8. TRANSPORTATION

The following technology areas are addressed in the Transportation category:

- Aerodynamics
- Avionics and Controls
- Propulsion and Power
- Systems Integration
- Human Interface

At a more specific technology level, the report discusses aircraft and surface vehicle aerodynamics, aircraft and spacecraft avionics, surface transportation controls, aircraft turbines and spacecraft power systems. At the level of systems integration and human-machine interface, the report discusses intelligent transportation systems, spacecraft and aircraft integration, human factors engineering (as it relates to transportation systems) and spacecraft life support systems.

The area of intelligent transportation systems is one where the U.S., Western Europe, and Japan are all engaged in various private and public efforts to develop more effective and efficient surface transportation systems. This area will ultimately involve radical changes in both vehicular technology and infrastructure that have the capacity to alter the American transportation system by better incorporating modern information technology into virtually every phase of passenger and freight transportation including its intermodal elements.

The U.S. has preeminence in most transportation areas, except for Western European developments in commercial aircraft technology, the leadership of France, Germany and Japan in fielding high speed rail systems, and German and Japanese advances in mag-lev technology. The specifics of the assessment are presented in the text of the section. The summary of the U.S. relative position and trends from 1990 to 1994 are shown in Figure 8.1.

AERODYNAMICS

Aircraft aerodynamics

Aerodynamic efficiency is one of the key parameters that determines the weight and cost of an aircraft. Roughly speaking, an aircraft's range is directly proportional to its aerodynamic efficiency without any increase in fuel usage. Such fairly-recent aerodynamic technologies as supercritical airfoils and winglets have already provided substantial increases in aerodynamic efficiency over first-generation jet transports, and there are many emerging aerodynamics technologies worthy of development and implementation. One of the most

Figure 8.1
Transportation
Technology Position and 1990-94 Trend

US Technology Position Relative to:
Japan ▷ , ○ , or ◁
Europe ▶ , ● , or ◀

1990–94 Trend
Improved ▷
Declined ◁
Maintained ○

	Lag: Substantial	Lag: Slight	Parity	Lead: Slight	Lead: Substantial
Transportation					
Aerodynamics				●	◁
aircraft aerodynamics				●	◁
surface vehicle aerodynamics (?)				○ ●	
Avionics & Controls				◀	◁
aircraft and spacecraft avionics				◀	◁
surface transport controls					
Propulsion & Power				◁ ●	
aircraft turbines				●	◁
spacecraft power systems				○ ●	
electrically powered vehicles			○	●	
Systems Integration				●	○
intelligent transportation systems					
spacecraft and aircraft integration				●	○
Human Interface					
human factors engineering					○ ●
spacecraft life support				●*	▷ ▶

*Russia (?) based on limited information

promising, especially for improving efficiency in jet transports, is laminar flow control.

Improved aerodynamics is critical to both commercial and military aircraft, including rotary wing aircraft. For commercial aircraft, improved aerodynamics reduces operating costs, thereby making the aircraft more competitive on international markets. It also significantly contributes to the national security by improving efficiency and performance of military aircraft.

Europe—primarily Germany, France, and the United Kingdom—is only slightly behind the United States in aircraft aerodynamics. Europe's hypersonic programs have been slowed significantly for economic reasons, but the test infrastructure continues to advance. European aerospace firms are investigating laminar flow airfoil technology to improve the competitiveness of their commercial aircraft. Current R&D efforts include the multinational European Laminar Flow Investigation (ELFIN) project which involves evolutionary improvements in and optimization of airfoil geometry as well as hybrid laminar flow techniques (HLFTs). Europe is conducting HLFT tests on the tail fin of an A320 and planning wingtip-to-wingtip tests on an A340. In addition, France's Dassault began HLFT tests in early 1993 on its Falcon 900 business jet. Airbus has also done extensive testing of riblets—originally developed by NASA and U.S. companies—on an A320 and A340 to create laminar flow over large regions of the aircraft's surface.

Japanese firms are substantially behind firms in both Europe and the United States, but joint work on the FS-X has allowed an infusion of U.S. aerodynamic technology that is improving their capabilities. Japanese research in laminar flow control has been limited by the lack of domestic commercial aircraft programs. Russia generally is behind the leaders in computational capability and advanced computational fluid dynamics codes for hypersonics and progress is slowing because of political and economic uncertainties. The United States also has a slight lead in technology for surface vehicle aerodynamics, based in large part on capabilities derived from the aerospace industry.

Surface vehicle aerodynamics

Surface vehicle aerodynamics provide the scientific foundations for developing lower drag shapes for automobiles, buses, trucks, and trains. As vehicle speed increases, aerodynamic drag becomes a major contributor to vehicle inefficiency and increased fuel consumption. The same phenomena that lead to increased drag-airflow separation and unsteady eddy formation-also lead to higher levels of flow noise and vehicle control problems. Aerodynamically designed vehicles can be both quiet and more efficient than existing vehicles, although current vehicles already incorporate efficient aerodynamic shapes. Given that drag reduction translates into reduced energy consumption, more efficient vehicles and ultimately lower demand for foreign oil.

AVIONICS AND CONTROLS

The United States is the world leader in most avionics and controls technology and is likely to maintain but not increase its edge over the next several years. Two European firms, France's Sextant Avionique and the UK's General Electric Company (GEC), are challenging traditional U.S. leaders across a wide range of avionics products but with the current downturn in military budgets, commercial developments will be slowed as few companies will be willing to risk large investments solely for the commercial market. Fewer new programs will make it difficult for foreign countries to decrease the gap or for the United States to increase it.

Aircraft and spacecraft avionics

Several goals drive development of fly-by-light (FBL) control systems: increased resistance to electromagnetic interference (EMI), increased bandwidth, and weight reductions. The increasing use of composite materials in aircraft structures has decreased EMI shielding previously provided by metal structures. Consequently, electrical cables used in fly-by-wire (FBW) systems are subjected to greater electrical interference which can degrade performance. In contrast to traditional electrical data busses, optical pulses transmitted by FBL systems are unaffected by the much lower frequency electromagnetic waves that characterize the EMI threat. FBL systems also provide better protection against lightning strikes. Moreover, fiber-optic cables can carry vast amounts of data and offer potential weight advantages. FBL technology will probably not be used in commercial transports until the 21st century, as the first production applications of fully FBL technology will probably be in military helicopters because of their extensive use of composite airframe structures.

During the 1980s, ring laser gyroscopes (RLGs)—first produced by U.S. firms for commercial aircraft—began replacing mechanical gyros in inertial navigation systems. During this same period, fiber-optic gyroscopes (FOGs) were also developed. Although FOGs initially promised equivalent performance to RLGs at lower cost, they have not yet met these expectations. Industry experts believe that FOGs are competitive in some low-to-medium-accuracy applications—such as attitude and heading indicators—but have not yet challenged RLGs in the high accuracy market. FOG systems—updated by global positioning system satellites—offer some long-term promise, particularly if FOG drift rate reduction programs are successful.

Avionics technologies have a huge impact on military aircraft, and leadership in areas such as radar, fire-control, countermeasures, stealth, and command and control must be maintained for the implementation of national security policy and strategy. Avionics technologies also have a large effect on commercial aircraft, and this impact will grow in future years. Active controls technologies as pioneered by U.S. aircraft such as the F-16 are now providing reduced fuel consumption and maintenance costs for the European Airbus and other foreign competitors to U.S. commercial aircraft. Advanced cockpit displays and controls, such as the "glass cockpit" reduce crew expenses and increase safety. Rotocraft are also likely to benefit from advances in avionics leading to improved safety and efficiency. Upcoming advancements in air traffic technologies should permit increased airspace usage with greater safety. Integration of aircraft and air traffic control systems of the future will be key to reducing delays and increasing capacity.

Advanced avionics make a direct contribution to the competitiveness of U.S. aircraft on world markets. They certainly play an important role in the U.S. ability to meet its national security and warfighting objectives.

European firms are at parity with U.S. firms in fly-by-wire (FBW) technology and ahead in its application to commercial aircraft. Although FBW systems have been in use on military aircraft since the mid-1970s, they were not introduced on commercial transports until the mid-1980s. Operating costs and safety considerations drive commercial FBW applications through reduced weight, improved fuel efficiency, increased reliability, and less unscheduled maintenance. European success can be attributed to two factors —aggressive application of military flight control technology to commercial aircraft and a wave of consolidation within the avionics industries. Although FBW technology was originally developed by U.S. firms for military aircraft, European firms—Britain's GEC and France's Sextant—were the first to apply the technology to a commercial aircraft, the Airbus A320. In late 1990, GEC won the contract to supply the FBW system for the Boeing 777—the first U.S.-produced commercial aircraft to incorporate FBW technology. Because new commercial transport programs like the Boeing 777 are launched so infrequently, GEC is gaining a significant advantage over U.S. firms in the commercial application of FBW technology. Japan, by contrast, has only a basic capability in FBW technology, through the FSX fighter program, and currently lacks a commercial program to gain experience.

U.S. firms—led by McDonnell Douglas—appear to have the lead in fly-by-light (FBL) developments. Much of the impetus for the U.S. developments comes from ARPA's technology reinvestment program. Limited reporting indicates that GEC and France's Dassault lead the Europeans in FBL development. GEC gained important experience through the FBL system it built for a dirigible. Japan has shown interest in FBL, but has allocated relatively small budgets for its development. Further development in FBL technology will likely require an appropriate military program and will give the country sponsoring the effort a significant advantage in FBL technology. NASA AST FBL program is also a major contributor to this technology development for the civil sector.

The United States is the leader in ring laser gyro (RLG) technology but several foreign firms have developed strong RLG capabilities. British Aerospace and the French firms SAGEM and Sextant are producing RLGs with long-term drift rates adequate for aircraft navigation. Foreign firms, however, lag U.S. firms in reducing gyro size while maintaining high accuracy. Foreign firms also remain secondary players in the RLG market because they are not cost competitive with U.S. firms. As Sextant's RLG production technology matures, the firm may attempt to win navigation contracts for Airbus aircraft—currently supplied by Honeywell. Japan Aviation Electronics originally based its development of RLG technology on licenses from a U.S. firm but now has an independent capability in the technology. Future foreign RLG developments will depend on whether those firms continue to fund RLG research or change their focus to fiber optic gyroscope or the Global Positioning System (GPS). The United States has a slight lead in fiber optic gyroscopes—an alternative technology for aircraft inertial-grade accuracy. Foreign efforts include work by the French firm, Photonetics, and Japan Aviation Electronics. U.S. manufacturers retain a lead in global positioning systems (GPS) receivers and processing equipment, largely because of their experience developing the satellite system. Europeans and Japanese each have a number of firms working on GPS receivers, but industry experts predict the U.S. will maintain its position over the next several years.

Japanese firms do not have strong technical capabilities across broad product lines but are strong in avionics display technologies. Japanese firms such as Hosiden, Sharp, Hitachi, NEC, and Toshiba have very high production yields and account for 95 percent of the world's active matrix liquid crystal displays—the technology of choice for most high-performance flat panel display (FPD) applications. Cockpit displays have evolved over the last decade from complex electromechanical instruments to electronic multifunction displays. The most advanced current commercial aircraft have displays based on cathode ray tubes, but FPDs are lighter, take up less space, consume less power, and offer increased display areas. Japanese firms were the first to achieve FPD sizes large enough for aircraft, and are now selling them on the commercial market (Boeing 777). Japan's FPD producers have only limited interest in producing FPDs for avionics applications, primarily because production runs are very small relative to the large FPD orders for computer and consumer electronic applications. Over the next several years, the United States could close the technology gap with Japan, based on government support for FPD and manufacturing technology development.

Spacecraft avionics currently involves issues of reliability, space certification, miniaturization, reduced power consumption, and "black box" modularity. Spacecraft control systems, on-board navigation systems, and precise engine throttling would all benefit from further improvements in this area. There is a growing trend towards the standardization and assembly of building block components to achieve a number of different functions and in this way to avoid a requirement to develop a large quantity of special purpose systems.

Surface transportation controls

Surface transportation controls span such applications as microprocessor based emissions control systems for monitoring and controlling engine performance to reduce emissions and optimize engine performance to the myriad components that would be essential to attain an intelligent vehicle highway system. A critical examination of the emissions control application suggests that these systems may operate effectively for much of a vehicles useful life, but ultimately, many of these systems may degrade and exhibit highly variable behavior that is accompanied by gross emissions of hydrocarbons, CO, and NOx. Thus, the issue is not to develop systems whose performance when new is exemplary. Rather, it is to develop reliable maintenance free emission control systems that will operate at close to new car levels when a vehicle is well past 100,000 miles and into its third, fourth, or fifth level of ownership. This remains a major challenge, particularly if years of neglect and poor maintenance are considered. In general, it seems plausible to think that reliable emission control systems for exhaust and evaporative emissions hold the key to reducing urban emissions and ozone formation in many areas, particularly in California, where 40 percent of vehicles have more than 100,000 miles on their odometer. The U.S. is pre-eminent in this technology area, driven by our commitment to clean air.

PROPULSION AND POWER

Propulsion technologies are important to both national security and economic prosperity because better engines improve fuel economy and reduce maintenance costs, and also allow designing a smaller, cheaper aircraft to perform some required mission. The interaction of propulsion and aerodynamics is essential for developing powered lift vehicles.

Aircraft turbines

For the turbojet engine, a key objective of the last 40 years has been to increase combustion temperatures for better efficiency and reduced fuel consumption, without burning up the turbine blades. This is done by better materials such as the ceramics mentioned elsewhere, better cooling approaches, and by better computational analysis methods. Reduced emissions and reduced noise are also becoming extremely important for the civil sector. Performance improvements in core engine technology have historically been driven by military programs, and commercial engine development will continue to benefit from military research efforts. Hot section advances are most directly linked to materials development and innovation in cooling techniques. Improved transmissions would be instrumental in moving forward with advanced rotocraft designs, such as the next generation of the tilt-rotor.

Efficiency of aircraft turbines significantly affects purchase price and operating costs of aircraft. Improved engines contribute to job creation in the aerospace sector, as well as to the competitiveness of the U.S. aerospace industry, because the U.S. is a major player in international aerospace markets. They also contribute to improvements in environmental quality by reducing emissions from aircraft engines and reduced energy consumption. Greater efficiency of aircraft engines also contributes to the warfighting capability of rapid global power projection.

The United States has the overall lead in aircraft turbine engine technology, based on its superior military technology, but shares the lead in commercial propulsion systems technology with the UK's Rolls Royce. Europe has an edge in facilities for propulsion/airframe integration testing of large models at high Reynolds Numbers. They may also have an edge in technologies for noise reduction. Second-tier manufacturers in France, Germany, and Japan have seen their capabilities increase through international joint ventures and European military development programs. This general pattern is likely to continue with France (likely to become more competitive with the United States over the next five years as they assume responsibilities for a greater percentage of engine designs and component manufacturing) leading the way and Japan bringing up the rear. While Japan will likely become a more attractive joint venture partner—almost certainly the country's prime goal—technology transfer is unlikely to be enough to significantly alter capabilities relative to the world leaders over the next several years.

Because of the trend towards higher thrust engines, in concert with the trend towards larger aircraft, by the year 2000, deliveries of engines with greater than 45,000 lb thrust are forecast to be more than 50 percent of the market by value. The trend towards higher-thrust engines has two general consequences for the competitiveness of engine manufacturers. The higher costs associated with development of these large engines have led to more joint international programs and transfer of technology to second-tier manufacturers. Secondly, with the attention of the technology leaders focused at the high-thrust end of the market, second-tier manufacturers are increasing their roles in the development of smaller engines. This is particularly true of the French firm SNECMA, which has recently announced its intention to lead the development of a new turbofan for civil applications based around the core of its latest fighter engine.

Performance improvements in propulsion systems are driven by core technology advances in engine component technologies, manufacturing capabilities, and systems integration. Europe continues to lag in turbine-blade technologies, but is keeping pace with U.S. developments. The United Kingdom and France are slightly behind the U.S., but have introduced some technologies first. For example, the United Kingdom was the first to introduce hollow fan blades, instrumental for reducing engine weight. France is a leader in advanced composite materials and has introduced silicon carbide nozzle flaps for their M88 engine.

Wide-chord fans—which do not require part-span shrouds and are therefore more efficient—are quickly being adopted industry-wide. Some operators of engines with wide-chord fans have also claimed that the fan blades' ability to flex makes them more resistant to birdstrike damage. Next generation engines will likely also incorporate swept aerodynamics in both fans and compressors to provide additional increases in efficiency. High strength-to-weight compressor materials are being developed to permit increased rotational speeds that—along with the adoption of low aspect ratio blade shapes—will enable reductions in the number of airfoils required.

Rolls Royce's development of the wide-chord fan gave it a technology lead in this area, but U.S. firms reacted quickly to close the gap and are likely to move ahead over the next several years, as composite fan blades are introduced on the GE90 and Pratt and Whitney's Advanced Ducted Prop engine. Research and development of active compressor stability control and high strength-to-weight ratio materials—including metal matrix composites—proposed by the European Aero-Engine Industry Group parallel U.S. efforts. Japan's responsibility within the IAE consortium for the fan and low pressure compressor is its first major share of a commercial engine program. Although the fan was derived from an existing Rolls Royce design, it is worth noting that the V2500 passed every ingestion and fan-blade-off test the first time the engine was tested. Despite this improvement, problems experienced on other indigenous efforts suggest that Japan still has a substantial technology lag.

Rolls Royce combustor technology is at parity with that of U.S. manufacturers; however, the company slightly lags in the application of turbine technology to commercial engines. Its latest civil engine offering—the Trent—still uses directionally solidified high-pressure turbine blades. While Rolls Royce and the UK Ministry of Defense are jointly funding high-pressure turbine design research, improvements resulting from this program will likely be offset by advances already achieved in a similar U.S. effort. Japan's responsibility for the low-pressure turbine on the GE90 program complements its role in the IAE consortium.

Rolls Royce now uses full authority digital engine controls (FADECs) on all of its engines and France has demonstrated improvement through production of a FADEC for SNECMA's latest military engine and controls components for the CFM56 and CF6-80. Japan has an indigenously developed FADEC that has reportedly been successfully ground and flight tested. However, the system is intended for use on the FSX fighter and has yet to be validated in service.

Spacecraft power systems

Spacecraft power systems provide power for spacecraft mission, communications, and housekeeping functions. In the case of lunar or planetary missions that involve instrumented or human landings, surface power systems must also be provided. Efficiency, power density, reliability, environmental risk, safety, shielding, etc. must all be considered in any power system. The following issues are important for space or surface power systems.

- Power generation (the energy source) Possible options include solar (photovoltaic, thermoelectric, thermionic, or dynamic), batteries and fuel cells, nuclear (radioisotopes, fission, fusion), other (antimatter, winds, chemical)

- Energy storage, with options such as batteries, fuel cells, flywheels, capacitors, and superconducting rings

- Power handling, including conditioning, control, packaging, enhancement, and conversion

- Thermal management, as a means of handling system heat including heat transfer rejection or storage as well as thermodynamic, thermoelectric, and thermionic cycles

- Power transmission, using laser, microwave, or millimeter waves over long distances, or perhaps cables and/or fiber optics for connecting components on lunar or planetary surfaces.

Space power systems are relevant to both economic progress and national security. They contribute to sustainable economic growth through promoting efficient energy production and utilization technology, and help the environmental monitoring and assessment function through their ability to provide long term power for environmental monitoring satellites. They contribute to national security through their ability to provide energy sources for military surveillance systems.

The U.S. is preeminent in spacecraft power systems, based largely on the relative scale and sophistication of its space effort. Only the U.S. and Russia are manufacturing radioisotope thermal generators (RTGs) essential for the space mission to the planets, but there is a possibility that the U.S. will abandon research in this technology.

Electrically powered vehicles

The relevant electrically-powered vehicle technologies are discussed under "Energy."

SYSTEMS INTEGRATION

Systems integration refers to the ability to design, produce, test, and implement large-scale complex systems whose individual elements often utilize advanced technology components. The most widely cited example is manned space flight, particularly the Apollo program, that assembled, integrated, and tested new and existing systems to achieve its mission. Many aerospace companies define their activities as system integrators rather than as technology developers. Although systems integration is particularly important in space and missile defense system applications, we concentrate on two main sub-areas that offer considerable potential. One area, Intelligent Transportation Systems, is a recent generalization of the Intelligent Vehicle Highway Systems (IVHS), that could literally transform the U.S. surface transportation system. The other area, space and aircraft integration, reflects a virtual revolution in our ability to design spacecraft and aircraft.

Intelligent transportation systems

Intelligent transportation systems (ITS) utilize advanced computers, sensors, electronics, communications, and other technologies to improve the safety and efficiency of all modes of surface transportation for people and goods, including intermodal transfers.

The following areas are currently being emphasized in ITS research:

1. Travel and Transportation Management includes real time information about routes and services for motor vehicles operators, traffic control and management of highway incidents, and on-board emissions testing.

2. Travel Demand Management includes travel information, ride matching and reservations, perhaps using interactive media—to assist travelers to optimize their overall origin-to-destination journey in terms of time and cost, and across various transportation modalities and to assist transportation system operators to better tailor their services via demand matching.

3. Public Transportation Operations include improved management of transit systems, en-route transit information for individual vehicles (vehicle locators), personalized public transit (dial-a-ride), and public travel security. The goals are to improve operational performance of transit systems and to improve the user-friendliness of public transit to attract non-traditional users.

4. Commercial Vehicle Operations enhancements, such as electronic document clearance and fee payment, roadside and on-board safety and weight monitoring, vehicle locator systems, etc. would improve commercial fleet management of freight trucks and rail cars, and reduce administrative costs. Another safety related enhancement would be to develop systems to prevent collisions at highway-rail grade crossings.

5. Emergency Management would involve detecting, predicting, and avoiding possible emergencies. Systems that trip an automatic distress alert when an airbag opens, that alert distracted or dozing drivers to their erratic driving behavior, that warn of imminent danger ahead, perhaps due to weather or other upcoming hazard, would be particularly useful by helping to prevent accidents and by reacting quickly to those that do occur. This is particularly important in rural settings where 60 percent of traffic fatalities occur. Several low technology approaches for assessing the utility of wireless or kiosk-based road and weather information delivery systems are under investigation in many states.

6. Vehicle Control and Safety Systems that would eventually culminate in an automated highway system, include different types of collision avoidance systems, vision enhancement, improved safety readiness, and pre-crash restraint deployment. On some stretches of highway, automatic platooning of

vehicles that are controlled electronically could increase lane capacity by factors of three or four.

In addition to these six major areas, electronic payment services would improve convenience and efficiency, for toll collection, personal vehicle use, interstate tracking, and for public transit users who might rely on "smart" fare cards. Some of these systems are already fielded around the country.

Forecasts suggest that traffic fatalities, accidents and congestion would markedly decrease when ITS becomes operational. In fact, successful deployment of ITS has the potential to vastly improve surface transport in the U.S. while improving energy efficiency and reducing pollution from transportation. Although much of ITS progress thus far has targeted private and commercial motor vehicles, it is expected that rail system and public transportation operations will also benefit. Although the major benefits would promote health, safety, and economic security, important national security benefits would stem from more efficient use of existing highways in times of crisis or war.

There seems to be no clear leader in intelligent transportation systems technologies since the U.S., Western Europe, and Japan are all pursuing active programs involving both private and public resources.

Spacecraft and aircraft integration

Complete integration of an aircraft or spacecraft, as opposed to mere component design, requires broad experience, a complete understanding of all component technologies, and a design infrastructure including methods, tools, and people. The added complexity of making many sub-systems operate simultaneously without interference with each other requires a special set of skills which are different from skills required to design and build an individual component.

One emerging tool for enhanced systems integration is multidisciplinary design optimization. It is an emerging computational technique which has high promise for the overall improvement of design quality and resulting aircraft efficiency. It includes several numerical techniques for finding an optimal system solution across numerous functional disciplines such as aerodynamics, structures, and controls. While this has always been a goal, attacked by such time-honored techniques as the carpet plot, it has been virtually impossible to simultaneously optimize any complex system due to the number of variables required.

Multidisciplinary Optimization techniques such as "Decomposition" hope to break this logjam and allow complex system optimization of hundreds or thousands of variables. This will find more-optimal solutions resulting in lower aircraft weight and cost. Lower weight and cost will, in turn, improve the competitiveness of U.S. aircraft on world markets, and will result in aircraft which are more friendly to the environment because they will use less fuel and producing fewer emissions. In addition, multidisciplinary aircraft design will allow designers to produce better military aircraft, contributing to national security and warfighting capabilities.

Europe is slightly behind the United States in overall systems integration capability for civil and military aerospace systems. With the development of the Boeing 777, the United States took the lead in the design and manufacture of commercial aircraft. Boeing used an integrated approach through fully digital product definition with all parts created by CATIA CAD/CAM systems. Airbus has not yet used this approach and may not for the next several years. However, Europe does have the capability to integrate increasingly complex aircraft systems as demonstrated in a host of commercial and military aircraft. Japan, on the other hand, has not yet led a major commercial development and has had difficulty with systems integration on its military programs. Japanese firms, although members of Boeing's design team, have not independently designed and manufactured their own modern commercial aircraft. Japan also trails the United States and Europe in spacecraft systems integration capability, including satellites and launch vehicles.

HUMAN INTERFACE

A human interface is an essential element in the successful design and safe, reliable operation of any transportation system. The field of study that leads to proper design focuses on human capabilities, limitations, behavior and performance while interacting with complex engineered systems and environments. The role of the human operator in the control loop has changed greatly—from driving, navigation, and piloting as traditionally conceived to the control of complex systems in relatively infrequent off-nominal, potentially high risk situations. In the case of commercial aircraft, human factors involves both crew-machine and behavioral interactions on the flight deck to improve effectiveness and safety. For military pilots, it involves improving pilot function and situational awareness under conditions of fatigue and/or physical stress including high "g" associated with maneuvers and acceleration/deceleration. For the surface vehicle driver, it may involve ergonomic design, and integration with systems that are likely to be part of the intelligent transportation system of the future. For space flight, human factors involve issues of human performance and behavior in stressful, isolated, confined environments for extended periods.

The willingness to use and perhaps depend on technology is a cultural phenomena not simply bounded by the basic technology. A primary case in point is the degree of automation entailed in the Airbus flight control systems. As automation becomes more capable, the degree of keeping humans in the control loop and the ability to over-ride the control system will become more of an issue. In the case of highly unstable, non-linear control regimens where computer control is the only option, operator training and operator acceptance pose difficult problems - particularly as to the judgment of when and how to over-ride.

Human factors engineering

As the limits of human capabilities are becoming an important factor is safe and effective operation of transportation systems, several technologies are being used to extend or obviate these limits. In order to significantly increase the data analysis and response capabilities of drivers and flight crews, a modern "glass cockpit" is being designed to enhance readability and minimize the possibility for inappropriate interpretation of displays or activation of systems.

For the surface vehicle driver, creating a good interface may involve ergonomic design, and integration with systems that are likely to be part of the intelligent transportation system of the future. As part of an initiative to improve the safety and efficiency of the nations highways, work has been done to provide in-vehicle signing information and safety warning systems, sensory systems which provide extended line of sight during reduced visibility conditions, and obstacle detection and avoidance systems. This is intended to lead up to a fully automated highway system.

High "g" loads experienced by military pilots reduce the availability of well oxygenated blood to the retina, resulting in gray out and a tunneling of vision, and eventually loss of blood flow to the brain resulting in loss of consciousness. Countermeasures using small ultrasonic transducers are able to sense the reversal of blood flow at high "g" and used to control the pressure in a lower body garment intended to restrict the pooling of blood in the lower abdomen and legs. Lessons learned from the deterioration of the visual field under high "g" loads have also been applied to instrument design, head-up-displays, and alarm systems intended to catch a pilots attention even in a high noise, high stimulus environment.

Meaningful analog studies on Earth and in space are required for long duration flights. Ongoing work using the Antarctic as an analog has been quite productive. Another challenge facing crews in remote, isolated situations is that abnormal maladaptive behavior due to exposure to toxic substances may be indistinguishable from psychosis. Senior observers of military and exploration efforts have pointed out that human factors were responsible for mission failure more often than equipment factors. As in most complex systems, habitability and ergonomics also require more support and integration into spacecraft systems design.

Research, development and testing of human factors and the underlying assessment technologies based on physiological measurements has been conducted by the U.S. national laboratories, and their associated universities and contractors. Individual private corporations have conducted little work in this area beyond noise reduction and seating design; focusing more on appealing to consumer interest than in functional design issues. Automotive manufacturers here and abroad have demonstrated many concept vehicles with alternative interior and gauge designs; but these tend to driven more on visual graphic impact than meaningful contributions to improved human performance or control. Ergonomics has been most extensively studied and reduced to practice in the past by the Europeans, but as its value for differentiating consumer products has been more widely acknowledged in the past few years, manufacturers are beginning to draw on the established data bases.

The U.S. has a clear-cut lead in anti-g countermeasures in high performance aircraft, and even cockpit display and instrumentation. As the pressure suits universally worn by fighter pilots are capable of being pressurized, it is more of a deployment decision rather than one of underlying technology. The ultrasonic Doppler flow techniques for assessing individual pilot status during high-g have been more fully evaluated, control algorithms refined and reduced to practice in the U.S.

Spacecraft life support

Spacecraft life support involves issues of reliable, closed, physical-chemical, and/or bioregenerative systems. The goal is an integrated, stable ecosystem with greater simplification, minimal resupply, and greater degrees of closure. Current baseline designs for the space station depend entirely on reliable resupply of air and water consumables from the ground. The mass costs are unacceptable for any extended-duration manned missions, either on the Lunar surface or for Mars transit and exploration. While the Russians believe they could simply stock supplies for a two-year mission, serious long-term exploration requires a commitment to bioregenerative, closed, ecological life support systems. These systems must be capable of recycling and providing air, water, and food, while controlling toxics and bacterial or viral contamination. Stable, robust life support systems are essential to reducing remote outpost dependencies on resupply missions. In order of complexity, partially closed physical-chemical systems would be first, followed by closed physical-chemical systems.

In the broader perspective of the many sub-systems which comprise an integrated life support system, the Space Shuttle Extended Duration Orbiters provide an example at the 14 to 17 day end of the scale, with the pending Space Station exemplifying low development risk systems which can be ready evolved once the basic operational platform is in orbit. The critical areas include atmosphere control and supply, atmosphere revitalization, potable and wash water systems, waste management systems, temperature and humidity control, water recovery and management, microbial and toxics decontamination, and fire detection and suppression. All of these sub-systems are designed to evolve during the lifetime of the station, with eventual closure of the air, water, and potentially even the food loop as goals for long duration space flight. As designed, the base-lined filtration systems will be swapped out every 30 days with a 90 day resupply cycle from the ground. Water and CO_2 scrubber systems now in development could have their mass significantly reduced but with a corresponding increase in their power requirement.

Pilot plant evaluation, scale-up, and in-space validation must be performed under actual operating conditions, in zero gravity or on the Lunar surface. Lunar validation of such systems should precede any situation of long-term dependency. Advances in this area would contribute to maintaining leadership of the U.S. in science, mathematics, and engineering by improving our ability to facilitate long term space flight and by facilitating closed loop processing of materials with minimal environmental impact.

As the Russian "Mir" is the only permanently manned platform currently in space, it provides an example of the capabilities of water recycling and CO_2 removal but with total dependency on ground based resupply of oxygen. The Russians systems which have been of particular interest, water recycling and CO_2 removal, are the subject of a contractual relationship between Hamilton-Standard (one of the U.S. companies with a long-term involvement in this area) and the Russia groups. Several studies have been performed to assess the utility of the Russian work for early Station configurations.

9. ACTIVITIES RELATED TO CRITICAL TECHNOLOGIES

A large number of programs and development plans for technologies designated here as National Critical Technologies already exists in government and the private sector. Given the breadth of technologies covered by the list, it is impossible to describe or even list most of these here. This section discusses the areas in which different agencies perform R&D relevant to critical technologies, and provides some examples of specific programs in each technology category. It also provides some examples of government-private sector partnerships and non-government initiatives.

FEDERAL GOVERNMENT ACTIVITIES

A significant proportion of the approximately $70 billion devoted annually by the federal government to the support of R&D directly involves the development of critical technologies. Two other categories of R&D activities account for the remainder of the federal R&D budget.

The first encompasses the approximately $14 billion spent annually by the federal government on the conduct of "basic research." This portion of the federal R&D budget is not considered directly relevant to critical technologies because these monies involve the pursuit of greater knowledge or understanding without a specific technological application in mind. As a result, all activities falling within DOD's Budget Category 6.1 (Basic Research) are excluded, as is the "basic research" of all other federal agencies. The only notable exceptions involve the Department of Health and Human Services and the National Science Foundation, both of which are agencies with the preponderance of their R&D activities officially constituting "basic research," but which also are centrally involved in key areas on the Critical Technologies list (i.e., Biotechnology and most areas of Information and Communication, respectively).

Also excluded from R&D directly relevant to critical technologies are the activities of DOD that involve the demonstration and validation of integrated military technologies (6.4), engineering and manufacturing development for military use (6.5), miltary R&D management support (6.6), and military operational systems development (6.7). While activities within these categories (i.e., 6.4 and 6.5) clearly involve the advanced development and application of critical technologies, it is impossible to separate these from the overall missions of programs, and as a result, the approximately $26 billion spent annually within these four DOD Budget Activity categories is not generally included among the resource totals relevant to critical technologies.

Consequently, the "core" of federal R&D budget—the "applied research" and "development" as these terms are generally defined for all federal agencies—also forms the foundation for the nation's critical technology R&D. In the case of the Department of Defense, this includes those activities which fall within DOD's Budget Activities 6.2 (Exploratory Development) and 6.3 (Advanced Development). Similarly, for other agencies, it includes those activities that do not generally constitute "basic research" (note exception described above). Below are brief descriptions of the critical technology areas in which R&D activities of the major agencies are concentrated.

Activities by agency

Department of Defense

The Department of Defense is a major contributor to work in virtually every area of critical technologies. The critical technology most dominated by work housed within DOD involves Sensors within Information and Communication. Among these programs are ones involving signal processing, night vision, signal verification, guidance assistance, and the detection of various substances and movements. DOD also dominates efforts to develop technology for education and training focusing on simulation.

National Aeronautics and Space Administration

The National Aeronautical and Space Administration's R&D work focuses mostly in three major critical technologies areas: transportation, aeronautics and communications. The remainder of NASA's critical technology work reflects the importance of flight-worthy spacecraft, lower cost space launch, and reliable communications in all space missions. In addition, Mission to Planet Earth Program focuses on monitoring and assessment of the quality of the environment. The Space Station Program is concerned with systems integration. NASA is also an important contributor to the work on human factors engineering and human-machine interface.

Department of Energy

While DOE has a presence in every critical technology area, its major programs in Fossil Fuels, Nuclear Energy, Fusion Energy, and Solar Energy constitute virtually the entirety of the Federal Government's R&D efforts to improve the generation of energy. Similarly, DOE's activities dominate the government-wide R&D efforts in environmental remediation and restoration and energy efficiency. The DOE's Los Alamos National Laboratory is leading the Human Genome project, the most significant effort in human genetic mapping in the world.

Department of Health and Human Services

While the majority of R&D activities of the Department of Health and Human Services involve "basic research," over half of all on-going work in technologies critical to living systems is performed by its National Institutes of Health. Augmenting the work of these institutes in this critical technology area is work by the Centers for Disease Control and Prevention in vaccines and infectious diseases and the Food and Drug Administration in the promotion of food safety and medical devices. In addition, work at NIH in the critical technology area of Information and Communication has broken new ground for scope and imagination (i.e., the National Library of Medicine's enormous project on the visible man).

Department of Agriculture

Virtually all work in advancing sustainable agricultural production is housed in the Department of Agriculture, shared relatively equally by its bureaus—the Agricultural Research Service and the Cooperative State Research Service. The remainder of USDA's critical technology activity focuses primarily on the monitoring and assessment of environmental quality and is housed in the Forest Service.

Environmental Protection Agency

The EPA's R&D focuses intensely on monitoring and assessment activities to preserve and improve the quality of our environment. The EPA has research programs in air quality, water quality, drinking water, pesticides, hazardous waste, toxic substances radiation, and multimedia research, as well as the lesser volume work in pollution control.

While the EPA is the recipient of record for the R&D funding associated with Superfund activities, a large portion of the money actually ends up at the National Institute of Environmental Health Sciences in the National Institutes of Health at the Department of Health and Human Services. The primary focus of this program is remediation and restoration.

National Science Foundation

The vast majority of the R&D conducted by the National Science Foundation is "basic research" and so outside the scope of the Critical Technologies Report. The two notable exceptions to this are the work of NSF's Directorate of Computer and Information Science and Engineering (CISE) and Directorate of Engineering. The work of NSF in Information and Communications is dominated by CISE; the work of the Engineering Directorate is in the areas of Manufacturing and Materials. In addition, the work of the Directorate of Geosciences is of major importance to the monitoring and assessment of environmental quality.

Department of Interior

The R&D activities of the Department of Labor's Geological Survey and National Biological Survey (still resident in the Fish and Wildlife Service in FY 1993), comprise a notable portion of the nation's effort to monitor and assess the quality of our environment.

Department of Commerce

The critical technology activities of the Department of Commerce are split between its two bureaus—the National Oceanic and Atmospheric Administration and the National Institute of Standards and Technology. The entirety of NOAA's Office of Oceanic and Atmospheric Research and the National Environmental Satellite, Data, and Information Service are devoted to monitoring and assessing the quality of our environment. In addition, the National Marine Fisheries Service within NOAA is a principal promoter of technology to advance the commercial fishing industry.

That portion of R&D conducted by NIST that does not concentrate on metrics and calibration is central to the advancement of critical technologies in Manufacturing, Materials, and Information and Communication, albeit the effort is modest when compared in scale to the resources devoted to these activities by larger agencies. A notable portion of NIST's critical technology work is accounted for by the activities of its Advanced Technology Program.

Department of Transportation

As an amalgam of "administrations" regulating the various modes of transportation, the Department of Transportation's R&D efforts emphasize matters of prevention and safety. As a result, DOT, especially the Federal Aviation Administration, contributes to work in the critical technology area of Information and Communication to ensure the safe operation of both commercial and non-commercial aircraft.

Examples of programs

The government programs which comprise the R&D expenditures described above are many and varied. They include the Technology Reinvestment Project (TRP) used to stimulate the transition from separate defense and civilian industrial bases to a "growing, integrated, national industrial capability,"[1] the Advanced Technology Program which works with industry to share the cost of developing high-risk but powerful enabling technologies for commercial applications, and others. In order to provide a "flavor" for the breadth of the federal R&D enterprise, selected programs and the primary technical challenges which they address are discussed below.

Wind turbines

The primary technical challenge in improving wind-energy efficiency is to develop a turbine which can operate efficiently and reliably under conditions of wide fluctuations in wind velocity, with low maintenance and low capital costs. Improvements in blade design and development of variable-speed turbine

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[1]Technology for Economic Growth, p. 12.

systems combined with power-handling electronics are the focus of research programs in the U.S. and Europe.

The stall-controlled turbine is one of two competing conceptual designs being developed in the U.S. under funding from the Department of Energy. Variable-speed wind turbines utilize power-handling electronics to enable the rotor to rotate at variable speeds. This increases annual energy output, improves power supply quality to the grid, and reduces structural loads. Power -handling electronics serve to suppress harmonic currents and reduce transmission losses by controlling the power factor when current and voltage are not in phase. Controls can also be introduced to reduce structural dynamic load (reducing the stress on structural interaction, as that between the rotor and the tower, when rotor angular velocity is variable).

Environmental quality

It was estimated that the federal government has spent approximately $550 million for research, development, and demonstration of remediation technologies in 1994. These expenditures represent approximately 15 percent of the total federal investment in research, development, and demonstration for all environmental technologies.

DOE programs, which fund more than 40 percent of the work in this area, include remediation of high-level waste tanks; contaminant plume containment and remediation; contaminated solids and buried waste; mixed waste characterization, treatment, and disposal; and facility transition, decommissioning, and final disposal. DOE, along with DOD, have a particular interest in remediation and restoration technologies because of their sizable tasks involved in cleaning up toxic contamination at their facilities. The USDA also has a substantial program that includes technologies to improve degraded lands and develop biological means to generate wood pulp and degrade wood preservatives. At EPA, resources are used for research in areas such as bioremediation technologies for clean up toxic wastes. The EPA also administers the SITE (Superfund Innovative Technology Evaluation) program, which provides an opportunity for technology developers to demonstrate capabilities to successfully remediate Superfund waste. SITE programs have looked at techniques as varied as photocatalytic oxidation, in-situ vapor extraction, and biological degradation in immobilized cell bioreactors.

In 1991, the Western Governors Association, the Departments of Defense, Energy, and Interior, and the Environmental Protection Agency signed a memorandum of understanding to create a state-federal partnership to test ways to expedite testing of innovative clean-up technologies. In 1992, the Western Governors and the four federal agencies established the Federal Advisory Committee to Develop On-Site Innovative Technologies (DOIT) to oversee the development of new approaches to remediation technology development, deployment and commercialization. The DOIT committee activities are ongoing.

State governments are also starting to become players in the environmental technology arena, often out of fear that technologies to remediate wastes in their states will not be available when needed. For example, the new Center for Evaluation of New Environmental Technologies is a joint effort of the California Department of Toxic Substances Control and the University of California Davis. This joint state government-academic center has picked five commercially developed technologies for evaluation and demonstration, starting in 1994.

The U.S. government has begun coordinating research and development work in environmental technologies through the National Science and Technology Council (NSTC) joint-subcommittee on environmental technologies (JSET), which is derived from the committees on Civilian Industrial Technology and Environmental and Natural Resources. In addition, the National Science and Technology Council and the White House Office of Science and Technology Policy are developing a strategy for promoting environmental technologies to achieve sustainable development.

In the FY94 Technology Reinvestment Program (TRP) awards, there were several in the sensors area that are relevant to environmental monitoring, site characterization, or other detection of hazardous agents. These include:

- The E-SMART System for In-Situ Detection of Environmental Contaminants (General Atomics, Air Force/Armstrong Laboratory, Georgia Tech Research Institute, Isco, Inc., Photonic Sensor Systems, Inc., Science & Engineering Analysis Corporation, $5.4 million, 24 months)

- Volatile Organic Compound (VOC) Sensors, Communications, Processing, and Display (Hughes Aircraft Company, AAI-ABTECH, GM Hughes Electronics Research Laboratories, University of Pennsylvania, $2.5 million, 24 months)

- UV DIAL Lidar (OCA Applied Optics, Los Alamos Science, $2.0 million, 12 months)

- Field-Deployable, Continuous Monitoring Mass Spectrometer (Teledyne Electronic Technologies; DOE/Oak Ridge National Laboratory/MMES; Monsanto Company; Phillips Petroleum Company, Scientific Services Div.; Scientific Instrument Services, Inc.; Synergist, Inc., $6.9 million, 24 months)

- IMAS: An Intelligent Modular-Array System for the Monitoring of VOCs in the Environment (Tektronix, Inc.; Battelle, Pacific Northwest Laboratories; DOE/Sandia National Laboratories; Sawtek Inc., $2.1 million, 23 months)

<u>Flat panel displays</u>

The DOD's flat-panel display initiative is a five year, $587 million program to provide Defense with early, assured, and affordable access to advanced flat panel display technology by supporting domestic investments in dual use display capability. The prerequisite industry matching funds should bring the total investment to $1.2 billion.

A major element of the initiative is a focused R&D competition for next generation display technologies limited to firms that demonstrate commitment to produce current generation displays to meet defense needs. The R&D program will be conducted on a cost-shared basis to ensure that the participating firms have commitment to bring the technology developments into application. The DOD is planning to have four such competitions over the next five years. International companies are eligible to participate based on criteria of the Technology Reinvestment Project. Each of these competitions is designed to be neutral regarding any specific display technology and judged on the quality of the proposed research and development, the soundness of the technical plan, the adequacy and appropriateness of the proposed cost sharing, and demonstration of commitment to production of current generation displays.

The DOD' flat panel display initiative is the largest government initiative for advanced displays systems. Other smaller efforts include support for the development of generic technologies through ARPA and NIST. The Clinton administration has also established a link between the National Information Infrastructure and advanced displays. The administration favors letting private industry build the NII but is willing to fund high-risk R&D for overcoming technological obstacles. Advanced displays have been designated as one of the primary obstacles to the success of NII.

Software

The time, expense, and great uncertainty involved in all large-scale software development projects is the greatest software-related problem. Projects routinely run 50% to 200% over budget and beyond schedule, and are sometimes abandoned in midstream. One continuing hope is that a science of "rapid prototyping" will evolve to allow early risk reduction through iterative test and evaluation of critical components, user interfaces, and designs at a stage where changes can be made easily before major design commitments are made. Other research thrusts in software engineering involve the attempt to "manufacture" software from standard modules and with standard procedures, to emulate other engineering and production disciplines that are able to predict costs and schedule for development. To better assess the state of U.S. software engineering and promote effective practices, the Software Engineering Institute (SEI) was established as a Federally Funded Research and Development Center (FFRDC) in 1984 by DOD through the Advanced Research Projects Agency (ARPA). It is located in Pittsburgh PA, in association with Carnegie-Mellon University.

One focus of rapid software development is the use of object technology to create libraries of reusable code modules based on object oriented software. The U.S.

FY94 Technology Reinvestment Program (TRP) awarded three contracts in this area:

- Object Technology for Rapid Software Development and Delivery (Anderson Consulting, CoGenTex Inc, Expersoft Corporation, Raytheon Company's Missile Systems Division); $24.5 million, 24 months

- LEGOS: Object-based Software Components for Mission-Critical Systems (I-Kinetics Inc., Heuristicrats Research Inc, Iona Technologies Ltd, Navy/Naval Sea Command Inc, SunSoft, UTC Pratt & Whitney, Government Engines & Space Propulsion); $8 million, 24 months

- Object Technology for Rapid Software Development and Delivery (Template Software Inc, Honeywell Technology Center, IBM Corporation, ISX Corporation); $12 million, 24 months

The NIST Advanced Technology Program is also investing in software development. One of its major thrusts, a 5-year $150 million Component Based Software Program, is an effort to help industry create fine-grained software components and specialized high-performance tools. The aim is to enable semantic-based software creation in which systematically reusable software components can be automatically assembled into a broad array of application specific systems.

Recombinant DNA technologies

The Human Genome project is an international effort to locate and catalog every gene, changing our understanding of human biology at its most basic level and revolutionizing the practice of medicine. Genetic susceptibilities have been implicated in many major disabling and fatal diseases including heart disease, stroke, diabetes, and several kinds of cancers. As the genetic mechanisms of inherited disease are determined, it will provide the ability to identify people who have or carry genetic disease. The identification of these genes and their proteins will pave the way for more effective preventative measures and therapies. Indentification will inevitably occur before treatments are developed, so that each success in the gene-mapping project will create new ethical and social policy dilemmas. The potential presymptomatic diagnosis of disease will present substantial challenges related to individual privacy and insurability.

A major component of the Human Genome Project is the development of automated sequencing technology that is faster, more sensitive, accurate and economical. The present gel-based equipment can sequence only 50,000 to 100,000 bases per year at a cost of $1 to $2 per base. The current goal is to develop technology capable of 100,000 or more bases per day at a cost of $.50 per base, with subsequent technologies offering a further factor of 10 reduction in processing costs. High voltage capillary and ultrathin electrophoresis to increase separation rate and the use of resonance ionization spectroscopy to detect stable isotope labels look promising. Third generation gel-less sequencing technologies include (1) enhanced fluoresce detection of individual labeled bases in flow cytometry, (2) direct reading of the base sequence on a DNA strand with the use of scanning tunneling or atomic force microscopies, (3) enhanced mass spectroscopic analysis of DNA sequences, and (4) sequencing by hybridization to short panels of nucleotides of known sequence.

Electronic data management and publishing systems are increasingly essential components of genome reearch as the on-going projects are generating volumes of information that cannot be readily incorporated by traditional publishing. Correlating mapping data from different laboratories has been a problem because of different methods of generating, isolating and mapping DNA fragments. In addition to laboratory methods, the emerging field of Genetic Informatics is making a significant contribution to the ability to constucting and searching the maps and sequences in order to find specific genes. Major databases are globally distributed (U.S., Germany, France, Italy, Australia, Japan, Israel, Switzerland) and accessible via the InterNet.

National Institute of Standards (NIST) has announced the Tools for DNA Diagnostics Program which focuses of the development of low-cost, integrated, miniaturized, high throughput, parallelizable, automated systems that can be used to obtain DNA sequence information efficiently and accurately. The largest award under the program, $31.5 million, went to a joint venture between Affymetrix Inc. and Molecular Dynamics Inc which are developing a device that will diagnose diseases by analyzing a patient's DNA on the surface of a silicon microchip that is read by a laser scanner. Another award, $14.7 million, went to the C. Everett Koop institute for a project to help the health care industry take advantage of the information superhighway.

Vaccines

It is currently estimated that over 20 federal agencies play a role in the development, testing, distribution, and use of vaccines in the U.S. From 14 U.S. companies in 1980, only four remain largely because of problems related to liability and profitability. The entire global vaccine market is estimated by a recent UNICEF study to be about $3 billion. NIH spent an estimated $300 million on vaccine research and the CDC spent another $528 million on vaccine purchase, research, and testing. DOD is responsible for military vaccine needs and global emergencies.

The development of a vaccine for AIDS continues to be elusive. It is estimated that expenditures are about $160M worldwide, with industry spending about $25 million globally and the U.S. government spending about $111 million. The perception is that most of this work is done in the smaller biotechnology companies.

Manufacturing

Government support has long been associated with developments in manufacturing. Much of NIST's industrial research has supported the development of standards. In the Department of Defense, support has come through programs like MANTECH. What is new today is the promise of the "lean manufacturing" paradigm, which has also been supported in the Department of Defense. In some industries, transformation to lean manufacturing is being promoted by the federal government, as in the Department of Defense "lean" aircraft initiative, a collaborative effort involving industrial firms, the Air Force, and the Massachusetts Institute of Technologies.

In addition to developing specific manufacturing technologies, the federal government is also involved in helping diffuse best manufacturing practices through the NIST Manufacturing Extension Partnership. MEP centers, located throughout the country, help small and medium-size businesses adopt modern equipment and manufacturing and management techniques in order to become more competitive in domestic and international markets.

Here is one specific example. The evolution of more sophisticated manufacturing techniques is critical to the realization of advanced coatings with enhanced hardness, corrosion-resistance, thermal, and wear characteristics. One of the most exciting candidates is the large-scale production of high quality diamond thin films.

Given the increasing dependence of the military on high technology products, it is apparent that continued investment in artificial structuring methods is essential for sustained security. For example, the Department of Defense is presently the largest customer of high definition displays, and the manufacture of these displays is dependent, among other things, on advanced thin film techniques. Also, the successful development of diamond coatings has applications ranging from aircraft windshield coatings to high speed electronic components.

Research funding for thin film manufacturing techniques is shared by federal and private sector sources. The DOD has significant investments through ARPA and other bureaus. In particular, it is estimated that $100 million annually is invested by private companies and the government on research into producing diamond films with the largest spender being DOD. Much of this funding has stemmed from the former Strategic Defense Initiative Office, now renamed Ballistic Missile Defense Office (BMDO). Additional funding of thin film deposition research originates in the Departments of Commerce, Energy and the National Science Foundation. DOE also sustains research efforts itself and has worked to establish joint ventures with industry in this field.

While the United States is not the industry leader in many of the applications reliant on artificial structuring manufacturing methods, it is competitively positioned in thin film deposition technologies. However, there are major challenges for the advancement of existing techniques as well as for the development of emerging manufacturing capabilities. The key technological challenge for new techniques is the transfer of laboratory successes into large scale production. The primary impediment is that growth rates are severely limited for many of these new technologies and materials. For example, molecular beam epitaxy has demonstrated the ability to fabricate unique structures but is primarily a research tool for this reason.

The development of these technologies is also capital intensive. Diamond thin films are a dramatic example of a major investment without any, as yet, marked returns. As a result, commercial activities often view ease of manufacture as the primary requirement for a technology. Consequently, research investment efforts often focus on manufacturability.

Materials

The federal government has long promoted the development of new materials. This effort started under the old Federal Coordinating Council for Science, Engineering, and Technology as the Advanced Materials and Processing Program. As we note in a discussion of composite materials below, the interrelation of materials to material processing is still an important factor that should shape any program. The federal attention to materials is now continuing under the Civilian Industrial Technology Committee of the National Science and Technology Council.

A coordinating mechanism for materials research has proved useful in the past, because of the spread of research on materials across agencies. The Departments of Commerce, Energy, Defense, the Interior, Transportation, Health and Human Services, and Agriculture all support important programs, as does the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Science Foundation. Avoiding duplication while assuring important leads are followed requires coordination.

The diversity of supporting agencies is driven by the ubiquitous effects of materials. Each agency has important applications or classes of materials that are uniquely theirs. Each agency also understands the demands of its applications very well, whether that is a low observable material for the Department of Defense or a new paving repair product for the Department of Transportation. Keeping the material development connected to this understanding is important in quickly tapping new opportunities. As materials develop, though, new applications become interesting, such as the use of wood fiber to reinforce cement. Making the other interested agencies aware of such developments is the other major function and benefit of high-level coordination.

The current coordination of materials development led by the NSTC has focused material developments on the priorities of the government. Among others, emphases have been created on the automotive sector, supporting the PNGV; the building and construction sector as well as the built infrastructure of roads and bridges; the electronics industry; and the aerospace industry. These areas have been supported, in part, through programs like the ATP.

Another important aspect of this coordination is the maintenance of the user facilities. The federal government is the provider of most important user facilities. These facilities are important to the development and characterization of many new materials. They are spread across a range of agencies, reflecting the range of interests in materials. There are many such facilities. A selection illustrating their variety follows:

- Cold Neutron Research Facility (supported by the National Institute of Standards and Technology of the Department of Commerce) and the associated Center for High Resolution Neutron Scattering (supported by the National Science Foundation)

- Cornell High Energy Synchrotron Source (supported by the National Science Foundation)

- National Synchroton Light Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Stanford Synchroton Radiation Laboratory (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Advanced Light Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Advanced Photon Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- High Flux Beam Reactor (supported by the Office of Basic Energy Sciences of the Department of Energy)

- High Flux Isotope Reactor (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Intense Pulsed Neutron Source (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Manual Lujan Jr. Neutron Scattering Center (supported by the Office of Basic Energy Sciences of the Department of Energy)

- Center for High Resolution Electron Microscopy (supported by the National Science Foundation)

- Francis Bitter National Magnet Laboratory (supported by the National Science Foundation)
- National High Magnetic Field Laboratory (supported by the National Science Foundation)
- National Nanofabrication Users Network (supported by the National Science Foundation)

Most user facilities have been developed to meet specific needs of researchers in materials across all sectors of our society. They differ in important details, such as the energy of the electrons in the synchrotrons, and thus in the wavelength of the emitted light. This allows each facility to probe a different aspect of a material, or a different property. The facilities also support non-materials work, including fundamental science, but the core of their work remains materials characterization. The need for many of these facilities has been validated by several studies from the National Research Council, and some of the facilities themselves are being duplicated in both Europe and Japan, where their importance is apparent.

Composites

The metal-matrix composites use metal rather than plastic as the matrix. Usually the metal is in the form of a powder which is combined with the reinforcing fibers in a mold, where the combination is subjected to heat and pressure to fuse the part together. Metal matrix composites (MMC's) have advantageous properties of higher strength, stiffness, wear resistance and elevated temperature properties, and are especially applicable for high-temperature uses such as in jet engines. Many metal matrix-composites can be machined on the same apparatus used for traditional metals and some can be welded. NASA is currently validating their use up to a temperature of 2300^{o} F. Matrix materials include nickel, superalloys, titanium alloys, aluminum alloys, magnesium, copper, intermetallics, and steels. Fibers include, silicon carbide (SiC), refractory metal wires, and carbon fibers, among others.

Metal matrix composites have the potential to significantly affect future propulsion systems, as well as airframes. One metal matrix composite being investigated is fiber-reinforced titanium which is about three times stronger for a given weight than nickel superalloy at temperatures up to 1500^{o} F. Compressor discs of SiC reinforced titanium have been manufactured by Textron. For the IHPTET (Integrated High Performance Turbine Engine Technology) program Allison Gas Turbines tested a compressor fabricated with metal matrix composites. It achieved an 80% reduction in weight over a conventional compressor stage.

The basic limitation for metal matrix composites is cost. SiC fiber costs $2500/lb, however this is due to the relatively low volume at which SiC is produced. It is estimated that cost could drop to $100-200/lb with production of 40,000 lbs a year. Textron Specialty Materials will demonstrate the production of SiC in a titanium metal matrix this year under a contract from the Air Force (NASP funding). The experiment will attempt to automate the production process and demonstrate the ability to produce the material at lower cost. New intermetallic compounds (titanium aluminide, nickel aluminide, iron aluminide), when used as a matrix material, will further improve the high-temperature properties of metal matrix composites. Incomplete information on property data and fabrication techniques are two limitations that exist at this time. These limitations are being addressed and are not nearly as much of a concern as cost.

Another type of composite is ceramic matrix composite. Ceramics offer increased turbine inlet temperatures while lowering overall weight. The problem with ceramics is their brittleness, cost, and difficulty of manufacture. The high brittleness makes the ceramic parts extremely prone to impact damage, usually resulting in catastrophic failure. Brittleness might be overcome by using ceramic matrix composites or by new superplastic ceramic technology. Monolithic ceramics will, most likely, see only limited application on advanced turbine engines. One of these applications is the use of ceramics in advanced engine bearings. Significant weight savings over metal bearings will allow engines to achieve higher shaft speeds. There are several companies involved in the research and development of advanced ceramic materials including, Eaton, GTE, Norton, and TRW. The Department of Energy is also sponsoring a research program called the Advanced Turbine Technology Applications Project (ATTAP) at Garrett Turbine Engine and Allison Gas Turbine Division.

Structures

Today's most advanced fighter aircraft such as the F-22 and EF-2000 make extensive use of composite materials in primary structure such as wing and fuselage. Transport aircraft are using them already in less-critical structural areas, but will undoubtedly incorporate them soon in primary structure for greater weight and cost savings. In the future, the use of composites will be expanded and optimized for weight and producibility through better manufacturing approaches and large scale integration, and even newer technologies such as smart structures and adaptive structures will become reality. These are described below.

Large-scale integration, or co-cured composite structures offer the potential of very large reductions in structural manufacturing costs. This technology, in development for many years, involves the lay-up and simultaneous cure ("cocure") of entire structural elements such as the wing box, rather than separately curing small parts then fastening them together. The elimination of conventional fasteners from the skin of an aircraft reduces drag and complexity, as well as weight and fuel leakage problems. Problems remain, however, with repairability (because the structure cannot be disassembled), quality control, inspection, and scrap costs.

Research in these areas is under way at numerous industry and government facilities. NASA's Advanced Composites Technology (ACT) program is developing technologies that will further the introduction of composites into the primary structures of future commercial transportation aircraft. Research is also being conducted at NASA Langley, as well as Boeing, McDonnell Douglas, Lockheed, and 12 other companies.

A more-exotic structural concept is the "smart structure". A smart structure is one that is "aware" of its state, through embedded sensors and intelligent computer systems. On composite structures the sensors might be optical fibers embedded in the matrix, whereas conventional airframes would have strain gauges or optical fibers bonded to the airframe. If the structure also has the ability to make corrections and adjustments based on measurements from sensors embedded in the structure then it is considered to be an "adaptive smart structure". For example, the sensors in the structure would inform the pilot about the extent of damage incurred in a battle, or it might tailor the control surfaces for greater aerodynamic efficiency based on flight conditions, or it might suppress vibration during flight.

Smart structures have the potential to revolutionize operational cost. Typically, the required intervals for repairs or inspections are statistical evaluations of aircraft life, with much conservatism to ensure that the "worst" airframe is inspected and serviced often enough for safety. Using the smart structure concept, airframe fatigue and other life-related problems would be measured and calculated on-board the aircraft. With appropriate changes in civil regulations, this could permit a safe reduction in inspection and regular maintenance costs with substantial impact on the economics of commercial transports.

Research in this area is being conducted by the Air Force (primarily at Wright Laboratories), Navy, DARPA, and NASA, as well as on the contractor level. Boeing, United Technologies, and McDonnell Douglas have been conducting tests on flight articles. NASA is flight testing an F-15, as part of the HIDEC program, which eventually will sense control surface damage and then reconfigure the flight control system to land the aircraft safely.

Propulsion

Several U.S. programs are in place to promote research into advanced aircraft engine technologies including IHPTET (Integrated High Performance Turbine Engine Technology), HITEMP (High Temperature Engine Materials Program), ATTAP (Advanced Turbine Technology Applications Project), and EPM (Enabling Propulsion Materials Project). IHPTET, the most prominent of the programs, is a comprehensive propulsion technology program managed by the Aero Propulsion Laboratory, which is part of the USAF's Wright Laboratories. The program has as its goal the doubling of gas turbine performance by the end of the century. Also, the Air Force is funding the Advanced Turbine Engine Gas Generator (ATEGG) program and the Joint Technology Demonstrator Engines

(JTDE - also funded by the Navy). Allison and Pratt & Whitney have tested ATEGG engines while GE and Pratt & Whitney have tested JTDE engines. Finally, the considerable ongoing investment in the development of the engines for the F-22 can be expected to have a vast "spin-off" for advanced commercial and military aircraft.

GOVERNMENT-INDUSTRY PARTNERSHIPS

An increasing number of programs, especially ones with potential commercial applications, are being funded and performed by partnerships between the government and the private sector. Such partnerships are characterized by substantial financial contributions from member-companies and the government, as well as by arrangements for joint decision-making with regard to the direction of R&D.

Partnerships allow the government to leverage its resources in the days of tight R&D budgets by funding technologies and applications which may be risky for industry but essential for the nation's future. At the same time, substantial financial contributions made by the private sector partners assure that these companies have a stake in the successful outcome and commercialization of the R&D. Several examples of industry-government partnerships are discussed below.

Advanced batteries

In 1991, Chrysler, Ford, General Motors, the Electric Power Research Institute, and the U.S. Department of Energy created the U.S. Advanced Battery Consortium (USABC), to fund advanced battery research and development. USABC set performance goals for medium-term batteries which would "result in mass production of electric vehicle batteries potentially in this decade" and far-term batteries which will provide electric vehicle performance competitive with today's internal combustion engines. While there are no clear winners yet, a number of battery technologies appear capable of meeting USABC goals.

Extensive re-engineering of lead-acid battery technology has produced several systems which exceed the USABC medium-term goals for cycle life and cost, far exceed the power goal, and come within about 75% of the energy storage goal. Nickel-metal-hydride battery technologies have received approximately $20 million of USABC funding. Extensive re-engineering of lead-acid battery technology for commercial transportation applications has produced several systems which exceed the USABC medium-term goals for cycle life and cost, far exceed the power goal, and come within about 75% of the energy storage goal. For instance, a lead-acid battery produced by the Optima Corp is currently used in a commercially available, four-passenger electric car which a range of over 100 miles and high performance acceleration of 0 to 60 mph in 6 seconds. However, current lead-acid batteries are inadequate for military applications such as battlefield vehicles due to their low specific energy. The need for compactness and mobility makes advanced batteries with long-life and high specific energy density more important for military vehicles than commercial vehicles. A battery developed by the Ovonics Battery Company is projected to achieve all USABC requirements except for cost, though the power density of current designs still falls short. A sodium-nickel-chloride battery developed by AEG Corporation is projected to meet all USABC mid-term goals except cost. The technology is currently being tested in European vehicle demonstrations and is available for automobile manufacturers for testing. AEG is currently developing a pilot plant and is working to remedy problems of low power densities at low charge states for the battery.

The far-term USABC goals are most likely to be met by lithium polymer battery technology. The lithium-iron-disulfide battery offers high power and energy densities, and possibly low-cost manufacturing via thin films. Currently Westinghouse has developed a monopolar form of this battery for use in electric lawnmowers.

Partnership for the New Generation of Vehicles

On September 29, 1993, President Clinton, Vice President Gore and the chief executives of the Big Three automakers announced the formation of a government-industry Partnership for the New Generation of Vehicles (PNGV). The goals of the partnership are to significantly improve national manufacturing technology, including adoption of agile and flexible manufacturing; to implement commercially viable innovation from ongoing research on conventional vehicles; and to develop a vehicle to achieve up to three times fuel efficiency of today's comparable vehicles without loss of quality performance and utility. The goals are interrelated, focused both on the near-term and the longer term.

Because an automobile involves many different technologies, the success of the PNGV will involve improvements in many different technical areas, many of them on the National Critical Technologies List. Included are lightweight materials, advanced catalysts, aerodynamics, and energy storage technologies. A number of different administrative and program mechanisms will be used as well, ranging from TRP to take advantage of technologies being developed by the DOD, to NSF grants, to contracts under the ATP, to DOE CRADAs. In addition to the Big Three automakers, program participants will include suppliers, universities, and other consortia which can contribute relevant knowledge.

U.S. Display Consortium

The ARPA HDS program began in 1988 and focused on underlying technologies required for the production of advanced displays. It was established with a dual-use strategy. The Clinton Administration increased the funding allocated to the program. By February of 1993, 85 projects had been funded with a total cost of

$70 million. Both universities and private firms have been supported. Research on AMLCD was combined with field emission displays, color electroluminescent, and color plasma, which are the four major competing technologies underlying advanced displays. Support is continuing through the DOD initiative and through NIST.

The ARPA program has now transformed into a program that involves a large consortium of companies. In July of 1993 the U.S. Display Consortium (USDC) was established by ARPA, AT&T, Xerox, Tektronix, and a number of smaller display manufacturers. The mission of USDC is to "develop the U.S. manufacturing infrastructure required to support a world-class U.S. based production capability for high definition flat-panel displays." The consortium is open to display manufacturers, the manufacturer equipment makers, and to companies that use displays in their products. By pooling the cost for R&D expenditures the overall economic barriers for high volume production of advanced displays should be significantly lowered. Since this is an ARPA led project the majority of the funds that have been spent on smaller research programs will now be invested in the USDC.

National Electronics Manufacturing Initiative (NEMI)

The National Electronics Manufacturing Initiative (NEMI) is a project designed by both industry and government electronics research managers to better coordinate important research in critical electronics technologies. NEMI grew out of the Electronics Subcommittee of the National Science and Technology Council (NSTC), a subcommittee that provides Federal interagency coordination for technical planning, budgeting, reporting, and evaluation of Federal programs in electronics science and technology, and supports two-way communications on these programs within the government and with the private sector.
The goal of the NEMI is to promote joint industry/government development of the underlying technology and infrastructure required to enable and encourage manufacture in the United States of new, high technology electronics products, such as the hardware for accessing the Information Superhighway. NEMI aims at coordinating R&D in enabling technologies, improving the manufacturing infrastructure for specific electronics technologies, demonstrating projects in support of National priorities and to meet specific government agency missions, and to develop recommendations on improving the U.S. business environment for electronics manufacturing. The technologies that NEMI has targeted for specific attention are:

- microelectronics
- human interface technology
- low-cost integrated packaging
- mass memory
- power management
- precision mechanical parts and assembly

- design and manufacture for mass-customization
- computer-based design and manufacturing
- information access technologies
- advanced materials

Photonics and optoelectronics

Currently many government R&D funding programs for photonics research require a consortium of companies to work together or companies to work with the government labs. Companies and government labs working together to share information on manufacturing problems are intended to help the photonics industry to reach a consensus on standards that are critical to the development of platform processes. The alliance model among companies in the private sector is becoming more and more common, since the cost to develop flexible standardized platforms for manufacturing photonic devices is extraordinarily high. Nevertheless, the lack of consensus and the current competitive atmosphere in the photonics arena prevent the quick development of these essential standard platforms. The government programs are helping to lower the high initial investment for individual companies and are beginning to consolidate research studies which could ultimately lead to a consensus on certain platform technologies.

There is considerable federal investment in the optical computing area. The Advanced Research Projects Agency (ARPA) is sponsoring a consortium in Optoelectronic Module Technology (OETC). The principle investigators in this project are Martin Marietta Electronics Laboratory, AT&T Bell Laboratories, Honeywell Technology Center, and IBM T. J. Watson Research Center. The purpose of OETC is to expedite the development of high bandwidth and high density optical interconnect components and to facilitate the implementation and proliferation of the developed products. This project's ultimate goal is to position the U.S. as the world leader in optical interconnect technology. Four out of seven technology areas chosen for the ARPA Technology Reinvestment Project (TRP) for fiscal year 1994 will involve photonics or optoelectronics. These include: high density data storage systems, high definition systems manufacturing, uncooled infrared sensors, and environmental sensors. There are also several other government initiatives for continued research in photonics and optoelectronics manufacturing research through the National Institute of Standards and Technology.

$11 million of TRP money has been also been invested in a university-industrial consortium to develop a rewritable optical storage system, exploiting blue/green lasers, that will store up to 10 Gigabytes in a single 5.25" optical disc. This effort is expected to result in a factor of 5-10 increase in storage capacity of the state-of-the-art commercial systems today.

NON-GOVERNMENT INITIATIVES

In addition to their participation in various consortia and government programs, companies, universities, and non-profit organizations have programs of their own which are relevant to technologies on the National Critical Technologies list. Several of these initiatives are expressed as development roadmaps which specify technical goals to be achieved by specific dates, and strategies for achieving these goals. Many of the roadmaps include a description of roles expected by all participants in the industry: companies, government, universities. They also bring together in a holistic way various technologies necessary for the achievement of advances in an industry.

Environmental quality

Less than 10 percent of all U.S. investment in environmental technology innovation is directly attributable to federal and state agencies, although this figure may be expected to be somewhat higher specifically in the remediation area. Joint efforts between government, industry, and academe account for a significant additional share of investment, but private investment by U.S. firms also abounds. These investments in environmental technology tend not to be as part of large-scale technology initiatives in the private sector, however, but tend rather to be small-to-medium size efforts by individual or small groups of firms. For example, private sector remediation technology development reported in just one recent issue of *Environmental Business Journal* include a vitrification system for radioactive waste being developed by Numatec, Inc., a funnel and gate system designed to contain contaminated groundwater plumes and channel them to in-situ bioreactors for treatment being developed by the Waterloo Center for Groundwater Research, a biofiltration system to process the vapors produced by soil vacuum extraction systems being developed by EG&G, Inc., a photocatalytic oxidation system for treatment of organic pollutants in water being developed by Solarchem Environmental Systems, and a fluidized bed bioreactor to break down pentachlorophenol used in wood preservatives being developed by Warzyn, Inc.

High-density data storage

There is considerable activity in the data storage area at the present time, since the requirements for ever-increasing storage in any level of the computing industry continue to grow. At the high end, the development of processors that can address larger and larger amounts of memory, and the construction of multiprocessor machines, often with separate memories for each processor, has led to increasing expectations on primary memory size from the user community. Increasing amounts of data from various sensors has led to requirements for larger secondary and tertiary memories. Requirements for terabytes of storage are becoming increasingly common. At the consumer end of the market, similar growths in storage requirements are evident. Recent software offerings from companies such as Microsoft require as much as 16 megabytes of

RAM for optimal performance, and require increasing amounts of mass storage for programs -- for example, modern word processors can take tens of megabytes of storage if all options are installed. The memory industry has responded by producing increasingly higher capacity products at lower unit prices, lower power consumption and smaller form factors. For example, the price for a megabyte of magnetic disk storage is now below 50 cents, whereas only a few years ago, it was tens of dollars. Small factor disks for laptops (for example in the popular PCMCIA II format) have recently been announced in capacities of more than 100 megabytes. Other technologies in the developmental stage offer storage capacities many times these numbers in similar sized packages.

At the present time, U.S. companies dominate the magnetic disk market, and are usually the first to produce larger capacity products. In particular, U.S.-developed improvements in recording head technology will shortly lead to another round of capacity enhancements. Competition is very severe, however, with disk prices falling by half every year at the present time. The major U.S. players, including Conner Peripherals, Maxtor, Seagate Technology and Western Digital, spend of the order of 10% of their revenues on research and development, essentially all in-house, to keep up with the competition. The goals are obvious: to increase capacity per unit volume, decrease cost per megabyte, and increase reliability. $20 million of TRP funds have also been awarded to a consortium of seven other companies to develop high density magnetic disk storage for portable information systems.

Until recently, the Japanese led in the RAM market. However, at the present time, the playing field is more equally balanced between Japanese, Korean, European and U.S. producers, although the Japanese still have the leading market share. More importantly, the costs of building a leading-edge RAM manufacturing facility have risen to the billion dollar level, forcing individual companies to form global partnerships in this area in order to share the cost. Such partnerships include IBM, Siemens and Toshiba, Hitachi and Goldstar (South Korea), and Hitachi and Texas Instruments. As a result, there is a global sharing of information on the production of such components. This trend will continue unless cheaper fabrication methods are developed.

The value of the RAM market to U.S. companies is of the order of $30 to $40 billion annually. Essentially all research is done by the companies themselves, with limited cooperation from university research centers.

10. CONCLUSIONS

As shown by the analysis presented in this report, the United States is well positioned in those technologies which are deemed to be critical to the nation's economic prosperity or national security. Although we do not lead in every specific technology, our technological capabilities are either better than or on par with the best in the world in all 27 critical technology areas, as shown in Figure 10.1. That is an accomplishment of which the nation can be proud.

Nevertheless, given the rapid nature of technological progress and the increasing intensity of global competition, we must continue to improve both our development efforts and our efforts to diffuse advanced technology widely into the economy and into systems and components used by the military to protect the nation's security. The trends in Figure 10.1 indicate that the size of the U.S. lead has either declined or remained constant, which argues for continued U.S. investment in technology development if the U.S. position is to be preserved. In times of constrained resources we must do these things more efficiently, as well.

The cabinet-level National Science and Technology Council (NSTC) is an important instrument for assuring the nation's continuing technological leadership. The NSTC's principal purposes are: to establish clear national goals for federal S&T investments, to ensure that policies and programs are developed and implemented to support those goals; and harness S&T to improve quality of life and long-term economic strength of the United States. The NSTC provides a formal mechanism by which the vast Federal R&D enterprise can be coordinated, priorities can be explicitly set, and unnecessary duplication of effort can be eliminated.

In addition to increased coordination of the Federal R&D enterprise, the Administration has placed an emphasis on coordinating federal R&D programs with the private sector and on forming collaborative programs and partnerships. The private sector is given an opportunity to provide its input in a variety of ways, ranging from the advice given by the President's Committee of Advisors on Science and Technology (PCAST), to workshops and white papers to help identify technology areas for investment by the Advanced Technology Program, to joint funding and direction of programs like the Partnership for the New Generation Vehicle. This collaborative relationship will help assure the long-term health of the U.S. technology base and the nation's ability to take full advantage of the products, processes and information it creates.

While the National Critical Technologies are not the only technologies important to the long-term economic health or national security of the United States, they are those which have the greatest impact. The process of identifying these technologies has been one part of the continuing effort to use technology to assure a brighter future for the nation.

Figure 10.1
National Critical Technologies
Technology Position and 1990-1994 Trend

US Technology Position Relative to:
- Japan ▷, ○, or ◁
- Europe ▶, ●, or ◀

1990–94 Trend
- Improved ▷
- Declined ◁
- Maintained ○

	Lag			Lead	
	Substantial	Slight	Parity	Slight	Substantial
Energy					
Energy Efficiency			▶	○	
Storage, Conditioning, Distribution, and Transmission			●	○	
Improved Generation			●	○	
Environmental Quality					
Monitoring and Assessment				◁ ◀	
Pollution Control			○ ●		
Remediation and Restoration			◀	◁	
Information and Communication					
Components			▷	●	
Communications				●	◁
Computing Systems				●	◁
Information Management					▷
Intelligent Complex Adaptive Systems*			○	◀	
Sensors			▷ ▶		
Software and Toolkits				●	▷
Living Systems					
Biotechnology				○ ▶	
Medical Technologies				▷ ●	
Agriculture and Food Technologies				◁ ▶	
Human Systems				▶	▷
Manufacturing					
Discrete Product Manufacturing				○ ●	
Continuous Materials Processing*			○ ●		
Micro/Nanofabrication and Machining			▷	●	
Materials					
Materials				◁ ●	
Structures				●	◁
Transportation					
Aerodynamics				●	◁
Avionics & Controls				◀	◁
Propulsion & Power				◁ ●	
Systems Integration				●	○
Human Interface*					▷ ▶

*based on limited information

APPENDIX A

NATIONAL CRITICAL TECHNOLOGIES LIST

The section provides the definition of critical technologies and then discusses the structure of the list. The complete list is presented in Table A.2.

WHAT IS A "CRITICAL TECHNOLOGY"?

The precedence for identifying select goods as "critical" arose in the 1920s when dependence on foreign imports of certain materials was judged to be a vulnerability for the U.S. military. Accordingly, Congress required that the U.S. maintain a strategic reserve of such "critical materials" in order to ensure readiness in case of military conflict. An extension of the same idea, i.e., that some technologies are critical for military readiness but also as fuel for economic growth, informed the Congress's use of the term in PL 101-189. In this legislation mandating a critical technologies report, Congress defined "critical technologies" as "essential for the United States to develop to further the long-term national security or economic prosperity of the United States."[1] The phrase "critical technologies" as used in the legislation implies that some technologies are so fundamental to national security or so highly enabling of economic growth that the capability to produce these technologies must be retained or developed in the United States.

Since the requirement for a National Critical Technologies report was established in the 1990 Defense Appropriations Act, several critical technologies lists have come into existence. Various departments and agencies of the Federal government have carried out or publish critical technology assessments, including the Department of Defense, the Department of Commerce, and the National Aeronautics and Space Administration. Additionally, a number of private sector lists have been generated. Other industrialized countries have also identified national critical technologies. For example, both Germany and Japan engage in a formal Delphi process involving government, industry and academia to evaluate the importance and status of a broad set of technologies.

This list-making activity should not be seen as redundant. Different lists are generated for different purposes, and the technologies on these lists are selected for their potential to aid in achieving specific goals. That is, the technologies on different lists are "critical" for different reasons. In the case of the critical technologies activities of the Department of Defense, for example, technologies are examined in relation to five Future Joint Warfighting Capabilities most needed by the U.S. Combatant Commands. The Commerce Department's emerging technologies list, published in 1990, was based on market potential dictated by the department's mission to promote and improve commerce.

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[1] US Code, Title 42, Section 6683.

Differing criteria, purposes and legislative references aside, many observers have noted strong similarities between the critical technology lists.[2] In a highly interdependent economy with substantial overlap between civilian and defense applications, this similarity is not surprising. Integrating various critical technologies lists and capturing the similarities—which reveal complex relationships within the economy and between sets of national and sub-national goals—in a consistently aggregated, rationally organized way was the first important task in producing this report.

Because the U.S. economy is broad and technologically advanced, many technologies are important to some aspect of economic prosperity or national security. Choosing those that are "critical" on the national level requires some careful thinking about definitions. The first necessary definition is that of "technologies" since "critical technologies" are a subset of the larger group. Technology involves knowledge. In order to differentiate technology from other forms of knowledge, this report defines technology as knowledge that has the following characteristics:

- Systematized and practical, based on experimentation and/or scientific theory
- May involve new discoveries, current knowledge, or a combination of both
- Directed toward application or achieving a goal rather than only toward understanding
- Involves direct manipulation of materials or biological systems, or the implementation of mathematical algorithms
- Is reproducible and transferable

This definition excludes much basic science which is directed at pure understanding of natural phenomena. However, the definition is broad enough to include knowledge built on scientific understanding and knowledge acquired through experimentation or accident.

Once the realm of "technologies" is defined, it is necessary to define what we mean by "critical." The definition in this National Critical Technologies report assumes that the criticality of a technology is determined by the importance of the application to which the technology is put. That is,

criticality is derived from the importance of the outputs of the system of which the technology is a constituent part, as well as from the significance the technology has for enabling that system

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[2]Comparisons of various critical technology lists may be found in Mogee, Mary Ellen, *Technology Policy and Critical Technologies: A Summary of Recent Reports,* The Manufacturing Forum, National Academy Press, Washington, D.C., December 1991 and in Knezo, Genevieve J., *Critical Technologies: Legislative and Executive Branch Activities,* Congressional Research Service 93-734 SPR, Washington, D.C., 5 August 1993.

This definition explicitly answers the question "Critical for what?" thereby helping to link policy objectives to choices of technologies. For example, since improvements in education at all levels are considered essential to the future economic prosperity and national security of the United States, education and training software which enables advanced education and training methods and systems is a critical technology that meets the definition above.

CLASSIFICATION AND AGGREGATION METHODOLOGY

The National Critical Technologies Report defines "criticality" in the broadest possible way—to "develop and further the long-term national security or economic prosperity of the United States." Thus, this list must be *integrative* in a fundamental sense, incorporating the diverse concerns and objectives which comprise ideas of security and prosperity and which drive much of the other list-making activity. It must also identify areas not captured in extant lists because they span the concerns or responsibilities of several different agencies or groups.

The 1995 National Critical Technologies list was created through a process of input from multiple constituencies in a traceable and reproducible manner, described in greater detail in Appendix B. The process began with a candidate list which included technologies appearing in the first Report of the National Critical Technologies Panel (March 1991), as well as the lists published by the Department of Commerce, Department of Defense, Department of Energy and by NASA. A four-level hierarchical structure was used to integrate lists based on different organizational schemes and levels of aggregation. Sample or illustrative applications to which the technologies contributed were also included, although the list of applications was not expected to be exhaustive. Technology experts were utilized to include knowledge of specific technologies and applications where existing lists did not contain a sufficient level of detail. In addition, the candidate list indicated whether each specific technology contributed primarily to economic prosperity, national security, or both.

The six major technology categories in the 1991 list[3] were changed to seven. The descriptions of the seven categories are shown in Table A.1. The candidate list classified technologies according to the nature of the skills and problems involved in their development, not by the technologies' applications. This focus on underlying technologies rather than applications streamlined the list. Many technologies support multiple applications, so an application-based taxonomy complicates a technology list by forcing the same technology to be placed in multiple categories. Technology focus was also deemed to be more helpful to users because it allowed them to see the breadth of influence of a technology and to determine whether a technology meets their requirements for criticality based on applications it supports.

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[3]The 1993 Panel did not re-write or alter the 1991 list.

Table A.1
Description of technology categories

Technology Category	Description
Materials	Substance of physical objects
Manufacturing	Producing physical objects
Information and Communications	Producing, storing, manipulating, and moving information
Transportation	Physically moving people and objects
Living Systems	Creating and modifying biological processes
Energy	Powering the other categories
Environmental Quality	Dealing with environmental consequences of past, present, and future activities

Table A.2

National Critical Technologies List

Energy

Energy Efficiency
Energy Storage, Conditioning, Distribution and Transmission
Improved Generation

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Improved Generation	**gas turbines**	combuster design	•		highly efficient energy generation with minimum pollution
		high-temperature materials (see "Materials)	•		
	fuel cells	proton exchange membrane	•		commercial development of fuel cell technology for distributed generation, transport
		phophoric acid fuel cells	•		
		molten carbonate fuel cells	•		
		solid oxide fuel cells	•		using hydrogen and hydrocarbon fuels
	next generation nuclear reactors	light-water	•		increased safety margines, reduced relative costs through passive response to non-normal conditions, simplified systems, inherently improved thermal management, tolerance
		inherently stable reactor technology	•		
	power supplies	high energy density, low mass supplies	•	•	improved weapons systems/reconnaissance vehicles, electronic warfare systems
		pulse supplies		•	simulating nuclear weapons effects
	renewable energy	**solar thermal power technologies**	•		mass production of devices for direct sunlight conversion and competitive prices
		photovoltaics	•		
		wind turbines	•		improved performance in a wider range of wind resource sites
		biomass fuels	•		comversion to synthesis gas or oil for production of electric power, liquid/gasseous fuels

Environmental Quality

Monitoring and Assessment
Pollution Control
Remediation and Restoration

Environmental Quality

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Monitoring and Assessment	integrated environ monitoring	sensors (see "Info. and Comm.")	•	•	global climate/ocean observing systems; battlefield identification of dangerous chemical and biological agents; proliferation monitoring
		software (see "Info. and Comm.")	•	•	
		networking (see "Info. and Comm.")	•	•	
		simulation (see "Info. and Comm.")	•	•	
	remote assessment of biosystem	ground truth biomarkers and pattern recognition	•	•	forestry and fisheries management, crop yield prediction
Pollution Control	pollution control	physical separation	•		increase fraction of waste stream recovered for recycling and reuse by increasing efficiency and lowering cost with which components of stream can be separated
		component separation	•		
		chemical transformation	•		
		biological agent separaton	•		
		waste elimination	•		
Remediation and Restoration	remediation and restoration	soil washing	•		increase efficiency of, reduce cost and cycles required to remediate sites, especially those with multiple contaminants, habitat restoration
		thermal desorption	•		
		composting	•		
		electrochemical separation	•		
		super-critical water oxidation	•		
		recovery of spilled oil and other hazardous subst.	•		
	bioremediation	microbal metabolism of organic pollutants	•		
		sequestration of heavy materials	•		
	nuclear wastes storage/disposal	storage	•	•	increased safety/decreased uncertainty for storage and containment of nuclear waste
		treatment	•	•	
		separation	•	•	

EP= Economic Prosperity; NS = National Security

Environmental Quality

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Monitoring and Assessment	integrated environ monitoring	sensors (see "Info. and Comm.")	•	•	global climate/ocean observing systems; battlefield identification of dangerous chemical and biological agents; proliferation monitoring
		software (see "Info. and Comm.")	•	•	
		networking (see "Info. and Comm.")	•	•	
		simulation (see "Info. and Comm.")	•	•	
	remote assessment of biosysten	ground truth biomarkers and pattern recognition	•	•	forestry and fisheries management, crop yield prediction
Pollution Control	pollution control	physical separation	•		increase fraction of waste stream recovered for recycling and reuse by increasing efficiency and lowering cost with which components of stream can be separated
		component separation	•		
		chemical transformation	•		
		biological agent separaton	•		
		waste elimination	•		
Remediation and Restoration	remediation and restoration	soil washing	•		increase efficiency of, reduce cost and cycles required to remediate sites, especially those with multiple contaminants, habitat restoration
		thermal desorption	•		
		composting	•		
		electrochemical separation	•		
		super-critical water oxidation	•		
		recovery of spilled oil and other hazardous subst..	•		
	bioremediation	microbal metabolism of organic pollutants	•		
		sequestration of heavy materials	•		
	nuclear wastes storage/disposal	storage	•	•	increased safety/decreased uncertainty for storage and containment of nuclear waste
		treatment	•	•	
		separation	•	•	

EP= Economic Prosperity; NS = National Security

Information and Communication

Components
Communications
Computer Systems
Information Management
Intelligent Complex Adaptive Systems
Sensors
Software and Toolkits

Information and Communication

Components
Communications
Computer Systems
Information Management
Intelligent Complex Adaptive Systems
Sensors
Software and Toolkits

Information and Communication

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Components	high-density data storage	thin-film recording head transducers	•		1-gigabyte micro-floppies
		recording media	•		storgage requirements for high-definition displays, high-performance computing
		high-density RAM	•	•	
		format compatibility/standards for optical storage	•		long-term commercial viability of media, storage requirements for high-def displays
		magneto-optical storage	•		eraseable data storage w/ conventional optical disk data density
		holographic optical elements	•		improved access time, reduced weight, cost
		parallel data storage controllers	•	•	meet storage requirements of massively parallel computers
	high definition displays	lithography (see Micro/Nano Fabrication)	•	•	competitive high-definition display manufacturing capability supporting
		circuitry patterning	•	•	(eg) flat panel, HDTV, military systems
		glass sheet production	•	•	
		thin-film techniques	•	•	
		holographic displays	•	•	displays for military and commercial systems
	high-resolution scanning techs	high yield detector arrays (see Sensors)	•	•	search engines on optical storage
Communications	data compression	chaotic graphics compression	•	•	high data-transfer requirement applications, eg HDTV
	signal conditioning and validation		•	•	support high-performance, arrayed/multi-spectral sensor applications: target recognition, munitions guidance, CIM, environmental monitoring
	telecom/data routing	broadband switching	•		full utilization of fibre-optic capacity especially in support of NII
		programmable radios		•	all-spectrum/format radios for military interoperability, reduced costs
		wireless communic tech	•	•	improved economics, technical characteristics to support maximum access to NII
		cable	•	•	and robust military comm system
		fibre	•	•	
		satellite-ground communic protocols	•	•	improved space-ground interoperability.
		mobile computing systems	•	•	
Computer Systems	interoperability	data interchange standards	•	•	full standardized multi-media data exchange on NII or other systems
		product data exchange	•	•	full exchange of product characteristic data between systems
	parallel processing	MIMD (Multiple Instruct, Mult Data Stream)	•	•	parallel-processing hardware and software to support high-performance
		SIMD (Single Instruction, Multiple Data Stream)	•	•	computing activities in: prediction and analysis of complex systems,
		VLIW (Very Large Instruction Word)	•	•	management, simulation and design of complex systems/processes
		systolic arrays	•	•	
		specialized parallel coprocessors	•	•	
		hypercubes	•	•	
		parallel data storage architecture	•	•	

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Information Management	data fusion	multi-spectral data processing	•	•	advanced targeting and guidance, environmental monitoring, machine vision, intelligence capabilities, anti-stealth techniques
		distributed array processing	•	•	
	large-scale info. systems	very large database management tools	•	•	finanancial systems, electrical power grids, battlefield surveillance systems, fusion of global ocean and climate observing data
		real-time large scale info retrieval tools	•	•	
	health systems and services	integrated systems of electronic patient records and decision support systems	•	•	patient management and outcome studies, telemedicine, virtual medical groups, evaluation of preventive interventions, health resource allocation
		user interfaces	•	•	
	integrated nav. systems	electronic charts data information systems	•	•	improved ship navigation capabilities, navigation systems for air traffic control, intelligent transportation systems
		on-the-fly DGPS positioning	•	•	
		real-time environmental info. systems	•	•	
Intelligent Complex Adaptive Systems	autonomous robotic devices	sensors	•	•	automatic sentries, hazardous materials handling, mine detection & removal, counterterrorist ops, law enforcement, environ. remediation, public disaster responses
		signal processing	•	•	
		software	•	•	
		robotics	•	•	
	artificial intelligence	knowledge representation	•	•	AI systems for military and commercial/manufacturing use
		comp-based reasoning methods	•	•	
		machine learning methods	•	•	
Sensors	physical devices	microsensors	•	•	integrated sensing/signal processing, expanded in-situ monitoring, integrated systems
		biosensors	•	•	diagnostics, environ/exposure monitoring, nano-controls, biological weapons use detec
		chemical sensors	•	•	process control, environmental monitoring, chemical weapons use detection
		passive thermal imagers	•	•	battlefield night vision, medical diagnostics
		IRST systems (point source passive thermal imag)		•	passive targeting systems, identification, kill assessment
		high yield, high-density photo/IR detectors	•	•	HDTV, scanning, medical imaging, environmental monitoring, night vision systems, machine vision, advanced targeting and precision-guided munitions
		multi-spectral integrated sensors	•	•	
	integrated signal processing	IR/radar sensors	•	•	improved miniatuarized sensors w/ sensor and processing circuitry on same chip

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Software and Toolkits	education/training software	military training--see "simulation software"		•	battle simulation and training
		multi-media authoring tools	•	•	more effective education and life-long training
	network and system software	navigation and resource discovery tools	•		high utility, easy-access NII via tools for organizing and finding information
		directories	•		
		registries	•		
		transparent embedding software	•	•	integrated heterogenous concurrently operating systems in distributed env
		operating systems	•	•	
		run-time execution systems	•	•	
		programming languages	•	•	
		interpreters	•	•	
		compilers	•	•	
	modeling and simulation software	virtual battlefields & weapons systems		•	improved effectiveness, economics of training, "virtual prototyping"
		atmospheric and global systems	•	•	improved prediction of weather, knowledge of global change phenomena
		computational fluid dynamics	•	•	better aero/hydro-dynamic design, combustion and industrial process design
		agriculture	•		sustainable agric practices, optimized yields
		cellular/biomolecular function	•		
		computational physics	•	•	
		computational chemistry	•	•	rational design of new chemicals and pharmaceuticals; countermeasures against bio. wa
		economic systems	•		
		numerical control simulation	•	•	visualization of machining process: design for min waste, CIM
		manufacturing	•	•	"virtual CIM" of products: allow rapid prototyping, reduced startup costs
	software engineering tools	CASE (Computer-Aided Software Engineering) too	•	•	increased efficiency of software authoring, better software maintainability
		user interface design tools	•	•	contain software costs
		software testing tools	•	•	increased reliability, reduced cost of software, especially in complex systems
		IC design tools	•	•	improved design capabilities for complex ICs
	pattern recognition	virtual reality software	•	•	
		natural language recognition (speech, handwriting)	•	•	
		multi-media operating systems	•	•	
	software production	rapid prototyping	•	•	reduced development costs, fewer development cycle iterations
		modular/object-oriented programming	•	•	

Living Systems

Living Systems

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Biotechnology	bioprocessing	drug, chemical, enzyme production	•		full commercialization of biotech by increased efficiency,
		mineral extraction	•		reduced cost of cell bioreactors/bioprocessing; aquaculture
	monoclonal antibody production	diagnostics	•	•	improved diagnostic capability for diseases and disorders
		therapeutics	•	•	improved treatment of variety of diseases
		separation processes	•		
		enzyme-like catalysts	•		cheaper, more effective processing of certain materials
	protein engineering	protein sequencing	•	•	site specific binding/blocking
		protein folding	•	•	achieving the right shape, not just the right sequence
		rationally designed drugs	•	•	improved potency and specificity
		structural biology	•		shaping molecules
		tailored protein catalysts	•		high selectivity and specificity catalysts: more effic synthesis (lower cost, waste m
		molecular electronics	•	•	ultra-high density/low-power memories
		biomolecular materials	•		
		molecular motors	•	•	
	recombinant DNA technologies	gene mapping/sequencing	•		diagnostics, prevention and therapy for diseases in humans,
		gene therapy/replacement	•		identification/manipulation of specific genes in plants and animals
		antisense	•		turning off specific protein production
		agricultural species modification	•		plant and livestock species with designed traits, plant pest/pathogen resistance
		transgenic cell cultures	•		modified cells to act as bioreactors
		therapeutic agents (see Vaccines)	•	•	
	vaccines	infectious disease	•	•	enhanced immunogenicity
		AIDS vaccine	•	•	contain spread of AIDs virus
		cancer (tumor type specific)	•		
Medical Technologies	health info systems/services	See "Information and Communication"	•	•	
	biocompatible materials	microcapsules	•		slow, targeted release of medication
		replacement materials	•	•	more durable, more effective materials for replacement of natural tissue or bone
		material surface characteristics	•	•	implantable devices, sensors, and electrodes
		tailoring immune system response	•	•	artificial blood, skin, tendons and ligaments
		tissue engineering	•	•	

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Medical Technologies, cont'd	functional diagnostic imaging	high-field spectroscopic MRI	•	•	electronic biopsy
		optical coherence tomography	•	•	biochemical functional assessment
		AI diagnostic support systems	•	•	
	bacterial/viral detect/screening	detection/ID at different concentrations, media, environments	•	•	food and water quality assurance, antibiotic selection, infection control
		epidemioloy statistical techniques	•	•	surveillance of new disease and spread of disease
	medical devices and equipment	patient monitoring equipment	•	•	
		biosensors	•	•	pressure, electrophysiology, blood chemistry
		functional electrical stimulation devices	•	•	functional restoration, including hearing, breathing, contenance and mobility
		critical care instrumentation	•	•	cardio-pulmonary bypass pumps, repirators
		blood chemistry auto-analyzers	•	•	
		de-contamination and sterilization	•	•	
		endoscopic/laporascopic surgical equipment	•	•	
Agriculture and Food Technologies	sustainable agri. produciton	genetic resource ID, preservation and utilizatio	•		improved bio. efficiency of agricultural organisms, bio. pest control, sustainable agricultual systems, soil and water conservation
		biological and engineering criteria	•		
		ecosystem management	•		
	food safety assurance	pathogen detection, isolation, reduction/ elimination	•	•	food safety, comprehensive HACCP
		drug and residue detection	•	•	
		waste management	•		byproduct recover and value-added product development
	aquaculture and fisheries		•	•	sustained population management and production, food quality assurance
Human Systems	advanced human-machine interfaces	psychophysiology of learning	•	•	education, training, performance enhancement
		mental workload assessment	•	•	
		neurotechnologies	•	•	
		software for AHCI/ see software	•	•	human-machine interfaces more accurately simulating natural experience for increased ease-of-use and utility
		sensors	•	•	
		signal processing	•	•	

Manufacturing

Discrete Product Manufacturing
Continuous Process Manufacturing
Micro/Nano Fabrication and Machining

Manufacturing

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Discrete Product Manufacturing	CIM support software	CAD (Computer-Aided Design)	•	•	improved solid-object representation design
		CAE (Computer-Aided Engineering)	•	•	improved interactive design/performance analysis of product
		process, machine performance databases	•	•	ensure consistency with high skills production and work systems
	equipment interoperability	group technology	•	•	improved factory, production efficiency, by IDing job/item similarities
		CAPP (Computer-Aided Process Planning)	•	•	optimized factory routing, production lead times with variant, generative CAPP
		data-driven management info systems	•	•	capabilities to effectively design, manage CIM
		factory scheduling tools	•	•	enhanced forecasting and scheduling capabilities for improved efficiency
	intelligent processing equipm	sensors (see Info & Communications/Sensors)	•	•	process monitoring and control; automated design of large-scale ICs
		next generation controller (see Info&Comm/softwr)	•	•	
	robotics		•	•	automated construction; de-mining
	auto. systems for facilities ops.	computer-aided production cycle management	•		
		building automation systems	•		
	net shape processing	hot isostatic pressing	•	•	more economic/technically feasible finishing of non-traditional materials
		metal injection molding	•	•	e.g.,ceramics, super-alloys
		superplastic forming	•	•	
		liquid transfer molding of polymer matrix composite	•	•	low cost manufacturing of large parts
	rapid solidification processing	spray forming	•	•	uniform microstructure alloys, esp for hard to shape alloys
		gas atomization	•	•	

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Continuous Materials Processing	catalysts	tailored protein catalysts	•		
		shape slective catalysts	•		fules and chemical production
		catalysts by design	•		increased efficiency thermal processing, pollution control catalysts
		biomimetic catalysts	•		carbon dioxide utilization
	surface treatments	laser hardening	•	•	selective surface hardening in: medical implants, high-perf bearings, extrusion dies
		thin films (see "artificial structuring methods")	•	•	
		grinding and machining of ceramics	•	•	reduced cost and increased reliability of parts
		ceramic coatings (see "ceramics')	•	•	
	ultrapure refining methods	various refining methods (non-specified)	•	•	OEICs, stronger polymer matrix composities and ceramics
		electron beam processing	•	•	high-purity alloys for jet turbines
	pollution avoidance	process design strategies	•		achieve lower levels of environmental loading
		improved processes	•		increase resource efficiency of process industries, e.g., petroleum refining, metals, etc.
		design for the environment	•		life-cycle approach to design of products and processes
		industrial ecology	•		multidimensional production and recycling/reuse systems
	predictive process control	sensors	•	•	
		data processing	•	•	
Micro/Nano Fabrication and Machining	microdevice manufacturing techs	silicon machining	•	•	better quality, expanded capability, lower-cost micro-machines for sensors, controls
	semiconductor manufacturing	x-ray lithography	•	•	miniaturization and cost containment for chip manufacture
		microwave plasma processing	•	•	
		electron/ion micro-beams	•	•	
		artificially structured materials	•	•	
		laser-assisted processing	•	•	
		metrology	•	•	
		design testing	•	•	
	semiconductor integration techs	integrated packaging	•		easier/lower cost integration/interconnection of multiple chips
		multichip modules	•		
	artificial structuring methods	chemical vapor & sputter deposition	•	•	thin films, high-speed microelectronics, OEICs
		molecular and chemical beam expitaxy	•	•	high performance alloys, ceramics, coatings (eg diamond) for improved wear, thermal,
		spin-on deposition	•	•	and radiation-resistance characteristics
		vaccum evaporation	•	•	

Materials

Materials
Structures

Materials

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Materials	alloys	light weight structural alloys	•	•	lighter, stiffer airframes, automobile frames
		intermetallic alloys (Ti/Ni/Fe aluminides)	•	•	high-temp structural applications in aerospace
	ceramic materials	ceramic IC packaging	•		improved interconnection/data rates for multi-IC assemblies
		ceramic matrix composites (see "composites")	•	•	
		ceramic coatings	•	•	improved wear characteristics in high-speed moving parts: turbine engines, cutting tools
	composites	polymer matrix composities	•	•	economical, bulk PMCs for jet engines, automobiles, high-T aerodynamic surf
		ceramic matrix composites	•	•	high-perf aircraft engines, automobile engines, advanced armor
		metal-matrix composites	•	•	space applic. for null-outgassing, rad-resist important, hypersonic aircraft, HSCT, armor
		carbon-carbon composites	•	•	ultra-high temperature aerospace applications (rocket nozzles, thermal surfaces)
		molecular-scale composites	•	•	
	electronic materials	GaAs	•	•	superior, economic GaAs-based ICs (faster and/or hardened electronics)
		thin-film dielectric materials	•	•	miniaturization of microwave communication devices
	photonic materials	semiconductor lasers/laser arrays	•	•	laser/detector techs to support communications
		advanced detectors	•	•	and optical data processing, with eventual goal of OEICs
	high energy-density materials	advanced solid and liquid propellants		•	space launch vehicles, longer-range artillery
		explosives		•	improved conventional weapons
	highway/infrastructure materials	paving	•		higher-durability, more economical materials to maintain surface transport infrastructure
		repair materials	•		
		polymer matrix composites	•		retrofit reinforcement for earthquake damage prevension
	biocompatible materials		•	•	See "Living Systems"
	stealth materials	radar-absorbing materials/coatings		•	increased abilities for military aircraft to operate unobserved by radar
	superconductors	high temperature superconductors	•	•	sensors, low-power electronics, power transmission, energy storage,
		advanced low-temp superconductors	•	•	powerful magnets for research, medical diagnostics, maglev technology

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Structures	aircraft structures	computational structural mechanics	•	•	enhance productivity of prototype development
		hot structures	•	•	hypersonic cruise/reentry functions
		actively cooled structures	•	•	
		materials life behavior prediction	•	•	improved safety, design for lifecycle
		life extension technologies	•	•	
		stealth structures		•	enhanced survivability, effectiveness of military aircract through reduced observability
		infrastructure materials		•	

Transportation

Aerodynamics
Avionics and Controls
Propulsion and Power
Systems Integration
Human Interface

Transportation

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Aerodynamics	aircraft aerodynamics	turbulence prediction and control	•	•	engine efficiency, aircraft stability improvements
		laminar flow control	•	•	
		noise control	•	•	reduced environmental impact aircraft, low-observable aircraft
		hypersonic/aero-assist/wave-rider designs	•	•	long-range, high-speed aircraft
	surface vehicles aerodynamics	low-drag designs	•		more efficient, lower-emissions vehicles
Avionics & Controls	aircraft/spacecraft avionics	glass cockpit techs	•	•	reduce pilot workload
		foul-weather flying systems	•	•	
		fly-by-light techs	•	•	reduced weight, increased reliability and stability control
		power-by-wire techs	•	•	
		highly integrated engine/airframe controls	•	•	high-speed (>m=3) applications
		space-qualifed computers	•	•	better performance, autonomous operations, improved reliability
	surface transport controls	advanced engine controls	•		more efficient, lower-emissions engines
Propulsion & Power	aircraft turbines	high-thrust turbines		•	sustained supersonic cruise w/out afterburners
		high-efficiency turbines	•	•	better specific fuel consumption
		multi-fuel/hybrid engines	•		develop more powerful engines w/ better fuel economy and lower NOx emissions
		advanced engine components	•	•	increased safety, quality assurance, lower manufacturing cost
	spacecraft power systems	high-efficiency solar cells	•	•	lower spacecraft weight
		high power compact sources	•	•	deep space mission requirements
		remote power transmission	•	•	in space/space to ground power transmission
		batteries (See "Energy")	•	•	lower spacecraft weight
	electrically powered vehicles	energy storage techs (see "Energy")	•		reduce emissions/secondary pollutant concentrations in urban areas

EP= Economic Prosperity; NS = National Security

Technology Area	Technology Sub-Area	Specific Technologies	EP	NS	Sample Applications to Which Specific Techs Contribute
Systems Integration	intelligent transportation syst	sensors	•		add information and control infrastructure to existing physical transport infrastructure to increase safety, capacity, driver convenience & reduce emissions, fuel consumption, congestion.
		networks	•		
		software	•		
		satellite navigation	•	•	
	aircraft/spacecraft integration	satellite assembly	•	•	industry-wide, common interface standards
		advanced fabrication, lay-up and joining techs	•	•	successful adaptation to new materials, reduced costs of design, prototyping
		multi-displinary aircraft design techniques	•	•	
Human Interface	human factors engineering	ergonomics	•		improved automobile control
		long-duration flight countermeasures	•	•	improve safety and situational awareness/counter aircrew fatigue
		high-g countermeasures		•	improve pilot function under high-g maneuvers
	spacecraft life support	closed/mostly closed extended life support sys	•		reduced space logistics costs

APPENDIX B
TECHNOLOGY SELECTION AND ANALYSIS

This appendix discusses the process for the selection and analysis of National Critical Technologies. It starts with the discussion of the legislative mandate for creating the National Critical Technologies Report. It then details the process by which particular technologies were selected for inclusion. Finally, it discusses the methodologies used for analysis and assessment.

LEGISLATIVE MANDATE

The National Critical Technologies Report is prepared biennially at the direction of the 101st U.S. Congress in Public Law 101-189. This law charges a panel of public and private sector officials with identifying no more than 30 national critical technologies "essential... to develop and further the long-term national security or economic prosperity of the United States." The current report is the third in the series.

NATIONAL CRITICAL TECHNOLOGIES REVIEW AND SELECTION PROCESS

Review and approval

The National Critical Technologies Review Group that approved the 1995 National Critical Technologies Report includes members of the President's Committee of Advisors on Science and Technology (PCAST) senior government officials. The government officials applinted by the Director of OSTP included the Associate Director of OSTP for Technology and the Associate Director of OSTP for National Security and International Affairs.

In addition to the National Critical Technologies Review Group, the 1995 Report was prepared with the participation from the committees of the National Science and Technology Council (NSTC). All relevant federal agencies that participate in NSTC committees had the opportunity to review and comment on the National Critical Technologies list, although the Committee on Civilian Industrial Technology and the Committee on National Security had the lead roles in the process. The primary focus of the content reviews by the agencies was to reflect current status and relative importance of various technologies, to fill in gaps, and to assure that the most important potential applications were included.

Following the NSTC review, the list was presented for review and approval to the National Critical Technologies Review Group. The report itself went through a similar process of review and approval, ensuring that all inputs and comments on earlier versions were addressed.

Selection criteria

As described in Appendix A, the process began with a candidate list. Technologies from this candidate list were selected for the final list if they met one or more of the following criteria.

Economic Prosperity

1. Directly and substantially supports major S&T goal(s) of the Administration as documented in the Memorandum on 1996 Research and Development (R&D) Priorities, dated May 6, 1994, as shown in Table B.1.
2. Directly and substantially contributes to the S&T base essential for maintaining or promoting a globally competitive position for one or more U.S. industries.
3. Meets tests of potential economic importance in the near-term for technologies of incremental change, and in the longer term for breakthrough technologies.
4. Has a high rate of discovery (i.e., will impact fast-moving technology intensive industries, such as telecommunications infrastructure and devices).
5. Meets a test that despite recognition of an industry need, sufficient R&D investments by the private sector will not occur without Federal support due to the magnitude or protracted payback period for the required investment, riskiness of the technological development, or generic nature of a technology in which no single company could expect to recover its R&D investment (the latter is a "commons" test).

National Security

1. Makes an essential contribution to enabling or advancing the future warfighting requirements, as shown in Table B.2.
2. Makes an essential contribution to mission areas under the administration national security priority R&D as stated in the Memorandum on 1996 Research and Development (R&D) Priorities, dated May 6, 1994 (Goal 6, Enhancing National Security)
3. Is essential to meeting other Defense requirements that are traceable through the 1994 Defense Science and Technology plan.

METHODOLOGICAL NOTES

International benchmarking

Assessments of foreign position and trends for the critical technology areas are based on analysis of specific technology sub-areas. Sub-area assessments are aggregated, based on analytical judgments regarding relative weighting or importance, to obtain assessments of each area. Assessments in some areas, e.g., biotechnology or predictive process control, are difficult because much of the overseas research and process development take place in corporate rather than academic environments, the work is considered proprietary, and there is little incentive to publish or to reveal the state of development to anyone who might be considered a potential competitor.

Other methodological points include:

- *Geographic regions.* Europe and Japan are the focus of this assessment, but other countries are considered when they are at or near the leading edge. Europe is treated as an aggregate and assessments are based on the best demonstrated capability in any European country rather than on an average across countries.

- *Technical vs. non-technical measures.* Assessments of current position and five-year trends are based on technical performance rather than on market success, competitiveness, government policy, corporate spending, or any other non-technical factor. In some cases, assessments are complicated by the need to separate design trade-offs from significant differences in technology capabilities. For example, telecommunications vendors are pursuing alternative R&D strategies for asynchronous transmission mode switches. Assessments must take into account the fact that alternative R&D strategies could reflect real differences in capability, such as weakness in software, or could simply be a result of different perceptions as to the best technical path.

- *Research vs. embedded technology.* The entire technology spectrum is considered, but with differing emphases depending on which technology is being assessed. For example, assessments of biotechnology stress the research portion of the innovation spectrum, whereas aircraft propulsion evaluations focus more heavily on what is actually in service.

Table B.1
Research and Development (R&D) Priorities

Goal areas	Priorities for research and development
1. A Healthy, Educated Citizenry	• Biomedical research, health promotion and disease and injury prevention research • Food production, safety and security research • Health systems and services research • Basic research on learning and cognitive processes • New models to evaluate learning productivity • Technology development for high-quality, affordable learning tools • Demonstration of innovative technology and networking applications • Systemic mathematics and science education curricular reform
2. Job Creation and Economic Growth	• Industry-initiated competitive cost-shared R&D partnerships • The Partnership for a New Generation of Vehicles • The National Electronics Manufacturing Initiative • Construction and building • Manufacturing infrastructure • Materials technology • Biotechnologies • Transportation system assessment • Physical infrastructure for transportation • Information infrastructure for transportation • Aeronautics • Energy Production and utilization technologies • Space launch
3. World Leadership in Science, Mathematics and Engineering	• Strengthening fundamental science • Human resources policy for science and technology • Strengthening U.S. S&T capacity through physical infrastructure
4. Improved Environmental Quality	• Scientific basis for integrated ecosystem management • Socioeconomic dimensions of environmental change • Development of science policy tools • Observations, and information and data management • Environmental technologies
5. Harnessing Information Technology	• Computing systems • Networking and communications • Software, algorithms and basic research • Information infrastructure services • Human-computer interaction • Computing and communications applications
6. Enhanced National Security	• Support our military strategy • S&T applications to new post-cold-war missions • Weapons of mass destruction

Table B.2
Future Joint Warfighting Capabilities

1.	To maintain near perfect real-time knowledge of the enemy and communicate that to all forces in near-real time.
2.	To engage regional forces promptly in decisive combat, on a global basis.
3.	To employ a range of capabilities more suitable to actions at the lower end of the full range of military operations which alow achievement of military objectives with minimum casualties and collateral damage.
4.	To control the use of space.
5.	To counter the threat of weapons of mass destruction and future ballistic and cruise missiles to mthe CONUS and deployed forces.

Source: *Defense Science and Technology Strategy*, September 1994.

ACRONYMS AND ABBREVIATIONS

ACM	Advanced Composite Materials
ACT	Advanced Composites Technology
AHCI	Advanced Human-Computer Intervace
AI	Artificial Intelligence
AMLCD	Active Matrix Liquid Crystal Displays
ARPA	Advanced Research Projects Agency
ATEGG	Advanced Turbine Engine Gas Generator
ATM	Asynchronous Transfer Mode
ATP	Advanced Technology Program
ATTAP	Advanced Turbine Technology Applications Project
BMDO	Ballistic Missile Defense Office
CAD	Computer Aided Design
CADAM	Computer Aided Design and Manufacturing
CAM	Computer Aided Manufacturing
CASE	Computer-Aided Software Engineering
CCD	Charge-Coupled Devices
CD-ROM	Compact Disk Read-Only Memory
CFC	Chlorofluorocarbons
CIM	Computer Integrated Manufacturing
CMC	Ceramic Matrix Composites
CNC	Computer Numerical Controls
CONUS	Continental United States
COTS	Commercially Available Off-The-Shelf
CRADA	Cooperative Research and Development Agreement
CVD	Chemical Vapor Deposition
DARPA	Defense Advanced Research Projects Agency
DMSO	Defense Modeling and Simulation Office
DOD	Department of Defense
DOE	Department of Energy
DOIT	Develop On-Site Innovative Technologies
DOS	Disk Operating System
DRAM	Digital Random Access Memory
DSP	Digital Signal Processing
ELFIN	European Laminar Flow Investigation
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EPA	Environmental Protection Agency
EPM	Enabling Propulsion Materials Project

EPRI	Electric Power Research Institute
ESA	European Space Agency
EV	Electric Vehicle
FADEC	Full Authority Digital Engine Control
FBL	Fly-By-Light
FBW	Fly-By-Wire
FEA	Finite Eleme nt Analysis
FES	Functional Electrical Stimulation
FFRDC	Federally Funded Research and Development Center
FOG	Fiber-Optic Gyroscope
FPD	Flat Panel Display
GaAlAs	Gallium Aluminum Arsenide
GaAs	Gallium Arsenide
GATT	General Agreement on Tarrifs and Trade
GEC	General Electric Company
GPS	Global Positioning System
HDTV	High Definition Television
HITEMP	High Temperature Engin Materials Program
HLFT	Hybrid Laminar Flow Technique
HPA	High Performance Asphalt
HPC	High Performance Concrete
HPCC	High Performance Computing and Communication
HPM	High-Power Microwave
HPS	High Performance Steel
HTS	High-Temperature Superconductors
IC	Internal Combustion
IHPTET	Integrated High Performance Turbine Engine Technology
IMAS	Intelligent Modular-Array System
ITS	Intelligent Transportation System
IVHS	Intelligent Vehicle Highway Systems
JSET	Joint-Subcommittee on Environmental Techn ologies
JTDE	Joint Technology Demonstrator Engine
LAN	Local Area Network
LTS	Low-Temperature Superconductors
MAN	Metropolitan Area Network
MANTECH	MANufacturing TECHnology Program
MEMS	Microelectromechanical Systems
MEP	Manufacturing Extension Partnership
MIMD	Multiple Instruction, Multiple Data Stream

MITI	Ministry of International Trade and Industry (Japan)
MMC	Metal Matrix Composites
MPP	Massively Parallel Processors
MRP	Materials Requirements Planning
MRP II	Manufacturing Resource Planning
MW	Megawatts
NAFTA	North American Free Trade Area
NAL	Natonal Aerospace Laboratory
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Aeronautics and Space Development Agency (Japan)
NASP	National Aerospace Plane
NEMI	National Electronics Manufacturing Initiative
Ni-Cd	Nickel-Cadmium
Ni-H_2	Nickel-Hydrogen
NIH	National Institutes of Health
NiH	Nickel-Hydrogen
NII	National Information Infrastructure
NiMH	Nickel-Metal-Hydride
NIST	National Institure of Standards
NSF	National Science Foundation
NSTC	National Science and Technology Council
OETC	Optoelectronic Module Technology
OTA	Office of Technology Assessment
PCR	Polymerize Chain Reaction
PMC	Polymer Matrix Composite
PNGV	Partnership for the New Generation of Vehicles
PURPA	Public Utilities Regulatory Policies Act
PV	Photovoltaic
PVD	Physical Vapor Deposition
R&D	Research & Development
RAM	Random Access Memory
RFW	Radio -Frequency Weapons
RLG	Ring Laser Gyroscope
S&T	Science and Technology
SAFT	Societe des KAccumulateurs Fixes et de Traction
SAR	Synthetic Aperture Radar
SDH	Synchronous Digital Hierarchy
SE	Software Engineering
SEI	Software Engineering Institute
SEP	Societe Europeane Propulsion
SiC	Silicon Carbide
SITE	Superfund Innovative Technology Evaluation

SOF	Special Operations Forces
SPF	Superplastic Forming
STEP	Standard for the Exchange of Product Model Data
TMCP	Thermomechanical Controlled Processing
TRP	Technology Reinvestment Project
USABC	United States Advanced Battery Consortium
USDA	United States Department of Agriculture
USDC	United States Display Consortium
VOC	Volatile Organic Compound
WAN	Wide Area Network