.
- Include academia as a key participant in a national partnership on AEEs and other AEE development activities.
- Fund long-term, high-risk research on AEEs that industry is unlikely to support, including research on academic applications of AEE technologies and systems.
- Avoid overly restricting the direction or content of long-term, high-risk AEE research sponsored by the government.

Appendixes

Appendix A

Statement of Task

The National Research Council and the National Academy of Engineering will conduct a two-phase study of AEEs. The study will assess the current and future national context within which NASA's plans must fit. Phase 1 will focus on the near-term, especially the identification and assessment of needs, directions, and barriers during the next 5 years for the development and implementation of AEEs in a national framework. Phase 2 will focus on the far term and build on the results of Phase 1 to expand the assessment to the 5 to 15-year vision for incorporating AEE technologies and systems into both the current and future engineering workforces. Workshops may be used in both Phase 1 and Phase 2 to maximize participation by government, industry, and the academic community.

PHASE 1 STATEMENT OF TASK

The Phase 1 study will identify steps NASA can take in the near term to enhance the development of AEE technologies and systems with broad application in industry, government, and academia. Focusing on the near term, Phase 1 will complete the following specific tasks:

1. Develop an understanding of NASA's long-term vision of AEE, capabilities, and tools associated with the current state of the art in engineering environments, and near-term advances in engineering environments.
2. Conduct an independent assessment of requirements for, alternative approaches to, and applications of AEEs to aerospace engineering, considering both near- and long-term objectives.
3. At a high level, explore the potential payoffs of AEEs on a national scale, emphasizing the relationships between aerospace engineering and other elements of the national engineering scene and identifying the necessary conditions for achieving these payoffs.
4. Evaluate how AEE technologies relate to the development of relevant technical standards (e.g., collaborative, distributed computing and software systems interoperability) and engineering economic assessments (e.g., cost and risk assessments).
5. Identify the following:
    - cultural and technical barriers (e.g., certification requirements, software and hardware incompatibilities, proprietary restrictions imposed by original equipment manufacturers, standards, policies, laws, etc.) to collaboration among the government, the aerospace industry, academia, and others for transferring AEE tools and methods from the development stage to public practice
    - opportunities that may be created by AEEs
    - needs for education and training
6. Recommend an approach for NASA to enable a state-of-the-art engineering environment capability that is compatible with other government, industry, and university programs and contributes to the overall effort to engender a broadly applicable, technology-based, engineering framework.
7. Prepare a report summarizing the key results of Phase 1 (i.e., the committee's Phase 1 report).

PHASE 2 STATEMENT OF TASK

As Phase 1 is nearing completion, NASA, the National Research Council, and the National Academy of Engineering will determine the feasibility of proceeding with Phase 2. Expanding on the results of Phase 1, Phase 2 will focus on assessing the long-term potential and feasibility of developing AEE technologies and systems that would foster increased creativity in the design process, improve processes for multidisciplinary integration, facilitate the interactive examination of new ideas, improve evaluations of technology, etc. Specific tasks are as follows:

1. Building on the recommendations and conclusions of Phase 1, evaluate the potential for AEEs to contribute to NASA's long-term goal of "engendering a revolution in the engineering culture" and the benefits that achieving this goal would produce.
2. At a high level, understand and assess the potential payoffs of AEEs on a national scale.
3. With regard to implementation of AEE capabilities and practices, examine broad issues such as those associated with infrastructure changes, clarity of interdisciplinary communications, and technology transfer and acceptance. Consider approaches for achieving the AEE vision, including the potential role of government, industry, academic, and professional organizations in resolving these issues.
4. Identify the key elements of long-term educational and training strategies that government, industry, and academia could adopt to foster acceptance and application of AEE technologies and systems by the existing and future workforces.
5. Prepare a report summarizing the key results of Phase 2 (i.e., the committee's Phase 2 report).

Appendix B

Recommendations from the Phase 1 Report

Listed below are the findings, recommendations, and barriers that appear in the Phase 1 report produced by the Committee on Advanced Engineering Environments, *Advanced Engineering Environments—Achieving the Vision* (1999).

A HISTORIC OPPORTUNITY

Finding 1. A historic opportunity now exists to develop AEE technologies and systems that could revolutionize computer-based engineering processes, just as the Internet has revolutionized computer-based communications. This opportunity is too big for any one organization to realize on its own.

Recommendation 1. To take full advantage of the opportunity represented by AEEs, a government-industry-academia partnership should be formed. This partnership should foster the development of AEE technologies and systems in the following ways:

- Develop open architectures and functional specifications for AEEs to guide the development of broadly applicable, interoperable tools.
- Create specific plans for transitioning the results of research and development by government and academic organizations to the commercial software industry and/or software users (e.g., the aerospace or automotive industries), as appropriate.
- Develop an approach for resolving information management and organizational issues.

Recommendation 2. As part of its ongoing AEE research and development, NASA should draft a plan for creating a broad government-industry-academia partnership. In addition, to demonstrate the utility of partnerships on a small scale, NASA should charter a joint industry-academia-government advisory panel that focuses on interactions between NASA and outside organizations. This panel should periodically identify areas of overlap (1) between high-payoff requirements of external users and NASA's research and development capabilities, and (2) between the capabilities of external organizations and NASA's own requirements. This would facilitate technology transfer and allow NASA to focus its AEE research and development on the areas of greatest need.

REQUIREMENTS AND BENEFITS

Recommendation 3. Current AEE research and development is too diffuse and should be focused on the following top-level objectives:

- Enable complex new systems, products, and missions.
- Greatly reduce product development cycle time and costs.

In addition, AEE technology and system developers should devise a comprehensive, multi-faceted implementation process that meets the following objectives:

- Lower technical, cultural, and educational barriers.
- Apply AEEs broadly across U.S. government, industry, and academia.

Finding 2. The top-level goals that NASA has established for the Intelligent Synthesis Environment functional initiative address important AEE requirements. However, given the resources that NASA plans to allocate to the initiative, the objectives of this initiative are overly ambitious. NASA plans to adjust the objectives accordingly.

Recommendation 4. NASA should establish an AEE "center of gravity" that is empowered to select the high-priority analyses and processes that will be developed, integrated, and deployed as a mission design system. To ensure success, the location, leadership, and staff of the center of gravity should be carefully selected to reflect the differing needs, capabilities, and perspectives of NASA's operational and research Centers. In addition, NASA should allocate resources for the ongoing maintenance of the mission design system and better coordinate related activities with outside organizations, in accordance with Recommendations 1 and 2.

BARRIERS

Finding 3. Efforts by industry and government to develop and deploy AEEs face significant barriers in the following areas:

- integration of tools, systems, and data
    - lack of tool interoperability
    - proliferation of tools
    - existing investments in legacy systems
- information management
    - proliferation of all types of information
    - configuration-management issues
- cultural, management, and economic issues
    - difficulty of justifying a strong corporate commitment to implementing AEE technologies or systems
    - lack of practical metrics for determining AEE effectiveness
    - unknowns concerning implementation costs
- education and training
    - training of the current workforce
    - education of the future workforce

Recommendations related to each of these areas appear below. A complete list of barriers appears in Table B-1.

Integration of Tools, Systems, and Data

Recommendation 5. For AEEs to succeed, a practical approach must be developed for improving the interoperability of new product and process models, tools, and systems and linking them with legacy tools, systems, and data. Sponsors of AEE research and development should consider the integration of AEE product and process models, tools, data, and technologies related to software, avionics, manufacturing, operations, maintenance, economics, and other areas as a fundamental requirement.

Recommendation 6. Government agencies and other organizations with a large stake in the successful development of AEEs should interact more effectively with standards groups to facilitate the development of interoperable product and process models, tools, systems, and data, as well as open system architectures. Specific high-priority interoperating capabilities should be defined along with action plans, incentives, and schedules for establishing appropriate standards and achieving specified levels of interoperability.

Information Management

Finding 4. There is a lack of commonality in product and process descriptions within user organizations, among user organizations, and between users and suppliers. As a result, users must often customize commercially available tools before they can be used, which greatly reduces the cost effectiveness of new tools.

Recommendation 7. Corporate and government leaders should seize the opportunity to develop robust and flexible AEE tools for creating, managing, and assessing computer-generated data; presenting relevant data to operators clearly and efficiently; maintaining configuration management records for products, processes, and resources; and storing appropriate data on a long-term basis.

Cultural, Management, and Economic Issues

Finding 5. Historically, not enough attention has been paid to the organizational, cultural, psychological, and social aspects of the user environment associated with AEE technologies.

Recommendation 8. AEEs should be integrated into the senior management culture of any organization that elects to make a major investment in developing or implementing AEE technologies or systems. Each organization should designate a "champion" with the responsibility, authority, and resources to achieve approved AEE objectives. The champion should be supported by a team of senior managers, technical experts (including human factors experts, social scientists, and psychologists), and other critical stakeholders (e.g., suppliers, subcontractors, and customers typically involved in major projects). Similar, subordinate teams should be assembled in major organizational elements or facilities involved in the AEE project. Guidance from these teams should be consistent with the organization's role in product development or mission operations and compatible with engineering practices already in place.

Finding 6. Government agencies have frequently used contract provisions to influence the business practices of their contractors. This approach has also been used, on occasion, to influence engineering practices.

Recommendation 9. Government agencies involved in the acquisition of complex engineering systems should provide incentives for contractors to implement appropriate AEE technologies and systems and to document lessons learned. For example, AEE research and development funds could be used to provide contractual incentives for contractors to develop, test, demonstrate, implement, and/or validate AEE technologies and systems as part of major procurements. These incentives should target both technical and non-technical (i.e., cultural, psychological, and social) aspects of AEE development and implementation.

Recommendation 10. NASA should define an agency-wide plan for the development and implementation of comprehensive, improved engineering processes, practices, and technologies. The NASA-wide teams directing the Intelligent Synthesis Environment functional initiative should be consolidated and strengthened to improve their ability to perform the following functions:

- Define distinct AEE requirements and goals for NASA operational and research Centers.
- Ensure that NASA's AEE activities take appropriate advantage of commercially available tools and systems to avoid duplication of effort.
- Overcome cultural barriers within NASA so that new AEE technologies and systems will be accepted and used.
- Disseminate AEE plans, information, and tools at all levels of NASA.
- Provide centralized oversight of AEE research and development conducted by NASA.

Education and Training

Recommendation 11. An advisory panel with representatives from industry, universities, the National Science Foundation, NASA Centers, and other government agencies and laboratories should be convened by NASA or some other federal agency involved in AEE research and development. The panel should define incentives for accelerating the incorporation of AEE technologies into the engineering curriculum, define the basic elements that would comprise a suitable AEE experience for students, and specify resource needs.

ORGANIZATIONAL ROLES

Recommendation 12. AEEs should use commercially available tools as much as possible. In general, the development of application-specific tools should be left to industry. Government agencies should not develop customized tools that duplicate the capabilities of commercially available tools. If available tools are inadequate, government agencies should consider providing incentives for the development of improved, broadly applicable tools by commercial software vendors instead of developing specialized tools themselves. Government agencies should take the following actions to support the development of broadly applicable AEE technologies, systems, and practices:

- Improve generic methodologies and automated tools for the more effective integration of existing tools and tools that will be developed in the future.
- Develop better models of specific physical processes that more accurately portray what happens in the real world and quantify uncertainties in model outputs.
- Identify gaps in the capabilities of currently available tools and support the development of tools that address those gaps, preferably by providing incentives for commercial software vendors to develop broadly applicable tools.
- Develop test beds that simulate user environments with high fidelity for validating the applicability and utility of new tools and systems.
- Develop methods to predict the future performance of AEE technologies and systems in specific applications and, once implemented, to measure their success in reaching specified goals.
- Explore the utility of engineering design theory as a tool for guiding the development of AEE technologies and systems.
- Use contracting requirements to encourage contractors to adopt available AEE technologies and systems, as appropriate.
- Address issues related to the organizational, cultural, psychological, and social aspects of the user environment.
- Provide incentives for the creation of government-industry-academia partnerships to foster the development of AEE technologies and systems.

Recommendation 13. NASA has many opportunities to achieve its objectives by leveraging the results of long-term AEE research and development by other organizations in government, industry, and academia. NASA also has opportunities to conduct AEE research and development that would be of value to other organizations. To maximize the effectiveness of both efforts, NASA must improve its understanding of the capabilities and requirements of external organizations. NASA should convene a standing, joint industry-academia-government advisory panel (see Recommendation 2) to facilitate technology transfer and enable NASA to focus its AEE research and development on the areas of greatest need.

TABLE B-1 Barriers to Achieving the AEE Vision (from the Phase 1 Report)

Integration of Tools, Systems, and Data

1. Lack of tool interoperability
2. Continued proliferation of tools, which aggravates interoperability issues
3. Existing investments in legacy systems and the difficulty of integrating legacy systems with advanced tools that support AEE capabilities
4. Little effort by most software vendors to address interoperability or data exchange issues outside of their own suite of tools
5. Multiple hardware platform issues—computers, hardware, databases, and operating systems
6. Lack of formal or informal standards for interfaces, files, and data terminology
7. Increasing complexity of the tools that would support AEE capabilities
8. Difficulty of inserting emerging and advanced technologies, tools, and processes into current product and service environments
9. Supplier integration issues
10. Difficulty of integrating AEE technologies and systems with other industry-wide initiatives, such as product data management, enterprise resource management, design for manufacturability/assembly, and supply chain management

Information Management

1. Proliferation of all types of information, which makes it difficult to identify and separate important information from the flood of available information
2. Difficulty of maintaining configuration management for product designs, processes, and resources
3. Need to provide system “agility” so that different types of users can easily input, extract, understand, move, change, and store data using familiar formats and terminology
4. Difficulty of upgrading internal infrastructures to support large bandwidths associated with sharing of data and information
5. Need to provide system security and to protect proprietary data without degrading system efficiency

Culture, Management, and Economics

1. Difficulty of justifying a strong corporate commitment to implementing AEE technologies or systems because of their complexity and uncertainties regarding costs, metrics, and benefits
2. Lack of practical metrics for determining the effectiveness of AEE technologies that have been implemented
3. Unknowns concerning the total costs of implementing AEE technologies and systems and the return on investment
4. Difficulty of securing funding to cover the often high initial and maintenance costs of new AEE technologies and systems in a cost-constrained environment
5. Risk—and someone to assume the risk (management, system providers, or customers)
6. Planning and timing issues—when to bring in the new and retire the old
7. Difficulty of managing constant change as vendors continually upgrade AEE tools and other technologies
8. Diversity of cultures among different units of the same company

Education and Training

1. Need to upgrade labor force skills along with technology and tools to support an AEE capability
2. Difficulty of incorporating AEE technologies into university design curricula

Appendix C

Recommendations from the Phase 2 Report

Listed below are all of the findings and recommendations contained in this, the Phase 2 report of the Committee on Advanced Engineering Environments.

Chapter 3: Expected Future

Finding 3-1. Industry, government, and academia can significantly improve their engineering practices by using available AEE technologies.

Finding 3-2. Government agencies (such as NASA) acting alone will not be able to achieve the 15-year visions of the Integrated Manufacturing Technology Roadmapping Initiative or NASA's Intelligent Synthesis Environment (ISE) Initiative. Similarly, actions such as linking the Army's Simulation and Modeling for Acquisition, Requirements, and Training (SMART) Program with the ISE initiative, although a step in the right direction, are unlikely to achieve these visions unless the partnerships are expanded to include other government, industry, and university programs with additional resources.

Recommendation 3-1. Until additional funding is made available to invigorate the recommended national partnership for AEEs, government agencies should make the most efficient use of the limited resources now available for the development of AEE technologies and systems by focusing their efforts on the types of missions and products that can benefit most from AEEs and on functional areas that are lagging behind the rapid advances being made in other areas, such as the speed, size, and cost of computer hardware. Research and development should be focused on the following areas:

- comprehensive processes for project design and development that integrate the design of mechanical systems with electrical system design and software development
- general-purpose methods of analyzing cost and determining the effects of risk and uncertainty to reduce the need for project-specific cost and risk analysis tools
- physics-based analysis of mission-specific phenomena if first-of-a-kind missions are a high priority

Recommendation 3-2. The federal government should carefully assess how the limited resources available for AEE research and development (such as the Intelligent Synthesis Environment Initiative) are allocated between the development of (1) general-purpose research with broad application (to improve engineering processes throughout the United States), and (2) engineering processes of particular relevance to agency missions (including activities by industry and academia). The guidelines in Recommendations 9 through 12 of *Advanced Engineering Environments: Achieving the Vision* (the Phase 1 report), which call for action by NASA and other federal agencies, remain relevant.[1]

Chapter 4: Overcoming Barriers

Finding 4-1. Interoperability and composability problems are a major barrier to realizing the AEE vision. The understanding of and technology base for developing interoperable and composable software architectures need to be improved.

Recommendation 4-1. The federal government should support basic research on the interoperability and composability of component software architectures in the context of open Internet computing to increase software reliability and encourage the widespread use of promising solutions. Efforts to resolve interoperability and composability problems should investigate approaches, such as open-source guidelines, for bringing together software designed for diverse

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[1] Appendix B of this report lists the recommendations from the Phase 1 report.

applications (e.g., mechanical, electrical, software, and biomedical systems).

Recommendation 4-2. Government, industry, and academia should seek consensus on interoperability standards.

Finding 4-2. Engineering tools and systems have been developed on a variety of incompatible operating systems and with a variety of programming languages. This situation is changing as more advanced tools and systems are being developed for Internet deployment.

Recommendation 4-3. Research and development by the federal government on the visualization of engineering and scientific data should focus on long-term goals that go beyond those of ongoing research and development by industry.

Finding 4-3. Advanced Internet technologies and applications are likely to provide the universal, high-bandwidth, low-latency communications network necessary to meet most communications needs for AEEs.

Recommendation 4-4. Research, development, and engineering organizations in government, industry, and academia should ensure that technical staff and students have access to advanced data communications networks as those systems become available.

Recommendation 4-5. The government and academia should conduct research to improve understanding of the following topics:

- the role of physical artifacts in supporting collaborative design processes and how that role can be fulfilled when physical artifacts are replaced by simulations, virtual objects, avatars, and other nonphysical artifacts
- methods for designing AEE systems that accommodate workers with a variety of work styles and improve the new work environment (e.g., by improving situational awareness for workers transitioning between tasks, teams, and projects)
- the psychological and temporal dimensions of engineering design work in synchronous, distributed collaborative activities, especially if team members are located in multiple time zones and work for organizations with different cultures and business goals

Finding 4-4. Research funding, interdepartmental cooperation, and organizational support for interdisciplinary programs has traditionally been difficult to obtain from the government or academia, largely because funding agencies have usually set narrow limits on the types of projects they are willing to support.

Recommendation 4-6. Accrediting organizations, industrial organizations, and professional societies should continue to advocate greater use of AEE technologies and systems in the academic environment at both the undergraduate and graduate levels.

Recommendation 4-7. Universities should appoint AEE champions to provide strong, long-term leadership for implementing AEE technologies and systems; establish the innovative, interdisciplinary educational programs and faculty needed to take full advantage of the capabilities of AEEs; increase the emphasis in undergraduate and graduate education on the scholarship of integration and application; and develop curricula with a stronger foundation in software development, including component software architecture, composability, and interoperability.

Recommendation 4-8. Initial and continuing education should include strategies for (1) maintaining scientific and engineering understanding of processes and tasks that will be done automatically by AEE technologies and (2) training people for the transition from conventional working environments and processes to the pace and structure of working as members of multiple, concurrent, rapidly reconfigurable teams.

Recommendation 4-9. AEE research and development should consider training and education requirements for undergraduate, graduate, and continuing education. The lessons learned from the development of advanced training simulators that incorporate AEE technologies and systems should be used to improve the training and educational capabilities of AEEs focused on other applications, including university education.

Finding 4-5. The costs of implementing AEEs may not be justifiable in the short term. However, pioneers in the use of AEE technologies are realizing economic benefits. As AEE technologies become more common and sophisticated, the long-term viability of most commercial design and manufacturing companies and other complex, technical enterprises will increasingly depend on their ability to implement AEE technologies and systems of increasing sophistication.

Recommendation 4-10. Because of the technical and social complexities involved in applying AEEs, efforts to implement them should include the following:

- processes for taking advantage of the lessons learned by AEE pioneers, especially with regard to the reduction of implementation costs, uncertainties, and risks
- realistic goals for the economic payoffs of implementing AEEs, especially the time needed to realize a positive return on investment

- innovative and determined management that is willing to accept risks; appoint a "champion" with broad, interdisciplinary authority; persevere despite temporary setbacks; and accept uncertainty in assessments of the cost and benefit of implementing AEE technologies
- Web-based AEE technologies with open architectures and improved interoperability and composability to reduce implementation costs

Chapter 5: General Approaches and Roles

Finding 5-1. The Phase 2 study reaffirmed the approach described in the Phase 1 report for developing AEE technologies and systems. That approach includes the following key steps:

- forming a national partnership of government, industry, and academia to take advantage of the current historic opportunity to develop AEEs
- forming government-industry-academia AEE partnerships by individual agencies, such as NASA, as an interim step for addressing agency-specific goals while a national partnership is being formed
- overcoming major barriers related to the integration of systems, tools, and data; information management; cultural, economic, and management issues; and education and training[2]
- facilitating the transfer of new capabilities to commercially available products by developing application-specific tools required by government through contracts with industry whenever practical
- focusing the government's AEE research and development on key objectives, such as (1) modeling key physical processes, (2) improving generic AEE methodologies and automated tools, (3) developing testbeds that simulate user environments, (4) developing accurate performance metrics, and (5) other areas where market-based incentives are not motivating adequate industry-sponsored research
- providing government incentives for (1) industry to adopt AEE technologies in government procurements, (2) academia to adopt AEE technologies in major government-sponsored research programs, and (3) industry and academia to collaborate in modernizing educational curricula to prepare students for an AEE work environment

Finding 5-2. Most government, industry, and academic organizations have yet to take advantage of AEE technologies because of technical, cultural, management, and economic problems, some real and others perceived, even though available technologies can tremendously improve products and processes. The advantages of using AEEs cannot be realized with business-as-usual approaches because of the high start-up costs and fundamental technological and cultural changes necessary to implement AEEs.

Recommendation 5-1. Federal agencies involved in AEE research and development should be more aggressive in forming a national partnership with industry and academia to develop AEEs that offer seamless, end-to-end engineering design capabilities that encompass the entire life cycles of products and missions.

Recommendation 5-2. To deploy AEEs successfully, organizations should identify and resolve organizational issues in addition to improving processes and tools. Each organization should also assign a strong leader or "champion" supported by the following:

- a knowledgeable team familiar with lessons learned from similar organizations that have implemented AEE technologies
- a plan for deploying AEEs that is tailored to the stated objectives and the barriers that must be overcome
- realization by all levels of the organization that both technical *and* nontechnical changes are needed in the near term and/or the long term for future success (or, perhaps, survival)
- long-term commitment by senior executives to the deployment of AEEs despite the costs of setting up new systems and processes and the risks of short-term setbacks
- willingness of the workforce to accept new methods

Finding 5-3. Advanced Internet technologies and applications (including operating systems, software architectures, and hardware) are one of the keys to developing AEEs that (1) overcome critical technical issues, such as those associated with interoperability and information management, and (2) facilitate the use of AEEs by small companies.

Recommendation 5-3. The government's AEE research and development programs should focus much more on approaches to AEEs that will be compatible with the Internet of the future and information technologies being developed by other programs, such as Internet-2, Next Generation Internet, very high performance Backbone Network Service, and Information Technology Research Initiative.

Finding 5-4. NASA could greatly benefit from increased use of AEEs. However, the conditions necessary for significant, widespread adoption of AEEs do not yet exist in the agency.

Recommendation 5-4. Successful implementation of AEEs by NASA will require sustained leadership and commitment, adequate funding, and a cohesive plan that includes all

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[2] See Chapter 4 and Table B-1.

NASA centers, as outlined in Recommendations 4, 10, 11, 12, and 13 of the Phase 1 report:

- NASA should not create a broad-based AEE research program to develop comprehensive AEE systems. Instead, NASA should provide for research and advocacy in areas that AEE research and development sponsored by other organizations do not adequately address, especially areas related to the needs of NASA and the rest of the aerospace industry.
- NASA should capitalize on industrial advances in AEE technologies. In particular, NASA should investigate how NASA-funded research related to AEEs and the Next Generation Internet can enhance the ability of Internet-related technologies and applications to meet AEE objectives.
- NASA should form a government-industry-academia partnership for AEEs to help advocate and implement AEEs in the agency and the nation.

Recommendation 5-5. The federal government should continue to support educational advances related to AEEs in the following ways:

- Continue to support the development and implementation of new educational methods through programs such as the National Science Foundation's engineering education coalitions and engineering research centers.
- Include academia as a key participant in a national partnership on AEEs and other AEE development activities.
- Fund long-term, high-risk research on AEEs that industry is unlikely to support, including research on academic applications of AEE technologies and systems.
- Avoid overly restricting the direction or content of long-term, high-risk AEE research sponsored by the government.

Appendix D

Biographical Sketches of Committee Members

Robert E. Deemer (chair) has 25 years of industry experience in the fields of simulation, modeling, virtual prototyping, collaborative engineering, computer design, onboard spacecraft processor design, and integrated network systems design. He has master's degrees in computer science, management science, business administration, history, and philosophy from California State University, Colorado Technical College, Pepperdine University, University of Southern California, and California State University, respectively. He also has undergraduate degrees in engineering, software design, economics, business management, and English literature. Currently, Mr. Deemer is the vice president of business development/marketing for Catalina Research, Incorporated, and an adjunct faculty member at Regis University, the University of Colorado, and Colorado State University, where he teaches graduate classes in future technology, international science and technology, operations management, and managing change. He also teaches Internet distance learning classes to graduate students from all over the world.

Tora K. Bikson, a senior behavioral scientist at RAND Corporation since 1976, is recognized for her research on the introduction of advanced communication and information technologies and their effects in varied contexts. She recently completed a project to define organizational needs and best practices for creating, managing, and distributing electronic documents (including compound, multimedia, and interactive documents) among United Nations organizations based in Europe, North America, and South America. In projects for other clients, such as the National Science Foundation, the World Bank, the Organization for Economic Co-operation and Development, and the Markle Foundation, she has addressed factors that affect the successful institutionalization of new interactive technologies in ongoing communities of practice, how these innovative media influence intra- and interorganizational structures and group processes, their impact on task performance and social outcomes, and their policy implications. Dr. Bikson has coauthored three recent books addressing these issues: *Teams and Technology* (Harvard Business School Press, 1996), *Universal Access to E-mail: Feasibility and Societal Implications* (RAND, 1995), and *Preserving the Present* (Sdu Publishers, 1993). Her work has also appeared in numerous journals and book chapters. Dr. Bikson holds a Ph.D. in philosophy from the University of Missouri and a Ph.D. in psychology from the University of California, Los Angeles.

Robert A. Davis is the retired corporate vice president of engineering for The Boeing Company. Since his 41-year career began in 1958 with the introduction of the commercial 707 series of aircraft, he has been associated with all Boeing jet transports in both engineering and management capacities. He led the modernization program for the 747 in 1985 as chief project engineer and became engineering vice president for all commercial airplanes in 1991. He participated in the 777 program, which worked exclusively with computer-aided design and has become an industry benchmark. Mr. Davis became corporate vice president of engineering in 1994, reporting directly to the president. He is a registered professional engineer with a B.S. from the University of British Columbia and an M.S. from the University of Washington. Mr. Davis is a fellow of the American Institute for Aeronautics and Astronautics and the Royal Aeronautical Society and president of the International Federation of Airworthiness, which is headquartered in the United Kingdom; a member of General Motors Science Advisory Committee; and a member of the National Research Council Board on Engineering and Manufacturing Design.

Richard T. Kouzes is a senior staff scientist at the U.S. Department of Energy's (DOE's) Pacific Northwest National Laboratory (PNNL), where he works in the area of disarmament and nonproliferation. Formerly, as the director of program development for science and engineering and professor of physics at West Virginia University (WVU), he was responsible for promoting the growth of research and economic development programs in the physical and biological sciences and engineering. His current research is in the field of collaborative computing for the enabling of scientific research independent of geographical location and nuclear physics for disarmament verification. Before moving to WVU, Dr. Kouzes was a staff scientist at PNNL and a principle investigator for DOE's Distributed Collaboratory Experimental Program. His research program at PNNL was in computer-assisted cooperative work, advanced data acquisition system development, neural network applications, and precision atomic mass measurements. Previously, Dr. Kouzes was a senior research physicist and lecturer at Princeton University, where for 15 years he was a leading researcher in solar neutrino and nuclear structure experimentation. Dr. Kouzes earned his Ph.D. in physics from Princeton University and did postdoctoral work at Indiana University. He is a founder and past chair of the Institute of Electrical and Electronics Engineers Committee for Computer Applications in Nuclear and Plasma Sciences and the author of more than 70 refereed papers.

R. Bowen Loftin has a B.S. in physics from Texas A&M University and an M.A. and Ph.D. in physics from Rice University. He is a professor of computer science and the director of the Virtual Environment Technology Laboratory at the University of Houston and a professor of physics at the University of Houston-Downtown. Dr. Loftin was previously on the faculty of Texas A&M University at Galveston and held a postdoctoral appointment in the Department of Mechanical Engineering at Rice University. Since 1983, Dr. Loftin, his students, and coworkers have been exploring the application of advanced software technologies, such as artificial intelligence and interactive, three-dimensional computer graphics, to the development of training systems. Dr. Loftin is a consultant to both industry and government in the areas of advanced training technologies and scientific/engineering data visualization. He serves on advisory committees and panels sponsored by numerous government and professional organizations. Awards received by Dr. Loftin include the University of Houston-Downtown Award for Excellence in Teaching and Service, the American Association of Artificial Intelligence Award for an innovative application of artificial intelligence, the National Aeronautics and Space Administration (NASA) Public Service Medal, the NASA Space Act Award, and the 1995 NASA Invention of the Year Award. He is the author or coauthor of more than 100 technical publications.

James A. Maniscalco has more than 25 years of experience in the energy, aerospace, and automotive industries. Currently, he is a general director of engineering of Delphi Automotive Systems, where he is responsible for the global engineering of Delphi's occupant protection and interior products. To increase Delphi's productivity and reduce its manufacturing costs, Dr. Maniscalco's work focuses on advanced engineering environments and lean engineering initiatives. In the past decade, he has focused primarily on using aerospace capabilities to solve automotive challenges. Key accomplishments include the development of new automotive products, such as electrically powered steering and active controlled suspension. Dr. Maniscalco began his professional career in the U.S. Navy, where he reached the rank of lieutenant commander, and he holds a B.S. in engineering from the U.S. Naval Academy. He was selected as a Fulbright Scholar and earned an M.S. in physics from the University of Turin in Italy. Dr. Maniscalco also has an M.S. and Ph.D. in engineering from Purdue University. He has been a member of the Society of Automotive Engineers since 1991 and is a past member of the American Nuclear Society. He has authored more than 40 technical publications on many topics, including lasers, fusion energy, and accelerators.

Robert J. Santoro is the director of the Propulsion Engineering Research Center and a distinguished professor of mechanical engineering at the Pennsylvania State University. He received a Ph.D. in physics from Boston College, where he also held a one-year position as a lecturer. He then joined the Fuels Research Laboratory in the Department of Mechanical and Aerospace Engineering at Princeton University as a research engineer. His research there emphasized the study of hydrocarbon oxidation and flame spread over liquids and solids. He left Princeton University to join the National Bureau of Standards (now the National Institute of Standards and Technology) in Washington, D.C., where he conducted combustion research until his departure in August 1986. Dr. Santoro was awarded the U.S. Department of Commerce Silver Medal in 1986 for his research on particle diagnostics and soot formation. He is a member of the Combustion Institute, the American Chemical Society, the American Institute of Aeronautical and Astronautics, and the American Physical Society. His research interests include rocket and gas turbine engines, soot formation in flames, liquid spray combustion, laser diagnostics, diesel engine combustion, combustion instability, chemical kinetics, and materials processing. Dr. Santoro collaborates with NASA and the rocket industry on the development of advanced space transportation technology.

Daniel P. Schrage has been a professor in the School of Aerospace Engineering at the Georgia Institute of Technology since 1984, director of the Center of Excellence in Rotorcraft Technology (CERT) since 1986, and codirector of the Center for Aerospace Systems Analysis (CASA) since 1998. Dr. Schrage has served as a member of the Army Science Board, the National Research Council Air Force Studies Board, and NASA's Aeronautics Research and Technology Committees. He has also served on the Industry

Affordability Executive Committee/Task Force of the National Center for Advanced Technologies, which has been industry's voice to the Office of the Secretary of Defense on affordability issues. Dr. Schrage has led much of the executive committee's work on integrated product and process development (IPPD), and the IPPD methodology he developed is being used by the Navy Acquisition Reform Office in much of its IPPD training. Prior to joining the faculty of Georgia Tech, Dr. Schrage served for 10 years as an engineer, manager, and senior executive with the U.S. Army Aviation Systems Command. He was the chief of the Structures and Aeromechanics Division and served on the source selection evaluation boards for the AH-64 Apache, UH-60 Black Hawk, and OH-58D Kiowa helicopters. He led the concept development of the LHX, which is now the RAH-66 Comanche helicopter. From 1967 to 1978, Dr. Schrage was on active duty as a U.S. Army field artillery officer and aviator. His service included tours of duty as a battery commander in Europe and as an aviation company platoon leader and battalion operations officer (S-3) in combat in Southeast Asia.

Allan Sherman is the chief technologist for Lockheed Martin Space Systems Company in Sunnyvale, California. He has 37 years of aerospace experience, particularly in technology development and the design, development, and testing of space systems. Prior to joining Lockheed Martin in 1997, Dr. Sherman was the director of engineering at NASA's Goddard Space Flight Center. During his 30 years with NASA, he was awarded the Exceptional Engineering Achievement, Outstanding Leadership, and Distinguished Service awards. Prior to his career in NASA, he held engineering positions with Pratt and Whitney and Aerojet-General corporations. Dr. Sherman earned a B.S. and M.S. in mechanical engineering from Cornell University and a Ph.D. in aerospace engineering from the University of Maryland. He chairs the Industrial Advisory Board for the Aerospace Engineering Department at the University of Maryland.

John Sullivan has been on the faculty of Purdue University since 1975, where he is currently a professor and the head of the School of Astronautics and Aeronautics. His research interests include laser instrumentation (e.g., laser Doppler velocimeters and particle image velocimeters), luminescent sensors for temperature and pressure measurements, and experimental aerodynamics, especially with regard to the comparison of experimental data and the results of computational analysis. Dr. Sullivan has received the John Fluke Award for Excellence in Laboratory Instruction. He holds a B.S. in mechanical and aerospace sciences from the University of Rochester and an M.S. and Sc.D. in aeronautical engineering from the Massachusetts Institute of Technology.

Gordon Willis is president of Gordon Willis Associates, a consulting firm specializing in the development and support of AEEs. Mr. Willis retired from Ford in 1999 as chief engineer of automatic transmissions, powertrain operations. He joined Ford in 1976and served in a number of research positions related to computer-aided engineering (CAE) and powertrain control. In 1987, he was named North American automotive operations CAE manager, a position he held for two years before becoming the director of product and manufacturing systems. He was the chassis chief engineer from 1992 to 1994, and then became vehicle chief engineer in Europe. He holds a B.S. and M.S. in mechanical engineering from the Massachusetts Institute of Technology and an M.B.A. from the University of Michigan.

Michael J. Zyda is a professor in the Department of Computer Science at the Naval Postgraduate School (NPS), Monterey, California, and chair of the NPS Modeling, Virtual Environments, and Simulation Academic Group. His research interests include computer graphics; large-scale, networked, three-dimensional virtual environments; computer-generated characters; video production; entertainment-defense collaboration; and modeling and simulation. Dr. Zyda was a member of the National Research Council Committee on Virtual Reality Research and Development and the chair of the Committee on Modeling and Simulation: Linking Entertainment and Defense. He is a senior editor for virtual environments for the MIT Press quarterly, *Presence,* a journal of teleoperation and virtual environments. Dr. Zyda is also a member of the Editorial Advisory Board of *Computers & Graphics* and a member of the Technical Advisory Board of the Fraunhofer Center for Research in Computer Graphics, Providence, Rhode Island. He received a B.A. in bioengineering from the University of California, San Diego, an M.S. in computer science from the University of Massachusetts, Amherst, and a D.Sc. in computer science from Washington University, St. Louis.

Dianne S. Wiley, Aeronautics and Space Engineering Board liaison to the Advanced Engineering Environments Committee, recently joined The Boeing Company Phantom Works, where she is responsible for transfer of advanced structures and materials technology to next-generation reusable launch vehicles. Previously, she was with Northrop Grumman for 20 years, where her last position was manager of materials and processes technology in the Integrated Systems and Aerostructures Sector. In that position, Dr. Wiley was responsible for research and development in materials and processes and technology transition to production. While at Northrop Grumman, Dr. Wiley also served as manager of airframe technology in the Business and Advanced Systems Development Group, where she directed five departments performing advanced development and technology transition in structural engineering, materials and processes, and manufacturing technology. During this time, she was responsible for transitioning airframe core technologies into three new business areas (space, biomedicine, and surface ships) to offset declines in traditional business. Previously, as a senior technical specialist on the B-2 program, Dr. Wiley was responsible for developing and implementing innovative structural solutions to ensure the structural integrity of the B-2 aircraft. Dr. Wiley's 25 years of technical experience have involved durability and damage tolerance, advanced composites (organic and ceramic), high-temperature structures, smart structures, low-observable structures, concurrent engineering, and rapid prototyping.

Appendix E

Participants in Committee Meetings

The full committee met four times between June and December 1999. Many smaller meetings were attended by one or more committee members and representatives of public and private organizations involved in the development and/or use of advanced engineering environments. The small group meetings were part of the committee's information-gathering process. Outside participants are listed below, grouped by organization:

Aerospace Corporation
Dwight Abbott
Ron Bywater
Andrew Dawdy
Ted Mohaugh
Sandy Page
Tom Trafton

Air Force Research Lab
Dee Andrews

Army Research Institute
Steve Goldberg

BCI, Inc.
Dennis White

The Boeing Company
David Kasik

Concepts ETI, Inc.
David Japikse

Electric Boat Corporation
John Alden
Fred Harris
John Holmander
Eric Jay
Pete Landry
Tom Skrmetti
Don Slawski
Andy Stoddard

Internet2 Central Laboratory
Jaron Lanier

Lawrence Berkeley National Laboratory
Stewart C. Loken

Microsoft Research
Jonathan Grudin

NASA Headquarters
Murray Hirschbein
Sam Venneri

NASA Jet Propulsion Laboratory
David Atkinson
Pat Liggett
Knut Oxnevad
Mike Sander
Peter Shames
David Smith
Steve Wall
Bill Weber

NASA Langley Research Center
Doug Craig
Brantley Hanks
Arlene Moore

National Institute of Standards and Technology
Albert Jones

National Science Foundation
Suzi Iacono

Raytheon Systems Company
Steve Olson

Solectron
Kim Hyland
Shrinivas Raos
Terri Zee

Sun Microsystems
Roger Day
Jack Herzog
Ron Melanson
Peter Rado
Cindy Reese

University of North Carolina
Prasun Dewan

U.S. Navy
Wendy Lawrence

Acronyms

AEE	advanced engineering environment
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacturing
CATIA	Computer-Aided Three-Dimensional Interactive Application (a CAD program)
EB	Electric Boat Corporation
IMTR	Integrated Manufacturing Technology Roadmapping (Initiative)
ISE	Intelligent Synthesis Environment (Initiative)
JSF	joint strike fighter
MFO	multifunctional optimization
NASA	National Aeronautics and Space Administration
NGI	Next Generation Internet
NSF	National Science Foundation
PC	personal computer
SMART	Simulation and Modeling for Acquisition, Requirements and Training (Program)
SSN	nuclear-powered attack submarine
vBNS	very high performance Backbone Network Service