DEPARTMENT OF DEFENSE

DEVELOPING SCIENCE AND TECHNOLOGIES LIST

SECTION 7: ENERGY SYSTEMS TECHNOLOGY

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Defense Threat Reduction Agency
Ft. Belvoir

PREFACE

The Developing Science and Technologies List (DSTL) is a product of the Militarily Critical Technologies Program (MCTP) process. This process provides a systematic, ongoing assessment and analysis of a wide spectrum of technologies of potential interest to the Department of Defense. The DSTL focuses on worldwide government and commercial scientific and technological capabilities that have the potential to significantly enhance or degrade US military capabilities in the future. It includes new and enabling technologies as well as those that can be retrofitted and integrated because of technological advances. It assigns values and parameters to the technologies and covers the worldwide technology spectrum.

The DSTL is oriented towards advanced research and development including science and technology. It is developed to be a reference for international cooperative technology programs. S&T includes basic research, applied research and advanced technology development.

SECTION 7—ENERGY SYSTEMS

Scope

Highlights

- Energy system technologies provide for power generation and energy conversion, energy storage, and power conditioning.
- High-energy density power converters are a technology priority.
- The military's goal is to increase system power densities by 2–5 times, depending upon the specific system.
- Power converters typically take up approximately 50 percent of system volume.
- Stringent military requirements demand reliable, intelligent/survivable, and affordable energy systems that can perform in battlefield threat environments.
- Budget pressures and the military's need for reduced volume and weight, increased performance, and graceful degradation make it difficult for military and commercial compatibility.
- Advances in power electronics, packaging, and thermal management will drive the performance advances in the state of the art.

OVERVIEW

This section discusses the developing critical technologies for energy systems embedded in the following subsections:

- Energy Conversion and Power Generation
- Energy Storage
- Power Conditioning
- Biological Energy.

Energy and power system technologies are among the least visible, and their functions are usually taken for granted because we assume that reliable power will always be available. However, many weapon system platforms, because of different energy and power requirements, integrate a host of diverse technologies for power generation, energy storage, and power conditioning. Because of the weapon system platforms' variance in application and mission criteria, a wide range of energy requirements exist. These platforms need not only pulsed or continuous power but also need many niches and diverse technologies to satisfy low-, medium-, and high-power requirements.

Factors that influence the development of military energy systems include the critical need to occupy smaller volume, have low weight, provide long life-cycle performance, and be highly reliable and survivable in threat and extreme environments. Because of the military's stringent performance requirements, the advances in power electronics packaging and integration and in thermal management will be the key drivers in the successful realization of the military's future vision. The Joint Chiefs have recognized high-density power converter systems are a technology priority, and these systems will require new technology design and packaging approaches that are expected to revolutionize the power electronics industry.

Specific load requirements (e.g., power level, duration, pulsed, or continuous) drive the system design and the component technologies. To a large extent, the power level required determines the primary energy source and often severely limits the options available to choose from. The mission duration is also a critical factor since certain power-system technologies have inherently useful lifetimes, while others are capable of continuous and extended missions. Finally, the distinctions between single-shot, repetitive, and continuous power systems are critical since the duty cycle places different stresses and performance requirements (e.g., voltage, current, frequency, and temperature) upon the components used. . . . Power levels range over many orders of magnitude—from milliwatts of continuous power in handheld electronic devices to terawatts in certain directed energy weapons. Durations range from small fractions of a second for single-shot, pulsed-power applications to months or even years for remote power and/or space systems.

Figure 7.0-1 addresses the complex taxonomy of energy systems. As a real-world example, take a mobile platform (e.g., an air vehicle) as the system. Integrated mission requirements include the ability to hunt and kill (mobility, navigation, and lethality), to communicate, and to ensure the safety of the aircraft and its crew (environment and survivability). Each mission requirement results in the need for distinct subsystems driven by either continuous or pulsed power. The power supply system is, therefore, a conglomeration of energy conversion and power-generation systems driving energy storage, power conditioning, and pulse-forming networks. The energy systems are subject to strict constraints of thermal management, scalability, and integrated functionality. Beneath this layer lie the supporting technologies and components that make everything possible. Stepping from one function to the next reduces output and capability by less than perfect efficiencies.

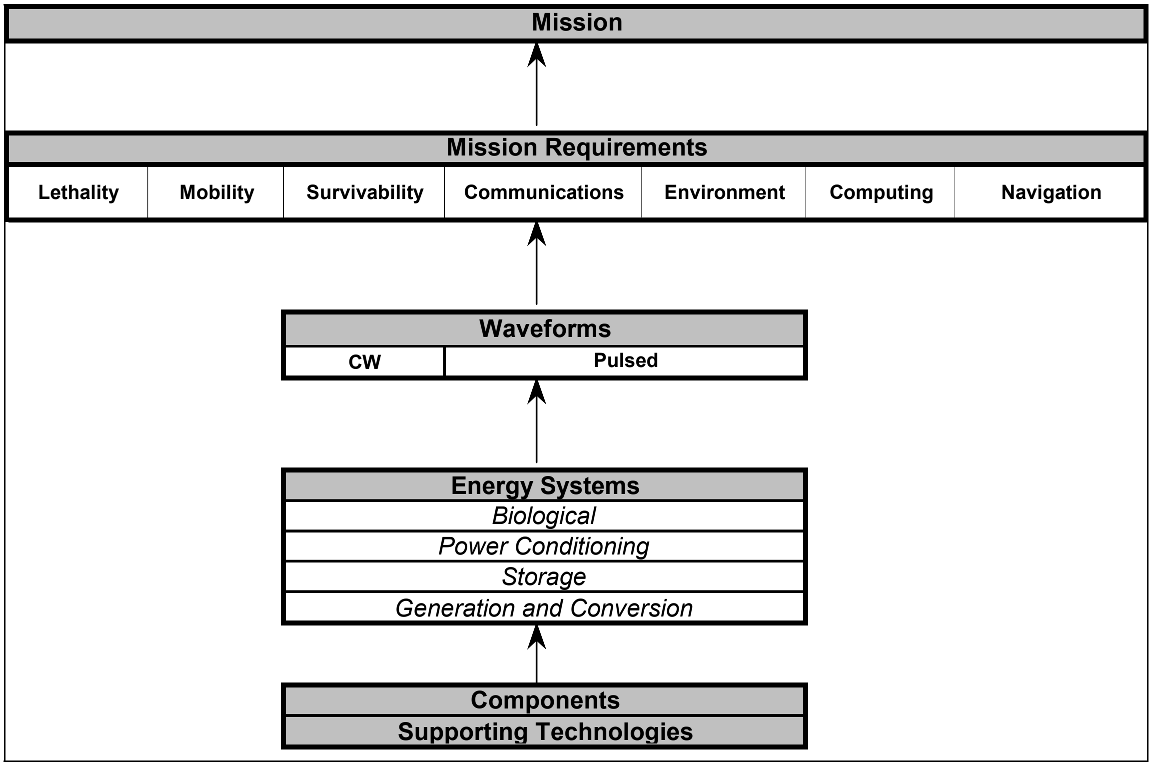


Figure 7.0-1. Energy Systems Taxonomy

Mobile Platform Energy Systems combine the propulsion and electric energy generation functions. In the future, mobile platforms may benefit from integrating the power system to include power for weapons and for propulsion (mobility) and other vehicle electric functions. With careful planning and a well-thought-out control strategy, a central power system may feed the continuous, transient, and pulsed loads while reducing the platform size and increasing the efficiency. Developing technologies are going to enable the military to move toward replacing heavy, inefficient systems with more efficient “more electric” platforms. Critically developing technologies are essentially converging towards all-electric vehicles. Currently, some commercial hybrid vehicles, primarily transit buses, are being made in quantity. In the United States and Europe, several programs have made prototypes or electric or hybrid-electric military vehicles, and some are even being tested.

BACKGROUND

To create useful power, energy is converted from potential to kinetic and either stored or conditioned and then delivered to a load. This power can be provided continuously or in pulses. Varying military applications require power to be delivered in time periods ranging from extremely short durations (on the order of nanoseconds, 10^{-9} sec) to continuous duty. Specifically, many specialized advanced weapons require pulsed power. Power electronics and other components used in continuous systems have very different characteristics from those used in pulsed systems.

Not only are the materials and component advancements in energy systems key, but design philosophies are essential for delivering a product in the most efficient and affordable manner. The approach of Synchronizing Enabling Technologies (SET) is the assessment and the development or implementation of enabling technologies to support a thrust area. It is analogous to knowing the ingredients for a recipe and timing their preparation and introduction into the amalgam. To be successful, a proper assessment of needed enablers should be completed during the early phases of a technology’s development. Enablers can range from parallel developments to components or materials, such as composites, that are in the research and testing phase. Synchronizing technologies is an important management issue that will be reiterated further in relevant technology areas.

Soldier Systems

Soldier Power Systems will provide the 21st century warrior with power sources that are enabling for a host of man-portable electronic devices ranging from communications and sensors to weapons. The warfighter will be the keystone of the future digitized armies. Power requirements have been estimated as high as 500 W, with 22.9 W as the current power assessment.

In the far term, nuclear power and rotating machinery (microturbines) offer choices for soldier power. Nuclear power has not yet come to practical design because of significant system-implementation issues associated with radiation near biological tissue and social feelings towards ionizing radiation. The specific energy of radioisotopes, however, which can be greater than 100 MW hrs/kg, combined with more efficient energy converters, could easily solve power-generation issues for the unmanned future soldier. Continued efforts may also see other power technologies come into use for the infantry. Such technologies include biological energy sources (for milliwatt applications) and advanced capacitors and converters.

Mobile Platform Energy Systems

Mobile military systems combine the prime propulsion and onboard electrical power-generation functions. The net effect is an energy system that has operational advantages of reduced signature, increased energy density, lower weight and volume, greater flexibility in configuration, and greater economy/reliability. Electrical energy components are characterized by a significant reduction in moving parts, the elimination of rigid connections, and an improved ability to use small and irregular spaces within a vehicle. Potential application areas for migrating to a more-electric drive include:

- Active suspension
- Active protection
- Drives
- Computations
- Motor controllers and electric filters
- Actuators

- Weapons
- Sensors.

Energy systems for all types of combat vehicles are broadly characterized by the level of energy required and the time over which the energy is demanded (pulsed or continuous). Components of the platform's energy system include an engine-generator, which is sized to meet the average energy requirements of the vehicle. (This is not always true, however, especially in critical military systems that must be redundant and survive battle damage.) Coupled to this are the energy-storage and energy-management components that make it possible for the system to meet the peak energy demands required in mission execution. Energy density, thermal management, cost, and packaging are critical parameters for military energy systems. Aggressive management, combined with deliberate restraint of system designs to those that satisfy required parameters, will be essential to producing economical, reliable, and high-performance systems. Thermal and electromagnetic capability (EMC) properties will remain essential design and performance parameters.

Electronic Packaging And Thermal Management

The method by which components and assemblies are integrated play a vital role in the performance and reliability of an end product. Some of the major advances in power technology—both in performance and in cost—will be the result of electro-mechanical-magnetic packaging. Packaging occurs at all levels of product development. Because it is ubiquitous, the following definition indicates how it is used in our discussions: Each level in the electronics hierarchy has within itself the combining of parts to make an assembly. For example, a semiconductor has a die, wire, housing, and leads to form a component. The manner in which these parts are put together is called packaging. Packaging mainly involves thermal management, structural integrity, interconnections, and electromagnetic compatibility. We can apply this same example to each level of assembly in an electronic system (e.g., begin with components and then move to subassemblies, power supplies, DC-DC converters, and functional systems). Finally, when all these parts are integrated together (system packaging), the result is an end product.

One of the revolutionary new packaging approaches is to integrate individual components into each other to form a new component that has increased functionality, lower cost, and higher reliability because of reduced interconnections. An example of this is integrating resistors and capacitors into the internal layers of a printed circuit board. This results in greater packaging density, lower cost and reduced interconnection (compared with discrete components) and, thus, higher reliability. Another example would be integrating semiconductor dies directly into magnetic assemblies, such as a transformer. This is a new approach and will have a profound impact on discrete component manufacturers as the technology matures. For example, if capacitors were directly embedded in a printed circuit board, the demand for discrete capacitors would be less. Understanding the physics and manufacturing processes needed in this functional integration is critical for making significant advances in packaging.

Electronic packaging is a rapidly advancing technology that has been fairly dormant for many years. While advanced electronic packaging techniques have been developed in microelectronics, little significant work has been done in the higher levels of the interconnect hierarchy (subsystems and systems packaging). Packaging, with respect to power systems, must be viewed from an end-use perspective in order for the system to be efficient and effective. This is becoming more important with the introduction of integrated functionality, where multiple discrete components are being integrated and built as a new discrete component. Advanced packaging is critical for meeting the demands of efficiency, thermal management, and power density in future power systems. Integration at all levels will be needed, including interconnections such as direct die attach technology.

To illustrate, capacitors and magnetics are critical components that require improvements to meet the new packaging demands. Further, high-temperature and high-efficiency power semiconductors are also important component needs. In all cases, necessary technological advances include the materials and processes used in building such components. Advances in thermal management will come from heat spreaders and selective cooling approaches.

In cases where integrated functionality is used, hybrid test equipment will be needed to evaluate the parameters and characteristics of multiple components in one (component). High-technology processing equipment will also be needed for areas previously satisfied by lower technology processes.

Education and establishing a systems-level packaging mentality are the main issues in evolving to advanced packaging capabilities. Change is required to overcome the headset of single-level packaging. Effecting this change will be difficult because of the subsystem mentality that exists and the way parts are designed and manufactured in today's environment.

Power technology has moved forward in the last several years at a fairly rapid pace, although, in general, it has not moved nearly as fast as it has within the semiconductor industry. This difference in sector performance is evident across the military and the industrial communities. Many of the packaging demands for higher density, higher performance, lower weight, and lower cost power systems are common to both areas, especially in the area of more cost-effective semiconductors. The comparatively large physical size of power system components, compared with the rest of the electronic package, has inhibited system density improvements. Reactive components tend to be large, heavy, and inefficient. Spatial compression of these components produces increased power density (W/cm^3), without decrease of thermal impedance, resulting in localized heat build up.

Semiconductor design philosophies can be extended to high-density power converters and to regulators, where system packaging is critical. Proper partitioning, with special attention given to electromagnetic interference and thermal management, will be needed. Thermal management will enlist a combination of active and passive cooling technologies to control "hot spots." Thermally conductive materials will play a bigger role in thermal management, with "heat spreading" being used to a larger degree. Systems packaging will require the integrator to understand clearly each subassembly and how it will affect system performance. The application of high-density power regulators into the systems architecture will be key to enhanced system performance.

Integrated Functionality

An area that is emerging from the packaging discipline is Integrated Functionality. The role of the packaging engineer is to integrate components into a functional assembly using processes and assembly techniques made available to the manufacturer. This in itself may be viewed as integrating functionality; however, it is also starting to emerge at a lower level. This function actually involves the discrete components, such as resistors, capacitors, and semiconductors used in assemblies. We call this integrating functionality at the component level. The result of this activity is the creation of new components that contain the collective features of multiple components (see Fig. 7.0-2). This change is profound since it will change the supplier base to the power supply industry. The rationale behind the development of integrated functional components is increased reliability, better performance, space reduction, and cost benefits—features that are desired in power product development programs at all levels.

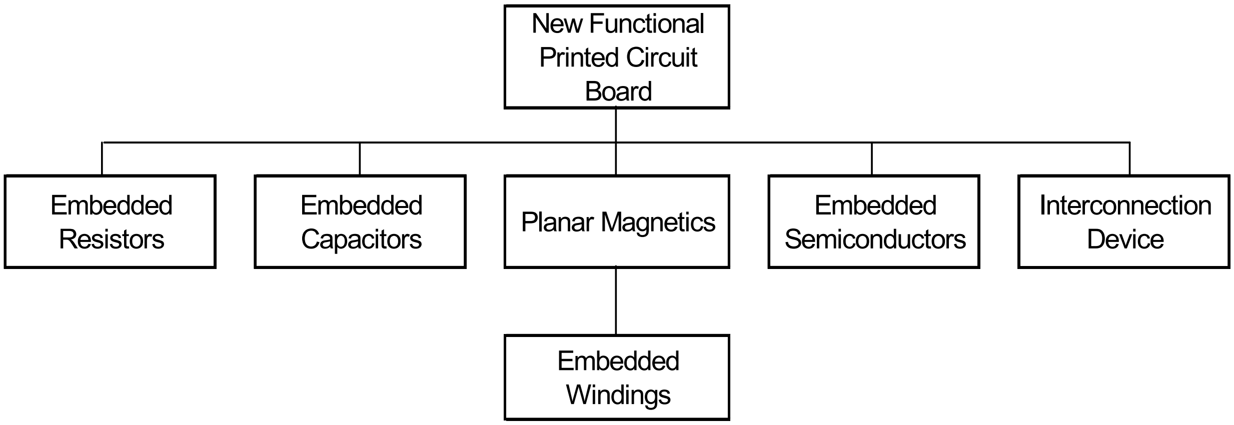


Figure 7.0-2. Example of Integrated Functionality

The challenges in integrating the functionality of components are significant but can result in major advances in end-product cost and reliability. For example, to be able to combine the desired features of multiple components, a good understanding of the individual components is necessary. This includes understanding the way in which the components are manufactured and knowing their constraints. With this knowledge, combining features of multiple components into one part can, in many cases, become a reality.

An example of integrated functionality can be seen in planar magnetics. This is where the windings for the magnetics are incorporated in the printed circuit board using etched circuit traces. The core material is inserted in holes or slots in the printed circuit board and bonded, to complete the magnetic assembly. This operation, in essence, replaces a discrete component. It also eliminates the core winder and creates a more functional printed circuit board. It takes manual labor out of the winding process, which, in turn, will improve cost and quality. The printed circuit board manufacturer is developing new skills in producing planar magnetics, but these new skills do not significantly affect the manufacturing process. A result of planar magnetics is the elimination of a discrete component in the overall assembly, which, in turn, increases reliability. The business ramification is a reduction in purchased magnetic assemblies. Eliminating the need for particular discrete magnetic components takes a certain amount of business from the transformer companies but also provides some packaging flexibility by core geometry selection, especially in low-profile applications.

While this change had little affect on the printed circuit industry, other component integrations will have a profound impact. An example is the emerging technology of embedded capacitors. Significant reductions to the size of a power supply can be realized by replacing discrete capacitors mounted on the printed circuit board by embedding capacitors within the layers of a printed circuit board. As new dielectric material technology with high-energy storage features becomes available, a breakthrough in power density could result. This integration would have a large impact on printed circuit board manufacturers. They would be building a capacitor(s) into their boards, thus becoming a manufacturer of an electronic component and an interconnection component. This would involve enhancing the knowledge base of printed-circuit people in many areas. They would be required to learn new manufacturing processes and deal with new materials and would have to be able to test their embedded capacitors. They would require much of the knowledge of capacitor manufacturers. This would be like building a capacitor without a package (as in a discrete component). Terminations of the capacitor would be included in circuit traces and plated through holes. The new processes that will be needed to build this product presently exist in the semiconductor and other industries and can be easily transitioned. The equipment required would include vacuum deposition equipment. Although the printed circuit business will change, the financial rewards could be huge. The power supply industry desperately needs higher power density and the replacement of discrete capacitors. Capacitors currently consume about 20–30 percent of the volume of a power supply, depending on the type of power supply. Capacitors also account for about 20 percent of the cost of a power supply. This could be a very lucrative new business. However, again, there are business ramifications. New capital equipment purchases would be needed and the labor force would have to be trained. This “new component” will affect the discrete capacitor manufacturing companies by decreasing the need for discrete components.

Other examples of integrated functionality have also had an impact on power electronics [e.g., application-specific integrated circuits (ASICs)]. ASICs have replaced many discrete components with a single package. Before ASICs, many electronic circuits required several discrete components to provide a certain function, such as housekeeping circuitry for sensing power supply functions. Some standardization was developed and ASICs became very practical devices. Replacing several discrete components with a single component that has the reliability of an integrated circuit has had a large effect on power supply reliability. A mean time between failure (MTBF) of over 1 million hours for a DC-DC converter is not unusual today. Much of this improvement can be attributed to integrated functionality and improved designs.

Direct die attach technology is another area being used more frequently. This eliminates a level of interconnection and can increase power density and improve reliability.

Other designs that demonstrate additional ways of integrating functionality (by combining parts and reducing the amount of interconnections) will soon be introduced to the market. This interesting trend will have a significant impact on today’s discrete component supplier. Suppliers that today sell discrete components must become involved in this activity if they want to preserve their markets or open new markets.

Improvements from military mobile systems with integrated functionality include:

- Simplicity
- Permanent magnetic materials
- Reliability
- Efficiency

- Operating temperature
- Power density
- Thermal management
- Energy extraction.

Electromagnetic Compatibility (EMC)

When dealing with electromagnetic emissions, two important considerations are conducted emissions and radiated emissions. Conducted emissions are generally managed with in-line electromagnetic interference (EMI) filters. Radiated emissions usually require containment with ferrous metal materials and shielding design approaches to eliminate radiation. Shielding materials would include products such as fingerstock and braided mesh for seams and doors or ports to the electronic equipment.

High-Energy Density Conventional Systems

High-density conventional systems will be used for many applications in mobile platforms. High-density conventional systems are those comprising components/subsystems rated at less than 500 kW. Such systems are found in almost every military operating system, including multiple components of major weapons. Critical technologies in this section cover both energy sources and power-conditioning activities. Energy systems are fundamental components, which are often specifically tailored for each of the other major technology areas within the Militarily Critical Technologies List (MCTL).

Technologies for components or systems rated at less than 500 kW are migrating toward revolutionary changes in energy density and precision. This is critical to the military because of the needed improvements in system performance: new capabilities are becoming possible. Power system miniaturization is an important element and has led to micropackaging on a chip and distributed packaging to perform a function such as track motor or flight control. In the near future, many weapons systems that now commonly use mechanical, hydraulic, or pneumatic components will rely on electrical systems. Major initiatives include the More-Electric Aircraft, All-Electric Ship, and the Future Combat Vehicle (Army). Military requirements for energy systems are distinguished primarily by the need for ruggedized packaging, and high-energy and high-power densities. Thermal stress is the primary concern, with shock stress an important secondary regard. Thermal management or components capable of functioning at high temperatures are keys to reduced failure rates and improved system survivability. Military demand for low failure (total life-cycle reliability) drives new design architectures. As a result, approximately 40 percent of the total demand for military energy systems results in custom-designed applications to fit military systems requirements. Such requirements create pervasive pressures to reduce production and product costs.

High-Density Converters

An example of high-density conventional systems would include high-energy density converters. DC-DC power regulators in the military and the commercial sectors have become smaller and more powerful. One of the driving factors in the military sectors is weight as it applies to a payload. In the commercial arena, this trend has been driven by the fast-moving semiconductor industry. Hardware size in telecommunications, networking, and computer systems has been greatly reduced by the high-performance semiconductors now in the marketplace. Slow to follow this technology trend are the DC-DC power regulators. However, in industry, significant gains have been achieved in reducing of the size and increasing the reliability of DC-DC power regulators. In industry, regulators designed today can be packaged in volumes of 70 to 100 W/in^3 and have a MTBF of over 1 million hours—numbers that would look very much like a military requirement just 5–10 years ago. The resulting designs of these high-power density regulators are accomplished by designing new topologies, developing new components, increasing the functionality of components, and mastering electro-mechanical packaging. This is the way to get to high-density regulators. However, as the semiconductors progress to lower and lower voltages and the chip power levels increase, the issues of high current distribution and the associated power losses become significant, putting more difficult constraints on the design engineers.

The National Technology Roadmap for Semiconductors developed by the Semiconductor Industry Association has projected the power supply voltage to be 1.8 V by the year 2001 and down to 0.9 V by the year 2010. The maximum power associated with these numbers is also projected to increase significantly. In 2001, the power at

1.8 V is expected to be 120 watts, and, in 2010, the power at 0.9 V is expected to be 180 W. With this level of chip power density, power regulator designers must consider several strategies.

Power system architecture ranks as one of the most important considerations. With the very-high-power requirements of the semiconductors, one design option is point-of-load power architecture, which means placing the regulator as close to the actual load as possible. This would minimize the power distribution losses. This would also require the designer to view the power supply at the system level, integrating it into the system efficiently. This effort requires the use of advanced systems-packaging designs with careful considerations for thermal management. Thermal cooling technologies become an important factor in this overall package, and chilled air becomes an important choice, especially in chip cooling.

Another option is distributed power. This approach would locate the power regulators close to the load but not at the point of load. This approach would use larger regulators that provide power to more than a single chip. The problem of power losses caused by the high current levels is addressed with power bussing techniques. The interconnection design must receive careful consideration. To minimize power losses, hard connections, such as bolted on bussbars, would be preferable to removable connectors. An advantage of this power architecture is that the approach will easily accommodate *n+1* redundancy. This configuration provides an extra regulator paralleled with the primary regulators. If a regulator fails, the extra regulator will automatically be activated. This will afford the overall system higher availability and will appear to the user as increased reliability. If current sharing is being used with the paralleled regulators, actual reliability is increased because of the reduced loading on the individual regulators. This approach is possible but not nearly as suitable as the point-of-load power architecture, since it would take up real estate that is not readily available and would not be as cost effective.

SECTION 7.1—ENERGY CONVERSION AND POWER GENERATION

Highlights

- The future battlefield will require systems supplying power at levels ranging from milliwatts to gigawatts.
- Advanced precision weapons, weapons of mass destruction (WMD), radar, and electronics countermeasures and communications systems are enabled through next-generation high-energy electronics systems, including the prime energy sources.

OVERVIEW

Energy conversion and power generation encompass the transformation of biological, chemical, electromagnetic, nuclear, mechanical, and thermal energy or reactions into electrical power. The output may pulsed, burst, or continuous. The future battlefield will require systems supplying power at levels ranging from milliwatts to gigawatts.

Pulsed power is generated by the inherently pulsed nature of the source, such as explosive technologies, or derived through the use of pulse-forming networks. Further, pulsed sources can be used in conjunction with fast switches to provide pulses of shorter duration, higher frequency, and greater peak power. Burst is a form of pulsed power with the duration between shots (“off”) being much greater than the “on” duration. Continuous power, by definition, is supplied on a continual basis by sources ranging in size from batteries to large turbines.

LIST OF TECHNOLOGY DATA SHEETS
7.1. ENERGY CONVERSION AND POWER GENERATION

DATA SHEET 7.1. LITHIUM THERMAL BATTERY (PRIMARY)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>Lithium thermal batteries are a fairly mature technology, and major advancements are not expected. They are an energetic system, capable of high power densities with ultra-low impedance (Z); can tolerate severe shock, vibration, and acceleration; will provide 1,500–2,000 W/s; and may be assembled in cell stacks for voltages ranging from 2.5–500 V.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (W hrs/kg)</td><td>850</td><td>Similar</td><td></td></tr>
<tr><td>Run times</td><td>seconds to hours</td><td>Similar</td><td></td></tr>
<tr><td>Shelf life (yrs)</td><td>over 15</td><td>Similar</td><td></td></tr>
<tr><td>Activation time (ms)</td><td>~ 1–10</td><td>Similar</td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Better cathodes; electrolytes; insulation materials and heat sources; thermal management systems; squib activators; molten salt electrolytes; separators that tolerate high temperatures; and boron nitride fibers and felts.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>None identified.</td></tr>
<tr><td>Affordability</td><td>Cost-to-performance ratio considerable (i.e., expensive).</td></tr>
</table>

DATA SHEET 7.1. PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC)

Developing Critical Technology Parameter

State-of-the-art PEMFCs can operate for thousands of hours with little loss of performance and can deliver about 700 mW/cm^2 at 80 °C, operating on pure hydrogen at 3–atmospheres pressure and oxygen or air at 5–atmospheres pressure. Catalyst loadings have been reduced to about 0.3 mg platinum/cm^2 for the cathode and less than 0.1 mg platinum/cm^2 for the anode. At ambient atmospheric pressure, performance is reduced to 350 mW/cm^2 of electrode area.

PEMFCs consist of a polymer film that permits the passage of protons while blocking electrons and gas.

Pulsed

Parameter	1999	Projected by 2010	Nature's Limit
Specific power (kW/kg)	1	2	
Specific power (kW/L)	1		
Operating temperature (°C)	40–80		
Efficiency (%)	40–50		

Continuous

Parameter	1999	Projected by 2010	Nature's Limit
Specific power (lb/kW)	6	0.1	
Operating temperature (°C)	40–80		
Efficiency (%)	40–50		

Critical Materials

High-conductivity electrolytes; materials for seals or seal technology; light fuel/oxidant storage; and high-performance electrodes.

Unique Test, Production, Inspection Equipment

None identified.

Unique Software

None identified.

Major Commercial Applications

EVs; on-site power, portable power, power substations or distributed power, and residential cogeneration.

Affordability

Because of their inherently slow reaction rate, PEMFCs require an expensive platinum catalyst to speed the process. They currently cost approximately $800–$1,000/kW, with $50–$100/kW forecasted by 2005.

DATA SHEET 7.1. SOLID OXIDE FUEL CELL (SOFC)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>For SOFCs, pulsed wave applications are mainly applied to weapons, while continuous applications are applied to utilities.
<table>
<tr><th colspan="4"><i>Pulsed</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Specific power (lb/kW)</td><td></td><td>0.05</td><td></td></tr>
<tr><td>Power Density (W/kg)</td><td>> 1,000</td><td></td><td></td></tr>
<tr><td>Power density (W/L)</td><td>> 1,000</td><td></td><td></td></tr>
<tr><td>Operating temperature (°C)</td><td>650–1,000</td><td></td><td></td></tr>
</table>
<table>
<tr><th colspan="4"><i>Continuous</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Specific power (lb/kW)</td><td>2</td><td>0.1</td><td></td></tr>
<tr><td>Operating temperature (°C)</td><td>> 1,000</td><td></td><td></td></tr>
<tr><td>Efficiency (%)</td><td>40–50</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>High conductivity electrolytes; materials for seals or seal technology; light fuel/oxidant storage; and high-performance electrodes.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>EVs, on-site power, residential power, cogeneration, and thermal power plants.</td></tr>
<tr><td>Affordability</td><td>About $1,000/kW by 2005.</td></tr>
</table>

DATA SHEET 7.1. MICROTURBINES

Developing Critical Technology Parameter	Microbearings spinning speeds: 1.2 million rpm Compressor efficiency: 65 percent (theoretical) May consume less than 10 gal/hr of hydrogen fuel 50 W of power with a volume < 1 cm^3 **Natures Limits** Power per unit airflow is set by: • Combustor exit temperature (material properties such as creep, oxidation) • Component efficiencies (fabrication constraints, viscous effects, and design technology) • Cycle selection (simple vs. recuperated, cooled vs. uncooled) • Overall pressure ratio (compressor wheel speed, and heat flow into the compressor). Airflow limits are set by: • Rotor blade height constrained by root stress (300–900 m) • Engine diameter (rotor dynamics, manufacturing) • Flow separations from “angular” geometries at low Reynolds Number (flow blockings can be > 50 percent).
Critical Materials	Liquid fuels; hydrogen; and silicon and SiC structures.
Unique Test, Production, Inspection Equipment	Deep reactive ion etching.
Unique Software	Small-scale flow and heat transfer code.
Major Commercial Applications	Power for sensors and portable communication systems.
Affordability	Costs of Si manufacturing of complex systems.

DATA SHEET 7.1. PHOTOVOLTAICS (PVs)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<p>Information concerning generation technologies that produce air mass 0 (AM0)-specific power densities > 400 W/kg is likely controlled. In addition, efficiencies are rated at about 18 percent for the space station, with up to 40-percent achievable (efficiencies are load specific) and a theoretical limit of approximately 50 percent.</p>
<p>For radiation-hardened, space-qualified PV arrays: specific power > 160 W/m^2 under 1 kW/m^2 tungsten at 2,800 K illumination at an operating temperature of +28 °C.</p>
<table>
<tr><th rowspan="2">Cell Technology</th><th rowspan="2">Commercial Availability</th><th rowspan="2">Cost</th><th rowspan="2">Power Density (W/m^2)</th><th colspan="2">Efficiency (%)</th></tr>
<tr><th>AM0 (space spectrum)</th><th>AM1.5 (terrestrial)</th></tr>
<tr><td>Amorphous silicon</td><td>Yes</td><td>?</td><td>50–70</td><td></td><td>5–10</td></tr>
<tr><td>Polycrystalline silicon</td><td>Yes</td><td>Low</td><td>130–140</td><td></td><td>14–15</td></tr>
<tr><td>Single-crystal silicon</td><td>Yes</td><td>High</td><td>200</td><td>18</td><td>20</td></tr>
<tr><td>Gallium arsenide</td><td>Yes</td><td>High</td><td>200</td><td></td><td>17–18</td></tr>
<tr><td>Indium phosphide</td><td>No</td><td>High</td><td>200</td><td></td><td>17–18</td></tr>
<tr><td>Copper indium diselinide</td><td>No</td><td>High</td><td>130</td><td></td><td>15–17</td></tr>
<tr><td>Multibandgap</td><td>Yes</td><td>High</td><td>250</td><td></td><td>25–30</td></tr>
<tr><td>Concentrator array</td><td>Limited</td><td>High</td><td>250</td><td></td><td>30</td></tr>
</table>
<p>Adapted from: NRC, 1997</p>
</td></tr>
<tr><td>Critical Materials</td><td>Semiconductor material names can be mentioned (i.e., GaAs, GaInP, and so forth), but specific semiconductor growth and solar cell device processing techniques may be classified if government and proprietary if commercial. Parameters such as layer thickness, doping densities, and metal organic chemical vapor depositions (MOCVD) growth gases, growth temperatures, and growth times may be classified if government and proprietary if commercial.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>High-power communication satellites, remote operations, village power, and recharging batteries.</td></tr>
<tr><td>Affordability</td><td>Conventional space Si cells can be ~ $100/W; high-efficiency Si cells are ~ $175/W; and the multijunction cells range from ~ $300–500/W.</td></tr>
</table>

DATA SHEET 7.1. THERMIONIC CONVERTERS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>Lightweight (< 1 kg/m^2), deployable, high-performance solar concentrators.<table><tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr><tr><td>Converter efficiency (%)</td><td>> 18</td><td>~ 30</td><td></td></tr></table></td></tr>
<tr><td>Critical Materials</td><td>High-temperature metals and ceramics; super alloys for vacuum envelops; mono- and polycrystalline refractory alloys for emitter and collector electrodes; oxidation-resistant vacuum envelop materials for terrestrial applications; and lightweight, high reflectivity materials for solar concentrators (e.g., inflatable space structures).</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Refractory alloy fabrication; metal-to-ceramic joining techniques for high-temperature applications; and single crystal refractory alloy manufacturing.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>High power for space satellites.</td></tr>
<tr><td>Affordability</td><td>Specialty materials (refractories, ceramics) contribute to present high cost.</td></tr>
</table>

BACKGROUND

Thermionic converters are simple, robust, radiation-hard energy conversion devices, which can make them competitive with other forms of energy conversion.

DATA SHEET 7.1. EXPLOSIVE MAGNETOHYDRODYNAMIC GENERATORS (EMHDGs)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>The following table assumes power conditioning for many pulses per second (pps).
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Efficiency (%)</td><td>5–12</td><td>> 12</td><td></td></tr>
<tr><td>Energy (depends on frequency: pulses per second)</td><td></td><td></td><td></td></tr>
<tr><td>1 pps</td><td>10 MJ</td><td>100 MJ</td><td></td></tr>
<tr><td>1–100 pps</td><td>100–500 kJ</td><td>1–10 MJ</td><td></td></tr>
<tr><td>100–1000 pps</td><td>1 kJ</td><td>> 1 kJ</td><td></td></tr>
<tr><td>Voltage, radial design (kV)</td><td>~ 20</td><td>> 20</td><td></td></tr>
</table>
(Source: ATAR)</td></tr>
<tr><td>Critical Materials</td><td>None identified.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>1D (Lagrangian), 2D (Eulerian), 3D (not yet available) magnetohydrodynamic (MHD) codes and other modeling software, such as circuit modeling for system integration and explosive modeling software (JWL EOS).</td></tr>
<tr><td>Major Commercial Applications</td><td>The commercial market for explosive magnetohydrodynamic (EMHD) technology is likely to be small because of the nature of the conversion process. The primary applications for MHD technologies are pulse generation, electric guns, radio frequency (RF) weapons, and so forth. Because this technology is in the early stage of development, predicting the size of the future market is difficult. The high-pulse energy generation aspect of the technology will probably never appeal to a wide market. EMHD technology, however, has definite potential for several high-energy military consumer applications.</td></tr>
<tr><td>Affordability</td><td>Not an issue.</td></tr>
</table>

BACKGROUND

MHD is an energy conversion technique. It converts the chemical energy of a gas, liquid, or solid fossil fuel directly into useable electricity.

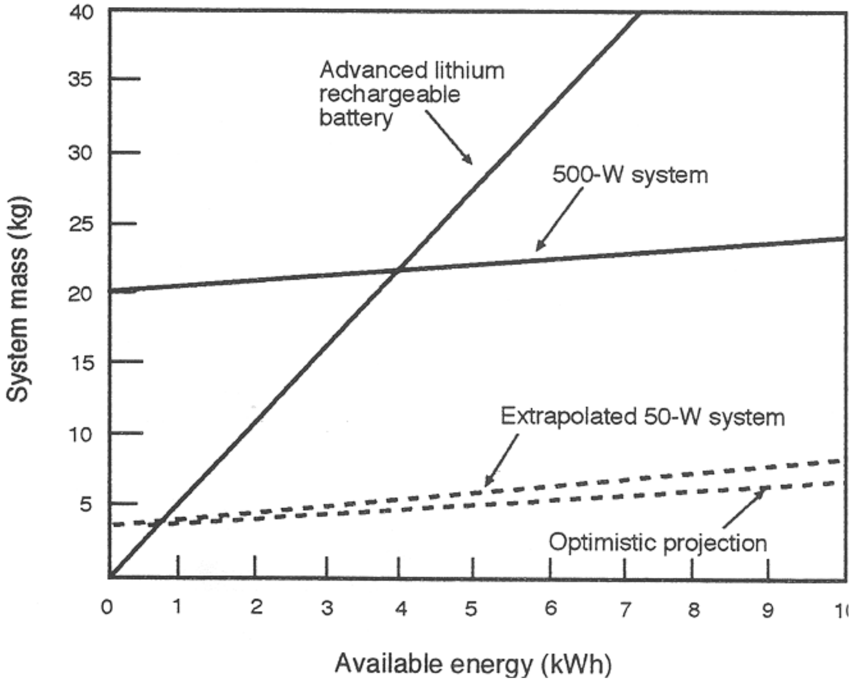
DATA SHEET 7.1. MAGNETIC FLUX COMPRESSION GENERATORS (MFCGs)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Discharge time (ms)</td><td>few to 500</td><td></td><td></td></tr>
<tr><td>Energy (eV/Å^3)</td><td>several</td><td>20</td><td></td></tr>
<tr><td>Current pulse (MA)</td><td>> 250</td><td></td><td></td></tr>
<tr><td>Efficiency (%)</td><td>< 10</td><td></td><td></td></tr>
</table>
<p>Discharge Time: varies from a few microseconds to 500 μs currently. This can be longer but probably begins to be impractical.</p>
<p>Energy: 20 eV/Å^3 (3 MJ/cm^3) projected by 2010.</p>
<p>Current Pulse: The limit is mainly an economic one. The output conductor should carry probably not much more than 700–800 kA/cm in the time scales for useful power sources. Thus, 1 GA needs a 10–15-m wide output conductor. Practically, one would parallel several smaller devices.</p>
<p>Efficiency: Efficiencies are very much generator type and load dependent, seldom exceeding a few percent for practical loads.</p>
</td></tr>
<tr><td>Critical Materials</td><td>Highly conductive materials, such as copper and aluminum. In addition, these materials should also have good elastic properties.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Helical flux compression generators (HFCGs) have low impedance and thus require conditioning to match that of the load. This conditioning must also provide temporal matching since loads may require very fast rise times (hundreds of nanoseconds).</td></tr>
<tr><td>Unique Software</td><td>MACH3: Three-dimensional (3–D) MHD code under development.</td></tr>
<tr><td>Major Commercial Applications</td><td>None, because of single-shot nature.</td></tr>
<tr><td>Affordability</td><td>None identified.</td></tr>
</table>

BACKGROUND

An MFCG uses explosive energy to compress a magnetic field, thereby creating an intense energy pulse. This technology is generally single shot since the explosion destroys parts of the device. An MFCG functions by building up a magnetic field in coils and setting off an explosion (destroying many of the windings). With the reluctance of the circuit altered, the magnetic flux is compressed, increasing the strength of the field and producing an intense current.

DATA SHEET 7.1. ALKALI METAL THERMAL TO ELECTRIC CONVERTER

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Cell efficiency (%)</td><td>25</td><td>30</td><td>50</td></tr>
<tr><td>System efficiency (%)</td><td>15</td><td>20</td><td>30</td></tr>
<tr><td>Total power (kW_e)</td><td>> 50</td><td>100</td><td>100</td></tr>
</table>


</td></tr>
<tr><td>Critical Materials</td><td>Beta alumina solid electrolyte, seals, membranes, bearings, and insulators.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Thermo-vac chambers.</td></tr>
<tr><td>Unique Software</td><td>Any thermodynamic-electrochemistry-coupled code.</td></tr>
<tr><td>Major Commercial Applications</td><td>Bottoming cycles for power-generation plants; cogeneration systems; stand-alone and remote power supplies; and space applications.</td></tr>
<tr><td>Affordability</td><td>This technology has the potential to become affordable ($\$10/W_e$) and must become so to compete with existing technologies terrestrially.</td></tr>
</table>

BACKGROUND

An AMTEC device can convert heat from any source to electric power. A solar thermal power conversion system based on an AMTEC has advantages over other technologies (including PV systems) in terms of the total power that can be achieved with such a system and the simplicity of the system [which includes the collector, energy storage (thermal storage with phase change material) and power conversion in a compact unit]. The overall system could achieve as high as 14 W_e/kg with present collector technology and future AMTEC conversion efficiencies. The energy storage system outperforms batteries, and the temperatures at which the system operates allows long life and reduced radiator size (heat reject temperature of 600 K).

SECTION 7.2—ENERGY STORAGE

Highlights

- Energy is stored either chemically, mechanically, or electrically, with durations of microseconds to years.
- Fast-storage devices are militarily critical for weaponry.

OVERVIEW

Energy storage devices are intended for pulsed applications requiring short-term storage (microsecond-to-second) through long-term storage (several years). These devices can be charged and discharged in a pulsed or near-continuous manner. Examples of technologies used as energy storage include batteries, capacitors, inductors, and flywheels or rotating machinery.

Energy can be stored chemically, mechanically, or electrically. For mechanical storage, the energy is stored in the rotary motion of machinery, such as a flywheel. For electrical storage, the energy is stored in the electric field of the dielectric medium, such as a capacitor, or in the magnetic field of the dielectric medium, such as an inductor. For chemical storage, the energy is stored in the reactants (as in batteries).

For pulsed-power applications, once energy is stored, it can then be extracted completely or in small portions. In the mechanical case, the flywheel storage device can be coupled to a switch or a switching network that, depending on the speed and other characteristics, can deliver pulses of power to some load. Some devices integrate the switching into the storage device and feed its pulsed output directly to the load. Once charging is complete, the switch is closed and a pulse is delivered to the load. High-frequency inverters (DC-to-AC) can be used as a power supply to charge the storage device in a few milliseconds. Once charging is complete, a switch is closed, and pulsed power is delivered to some load.

In the high-energy case, mainly for weapons applications, systems of average powers in excess of 100 MW, for times of seconds to minutes, are integrated with pulsed-energy conditioning to create gigawatt-class repetitive pulses of energy from milliseconds down through submicroseconds, at voltages from several kilovolts up to megavolts. There may emerge selected military applications, such as high-power radars, electronic countermeasures, and directed energy weapons (DEWs), that demand a class of precisely conditioned electric energy that has no direct foreseeable commercial or industrial application. However, industry may be able to use for different applications the components used to produce these levels of output. High-energy electronics have no current commercial applications. Assured development, therefore, will require government sponsorship.

Peak power, pulse shape, pulse duration, repetition rates, firing rates, silent watch, and system energy storage recharging times represent militarily critical performance parameters that, in many cases, transcend known commercial, industrial, or consumer applications. In addition, high-energy electronics packaging currently requires parallel/series combinations of components in the power train to achieve reliability, fault tolerance, and graceful aging at performance levels greater than 10 times today’s commercial standards.

LIST OF TECHNOLOGY DATA SHEETS
7.2. ENERGY STORAGE

DATA SHEET 7.2. FLYWHEELS

Developing Critical Technology Parameter	A flywheel is an energy storage system. As such, its performance is defined by the following parameters: • Total energy density (based upon maximum rotational speed) • Useable energy density ("depth of discharge," from maximum/minimum speed ratio) • Power density • Life (i.e., number of cycles to failure) • Output voltage variation (i.e., approaches that minimize this may be militarily critical) • Coefficient of friction (i.e., drag) caused by idling losses in support system. Since flywheels are spinning bodies, an additional parameter that defines acceptable vibration levels (e.g., allowable spectrum at bearing mounts) imparted to the host platform should be considered. Further, a key parameter is tip speed, the product of angular velocity and radius. Research objectives include high-energy density and high-energy rate (power) extraction for a variety of high-energy consumer applications (e.g., DEWs and HEVs).
Critical Materials	High strength-to-weight ratio materials (composites) for energy storage rotor; high-temperature superconducting materials for LOW-drag passive magnetic bearings; techniques for high-energy rate/high peak power extraction; magnetic (and other) bearing technologies for long storage life and efficient operation; and materials such as Kevlar, Metglass, and graphite epoxy.
Unique Test, Production, Inspection Equipment	Flywheels are typically high-energy devices that require a high-vacuum spin pit for operational testing. Fabrication of the flywheel typically requires precisely controlled filament winding machinery (if it is a spun composite wheel). Equipment is in place for balancing rotating electromagnetic equipment (at rotational rates > 2,500 rpm and having a rotating mass > 1,000 kg). However, one aspect of magnetic bearings is that they allow the rotor to spin about its inertial center. The rotor "auto-balances" when operated at typical speeds of interest for flywheels. The balance has to be fairly precise, but other applications are probably more demanding from this standpoint.
Unique Software	Active magnetic bearings are often used for flywheel suspension. The control logic is typically custom designed and implemented on a digital signal processor board. Specialized analysis codes, often proprietary, are used for analysis of flywheel stresses and system dynamics.
Major Commercial Applications	UPSs, utility-level energy storage, low earth orbit (LEO) satellites, and rock splitting (fracturing).
Affordability	Not an issue.

DATA SHEET 7.2. LITHIUM ION BATTERY (RECHARGEABLE)

Developing Critical Technology Parameter

The rechargeable lithium ion battery—a solid-state type battery system originally developed by Sony of Japan and based on lithium intercalculation chemistry and lithium-ion transport systems—is a relatively new and rapidly developing technology. This battery is a safe and sealed system, does not use metallic lithium, and can be recycled with reclaimed materials. Estimated cost is $400–600/kW.

By 2005, projections indicate a very high cell voltage (3.6–4.2 V/cell) and production in prismatic and cylindrical configurations. Expected commercial markets include EVs, computers, telecommunications, and portable electronics. This system is very attractive for military use in soldier systems. A 270-V and/or bipolar designs are expected.

Pulsed			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Energy density (W hrs/kg)	70–80	150–200	
Power density (W/kg)	360	1,000 (18–20 sec pulse)	
Cycle life (# cycles)	500–1,000	> 4,000	
Temperature range (°C)	–30 to +50	–30 to +50	
Recharge time (hrs)	2–4	2	

Continuous			
Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Energy density (W hrs/kg)	100–150	220	
Power density (W/kg)	250	800–1,200	
Cycle life (# cycles)	> 500	1,200–2,000 (up to 5 yrs.)	
Temperature range (°C)	–20 to +50	–30 to +50	
Recharge time (hrs)	> 10	~ 10	

Graphite Fiber–Lithium Ion Rechargeables (Projections)

Several R&D efforts are directed at a rechargeable battery based on graphite fiber electrodes and a lithium ionic salt in an organic electrolyte. Preliminary projections give:

Continuous		***Pulsed***
Parameter	**Projection**	**Projection**
Energy density (W hrs/kg)	120	
Power density (W/kg)	360	up to 1,000
Cycle life (# cycles)	1,000s	1,000s
Temperature range (°C)	–20 to +60	–20 to +60

Critical Materials

Carbon materials: powders, platelets, fibers, and nanotubes; new organic electrolytes and electrolytic additives to enhance lithium-ion conductivity and reduce resistivity; lithiated transition metal oxides of cobalt, nickel, and manganese; composite electrodes; spinels of managnese oxides (e.g. MnO_2 and M_2O_4); high-conductivity polymer electrolytes; and high-energy density anodes and cathodes.

Unique Test, Production, Inspection Equipment

None identified.

Unique Software

Modeling and software codes are advanced and possibly available to the commercial market.

Major Commercial Applications

Automobiles, aircraft, and avionics; air/sea rescue systems; navigation aids; marine and boating; EVs; commercial satellites; cell phones; laptop computers; and portable electronic devices. The last three applications are not driving military technology development. Most applications in this area are separate from the more robust military applications.

Affordability

Currently, commercial and military markets are quite disparate in this area.

DATA SHEET 7.2. LITHIUM POLYMER BATTERY (RECHARGEABLE)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<p>The rechargeable lithium polymer battery is a new and emerging technology (more recent than lithium ion batteries). It is a solid-state battery based on Ion conductivity in polymers. The system is lightweight and safe and uses non-toxic materials. The rawbacks are poor low temperature and high rate performance.</p>
<p>Pulsed applications include weapons and acceleration for HEVs, while CW applications may focus on EVs.</p>
<p>By 2005, the following are projected for rechargeable lithium polymer batteries: use of a solid conductive polymer membrane electrolyte or gel electrolyte; very compact size and cell design; more flexibility; and able to have battery molded in various shapes and configurations. Key problems are poor low temperature performance (below 0 ^{o}C) and low charge/discharge rates. Battery uses lightweight materials. Projected costs are ~ $200 to 300/kW.</p>
<table>
<tr><th colspan="4"><i>Pulsed</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (W hrs/kg)</td><td>125</td><td>300–400</td><td></td></tr>
<tr><td>Power density (W/kg)</td><td>200</td><td>400</td><td></td></tr>
<tr><td>Cycle life (# cycles)</td><td>200–300</td><td>2,000</td><td></td></tr>
<tr><td>Temperature range (°C)</td><td>–20 to +100</td><td>–40 to +150</td><td></td></tr>
<tr><td>Recharge time (min)</td><td>> 15</td><td>~ 15</td><td></td></tr>
</table>
<table>
<tr><th colspan="4"><i>Continuous</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (W hrs/kg)</td><td>< 125</td><td>300–400</td><td></td></tr>
<tr><td>Power density (W/kg)</td><td>100</td><td>400</td><td></td></tr>
<tr><td>Cycle life (# cycles)</td><td>300</td><td>500–1,000</td><td></td></tr>
<tr><td>Temperature range (°C)</td><td>–20 to +100</td><td>–40 to +150</td><td></td></tr>
<tr><td>Recharge time (min)</td><td>> 15</td><td>~ 15</td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>High conductivity polymer electrolytes and gels; high-energy density anodes and cathodes; gelionic materials; conductive elastomers (rubbers); complex organo-lithium salts; carbon powders; carbon platelets and fibers; and new polymers with high breakdown voltages.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Assembly or production must take place in a dry atmosphere because of lithium’s reactive nature with moisture. In addition, the battery must be hermetically sealed.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>Commercial satellites; cell phones; laptop computers; and portable electronic devices. Primary drive is form flexibility, high cell-packing density, and reduced weight. The last three applications are not driving military technology development.</td></tr>
<tr><td>Affordability</td><td>Not an issue.</td></tr>
</table>

DATA SHEET 7.2. NICKEL METAL HYDRIDE BATTERY (RECHARGEABLE)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>The rechargeable nickel metal hydride battery is a commercial technology developed to find an environmental replacement for NiCd batteries, particularly in portable electronic devices and EVs. These batteries are environmentally safer and offer longer operating times and higher energy output but cost approximately 25 percent more than similar-size NiCd batteries.
<table>
<tr><th colspan="4"><i>Pulsed</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (kW/kg)</td><td>> 1</td><td></td><td></td></tr>
<tr><td>Recharge time (min)</td><td>5–10</td><td>~ 5</td><td></td></tr>
</table>
<table>
<tr><th colspan="4"><i>Continuous</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (W hrs/kg)</td><td>65–90</td><td>160</td><td></td></tr>
<tr><td>Power density (W/kg)</td><td>160</td><td>500</td><td></td></tr>
<tr><td>Cycle life (# cycles)</td><td>600–1,000</td><td>1,500–3,000</td><td></td></tr>
<tr><td>Temperature range (°C)</td><td>–10 to +30</td><td>–25 to +50</td><td></td></tr>
<tr><td>Recharge time (min)</td><td>60–180</td><td>30</td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Metal hydride materials.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>Automobiles; commercial aircraft;power tools; and personal electronic devices.</td></tr>
<tr><td>Affordability</td><td>Prices currently driven by the personal electronic device applications. EV batteries are expensive because of limited production ($300–400/kWh). Projected costs for an aircraft battery are estimated at $500/A hr.</td></tr>
</table>

DATA SHEET 7.2. SILVER ZINC BATTERY (RECHARGEABLE)

Developing Critical Technology Parameter	The rechargeable silver zinc battery is a mature well-established technology with a limited, mostly military/aerospace market because of high cost. Because of the maturity of this technology, little progress or advancement is expected by 2005. Secondary silver zinc alkaline batteries are very energetic, have a cell voltage of about 1.8 V/cell, wide operational temperature range (–40 to +50 °C), and relatively high energy density (100–250 W hrs/kg) depending on battery and cell design. In addition, bipolar cells are capable of attaining high power densities (> 1 kW/kg). Such high power batteries must be cooled and do have a short life cycle. The drawbacks of these batteries are their high cost and relatively short life cycle (500–600 cycles max). These batteries have a flat discharge and can be designed for high-rate applications at the expense of a reduced cycle life. These batteries are used in tactical aircraft, submarines, satellites, and other aerospace systems. Silver zinc primary reserve batteries are a well-established, mature technology used mainly for the military/aerospace market. These energetic batteries have a cell voltage of 1.8 V/Cell and energy density of 100–300 W hrs/kg and can be designed for high discharge rate/high power output applications. The battery has a wide temperature range (–40 to +60 ^{o}C), and cells can tolerate extreme stress (acceleration, vibration, and shock). The battery is compact and can be activated by physical forces (acceleration or shock/impact) or by electric valve or gas pressure (remote activation). The activation time is in milliseconds and is highly reliable. The primary market is military systems (missiles, munitions, and torpedoes). These batteries are quite expensive.
Critical Materials	Electrolytic-grade silver foils, powders and fibers.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Commercial markets are limited because of very high costs.
Affordability	Expensive.

BACKGROUND

Silver zinc batteries are a highly reliable, energetic, compact, modular battery system capable of high-rate, high-power applications. These batteries have the potential to be enabling for high-energy weapon systems. Bipolar SiZn batteries can be used for space weaponry.

DATA SHEET 7.2. ELECTROSTATIC CAPACITORS

Developing Critical Technology Parameter

Pulsed

Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Energy density (J/g)	0–7	10	
Capacitance (μF)	1–10	1–10	
Pulse rate (pps)	0.2	10–20	
Dissipation factor (loss)	0.005	0.0001	
Temperature range (°C)	–55 to +80	–55to +200	

Continuous

Parameter	**1999**	**Projected by 2010**	**Nature's Limit**
Energy density (J/g)	0–3	8	
Capacitance (μF)	1–10	1–10	
Dissipation factor (loss)	0.005	0.0001	
Temperature range (°C)	–55 to +80	–55 to +200	

Critical Materials	Novel polymers, ceramics, diamonds, nitrides, glass-ceramic composites, ceramic-polymer composites, impregnants, and so forth.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Arc welding, oil/well drilling, medical defibrillators, high-power flash lamps, EVs, motor start circuits, and so forth.
Affordability	This technology will remain largely for military applications; however, cost can be reduced as other applications in the market become known.

DATA SHEET 7.2. ELECTROCHEMICAL CAPACITORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>Electrochemical capacitors: energy storage/pulse repetition rate/back-up power, milliseconds. Parameters are listed for commercially available devices. Pulsed and CW requirements will demand similar capacitor parameters.
<table>
<tr><th colspan="4"><i>Pulsed</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Capacitance (F/cm^3)</td><td>2.6</td><td>5.2</td><td></td></tr>
<tr><td>Series resistance (mohm)</td><td>4</td><td>1</td><td>1</td></tr>
<tr><td>Energy rensity (J/cm^3)</td><td>8</td><td>80</td><td></td></tr>
<tr><td>Power rensity (W/cm^3)</td><td>80</td><td>320</td><td></td></tr>
<tr><td colspan="4"></td></tr>
<tr><th colspan="4"><i>Continuous</i></th></tr>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Capacitance (F/cm^3)</td><td>2.6</td><td>5.2</td><td></td></tr>
<tr><td>Series resistance (mohm)</td><td>4</td><td>1</td><td>1</td></tr>
<tr><td>Energy density (J/cm^3)</td><td>8</td><td>80</td><td></td></tr>
<tr><td>Power density (W/cm^3)</td><td>80</td><td>320</td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Electrode materials and electrolyte. One also must perfect packaging process along with materials development. Another area that remains unexplored is the development of power electronic converters matched to the unique requirements of these devices.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Production methods for these devices are well known. Testing of these devices can be accomplished with relatively simple equipment. Test procedures borrowed from traditional capacitor and battery testing methods can be used.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>Advancements in power and/or energy density will enable more widespread use. Electrochemical caps will see aplication as a battery load leveler and a battery replacement (motor drive bus ride-through, UPS, portable electronics, automotive electronics). Presently used for memory backup.</td></tr>
<tr><td>Affordability</td><td>Cost is one limiting factor to the widespread use of these capacitors. Cost must come down to make these devices a viable commercial product. Current cost for Japanese capacitors is about $0.25/F.</td></tr>
</table>

DATA SHEET 7.2. HIGH-ENERGY AND POWER DENSITY PULSED ALTERNATORS AND COMPULSATORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (J/g)</td><td>1–2</td><td>10–20</td><td>100</td></tr>
</table>
<p>Compulsators have demonstrated 1 J/g energy density. Every indication is that pulsed disk alternators (PDAs) could achieve the same or better performance.</p>
</td></tr>
<tr><td>Critical Materials</td><td>High-strength fibers for composites; high-temperature, tough, low-conductivity resins; high-strength, high-conductivity, low-resistivity conductor materiel; silicon carbide switches.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>• Test. High-power electromagnetic railgun facility.
• Production. Not in production as of this date
• Inspection. Vertical plane imaging (VPI) ultrasound and x-ray tomography; electrical property measurement; and rotor balancing.</td></tr>
<tr><td>Unique Software</td><td>EMAP-3D (electro-thermodynamics code).</td></tr>
<tr><td>Major Commercial Applications</td><td>Launch of lightweight packages to LEO.</td></tr>
<tr><td>Affordability</td><td>Moderate.</td></tr>
</table>

SECTION 7.3—POWER CONDITIONING

Highlights

- Power conditioning is the process involved in modifying the source output to meet load characteristics.
- Voltage, current, time (pulse length), pulse shape, and frequency characterize power conditioning.
- Loads require power to be delivered in specifically shaped continuous or pulsed waveforms.
- Advanced weapons of precision and wide-area mass destruction, radar, countermeasures, and communications systems are enabled through next-generation-plus-high-energy electronics systems, including the prime energy sources.

OVERVIEW

Power conditioning is the process involved in modifying the source output to meet load characteristics. Such loads can include military and commercial applications. Military applications range from charging a battery or forming pulses for a weapon subsystem to electric motor drives. Two types of conditioning are defined by the amount of time over which power is supplied: continuous duty and pulsed or burst mode. To revisit, continuous duty is defined as power supplied to a load continuously, which, in this discussion, implies bursts lasting longer than 1 second (since semiconductor devices reach their thermal equilibrium in less than 1 second). Bursts lasting less than several seconds are considered pulsed power and generally have higher average powers. Pulsed power conditioning discharges a high-energy storage bank in a low repetition-rated burst mode (see Fig. 7.3-1). For some applications, long pulses that last from several microseconds to seconds may be fed into a fast conditioning stage, which creates bursts with high power lasting from microseconds and femtoseconds.

Pulse conditioning subsystems are comprised of both discrete and transmission-line-type components. The circuit functions can be described by lumped element equivalent circuitry provided that the characteristic times of energy discharge are far longer than parasitic IRC (inductor, resistor, capacitor) time constants of any system component. These subsystems are intimately tied to the load, with efficiency and reliability often constraining the types of near-term solutions available. In the future, advanced component development and enabling new energy control topologies will permit considerable reduction in system size and mass for next-generation systems.

A considerable aspect of power conditioning is the pulse-forming functions. Pulse formation is dominated by the characteristics of the switches used. Switch performance is summarized and defined in terms of the following parameters:

- **Peak voltage** is the maximum voltage that can be applied while the switch is open without breakdown.
- **Peak current** is the maximum current reached by the pulse.
- **Charge** is the amount of current a switch can pass while conducting over a period of time.
- **Voltage drop** is the maximum voltage across the device when the current has reached its maximum value.
- **Current density** is the current per unit area of conduction.
- **Action** in a switch is the impact that occurs in a short interval of time because of a force associated with the high-energy pulse. The force introduces stresses and strains in the switch. These stresses can induce microcracks and fractures, which ultimately lead to device failure. If the value of the action exceeds the fusing capability of a solid-state device, failure is catastrophic. As a result, solid-state switches have to be operated at action levels well below their fusing limit. When devices are connected in parallel, including a fuse in series with each switch may be necessary.

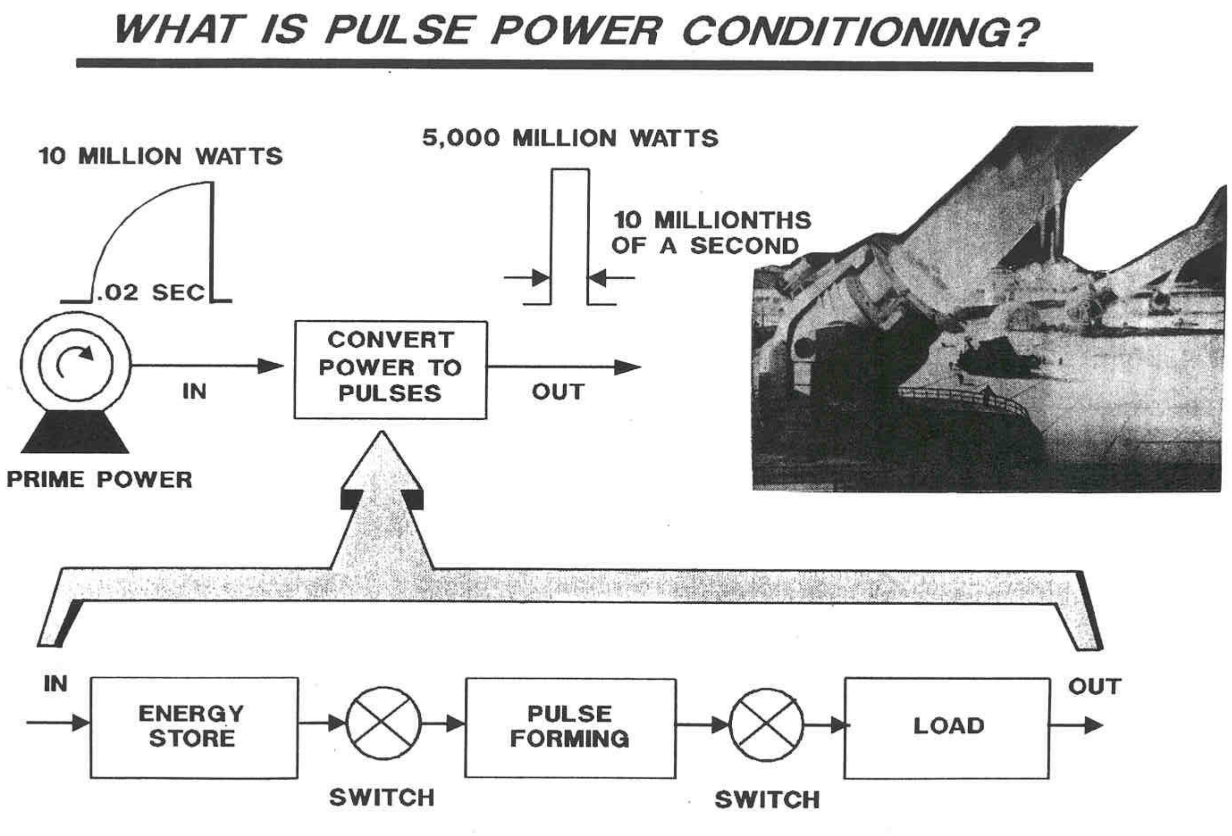


Figure 7.3-1. Pulsed Power Conditioning

- **di/dt** is the maximum rate of current rise that the switch can tolerate.
- **dv/dt** is the maximum rate of voltage rise that will not turn the switch on.
- **Thermal management** is the ability to remove heat energy generated by device.
- **Reverse blocking** is the peak voltage that can be applied across the device in reverse direction immediately after a high current in the forward direction.
- **System volume and mass** include the componentry: gate drives, protective drives, and so forth.
- **Life** is the predicted number of shots or pulses the device may deliver before failure.
- **Cost** is measured in dollars per switch.

Additional parameters include series and parallel operation, reliability, commercial availability, duration, and repetition rate.

LIST OF TECHNOLOGY DATA SHEETS
7.3. POWER CONDITIONING

DATA SHEET 7.3. LOW-REPETITION-RATE (LRR) AND BURST CAPACITORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
LRR is approximately 1–10 pulses per second, < 5-percent duty cycle
Burst operation is approximately 100 sec on-time, < 5-percent duty cycle
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (J/kg)</td><td>1500-2500</td><td>5,000</td><td></td></tr>
<tr><td>Energy density (J/cc)</td><td>3–15</td><td>15</td><td></td></tr>
<tr><td>Number of shots (nominal)</td><td>1,000</td><td>1,000</td><td>1,000's</td></tr>
<tr><td>Pulse repetition rate (Hz)</td><td>0.1–10</td><td>< 100</td><td>100</td></tr>
<tr><td>Discharge efficiency (%)</td><td>85</td><td>95</td><td>99</td></tr>
</table>
Very LRR: 0.1 Hz, 1 kJ/kg, 100 shot, 75 kJ, 50 kV
LRR: 600 J/Kg; 104 shots; 50 kJ; 20 kV
Burst: 180 J/Kg; 100 Hz; 105 shots, 0.5 kJ, 40 kV
</td></tr>
<tr><td>Critical Materials</td><td>Dielectrics.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Winding machines.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>Commercial power.</td></tr>
<tr><td>Affordability</td><td>None identified.</td></tr>
</table>

BACKGROUND

Some applications demand very high energy but only for very brief periods of time. Typically, LRR involves 1–10 pulses per second and a 5-percent-or-less duty cycle. This type of operation places extreme demands on capacitors (and other elements in the system) in terms of maximum voltage, current, and power that must be handled. The discharge rate and efficiency of different capacitor materials determines their application. For pulses on the order of tenths of a second duration, CDL capacitors hold great promise at high-energy densities. For pulses of millisecond or microsecond duration, polymer capacitors seem best suited. For very brief pulses (nanoseconds), ceramic capacitors are required.

Capacitors permit energy to be stored over a long period of time and then released as required over a very short period under controlled conditions. Burst operation involves high-power activity for intermittent periods. Typically, this might be 100 sec on-time and a 5-percent duty cycle. Peak levels are not as great as LRR, but the level is sustained for considerably longer periods and the limiting factor becomes heat dissipation. CDL and polymer capacitors are of most interest for this type of operation.

DATA SHEET 7.3. MEDIUM-REPETITION-RATE CAPACITORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>Medium repetition rate is nominally 100 Hz–20 kHz.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (J/kg)</td><td>55–200</td><td>1,000</td><td></td></tr>
<tr><td>Capacitance (μF/cm^3)</td><td>5–10</td><td>30</td><td></td></tr>
<tr><td>Resistance (ohms)</td><td>< 0.01–0.005</td><td>< 0.005</td><td></td></tr>
<tr><td>Temperature (°C)</td><td>–55 to +80</td><td>–55 to +125</td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Improved materials (dielectrics, films, foils, insulation, impregnants); improved package (novel winding and casing design); improved manufacturing techniques (deposition limit for film).</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>None identified.</td></tr>
<tr><td>Affordability</td><td>None identified.</td></tr>
</table>

BACKGROUND

A major function of these capacitors is to reduce ripple in DC power supplies and to filter out unwanted higher frequencies in AC power systems. In both cases, frequency response and thermal management become critical issues. Conditioning for electric drive vehicles is another important application. Capacitors for filtering and power conditioning must be capable of medium frequency operation at high efficiency with low volume and weight (high-energy density) and equivalent series resistance (ESR). The ESR times the energy density is a figure of merit.

DATA SHEET 7.3. HIGH-REPETITION-RATE (AND CONTINUOUS) CAPACITORS

<table>
<tr><td>Developing Critical Technology Parameter</td><td>High repetition rate is nominally greater than 20 kHz.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Energy density (J/kg)</td><td>55–200</td><td>1,000</td><td></td></tr>
<tr><td>Capacitance (μF/cm^3)</td><td>5–10</td><td>30</td><td></td></tr>
<tr><td>Resistance (ohms)</td><td>< 0.01–0.005</td><td>< 0.005</td><td></td></tr>
<tr><td>Temperature (°C)</td><td>–55 to +80</td><td>–55 to +125</td><td></td></tr>
</table>
Continuous: 20 J/Kg, 100 Hz, 108 shots.</td></tr>
<tr><td>Critical Materials</td><td>Improved materials (dielectrics, films, foils, insulation, impregnants); improved package (novel winding and casing design); improved manufacturing techniques (deposition limit for film); and fault tolerance for high i^2t energy pulses that can be applied during conditions found under survivability situations.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>None identified.</td></tr>
<tr><td>Affordability</td><td>Not an issue.</td></tr>
</table>

BACKGROUND

High-repetition-rate and continuous-operation capacitors have application in power conditioning, filtering, and inverters. A major function is to reduce ripple in DC power supplies and to filter out unwanted higher frequencies in AC power systems. In both cases, frequency response and thermal management become critical issues. Conditioning for electric drive vehicles is another important application. Capacitors for filtering and power conditioning must be capable of high-frequency operation at high efficiency with low volume and weight (high-energy density) and, in addition, very low internal inductance [equivalent series inductance (ESL)] and equivalent series resistance (ESR) to ensure high operational efficiency. The energy density divided by the product of ESR and ESL is a figure of merit.

DATASHEET 7.3. DIELECTRICS FOR PULSE-POWER CAPACITORS

Developing Critical Technology Parameter	Develop superior dielectrics with greatly improved dielectric constant, voltage breakdown strength, dissipation factor, and discharge capability.
Critical Materials	Polymers, polymer-polymer composites, polymer-ceramic composites, nitrides, diamond like carbon (DLC), and polycrystalline diamond.
Unique Test, Production, Inspection Equipment	Superior winding machines critical to fabricating reliable device.
Unique Software	None identified.
Major Commercial Applications	Utilities, oil/well drilling, medical defibrillators, aircraft, satellites, and lasers.
Affordability	Not determined.

DATA SHEET 7.3. CHEMICAL DOUBLE LAYER (CDL) CAPACITORS

Developing Critical Technology Parameter	Projected performance by 2005 for (pulsed) CDLs: • Discharge time of 1–300 sec • Charge time of 1–300 sec • Energy density ~ 5 W hrs/kg (inorganic electrolytes), 10–15 W hrs/kg (organic electrolytes) • Power densities > 10 kW/kg • Charge/discharge efficiencies ~ 80 percent at high rates and 98 percent at low rates • Cycle life >100,000 cycles at 100-percent depth of discharge • Charge and discharge current densities > 100 Å • Temperature range –55 to +85 °C, 98-percent-plus reliability. CDLs, which are produced in modular units and scalable in size for meeting power load requirements, are designed for HEVs. Most likely serially assembled in banks of capacitors to meet selected power loads. Produced mostly in cylindrical configurations out of materials that provide very large active surface areas for the electrode/electrolyte interface to support the generation and storage of ions along the surface.
Critical Materials	Improved organic and inorganic electrolytes with higher breakdown voltages; improved microporous polymeric separators; and improved active carbon materials with extremely large active surface areas (over 3,000 m/g) (e.g., carbon nanotubes and glassy carbon fibers).
Unique Test, Production, Inspection Equipment	CY91 R/T: CDL scaling verified to > 100-kJ levels R: intrinsic break down-laminates, impregnants and model sections T: continuous: > 30 J/Kg; 20 kHz; > $l0^8$ cycles; 2 F; 1.5 kV; inverter.
Unique Software	None identified.
Major Commercial Applications	HEVs, automotive ignition systems, portable electronics, computers, telecommunications, avionics, remotely controlled actuators, and emergency back-up power supplies. **Note:** *To date, very few CDL products are on the marketplace.*
Affordability	Not determined.

BACKGROUND

CDL capacitors are also known as ultra-capacitors, super capacitors, super-caps, and electric double layer capacitors. This type of energy storage represents a rapidly emerging and promising technology that can be used to develop high-power energy storage systems that are durable, reliable, affordable, compact in size, lightweight, and capable of having a long service life (over 100,000 cycles).

DATA SHEET 7.3. SOFT SWITCH INVERTERS

Developing Critical Technology Parameter	See parameter table below
Critical Materials	SiC Wide Bandgap (WB) materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Integrated microprocessor controls.
Major Commercial Applications	Computers, high-speed transportation (Maglevs), and EVs.
Affordability	Not determined.

Parameter	1999	Projected by 2010	Nature's Limit
Power density (MW/m^3)	5	20	
Switching speed (kHz)	20	100s–1000	

DATA SHEET 7.3. HIGH-TEMPERATURE SUPERCONDUCTING (HTS) WIRES

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>BSSCO critical current density (kA/cm^2)</td><td>70 (77 K,SF,short)</td><td>70 (77K,SF,long)</td><td></td></tr>
<tr><td>BSSCO conductor length (m)</td><td>1,000 (Jc=15 kA/cm^2)</td><td>> 1,000</td><td></td></tr>
<tr><td>BSCCO engineering current density (kA/cm^2)</td><td>13 (77 K,SF,long)</td><td>35 (77 K,SF,long)</td><td></td></tr>
<tr><td>YBCO critical current density (kA/cm^2)</td><td>2,000 (77 K,SF,short)</td><td>1,000 (77 K,SF,long)</td><td>> 10,000 (77 K,SF)</td></tr>
<tr><td>YBCO conductor length (m)</td><td>1</td><td>100's</td><td></td></tr>
<tr><td>YBCO engineering current density (kA/cm^2)</td><td>10 (77 K, SF)</td><td>50 (77 K,SF)</td><td></td></tr>
</table>
</td></tr>
<tr><td>Critical Materials</td><td>Reduction in the Ag content of the BiSrCaCuO conductor to reduce cost of the cable and development of YBCO-coated conductor architecture [non-magnetic substrates, buffer layer(s)].</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>Power cables for utility transmission lines; fault current limiters; smaller, more efficient transformers; and efficient, compact motors and generators.</td></tr>
<tr><td>Affordability</td><td>Ag sheathed BiSrCaCuO cable is expensive because of the large amount of Ag needed. YBaCuO wire is in development and may offer a less expensive alternative and the ability to maintain high current densities in large magnetic fields at 77 K.</td></tr>
</table>

BACKGROUND

Copper-based equipment generates waste heat and resistive loss, has limited capacity for carrying large currents, and is heavy. HTS wires are the converse. They generate minimal heat, may carry large currents, and are much lighter. Superconductivity offers significant theoretical advances in capability and performance for several power applications. Low-temperature superconducting (LTS) wire is being applied to magnetic resonance imaging (MRI) medical imaging and other systems (mechanical and magnetic).

High-temperature superconductivity has received a great deal of public attention, and, in many cases, exaggerated or premature claims have been made concerning the revolutionary changes it will effect. For the most part, high-temperature superconductivity is still in the early research stage. However, significant advances have occurred in the area of HTS wires. High-current cables consisting of high-temperature (77 K) superconductors are being fabricated in kilometer lengths. Presently, the drivers for this technology are in commercial power, specifically in coils and magnets, fault current limiters, transformers, and superconducting underground cables for power transmission, especially in urban areas needing increased power capacity (see Fig. 7.3-2).

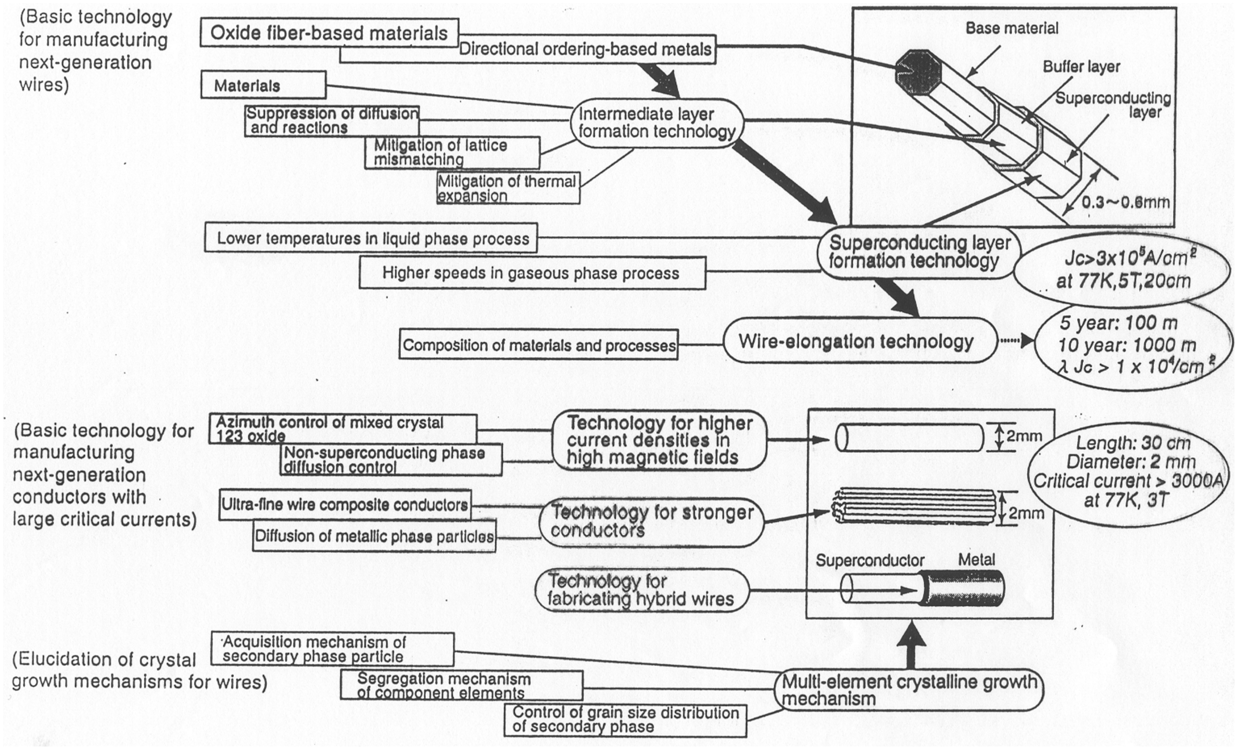


Figure 7.3-2. Basic Research Challenges on Superconducting Wire Materials

DATA SHEET 7.3. PULSE TRANSFORMERS

Developing Critical Technology Parameter	Fast charging: 0.1–1 μs. 1.5 MV; 20 Hz; 1.5 kJ (Air Core). 0.8 MV; 100 Hz; 27 kJ (Iron Core). Lightweighting by –10 X required: burst and continuous operation. Vacuum operation in some systems. Move to higher frequencies is counter to insulation strength trends. New materials needed. Space compatibility and traceability, reliability, maintainability, and availability (TRMA) require validation. Capacitor charging: 2 MV; 100 kJ; 20–100 μs; 1,000 Hz; 1,000-sec burst; 5-percent duty factor. Flat top: 1–3 MV; 100 kJ; 0.5–20 μs; 1,000 Hz; 1,000-sec burst.
Critical Materials	Core material (composites), ferrites. High T operations, Wire technology, HTS Magnetic materials/insulation: • New, low loss Metglas (2X) • High stress grading insulation with molecularly designed polymers (5X) • Near ultimate (25–30 kV/mil) insulation • Vapor mist.
Unique Test, Production, Inspection Equipment	Purity of raw materials/device design.
Unique Software	None identified.
Major Commercial Applications	Air pollution control, food processing, water purification, rock breaking, multikilohertz lasers, and research accelerators.
Affordability	Not determined.

BACKGROUND

Pulse transformers, or pulse-charging transformers, are a power-conditioning device and are used when high-voltage gains and efficiencies are required. Essentially, they are employed when one needs to tailor voltage to a load.

DATA SHEET 7.3. WIDE BANDGAP (WB) SEMICONDUCTORS

Developing Critical Technology Parameter	• 10- to > 100-kV-type levels; • discrete high current devices > 1,000 Amps; • high operating junction temperatures > 500 °C; • reliable device operating temps > 450 ºC; discrete device blocking voltages > 5,000 V; and • power switching frequencies > 200 kHz for power levels above 10 kW and > 500 kHz for power levels from 1–10 kW).
Critical Materials	WB semiconductor materials include SiC, III-Nitrides, BC, diamond, and TiC and thermally stable dielectric materials with low dielectric constants and large field strengths; low resistance; high thermal stability packaging; direct bended copper (DBC), aluminum indium nitrade (AIN)-based materials; low resistivity ($< 10^{-6}$ Ω-cm^2); thermally stable (> 600 °C) ohmic; and Schottky contact technology.
Unique Test, Production, Inspection Equipment	Surface mount technology; electro-deposition processes; large volume expitaxial reactors; large volume substrate production facilities for WB semiconductor materials such as SiC, III-Nitrides, BC, diamond, TiC; and thermally stable dielectric materials with low dielectric constants and large field strengths. Material issues: micropipe and other defect effects, and large area growth. Fabrication issues: dry etching, ion implantation, oxidation, ohmic contacts. Device design Issues: transistors, thyristors, dynistors, insulated gate bipolar transistors (IGBTs), metal-oxide semiconductor field-effect transistors (MOSFETs), and MOS-controlled thyristor (MCT) design. Growth of materials with near-zero defects.
Unique Software	None identified.
Major Commercial Applications	High-power utility electric power distribution, high-frequency tranceiver for personal communication; opto-electronic applications for visible emitters [blue and green light emitting diodes (LEDs) and laser diodes] with significantly reduced power consumption.
Affordability	Not determined.

BACKGROUND

SiC material properties offer the potential to develop devices with much higher (10-fold increase) voltage capability and much lower (by a factor of 100) power dissipation (at equal currents) than more conventional silicon devices. SiC's potential for making devices with higher operating temperatures (500 °C) makes it superior where cooling system size and weight are important and where very high-power handling capability or higher temperature operation is required. Near-term SiC Schottky diode rectifiers may provide higher voltage, faster switching, higher temperature, and lower loss replacements for the widely used silicon rectifier diodes.

The performance potential of the WB semiconductor materials for power semiconductor switching applications far exceeds that of present-day Si technology. Potentially realizable goals include 100X lower on-resistance and 10X reductions in switching losses.

SiC devices are expected to be able to withstand temperatures in excess of 500 °C in contrast to a temperature of 150 ºC for silicon. This significantly changes thermal management constraints when the device is integrated into a system (i.e., using engine oil to cool a switch).

DATA SHEET 7.3. DIAMOND SEMICONDUCTOR SWITCHES

Developing Critical Technology Parameter	These switches may have the following capabilities: operation at average power levels greater than 100 kW, duty cycles greater than or equal to 0.01, peak current density in pulsed mode greater than 100,000 A/cm^2, voltages greater than 100 kV, rise times less than 1 ns, and internal inductance < 1 nH/A. When used in pulse-forming networks for narrow-band HPM, they are required to deliver at least 1 MJ per pulse.
Critical Materials	These switches and related contacts and leads must be capable of operating at high temperatures because of the intrinsic energy dissipation inherent in switches. This would suggest materials that have high specific heat and high conductivity.
Unique Test, Production, Inspection Equipment	Equipment that can fabricate a system of switches that provide the required synchronism better than 1 ns for parallel operation.
Unique Software	Software that can support the fabrication process.
Major Commercial Applications	So far, the only applications for this technology have been military. Potential commercial opportunities include applications in electric power, the automotive industry, and electric drives.
Affordability	Too early to establish. Could be a big issue.

DATA SHEET 7.3. MOS-CONTROLLED THYRISTOR (MCT)

Developing Critical Technology Parameter	Research objectives: higher voltage, current, action, and current density.

Parameter	1999	Projected by 2010	Nature's Limit
Action (A^2 - sec)	0.25		1
Switching speed (kHz)	50–200	250	MHz
Current density (A/cm^2)	400–500	500	> 500
Max blocking voltage (kV)	2–3	4	5
Max peak current (kA)	0.15–1.2	1.2	

Critical Materials	High-temperature materials.
Unique Test, Production, Inspection Equipment	Production of devices on SiC and other high-temperature-capable substrates.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability	Not an issue.

BACKGROUND

The MCT is a high-power, high-frequency, low-conduction-drop, rugged device that seems to be the leader for medium- and high-power applications. It offers the power handling capability of a near-ideal thyristor but is controlled in turn-on/turn-off by an MOS transistor acting as a gating device. In addition to fewer losses and higher switching speed, MCT offers lighter weight, smaller space, and lower operating costs. It can be used in inverters, motor controllers, and power controllers but may also have application in pulsed-power systems. The MCT, because it can handle higher voltages, operate at higher temperatures, and offers higher current density (which means a smaller package is required), may take over the markets now dominated by gate turn-off thyristors (GTOs) and IGBTs. Devices being sold now for industrial applications can control up to 120 kW. Utility-scale MCTs are now available.

DATA SHEET 7.3. MOS TURN-OFF THYRISTOR

Developing Critical Technology Parameter	Parameter / 1999 / Projected by 2010 / Nature's Limit Turn-off time (ms) / 10's / < 10's / Turn-off gain / 4–5 / 100's /
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Monolithic processing.
Unique Software	None identified.
Major Commercial Applications	Power switching, power conditioning.
Affordability	Not an issue.

BACKGROUND

The MOS Turn-off Thyristor will replace the GTO because of its increased turn off time. GTO turn-off times are currently hundreds of microseconds where the MOS Turn-off Thyristors are currently tens of microseconds.

DATA SHEET 7.3. INTEGRATED PULSE-FORMING NETWORKS (IPFNs) AND CAPACITORS

Developing Critical Technology Parameter	Energy Discharge IPFN: • Material-limited; > 100 Hz prf; burst/continuous duty • 15–20 kJ/kg energy density IPFN at 15–20 MJ/m^3; multimegajoules per unit, including switching and inductors. Filter and inverter capacitors: • Material-limited: > 10 kHz prf; burst/continuous duty • > 10 MVA/kg power density installed in case.
Critical Materials	Materials with a high dielectric constant and strength.
Unique Test, Production, Inspection Equipment	Winding machines.
Unique Software	None identified.
Major Commercial Applications	Medical industry, food sterilization, and air pollution control.
Affordability	Depends on availability and cost of dielectrics.

SECTION 7.4—BIOLOGICAL ENERGY SYSTEMS

Highlights

- Results in biotechnology research indicate that low-power, energy-generating elements will be produced commercially.
- Proton pumps and electron transfer systems have been created from lipids that are capable of self-assembly (and thereby forming membranes) and from proteins that perform pump functions.
- Proteins functioning as molecular motors have diameters of 20–50 Å.
- Energy is derived either from the oxidation of organic molecules to carbon dioxide and water through the process of metabolism or from the absorption of energy from light sources.

OVERVIEW

During the past two decades, much has been learned about the mechanisms involved in the living systems' production of energy from nutrients and light. Living organisms generate electrical potentials, synthesize large organic molecules, and perform other tasks that require energy. Energy is derived either from the oxidation of organic molecules to carbon dioxide and water through the process of metabolism or from the absorption of energy from light sources.

The mechanisms involved in the oxidative phosphorylation metabolism of organic compounds and in the transduction of light energy to chemical energy require the generation of an electro-osmotic/electrochemical gradient across a membrane. The gradient is associated with transfer of electrons and/or protons, which results in the synthesis of high-energy compounds in the cell. The most ubiquitous of these high-energy compounds is adenosine triphosphate (ATP), which is recognized as a common currency of energy needs in a living cell.

In the metabolic process, the oxidation of the major nutrients results in the removal of electrons from the fat, carbohydrate, or amino acid substrate compounds and the stepwise transfer of the electrons in the mitochondrion to molecular oxygen, which then reacts with protons to form water. The removal of protons from the substrate and the creation of a proton pump across the cell membrane is an integral aspect of substrate oxidation. The production of ATP from adenosine diphosphate (ADP) by oxidative phosphorylation operates at an efficiency of approximately 40 percent and is, therefore, relatively efficient. The energy released by oxidation, not coupled to ATP production, is emitted as heat. Hibernating mammals use the oxidation of brown fat in a relatively uncoupled manner to generate heat needed to maintain body temperature.

In the photosynthetic process, larger organic compounds are generated from water and carbon dioxide using the energy of light. In this process, light interacts with a porphyrin-like tetrapyrrole component of chlorophyll in the thylakoid membrane of plant chloroplasts to cause the generation of molecular oxygen from water. The chlorophyll obtains an electron from the water as the molecular oxygen is generated. In this process, the electrons are passed from an antennae-like system of clustered chlorophyll molecules to a photochemical reaction center (PCRC). The PCRC has a particular arrangement of chlorophyll molecules that permit transfer of excited electrons from the antennae to electron receptor molecules. A proton pump, which generates ATP in a manner similar to that seen in the mitochondria during oxidative phosphorylation, is generated as part of the process. The time required for the processes is approximately 100 µs. In a related system, halophilic bacteria-like organisms, called halobacterium halobium, use a tetrapyrrole bacterial rhodopsin to generate a proton pump. For these systems to operate, an intact membrane is required, and the proteins acting as electron transfer agents are required to be organized in two dimensional (2-D) space. The proton pump is generated across the membrane, and the electron transfer process is generated in the plane of the membrane.

Because lipids are capable of self-assembling and thereby forming membranes, constructing proton pump and electron transfer systems is technically feasible. Such systems have been constructed. The generation of one molecule of molecular oxygen requires the transfer of four electrons. The production of six molecules of oxygen therefore requires 48 photons. Approximately 10,000 kJ are required to make 1 mole (mol) of glucose possessing 2,840 kJ.

From these considerations low power, energy generating elements will probably be produced commercially. These components can be used for generation of power for changing opaqueness of a visor, for driving sensors, or for read-write information storage components. In the Biological Technology section, the utility of bacterial rhodopsin as an information storage material is described.

Insertion of bioreceptor-ion channel molecules into lipid bilayers permits production of electrical switches at the nanometer scale. The lipid bilayer of electrically excitable tissues, such as muscle and nerve cells, contain molecular pumps that generate an ion gradient (hence a voltage drop of 70 mV) across the membrane. Sodium and potassium are the ions involved. Nerves and muscles also contain protein molecules that serve both as receptors and ion channels. The acetylcholine receptor (AChR) is an example of such a protein. When incorporated into a lipid bilayer 70-Å thick, these AChR molecules will bind to acetyl choline on one side of the membrane and cause an opening of the relevant ion channel. The ions will transiently cross the membrane resulting in a reduced gradient and lowering of the electrical potential.

LIST OF TECHNOLOGY DATA SHEETS
7.4. BIOLOGICAL ENERGY SYSTEMS

DATA SHEET 7.4. PHOTOCHEMICAL REACTION CENTER SYNTHESIS/STRUCTURE (PRCS)

<table>
<tr><td>Developing Critical Technology Parameter</td><td>This is a two-photon capture system. The primary critical parameter is a miniaturized power source.
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Highly conjugated porphynn-like center with extended conjugated carbon chain. Copmpound 50-A dimensions.</td><td>Isolated PCRC fragments of membranes with densely packed PCRC.</td><td>Densely packed arrays of PCRC aligned on surface.</td><td>Biomimetics can maximize PCRC packing density (nearest neighbor packing of PCRC is ultimate limit)</td></tr>
</table></td></tr>
<tr><td>Critical Materials</td><td>Requires a light source (e.g., sunlight).</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>Sensors (also military), charged-coupled devices (CCDs), data storage (read/write), camouflage, LEDs.</td></tr>
<tr><td>Affordability</td><td>Not determined.</td></tr>
</table>

BACKGROUND

The PCRC is used by chlorophyll in plants to capture photon transmission and transduce to chemical/electrical energy.

DATA SHEET 7.4. CHEMICALLY MODULATED ION CHANNEL

<table>
<tr><td>Developing Critical Technology Parameter</td><td>
<table>
<tr><th>Parameter</th><th>1999</th><th>Projected by 2010</th><th>Nature's Limit</th></tr>
<tr><td>Voltage flux (mV)</td><td>a few mV to +20</td><td>–150 to +20</td><td>~ 150 (lipid membranes)</td></tr>
<tr><td>Process time (ms)</td><td>< 10</td><td></td><td></td></tr>
</table></td></tr>
<tr><td>Critical Materials</td><td>Proteins that form channels and where channels open/close in response to chemical or voltage gradients.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>Production of lipid bilayer with ion channel proteins oriented appropriately.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>Sensors.</td></tr>
<tr><td>Affordability</td><td>Not determined.</td></tr>
</table>

BACKGROUND

Chemically modulated ion channels permit voltage flux to go from –70 mV to +20 mV in millisecond times by ion passage across gradient. The enabling phenomenon is the transduction of a chemical event to an electrical signal.

DATA SHEET 7.4. MOLECULAR MOTORS

Developing Critical Technology Parameter	The nanoscale molecular motors are protein molecules that exhibit vectorial movement along a surface. These proteins have diameters with dimensions of 20–50 Å. Dynein and kinesin are driven by the hydrolysis of ATP (~ 5–6 kcal/mol).
Critical Materials	Dynein moves in one direction while kinesin moves in the opposite direction. This behavior is analogous to the inverse flow of electrons and holes across a diode junction.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Switches (molecular).
Affordability	Not determined.

BACKGROUND

In recent years, proteins that function as molecular motors have been isolated from neural tissue. They propel themselves along a surface in a linear manner and are powered by the hydrolysis of a biomolecule and ATP. The attachment of several such motors to a particle will result in the propulsion of the particle in a fixed direction. Emerging biological energy system technologies are enabling for nanoscale motors.