Power Electronics Building Blocks (PEBB) Program

PEBB Bringing a Whole New Perspective to Power Control and Distribution

JOSEPH C. PIFF

The Power Electronics Building Blocks (PEBB) program was a government-sponsored research and development program with the vision of changing the paradigm for designing and manufacturing electrical high-power conversion and control products. Since the U.S. Government does not manufacture products, success of this program would be measured by the acceptance of the new concept by the power electronics manufacturing industry and by the various commercial and military users of these products. A change in the design and manufacturing paradigm would effect a change of emphasis from pure operational efficiency to a combination of operational and design and manufacturing cost efficiency.

New Power Electronics Program Generated, Funded by ONR

The Office of Naval Research (ONR) exists to invest taxpayer dollars in programs that define basic knowledge and exploit that knowledge to develop technology options that provide affordable capabilities to the Navy and Marine Corps. ONR pursues an integrated Science and Technology (S&T) program from basic research through manufacturing technologies. All programs are to consider the affordability of the final product. Research areas include oceanography; advanced materials; sensors; electronics; surveillance; mine counter-

__Piff__ is Manager, Technical Programs Department, Anteon Corp., in Arlington, Va. He holds an M.E. in Engineering Administration from The George Washington University and a B.S. in Engineering Physics from Cornell University. He has 30 years' experience as a defense contractor in planning, managing, coordinating, and executing R&D projects. Currently, he is working for ONR in several program offices. The author gratefully acknowledges the many Anteon staff members who furnished their expertise to the efforts described in this article, as well as __Terry Ericsen,__ ONR, who directed the program and developed the graphics.

Photo by David McLaughlin, Anteon Corp.

measures; weapons; and surface ship, submarine, and aircraft technologies.

The Power Electronics Building Blocks (PEBB) program, conceived in the ONR Ship Hull, Mechanical and Electrical Systems Science and Technology Division, and initiated in late 1994, included Research and Development (R&D) of electronics, materials, and manufacturing techniques. ONR funded the program at Anteon Corp., where the company performed program management assistance; PEBB design, fabrication, and testing; PEBB trade show; and PEBB communication system design and implementation work.

The primary responsibility of the ONR Program Management Officer, after conceiving the idea for the product and achieving an indication of interest from the user community, was to assemble a team of R&D organizations that could move from concept to reality in a relatively short period of time. At the same time, he had to incorporate evolving DoD and ONR procedures into his program plan to ensure program acceptability by ONR senior management personnel, who ultimately have funding authorization authority over specific agency research programs.

The Power Electronics Building Blocks (PEBB) program fabricated a special, lower-power demonstration unit that could be demonstrated at trade shows. Employing the latest technology, the demonstration unit could operate on single-phase, 220V input power. At each show, we continued to demonstrate increasingly varied and sophisticated types of electrical loads powering practical operating systems.

The PEBB concept requires a whole new way of thinking about power control and distribution. Navy procurement personnel and ship design and procurement personnel at organizations that design and build our nation's ships (i.e., shipyards) must be prepared to consider these new ideas as they are readied for implementation. Major procurement and life cycle cost savings, and space and weight savings were predicted after the success of the PEBB program.

Assembling a Team

To most quickly achieve this new way of thinking, we began educating the appropriate personnel as soon as practical. We also began preparing the PEBB program products for Fleet implementation by developing prototype demonstrations of predicted shipboard equipment as quickly as possible.

A relatively large team was assembled that included academia, a Navy laboratory, Federal Government laboratories, industrial manufacturers, and system integrators for commercial and military customers (Figure 1). Together, they tackled the management challenges of implementing PEBB using several available techniques, including electronic communication and collaboration, definition of an open architecture, public demonstration of interim product, and technology review workshops.

Additionally, the policies and procedures of ONR dictated schedule challenges that had to be addressed. The PEBB program was the first Concurrent Engineering S&T program undertaken at ONR, as well as the first S&T program to initiate Integrated Product and Process Development (IPPD) procedures under the then new Department of Defense Directives issued by the Secretary of Defense in 1995.

Terry Ericsen, ONR PEBB Program Management Officer, has stated that undertaking the management of a program implementing these new directives in a pervasive, highly aggressive technology program has been the greatest challenge of his career.

This article will address the management issues encountered during prosecution of the PEBB program.

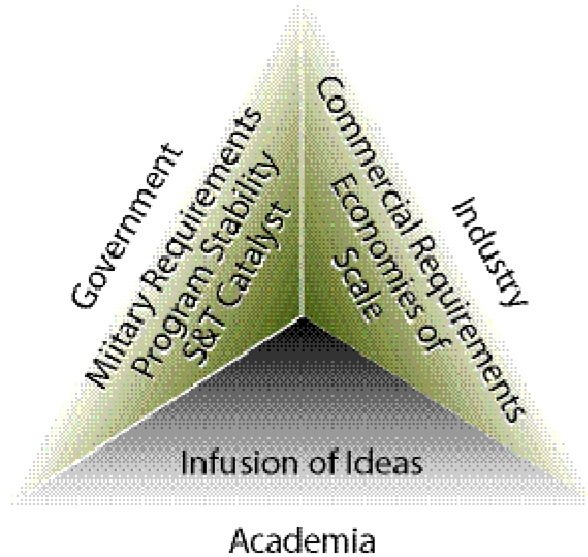
Market Information

Commercial and military organizations have been moving toward using electrical energy as the universal medium for transport of energy for several years. The concept of energy transport using electrical wires rather than by mass transport using steam, air, or other fluids in factories and in air, land, and sea vehicles offers many advantages, including reduced piece parts, ease of control, and minimized wear. The end result is the potential for a substantial increase in performance and a reduction in ownership cost of the end product.

The Navy has performed many studies of the benefits of employing more electric systems on ships, and concluded that both fabrication and operational benefits accrue. Additional cost benefits accrue if products have both a commercial and military application.

A primary enabling technology for the entire range of "more electric" applications is the rapid evolution in the field of power electronics (Figure 2, p. 49). A family of power electronics devices allows the production of power management modules that can handle all of the electric power control and conversion functions required to move power from the generating and storage sources to the ultimate loads. Consumers purchase the added value of electrification of our world in products such as automobiles that now, more often than not, incorporate electric windows and door locks. The PEBB program was initiated in recognition of the opportunities for cost reduction in power electronics by exploiting and improving emerging device technology (especially solid-state power devices), packaging concepts, and circuit topologies.

FIGURE 1. **Collaboration Triad**



The mission of the PEBB program was to design, develop, and demonstrate Power Electronics Building Blocks for commercial and military applications. The PEBB concept was to convert from complete system designs for each application—the clean sheet of paper approach—to a system design achieved by selecting from a small set of standard modules, i.e., a modular design approach. A PEBB was defined as a universal power processor that changes any electrical power input into any desired form of voltage, current, and frequency output (Figure 3, p. 50). Considering the wide range of power handling requirements, a family of devices was expected.

ONR was the developer and primary sponsor of all PEBB and PEBB-related R&D. Commercial applications include electric automobiles, utility distribution systems, motor controllers, and alternative (e.g., solar, fuel cell) power systems. Military applications include high-power propulsion, auxiliary, and weapon systems for ships, submarines, aircraft, and land vehicles that use intelligent control to manage electric power systems efficiently and provide reliable, uninterruptible power. The Navy needs standardized, intelligent, solid-state power control devices, capable of managing a few Watts to mega-Watts to prevent proliferation of high-cost, single application devices.

The Navy developed, fabricated, and demonstrated a family of universal, scaleable power control devices that deliver high-quality, digitally synthesized electric power for multiple applications. The PEBB, coupled with recently developed, power-dense MOS (Metal-Oxide Semiconductor)-Controlled Thyristor (MCT) switches, offers the opportunity to reduce size, weight, and cost of commercial and military power electronics systems by factors of 10 or more. A programmable multipurpose device, the PEBB is replacing many unique, high-cost power-conditioning elements used in previous system designs.

Engineering Approach

Product Description—Open Architecture. The PEBB is a complex device with electrical and mechanical boundaries that were purposefully set fuzzy at the beginning of the program to encourage broad, innovative, "out-of-the-box" thinking. A team of research and customer (or user) personnel was assembled to discuss the operational and physical requirements to be expected of the products and to place some structure and priority on the design concept. Team members were asked to develop a list of prioritized requirements for their application(s). Then, the team was assembled to discuss, weight, and score

> **A PEBB is defined as a universal power processor that changes any electrical power input into any desired form of voltage, current, and frequency output. Considering the wide range of power handling requirements, a family of devices was expected.**

the requirements to develop an indication of those features that were most important to the largest number of potential users.

In an effort to gain the greatest amount of customer satisfaction, the team used the "House of Quality" process to choose the best design characteristics for the Navy's investment. We expected that some requirements would be contradictory, at least according to the laws of physics as we understood them, and would have to be negotiated to achieve something practical. To gain a consensus opinion of what a PEBB is or should be, a categorized and prioritized list of requirements was developed that was then used to set a relative level of need by each participant.

In late 1998, ONR came up with the descriptive nomenclature of "Plug and Play," a concept very similar to that used in the personal computer industry. (Interestingly, the acronym for Plug and Play (P-n-P) plays off the solid-state device description of the interface: p-n or n-p.) Starting with a finite number of standard frames that are built to accommodate open, industry-standard electrical and mechanical interfaces, a manufacturer (or an individual) can purchase off-the-shelf components and assemble a functioning personal computer almost as easily as a child can assemble a structure from a set of blocks.

Because of the power levels involved, and to minimize the losses introduced by inefficient electrical design, the power electronics industry has been faced with the need to design specific solutions to each power conversion situation. The purpose of the PEBB program was to eliminate the need for most, if not all, of that unique design requirement in favor of a set of designated building blocks for assembly—much like a child's set of blocks. However, for this concept to work, both the supplier and customer needed to benefit. Therefore, the program needed to develop boundaries.

On one side of the boundary, the "plug" side, the interface specifications needed to be well known so that every manufacturer could produce a product that would work with every other manufacturer's product. On the other side of the boundary, the "play" side, there was room for unique engineering and, therefore, competition among suppliers, i.e., niche marketing. With this structure, PEBB manufacturers would have an incentive for entering the market with building blocks of their own.

Just as you can purchase a modem for your personal computer from any number of manufacturers, each with its own unique characteristics, the PEBB program developed an architecture that allows unique characteristic competition. For example, if a chip manufacturer wanted to sell complete inverters, that manufacturer would manufacture the chips, but would purchase all other components (e.g., filters, cabinets) from other manufacturers and assemble the complete system for sale. Likewise, that manufacturer may consistently buy components from the same set of suppliers or may have an in-house line of products, with a corresponding set of costs, which are assembled from components from multiple manufacturers. We wanted to encourage collaboration on the setting of standards for the interfaces between components. For plug and play to work, the system must be smart enough to recognize each com-

FIGURE 2. **Trends in Power Semiconductor Devices**

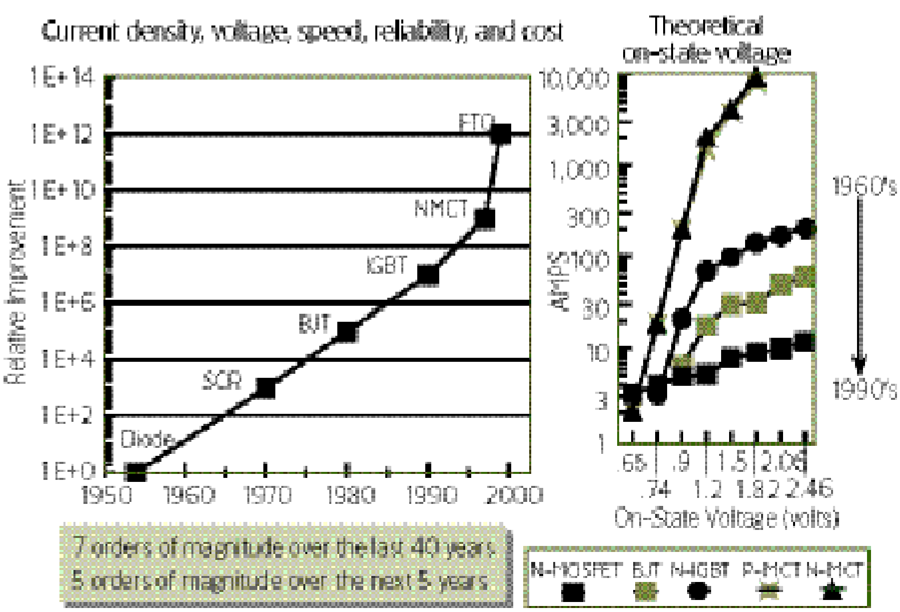
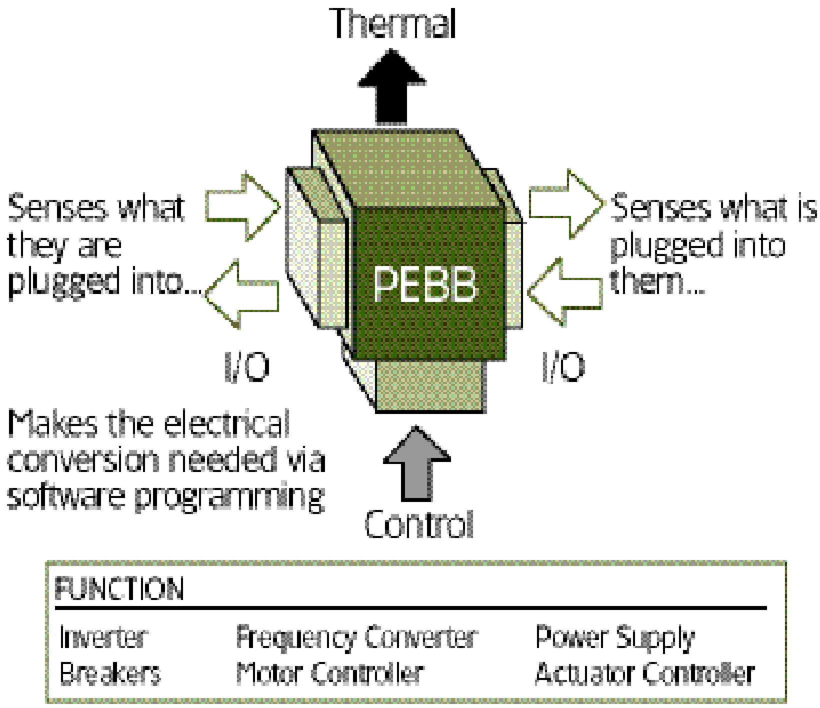


FIGURE 3. **PEBB Systems—A Simple Set of Blocks for Power Electronics**



ponent and adjust its operations to achieve the desired output with both the available input and grouping of components. However, the standards-setting process does not begin until a group of manufacturers in the hierarchical industry decide that standards are to their mutual financial advantage, so this part of the process is still ongoing.

Dual-Use Development. When commercial products are purchased and applied in military systems with little or no modification, the expectation is that, because of the competitiveness of the commercial market, the products are less expensive than products designed specifically for military application. The Navy desires: 1) to build systems based on pre-engineered, pre-tested, commercially applied building blocks instead of one-of-a-kind system developments; and 2) to buy hundreds of units from production lines that produce millions of units. Therefore, the PEBB concept was to initiate the development of a commercial product with pre-planned applicability to military systems. A market evaluation revealed that power electronics products were being engineered into commercial products and that this was a growing trend.

As conceived, the PEBB is software-reconfigurable; multi-purpose; smart; and is a universal device, replacing several specialized devices like circuit breakers, motor controllers, power conditioners, or inverters. The PEBB combines power-dense semiconductor developments with improved fabrication and packaging processes to reduce the size, weight, and cost of electric power conversion systems by a factor of 10 or more; and increases the efficiency in some areas by a factor of 100 (Figure 4 below).

Since it is a single, standardized unit of manufacture, production of this device in large quantities reduces its cost. And since its controller incorporates a microprocessor, it provides an interface for device-level feedback and system-level control. A PEBB, jointly developed with industry, meets both commercial and Navy specifications. Thus, commercial use of PEBB technology contributes to even further cost reductions. Potential savings for the military are enormous if it draws upon the civilian sector to jointly develop a PEBB and its market

The architectural similarity between Navy zonal electrical distribution and the proposed drive train for the Department of Energy (DOE) hybrid car is shown in Figure 5 (p. 52). The conceptual Naval zonal system shows zones for electrical propulsion equipment, power generation and conversion equipment, and "user" or "auxiliary" equipment. The conceptual electric/hybrid vehicle shows a power source (fuel cell, turbine, etc.), bi-directional inverters, an energy management and control system, energy storage, and an electric drive motor. In some applications, the power levels are similar, while the large loads onboard ships are significantly larger than those necessary in an automobile.

Concurrent Engineering. Concurrent Engineering was an early name for the currently implemented (and expanded) IPPD initiative within DoD. The DoD definition of IPPD is "a management technique that simultaneously integrates all essential acquisition activities through the use of multidisciplinary teams to optimize the design, manufacturing, and

FIGURE 4. **PEBB Program Achievements vs. Goals**

PERFORMANCE PARAMETER	UNITS	PRE-PEBB ACHIEVEMENT	PEBB GOAL	PEBB ACHIEVEMENT
Power Density	KW/ft3	5	50	50-600
Turn-Off Current	A/cm2	50	500	300
Turn-On di/dt	A/nsec	1	10	1500
Turn-Off Time	nsec	1200	120	400
Off State	Volts	1000	3500	6500
Switching Frequency	KHz	5	70	10-20

supportability processes. IPPD facilitates meeting cost and performance objectives from product concept through production, including field support."

One of the key IPPD tenets is multidisciplinary teamwork through Integrated Product Teams (IPTs). These IPTs are staffed with experts in the various technical fields (e.g., design engineering, manufacturing, quality control, logistics, product support) required to bring the product to fruition. When studied, many of the tenets of IPPD can be related to the concepts implemented in the International Standards Organization (ISO) 9000 Quality Standards. IPPD was implemented in DoD by direction of the Secretary of Defense on May 10, 1995, several months after the PEBB program had begun operations.

Ericsen, the ONR PEBB Program Management Officer, had already been working for several years prior to program initiation to establish realistic but aggressive goals for the program. He had been meeting with power electronics industry principals to determine the feasibility of the concept, to identify technical and manufacturing shortfalls, and to establish the alliances necessary for success. His IPT consisted of principals in the power electronics device design and manufacturing industry and those organizations that purchase those devices to assemble functioning power conversion units, along with Navy power electronics R&D personnel.

This team met frequently in the early years of the program and used the team communication system described on p. 52 to reduce the need for expensive face-to-face meetings. Its members possessed the correct mix of expertise to ensure that the design being developed could be produced using standard manufacturing equipment, would satisfy commercial/industrial and military requirements, and would have reasonable reliability and life cycle expectancy when deployed in practical applications.

The PEBB IPT, working with the PEBB Program Management Officer, established a series of intermediate milestones

The PEBB program was initiated in recognition of the opportunities for cost reduction in power electronics by exploiting and improving emerging device technology (especially solid-state power devices), packaging concepts, and circuit topologies.

for operating hardware. This new technology was a radical departure from current practice in the industry. As such, incremental demonstration of the developing capability was expected to be necessary for continuing acceptance of the feasibility of the concept. Therefore, ONR established three incremental demonstration milestones using standard Navy terminology for replacement equipment: function; form and function; and form, fit and function (Figure 6, p. 53).

- The first generation of PEBB devices used first-generation advanced power electronics solid-state technology to demonstrate in working models the functionality of the concept.

- The second generation of devices demonstrated multi-functionality by integrating the controlling microprocessor with the high-density power semiconductors to eliminate separate, unique devices for each required power electronics function.

- Finally, the third generation of devices demonstrated all of the foregoing in a compact, power-dense package suitable for both commercial and military applications.

Each step along this path to ultimate success was defined in a manner that would yield solid information for the next design step. If any technological difficulties were encountered, they would be addressed long before the point of no return. Additionally, ONR encouraged the Naval Sea Systems Command to become familiar with the technology by participating on the IPT and by developing and testing units manufactured by their traditional commercial/industrial suppliers.

Communication Management

Program Reviews. Early in the PEBB program, the primary method of communication among program participants was the quarterly Program Review. The largest contractor in the program was the silicon chip designer/manufacturer, and that contractor usually organized and conducted the reviews at its site.

The first day was usually set aside for proprietary information exchange between this contractor and the government concerning new chip design progress. Then, one or two days of open presentations from various program participants allowed for discussion of the meaning of the PEBB concept and further refinement of the architecture of the device. These reviews included "breakout" sessions wherein the audience was broken into smaller parts by choosing specific topic areas for detailed discussion.

As the program progressed and the team communication system described on p. 52 was implemented and improved, these program reviews were scheduled less often and were held at the locations of other program participants, including universities, Navy laboratories, and other government agency sites. These face-to-face meetings were highly successful at getting program participants into one-on-one discussions (especially during breaks in the presentations). These discussions were often the catalysts to major agreements for partnerships or for technological progress.

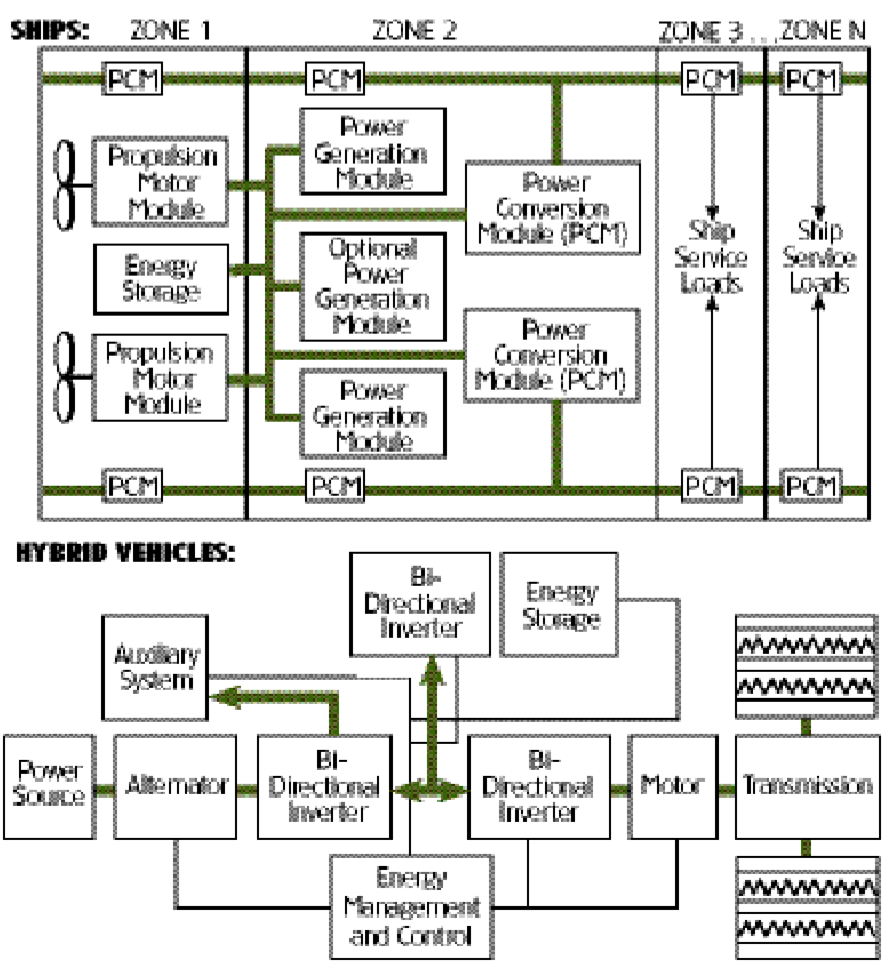
Team Communication. From the beginning of the PEBB program, it was obvious that an advanced communication system was going to be necessary to coordinate the operation of the program and to encourage program participants to collaborate during device development. The PEBB team of government laboratories, public and private universities, and commercial/industrial organizations was described as a "virtual company." The virtual company was defined to mean that all participating organizations would be considered to be "units" of a company structure and, therefore, communication among these units should be as seamless as it would be within a well-functioning single organization.

The team was formed, but the method of communication needed to be developed. Lotus Notes™, a commercially available product, was chosen because it provides e-mail, Internet browsing, Internet or Intranet site development and display, and database development and implementation for almost any conceivable purpose: project scheduling and tracking, collaborative document development, document routing, document and information sharing, and more.

Further, Lotus Notes includes a collaboration environment allowing for multiple program participants to comment on or edit a document. This allowed PEBB program participants to state their opinion about a topic, add more information about the topic, or ask questions about what someone else said. This capability is especially useful, for example, for the process of developing product interface specifications. One of the purposes of the ONR-sponsored program reviews was to allow interested participants to get to know each other and open a dialogue that would continue between reviews.

To encourage this interaction, we established "forums" within Lotus Notes that included databases containing the design thinking to date, and areas where individuals could share and "discuss" ideas. The forums established included Modeling and Simulation; Applications/Systems; Commercialization; Processing; Passive Components and Materials; Packaging; PEBB Demonstration; Electromagnetic Compatibility/Electromagnetic Interference (EMC/EMI); and Form, Fit, and Function (3F), also known as Plug and Play.

FIGURE 5. **Architectural Similarity of Ships and Hybrid Vehicles**

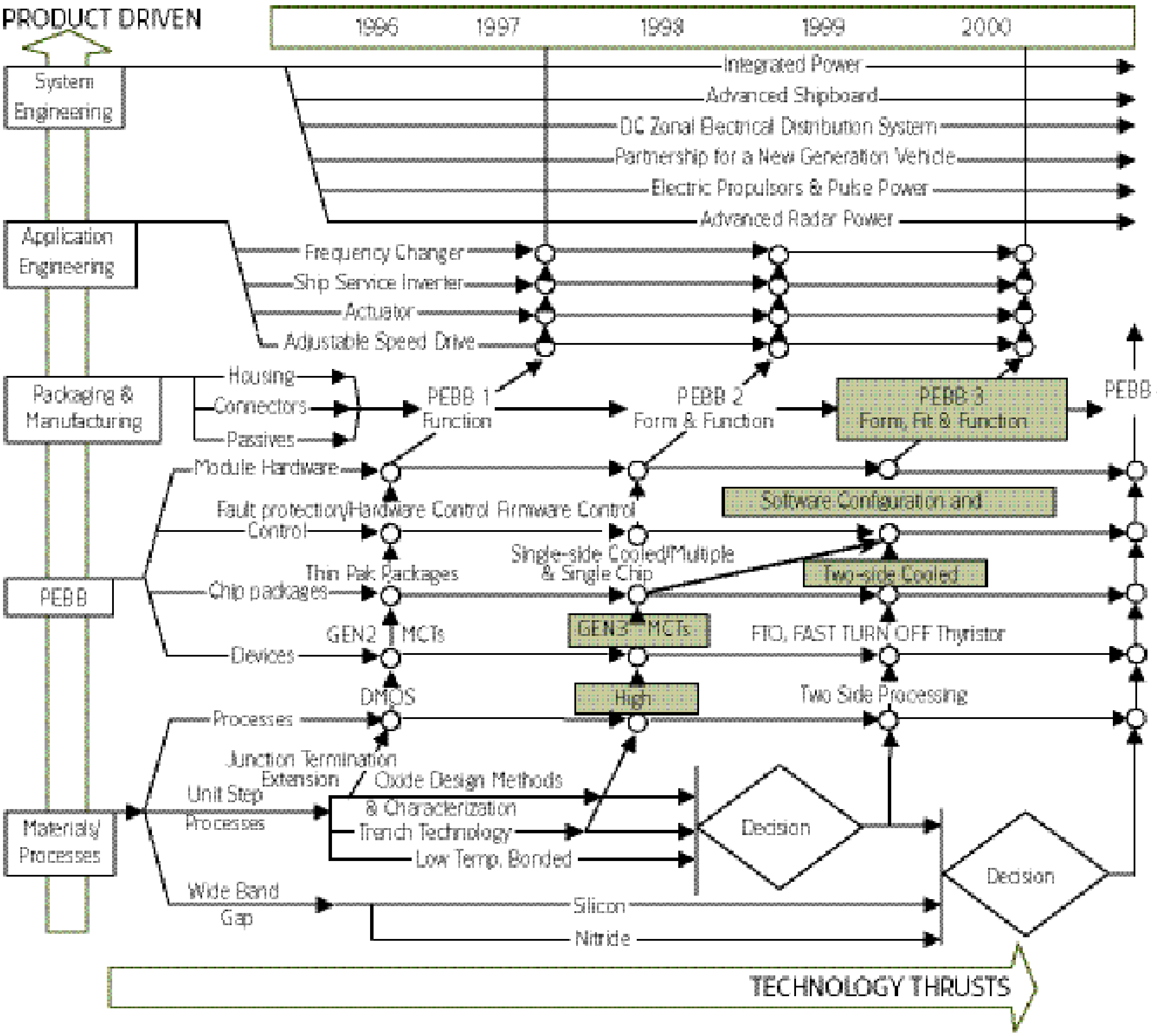


Public Demonstrations. For a large commercial market to develop, the PEBB vision needed to be shared with organizations that were not participating in the PEBB design and development program. As R&D projects yielded operating products, those devices were incorporated into practical operating systems that could be demonstrated at trade shows. For this purpose the PEBB program fabricated a special, lower-power demonstration unit that employed the latest technology, but that would operate on single-phase, 220V input power.

At each show, we demonstrated increasingly varied and sophisticated types of electrical loads. For example, we demonstrated an electrical motor operating a pump with a manual control valve to achieve a "needed" flow rate and compared that with operating the motor with PEBB control to achieve the same flow rate without the control valve and using less power, i.e., we could throttle the power rather than the flow.

The design of the PEBB supports control of electro-mechanical devices from a common base, thereby easing the

FIGURE 6. **PEBB Development Schedule**



manufacturer's requirements for developing specific control hardware and reducing the cost of delivery of final, operational product. For example, a linear motor manufacturer loaned a motor to be displayed as a load on the PEBB demonstrator. We eliminated the manufacturer's controller card and operated the motor with the latest version of the PEBB to demonstrate the ability to precisely control the acceleration rate of a projectile.

Workshops. In addition to the Forums implemented in Lotus Notes, specific topic-area workshops involving technology-specific experts were organized and conducted. We held an Applications Workshop and a Soft Switching and Resonant Converters Workshop.

Elements Contributing to Success of Program

The five-year, ONR-sponsored PEBB program was a highly aggressive technical program that developed new technology for application by commercial and military organizations. Commercial and military supply organizations have taken the concept and are proceeding with final engineering development. So, what were the elements that contributed to the success of this program?

First, a highly competent, highly dedicated program champion, Terry Ericsen of ONR, was consistently involved in all aspects of the program, from the intricate technical details to dealing with Congressional and Secretarial review and funding issues. His exceptional efforts to develop and hold together a large team of highly diverse personnel were perhaps the greatest contributor to the success of the PEBB Program.

Secondly, the communication system, both face-to-face and electronic, worked effectively to keep everyone informed as to the current state of development of the product and the plans for the future. However, the portion of this system designed to encourage the sharing of development ideas did not work as well as desired. We believe that lack of training and, possibly, the competitive nature of the government contracting business was the greatest impediment to this effort. People were either unwilling or unable to find the time to learn the collaborative software functions. Moreover, the possibility of a lack of trust among participants negated the positive factors evident in the software implementation. For this type of effort to succeed in a "virtual company," a lot of effort to establish mutual trust will need to be expended.

Finally, the timing was just right. Our experiences in talking to people in attendance at trade shows was that both the commercial and military markets were ready for less costly, more compact design of power electronics systems. The technology, especially in silicon-based chips, was at the point where practical devices could be designed to achieve new levels of performance. Another measure of success of a technology development program is the number of new patents issued—over 70 patents were issued to PEBB program participants.

This development approach demonstrated the limitless possibilities for product development from concept to reality when government, academia, and industry cooperate in the drive toward the major new technologies that will affect our lives in the 21st century.

A New Paradigm

ONR succeeded at instituting a new paradigm into the thinking of the designers of power electronics equipment. How does the Navy benefit? What are the next steps?

Several developments need to be continued in parallel. First, the heart of the PEBB is the switch as implemented in silicon. Further development of this technology to get the switching speed up from the current level of between 10 and 20 KHz to 70 KHz needs to be pursued. Several concepts are in process. At the same time, researchers in this technology area are considering material changes that could increase the high end of the temperature envelope, allowing a greater number of applications in harsh environments.

Secondly, continuing efforts to get industry to work together to establish interfaces between components and then effective minimum interface specifications are being pursued by ONR. Real plug and play cannot be achieved until this step is completed.

Finally, systems engineering needs to be pursued. The ONR PEBB Program Management Officer's next program responsibility is called the Advanced Electrical Power System (AEPS). The AEPS program will take Ericsen's success one step further and begin speculating about the many alternative system designs for future systems using low-cost, flexible, modular, smart electrical high-power control and conversion devices. One of the many applications of this technology in the Navy is to use linear motors to launch and retrieve aircraft from the decks of aircraft carriers.

The ingenuity of our ship system design engineers will be tasked to employ this new technology in a manner that improves the operability, maintainability, and survivability of our Fleet assets and reduces the overall cost of these systems.

Editor's Note: The author welcomes questions or comments on this article. Contact him at JPiff@Anteon.com. For more information on topics discussed in, or related to this article, visit the AEPS/PEBB and ONR Web sites at http://aeps.onr.navy.mil and http://www.onr.navy.mil.

DAU Award Presented to Outstanding Student

The Defense Acquisition University (DAU), in partnership with the Bryant Adult Alternative High School, presented Bryant student Marlene Luchi with DAU's Outstanding Student of the Year Award. The presentation took place during a Bryant Honors ceremony at the school in Alexandria, Va., on Feb. 7.

Selected by the counseling staff at Bryant, Luchi has attended the school since 2000 and participates in many activities. She is currently President of the Bryant National Honor Society and also serves on the Leadership Committee. Luchi holds two jobs, one of which is at DAU as an assistant in the Office of the President. As a Partner in Education with Bryant School, DAU presents this award twice a year to recognize students who exemplify leadership, learning, and service. This is the first time the awardee has also been an employee at DAU.

From left: Air Force Col. William McNally, Air Force Chair, DAU Executive Institute; Marlene Luchi, recipient of the Outstanding Student of the Year Award; Army Staff Sgt. Duane Adens, DAU; and Navy Senior Chief, James Pratt, DAU Enlisted Advisor.
Photo by Barbara Zenker.