PEBB
TECHNOLOGY DEVELOPMENT
AND
COST ASSESSMENTS
BENCHMARK
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Code 36

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I. INTRODUCTION

This report describes both the PEBB Technology Development and PEBB Cost Analyses conducted to date by most of the companies who have been involved with this research since it's inception. Approximately 51 sources were reviewed and information gained from the relevant ones are provided in this report. The PEBB program is vast in it's scope as well as in the number of participants involved. Every effort has been made to include factual input from as many of the program's participants as possible with no one omitted intentionally. Another challenge to this "snapshot in time" approach is that the research is a "moving target". This leads to situations where recent PEBB innovations, or developments are not always known by everyone within a given organization.

II. CONCLUSIONS

From the information compiled in this report, VECTOR has drawn the following conclusions that will be pertinent to the future market potential analyses to be conducted under the PEBB Commercialization Program. The three major categories of conclusions are:

(1) the Primary Industries anticipated to receive the greatest commercial benefit from incorporating PEBB modules into their systems;
(2) the Targeted Costs & Prices which have been estimated that the markets would bear; and
(3) the Major Cost Drivers which have the greatest effect on reducing costs.

For the purposes of this report, the term "price" shall be defined as the dollar amount paid by a user, while the term "cost" shall be defined as the dollar amount incurred by the manufacturer to produce an item. The superscript referencing notations used below refers to the numbering in Section IV (Cost Assessments) of this report.

The **Primary Industries** are the Automotive and Consumer Electronics Industries due to the potential economies of scale[B] as well as the Utility & Industrial Facility Industries which will drive cost reductions and technology innovations.[F4] For high power applications (≥1MW), the primary applications are in the Utilities, Navy and pulse power[H].

Regarding **Targeted Costs & Prices**, the Auto Industry goal is to obtain a PEBB cost reduction from $25/kW in 1997 to $7/kW in 2004.[D] The Navy's goal for Shipboard (SC-21) and Aircraft applications, are to acquire PEBB modules at $60/kW at 50kW/cuft[F2.] For high power applications, current PEBB technology supports a target price of $50/kW for an AC module in $750k high-speed transfer switches.[H] The future PEBB technology target price in high power applications is $30/kW for an AC module in a $500k high-speed transfer switch due to the elimination of the mechanical bypass switch.[H] The current PEBB technology supports a target price of $500/kW - $700/kW for a DC module in a 5MW – 15MW UPS system while the future PEBB technology target price is $250/kW in 3 years.[H] For generic high power applications (>10MW) the maximum price that the market will bear is $0.20/W rated.[K]

The **Major Cost Drivers** identified are as follows: In Navy ship applications[C] and Automotive applications[E], PEBB modules need to be able to perform multiple functions. Two major Integrated Power Module (IPM) cost drivers in the Auto Industry are (materials & components) and (assembly, labor and testing)[D]. The cost of silicon component dominates the cost of the power electronics and the cost of the power electronics dominates the cost of the electric vehicle power train.[F3] The Auto Industry IPM cost/kW is inversely proportional to kW.[D]

III. TECHNICAL DEVELOPMENT

A. PEBB Definition and Terms

PEBB is actually a concept rather than a particular product or device. The PEBB concept answers a major shortcoming of the power electronics world. At present, every power electronic circuit, whether it is for power conversion or power control, is designed from scratch using discrete components. Years ago, the analog signal processing and digital processing worlds went to standardized integrated circuits (IC) and microprocessors, eliminating millions of discrete components in common products. However, there is very little standardization in the design of rectifier circuits, inverter circuits, motor controllers and power distribution circuits. The Power Electronic Building Blocks will be the standard integrated components similar to operational amplifiers on signal processing or logic ICs in digital circuits. One of the attractive features of PEBB modules is that they can be “stacked” or connected in series to achieve higher power levels.

The intent of the PEBB program is to development or foster the development of a family of power electronic modules that can be used in 80% of the power conversion and power control applications in the commercial and military world. The PEBB family is expected to consist of the following modules organized by these approximate power ranges.

1. Low Power	10 kW to 100 kW
2. Medium Power	100 kW to 500 kW
3. High Power	500 kW to 10 MW

PEBB Terms:

1. ARCP – Auxiliary Resonant Commutated Pole topology is a flexible power electronic circuit design in the family of pulse width modulated (PWM) switching power converters. The circuit uses soft switching to perform many different conversion functions simply by changing the control algorithm of the transistor switches.
2. Hard Switching – Turning off a solid state switch while current is flowing through it.
3. Pulse Width Modulation – PWM is the lengthening or elimination of integer numbers of pulses to fabricate an approximation of desired output wave form.
4. Soft Switching – Turning off a solid state switch that is conducting AC current at the point where the current is passing through zero (zero current switching, ZCS), or at a time when the voltage across the switch is zero (zero voltage switching, ZVS).
5. Switching Speed or Frequency – Input power to the PWM power converter circuit is chopped by the solid state switching device at the switching frequency.

B. PEBB Goals

The technical goals for the PEBB modules/building blocks are as follows:

1. Size and packaging

   A 250 kW single phase PEBB module should fit in a volume roughly the size of a shoebox without the output filter circuits but with built-in provision for thermal management. Thermal management is accomplished by connecting hoses to the module and pumping cooling fluid through the module as needed.

2. Power conversion efficiency greater than 98%.

3. Output power quality less than 5% Total Harmonic Distortion (THD).

4. Electromagnetic Interference (EMI) levels below those specified in Mil Std 46.

C. PEBB Program Definition

It is the objective of the PEBB program to promote innovative development of a family of power electronic devices that satisfy the PEBB goals. These devices will not be developed and paid for solely by the ONR program, but will be produced by companies following the basic concept. These companies will produce these devices to remain competitive in the power electronics market. The objective of the program is to stimulate and support competing ideas in order to advance the state of the art and produce the best possible PEBB modules. Another goal is to have PEBB modules produced in the US by US manufacturers.

D. Status of the Program

Low power PEBB modules are being developed by SatCon Corporation and by Virginia Tech's Virginia Power Electronics Center (VPEC). These modules are in the range of 10 kW to 50 kW and are intended for use in the electric and hybrid-powered automobiles, and for use in the motor drives on shipboard pumps. The low power PEBB modules are based on Integral Gate Bipolar Transistors (IGBT's).

Medium power PEBB modules are being developed by Power Paragon Incorporated, Silicon Power Corporation (SPCO) and the Naval Surface Warfare Center (NSWC). These modules are in the range of 100 kW to 250 kW and are intended for use by the US Navy in such programs as DC Zonal Electric Distribution (ZED) on future ships such as the DD21 and the CVX. The medium power PEBB modules are based on IGBT's and the new Mos Controlled Thyristors (MCT's). Commercial applications of medium power PEBB modules include large solar panel installations, fuel cell installations and uninterruptible power supply installations where the electric power is produced in DC. The US Air Force Lab at Wright Patterson is currently pursuing research on a combined starter and generator unit for turbine engines with PEBB based power conversion and control for use in more electric aircraft.

High power PEBB modules are being developed by SPCO. These are referred to in the PEBB program as the H-PEBBs, and work in the 3 MW range. These PEBB modules are based on Mos-Turn-Off thyristors (MTO's), and Gate-Turn-Off thyristors (GTO's). These are intended for use in the new ship programs mentioned above as flexible primary power conversion systems and ship propulsion drives, and commercially in utilities and industrial plants where uninterruptible power systems are essential.

E. Products Under Development

The SatCon low power PEBB is a switching inverter operating at around 50 kW. It features an integral heat exchanger and electrical bus design that facilitates stacking or connecting of multiple modules in series for higher voltage or current applications. Also included in the module are the gate driver circuit boards that control the IGBT solid state switches and the controller that operates the gate driver boards.

The Power Systems Group of SPD/Power Paragon are developing a medium power PEBB DC/DC converter for use in the Navy DC ZEDS program. The converter uses MCT's in a soft switching circuit design that promises very high efficiency (99%), and low electromagnetic interference (EMI). SPD/Power Paragon is also developing the Power Node Control Panel (PNCP) that is the heart of the Power Node Control Center (PNCC). The PNCP uses the PEBB concept in the role of solid state breakers, current limiters, and power conversion. This effort has commercial applications in DC/DC conversions required in fuel systems for uninterruptible power supplies and hybrid vehicles.

The SPCO products were covered in the previous section.

Northrop-Grumman is producing PEBB controllers. In order to use PEBB modules in 80% of the power conversion and control applications, it is necessary to have a circuit design that is flexible, and can, with a change of software ,be reconfigured to handle a variety of input and output power types. The ARCP circuit topology will do this under the control of a programmable digital signal processor (DSP) based controller. Northrop-Grumman is developing such a controller with the objective of eventually producing a universal controller that can be used with many circuit topologies using PEBB modules, including but not limited to the ARCP design.

MCT based PEBB modules are being produced by Harris Semiconductor Co. Transistor devices come in two types designated P and N depending on the direction of positive current flow through the transistor. Having both types of transistors available for a given transistor design is a great advantage to the circuit designer. Harris has available two generations of PEBB modules for delivery to users. The PEBB 1 modules contain N type MCTs (n MCT) with the associated power diodes integrated into the same package with provisions for the attachment of a water-cooled base. PEBB 1.5 modules are also available from Harris, and integrate n MCTs, IGBTs, and diodes, with gate drivers and water cooling. Harris Semiconductor is developing PEBB 2 modules similar in layout to the PEBB 1.5 but with the IGBTs replaced by P type MCTs (p MCT). PEBB 2 modules will be available in the Fall of 1998.

IV. COST ASSESSMENTS

This report is intended to summarize various studies and reports that have been written which provide insight into either current PEBB module costs, future targeted costs, major cost factors and the greatest potential markets associated with the commercialization of PEBB modules. The organizations that were contacted for this report and responded are certainly not comprehensive although they do provide a snapshot in time of each organization's perspective of PEBB cost associated issues. Each organization that was solicited or study that was reviewed will be identified and conclusions will be summarized.

A. Office of Naval Research Current PEBB Foci January 4, 1994

The following predictions represent price projections for future inverter circuits based on PEBB MOS-Controlled Thyristor (MCT) modules. The chart compares these PEBB MCT converters with inverter circuits using hard and soft switching commercial-off-the-shelf (COTS) components.

1. Baseline Inverter – This inverter uses COTS Integrated Gated Bipolar Transistors (IGBT) and hard switching technology. This represents the actual price for the inverter.
2. Soft Switching Inverter – This inverter uses COTS IGBT technology and soft switching technology. High frequency switching reduces filtering by 50%. This also represents the actual price for the inverter.
3. MCT I Inverter – This inverter uses a mix of IGBT and MCT technology. The 3-phase device vs. 3 x 1-phase device reduces power electronics by 70%.
4. MCT II Inverter – This inverter uses a much higher frequency that contributes to lower component costs. At 70 kHz, the filtering is reduced by 90%, and partial integration reduces controls by 50%.

INVERTER COMPONENTS	BASELINE	SOFT SWITCHING	MCT I	MCT II
(% of Baseline)				
Filter	40	20	20	2
Power Elex	20	20	6	6
Controls	10	10	10	5
Misc.	30	21	15	6
TOTAL	100	71	51	19
PRICE	90K	64K	46K	17K

Predictions were also made as to the cost for the following 3 PEBB modules:

1. PEBB 1 – 5kW/cu. Ft @ $0.24/Watt
2. PEBB 2 – 45kW/cu. Ft @ $0.24/Watt
3. PEBB 3 – 50kW/cu. Ft @ $0.03/Watt

B. Global Associates, Ltd.
PEBB QFD APPLICATIONS BOUNDARY DEFINITION ANALYSIS
February 18, 1997

The objective of this study was to apply a Quality Function Deployment (QFD) method to define the customer requirements for power control devices and use those requirements to establish a boundary for the PEBB. The Office of Naval Research (ONR) has collected numerous documents that pertain to the development of a technically sound, cost effective PEBB. Global catalogued these pertinent documents in a database format for future reference. The following is a summary of PEBB cost related findings.

The study revealed cost related information for applications in the automotive and consumer electronics industries:

1. Automotive Applications (AA) would most likely drive much of the PEBB market due to the very high volume potential. They also concluded that cost would be the paramount driver of this application.
2. Consumer Electronics (CE) applications for Variable Frequency Converters was also considered. Global concluded that the HVAC community would be a large player and that PEBB would need to address the special needs of this community including high reliability at low cost.

A meeting was conducted to brainstorm the requirements of PEBB functions and capabilities concluded that the Cost Characteristic of PEBB would require the following:

1. Use of multiple technologies for choosing the right device for the right application.

2. Automated assembly/test equipment.

3. Commonality of hardware where possible.

4. Limited number of component suppliers.

5. High volume applications to generate cost effective part pricing

6. Short manufacturing cycle time.

7. Standardized sub-assembly process flows to eliminate “custom” work.

8. Not to Exceed (NTE) $0.20 / watt rated.

Cost characteristics were also identified for various potential PEBB markets and a Customer Requirements Survey was conducted to determine the importance of each characteristic. The following cost characteristics were identified:

1. Low cost
2. Interchangeability
3. Economy of scale
4. Fast production time

The scale for determining importance was as follows:

1 = Low importance
3 = Medium importance
9 = High importance

The survey was conducted with the following results. The numerical value for each characteristic is the average score from the respondents.

	Low Cost	Interchange-ability	Economy of Scale	Fast Production Time
Aircraft	6	7	5	2
Space	2	5	2	2
Ships	5	9	5	2
Utilities	6	9	6	3
Consumer	9	9	9	3
Auto/Vehicles	9	9	9	9
Combat Vehicles	3	9	9	1

The study also included a discussion of various Power Systems issues. Within Power Systems, a discussion of packaging standard form issues was conducted with the following cost related conclusions:

1. "Any possible opportunities to fuse functionalities into single components/operations may serve to facilitate reductions in module cost while simultaneously reducing losses of efficiency and reliability across device or material interfaces."
2. "The greatest potential for solid state devices like PEBB would be the ability to avoid the extraordinary complex nature of power electronics. An example might include processing of micro-channel heat exchange surfaces into the active material itself. These solutions may require the development of novel manufacturing techniques, but this investment would be easily returned if the final cost allowed commercialization of a large scale."
3. Plug-in feature capability to limit costs.

C. Global Associates, Ltd.
PEBB QUALITY FUNCTION DEPLOYMENT STUDY FINAL RESULTS
September 15, 1997

This report was commissioned by ONR Code 334 and contains the results of a Quality Function Deployment (QFD) study. The study's objective was to determine customer and technical requirements for the Power Electronic Building Blocks (PEBB) program and apply them to a product development QFD process. The results are a detailed assessment of how to design PEBB while giving full consideration to customer requirements. The study also includes the completion of one House of Quality (HOQ). A Technical Working Group (TWG) consisting of technical experts, defined the functional characteristics necessary to design a PEBB for generic use and apply this to the development of an inverter for Navy Shipboard use. The TWG was also tasked to keep generic PEBB requirements in the process.

This QFD study looked at various ship attributes and assessed their level of importance in relation to identified PEBB requirements. Cost was identified as one of the attributes and was broken down into the following categories:

1. Acceptance
2. Manning/training
3. Repair/maintenance
4. Upgrade/modification
5. Habitability
6. Pollution control
7. Consumables
8. Disposal
9. Offboard infrastructure

The rating system used to indicated importance is seen below:

1 = Low importance
3 = Medium importance
9 = High importance

The results of this QFD analysis that compared PEBB requirements and ship attributes including the Cost attributes are shown in Figure 1.

D. General Motors - Advanced Technology Vehicles
AUTOMOTIVE INDUSTRY'S REQUIREMENTS FOR EFFICIENT AND COST-EFFECTIVE POWER ELECTRONIC SYSTEMS
Dr. Sunil M. Chhaya
December 9, 1996
Presented at the PEBB Requirements Review Meeting

This study was done with the participation of General Motors, Ford and Chrysler representing the automotive industry as well as various power electronics and passive component suppliers as part of the Electrical and Electronics Technical Team (#2) of the Partnership for a New Generation of Vehicles (PNGV). The group is developing automotive requirements for baseline power electronics modules. The mission of the team is to:

1. Develop the guidelines for standardizing the integrated power electronics module.
2. Enable modular architectures for redundant, scaleable and low-cost systems.
3. Bring the power electronics cost down by HALF EVERY TWO YEARS.

The report concluded that cost reduction could be achieved through:

1. Increased level of integration on Silicon
2. Increased level of integration within hybrid module
3. Innovative thermal management
4. Application-flexible partitioning of the Integrated Power Module (IPM) functions
5. Increased production volume for IPM

The report also determined that from a cost-reduction perspective, the IPM should have:

1. Power semiconductors
2. Local control
   - Gate Drivers
   - Protection
   - Microcontroller/PGA for "smart" control
3. Integral cold plate
4. Busbars (Interconnect)
5. Small high-technology passive components to realize circuit operation

The presentation included a cost target analysis for the IPM. Two major cost drivers were identified.

1. Materials and components
2. Assembly labor and testing

It was concluded in Figure 2, that the dollar cost per kW ($/kW) is inversely proportional to kW, becoming less sensitive for higher kW.

The chart in Figure 3 depicts today's IPM cost by component and power level. These numbers are the best guestimates of suppliers' cost, not price. The suppliers are identified as Chrysler, Ford and General Motors.

The presentation also looked at various IPM components and the assumed cost reduction for each component for the years 1998 and 2000. The chart is shown in Figure 4. As a result of these reductions, the anticipated IPM cost reductions achieved for the years 1998 and 2000 are shown in Figure 5.

E. United States Council for Automotive Research (USCAR) and the Partnership for a New Generation of Vehicles (PNGV) AIPM SPECIFICATION REVIEW FOR POTENTIAL PRODUCT DEVELOPMENT

Allan Gale - Ford Motor Co., Sunil Chhaya, General Motors, Cyrus Ashtiani, Chrysler, David Hamilton, Department of Energy
July 8, 1998

This presentation recognized that the inverter cost is a major inhibitor to wide spread application of electric drivetrains for vehicles and that existing components and packages inhibit drive improvements and cost reductions.
It was determined that cost reduction could be achieved by:

1. Combining functions of the most commonly used power electronic block.
2. Combining component technologies with the most potential for cost reduction

Power electronics is a critical enabler to achieving PNGV goals with cost as a major issue. Figure 6 outlines the specific PNGV system and power electronic goals. The parameter of cost is defined as $/kW and has the goal of reducing the cost of the electronics (inverter/controller) from $25 in 1997 to $7 in 2004.

F. PEBB Applications Workshop
November 5-7, 1997
San Diego, California

This conference was held with the intention of gathering and assembling all interested parties that have a stake in the development and commercialization of PEBB modules. These include potential manufacturers, suppliers and users of PEBBs. The conference provided an opportunity for the general PEBB community to present their ideas and to exchange information with participants with the intent to improve and accelerate the commercial development of PEBB modules.

A review of the all presentations given at the conference has been conducted and has resulted in the identification of the following reports that have any significant cost related information.

F1. Office of Naval Research
DAWN OF THE MORE ELECTRIC SHIP
James E. Gagorik

This presentation was meant to convey the following realities of the 21st century:

a. New Acquisition Strategy
b. Performance Based Specifications
c. Cooperative, Cost Sharing Environment
d. Pro-Active Commercial Market

The presentation discusses the characteristics of various current and future Navy ships which leads to a discussion of new power distribution architectures that will improve the size, efficiency, and life-cycle cost of electrical distribution systems.

The graph in Figure 7 represents these improvements in weight, size and cost for the DD 963, the CG 47, and the SC 21. This graph show the intended cost objective for a 50 kW/cu ft PEBB of $.06/Watt for inclusion on the SC 21.

F2. Naval Air Systems Command
Electrical Systems Division
LOW POWER PEBB BASED CONVERTER APPLICATION FOR NAVAL AIRCRAFT
Steven Fagan, Sean Field, Charles Singer

Two of the objectives of this presentation were to:

a. Define the characteristics of low power (0-50 kW) PEBB based application for Naval aircraft.
b. Define potential cost, size and weight reductions through the use of PEBBs.

The presentation included a chart that shows the trends in military aircraft power conversion equipment. They represent power conversion equipment that is on the F-18, F-22 and the V-22 aircraft.

As the chart in Figure 8 indicates, the increased cost, size and weight are due to inverter complexity. The presentation summarizes that the solution to this problem would be a PEBB-based regulated converter that would be 50 kW/cu ft @ $0.06/Watt.

F3. Northrop Grumman Corporation
Electronic Sensors and Systems Division
PACKAGING FOR LOW COST PEBB MODULES
P. Sanger, F. Lindberg, W. Hall, W. Garsen, L. Lesster, T. Matty

This presentation identifies the goal to reduce the cost of the Si based Electric Vehicle Power Block by 50%. The module is a 600V / 200 A, 3 phase, 100hp inverter. The chart in Figure 9 represents the existing Power Block cost.

The chart concludes that:

a. The cost of the power electronics dominates the cost of the electric power train.
b. The cost of the silicon area dominates the cost of the power electronics.

This cost objective will be achieved by:

a. Integrating components
b. Minimizing waste in performance
c. Maximizing performance

F4. Babcox and Wilcox Product Development
Bell Labs, Lucent Technologies
MULTI-MW POWER ELECTRONICS DESIGN TRENDS AND COST ISSUES
Paulo F. Ribeiro
Hengchun Mao

This paper states that the power industry demands for flexible, faster and more efficient high power electronics components, devices and systems have produced a revolution in the high power electronics and applications areas. The paper discusses technology issues and trends for commercial and military multi-MW power electronics and considers power electronics to be an enabling technology that will provide a cost reduction benefit.

Figure 10 looks at conflicting requirements for various power electronics applications in an attempt to identify the industry that drives the power electronics development. The paper concludes that both the technology and cost is driven by the power utility / industrial applications.

G. Power Paragon
George Robinson

As part of the Dual Use Program, Power Paragon is using Government Furnished Equipment (GFE) PEBB modules (from Harris Corporation) to study DC to DC isolated power converters. As a manufacturer of power conversion and power conditioning equipment, Power Paragon is conducting its own studies to verify that PEBB can be used at higher frequencies which would translate into lower costs. The philosophy is that if PEBB can be manufactured and save on all the filtering equipment associated with power conversion, there would be a cost savings over traditional methods. A higher efficiency would translate into a higher power density which would reduce the size of the equipment. This reduction in the size of the equipment will drive the interest in PEBBs which should translate into a cost reduction of PEBB as well.

One of the advantages of the PEBB modular concept would be in the ability to take advantage of design improvements and evolutionary changes as they occur with minimal re-engineering cost impact. This would be of tremendous value to manufacturers as well as users.

It should be noted that Power Paragon focuses in small quantities for military applications therefore they are not as price sensitive for PEBB modules as, for example, the automotive industry or other industries.

H. Silicon Power Corporation
Dr. Harshad Mehta

The focus of SPCO has been in the area of high power PEBB applications that are defined as being in the 1 mega-watt or greater range. For these high power systems, the critical cost factor is considered to be dollars per kilo-watt ($/kW). The primary uses are for large electric utilities and pulse power applications as well as some Navy applications. There are two modular technologies that play a significant role in these applications; AC modules and DC modules.

AC Modules

An example of an AC module application would be for high-speed transfer switches. SPCO has a current target price of $50/kW. This is what the market would bear. This price would translate into a system cost of approximately $750 K for a high-speed electronic transfer switch. SPCO would see this target price lowered to $30/kW which would lower the overall system cost to under $500 K. At this price, SPCO believes that they could attract serious interest in their AC module. The current AC module has approximately 40% of the cost associated with the mechanical bypass switch, which is a redundant system that can be eliminated when the reliability of the module is proven. This would allow the module cost to be lowered to the $30/kW target cost. SPCO is currently pursuing this course and is confident that these cost goals can be realized in the near future.

DC Modules

There is an inherent higher performance criteria for this module, which would translate into higher costs. An example of a DC power module application would be for an Uninterrupted Power System (UPS). The UPS would regulate and modulate the power for a given system. The DC module would serve as a functional replacement system. SPCO estimates that the current target cost for a UPS system would be $500 - $700 per kW. A typical system is in the 5 MW to 15 MW range. SPCO is currently competitive in the lower range of 5 - 10 MW with a current cost of $440/kW. They believe that this cost will be lowered to $250/kW over the next 3 years by advances in component technology. As the industry advances in general, the price of various components will probably be reduced while the power increases.

SPCO focused their comments for the high PEBB applications but also will be investigating what they called the generic PEBB technology and applications. SPCO is presently in negotiations to buy a portion of the Harris Semiconductor company that includes the MCT/IGBT PEBB module development. These modules are planned for use in power conversion and control circuits in the range from 20kW to 250kWs. They are currently reviewing the status of the applicable technologies and will begin to do an assessment and talk to customers and their markets.

I. Satcon Technology Corporation
Bill Bonnice

Representatives of Satcon were contacted and invited to provide their perspective on cost related issues. After conferring with company officials, Satcon indicated that they would prefer to not discuss cost issues at this time.

J. ABB Corporate Research
Fredi Stucki
ABB Industry
Peter Steimer

A discussion was held with representatives of ABB Corporate Research to determine cost issues related to their PEBB module. ABB indicated that the target cost for the module that was presented to the PEBB community is $2000 per unit. This cost assumes a commercial volume production. The actual module that has been presented is a technology demonstrator, that was done at their research laboratory, and is not yet commercialized. ABB indicated that it is very difficult to discuss cost issues since many parts are special design, such as the cooling ground plate and the bus bars, etc.

ABB also indicated that the cost of PEBB modules are driven by components such as diodes. They indicated that the German company Semikron, producers of IGBT diodes have a cost of approximately $0.30 - $0.40 per amp for a 1200 V AGBT diode.

K. Northrop Grumman Corporation
Power/Control Systems Department
FINAL REPORT – THE FUNCTIONAL DEFINITION OF A PEBB
William Patalon

Northrop Grumman contacted representatives of various industries to identify common PEBB features and performance characteristics. It was determined that that there was a need for at least 6 different PEBB topologies as described below:

1. Utility – Driven by extremely high voltage and power requirements to include distribution system and transmission system level applications.
2. Automotive – Driven by intermediate to low DC voltage and power requirements and also driven by environmental and packaging constraints and costs.
3. Aircraft – Driven by low AC/DC voltage and power requirements with packaging constraints (weight, volume and reliability).
4. Space - Driven by voltage and power requirements with severe packaging constraints (weight, volume, reliability) and extreme environmental needs (temperature, pressure and radiation).
5. Industrial/Commercial - Not evaluated but the primary drivers are cost, wide range of power rating and performance.
6. Navy Shipboard - Driven by voltage and power requirements with severe performance requirements.

All of these applications require that widespread usage and affordable cost be considered. It was noted that with regards to initial acquisition cost, the following three elements must be considered:

1. Recurring costs
2. Non-recurring costs
3. Life cycle costs

It was also determined that in reviewing power conversion applications, they typically fell into several categories:

1. AC to DC conversion
2. AC to AC conversion
3. DC to DC conversion
4. DC to AC conversion

Any power converter is comprised of four essential elements.

1. Power switching element – The MCT device of choice should include the MCT, its gate driver circuit and the sensors and connection points that allow ready incorporation into a five-terminal module. This would reduce initial design costs.
2. Input and output filter elements – Filter designs will have to overcome serious cost issues regarding the use of advanced materials.
3. Control, protection and communications element
4. Heat removal interface

It was concluded that for high power applications (>10MW), the following requirements are recommended:

1. NTE $0.20/watt rated
2. High volume applications to generate cost effective pricing.
3. Automated assembly/test equipment
4. Factory assembled and tested

V. APPENDIX A

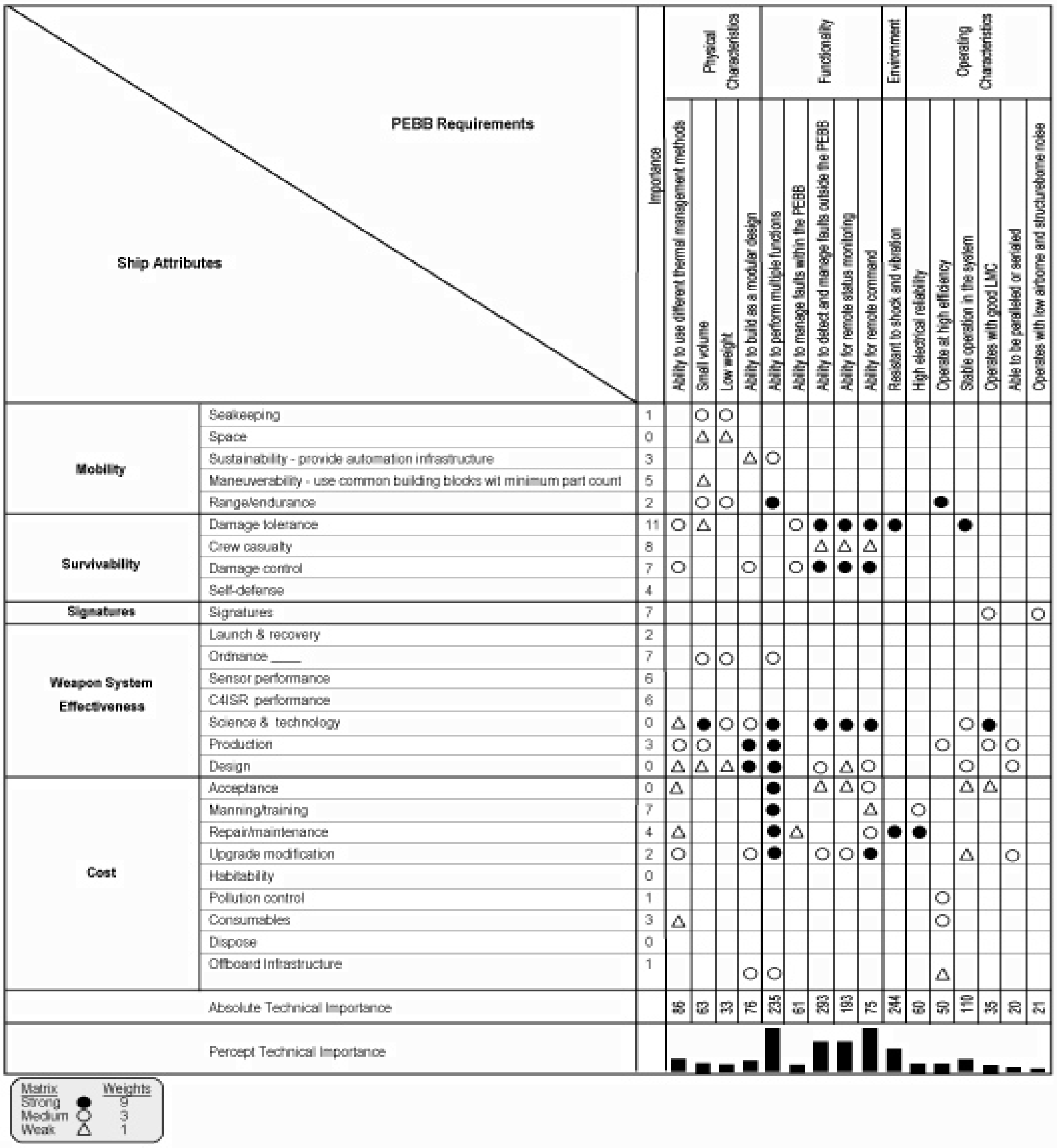

Figure 1 – PEBB Quality Function Deployment Matrix

AUTOMOTIVE PEBB REQUIREMENTS

GM – Advanced Technology Vehicles

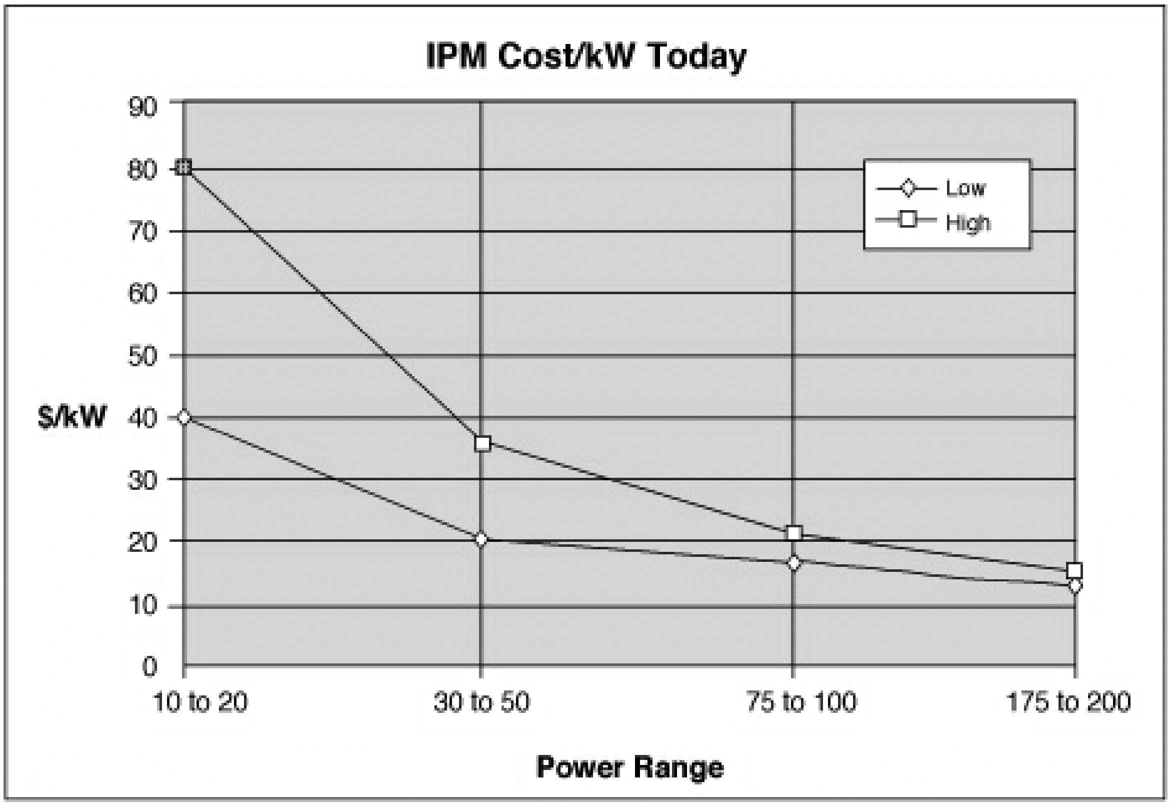

Figure 2 – Cost Target Analysis for Integrated Power Module (IPM)

	10-20kW	30-50kW	75-100kW	175-200kW
HPM	225	450	900	1800
Cold Plate	20	25	40	100
Busbars	35	50	75	125
GD/Ctrl DSP	125	150	175	200
Labor	200	200	200	200
Testing	200	200	200	200
Total	805	1075	1590	2625
Cost for kWL	40.2	21.5	15.9	13.1
Cost for kWH	80.5	35.8	21.2	15

Figure 3 – Today's IPM Cost by Component and Power Level

AUTOMOTIVE PEBB REQUIREMENTS

GM – Advanced Technology Vehicles

Component	Cost Reduction	
	1998	2000
HPM	-39%	-26%
Cold Plate	-50%	-30%
Busbars	-50%	-30%
Gate Driver/Control DSP	-20%	-30%
Labor	-50%	-90%
Testing	-0%	-20%

Figure 4 – Assumed Cost Reductions by Component

As a result, IPM cost reductions achieved are,

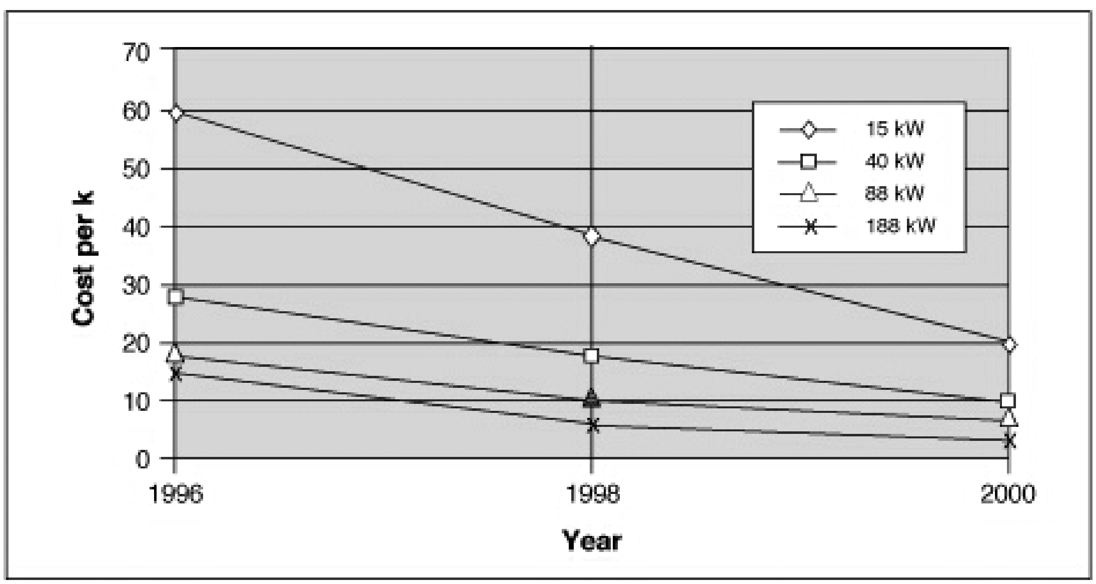

Figure 5 – IPM Cost Reductions

Parameter	1997	2000	2004
System:			
Driveline Efficiency (%)	70	75	80
Weight (w/o engine or energy storage) (kg)	175	140	102
Electronics (Inverter/Controller):			
Specific Power at Peak Load (kW/kg)	2	4	5
Volumetric Power Density (kW/l)	8.0	10.0	12
Cost ($/kW)	25	10	7
Efficiency (10% to 100% speed, FUD's cycle)	93	95	97-98

Figure 6 – PNGV System & Power Electronic Goals

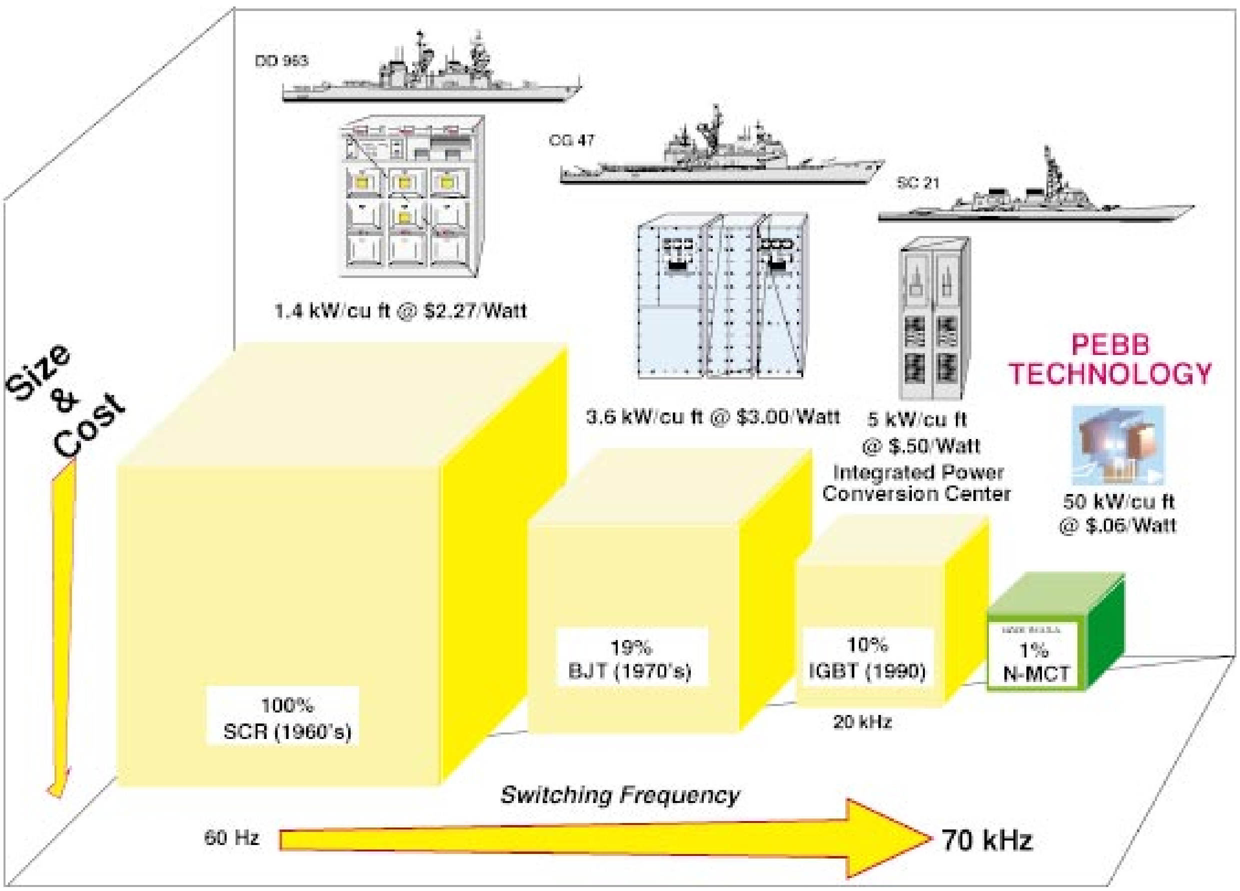

Figure 7 – Power Distribution Modules – Shipboard Power Supplies

F-18	F-18	F-22	V-22
Transformer-Rectifier	Battery Charger	DC-DC Regulated Converter	AC-DC Regulated Converter
Diode Bridge		MOSFET	MOSFET
4.2 kW	1.4 kW	2.1 kW	6 kW
21.26 kW/cu ft	20 kW/cu ft	9.86 kW/cu ft	12 kW/cu ft
0.28 kW/lb	0.23 kW/lb	0.175 kW/lb	0.149 kW/lb
@$1.53/watt	@ $2.12/watt	@$10.00/watt	@ $9.17/watt
Increased, Cost, Size And Weight Due To Converter Complexity			
Solution: PEBB-Based Regulated Converter **50 kW/cu ft @ $0.06/Watt**			

Figure 8 – Trends in Military Aircraft Power Conversion Equipment

Our goal is to reduce the cost of the Si based Electric Vehicle Power Block by 50%

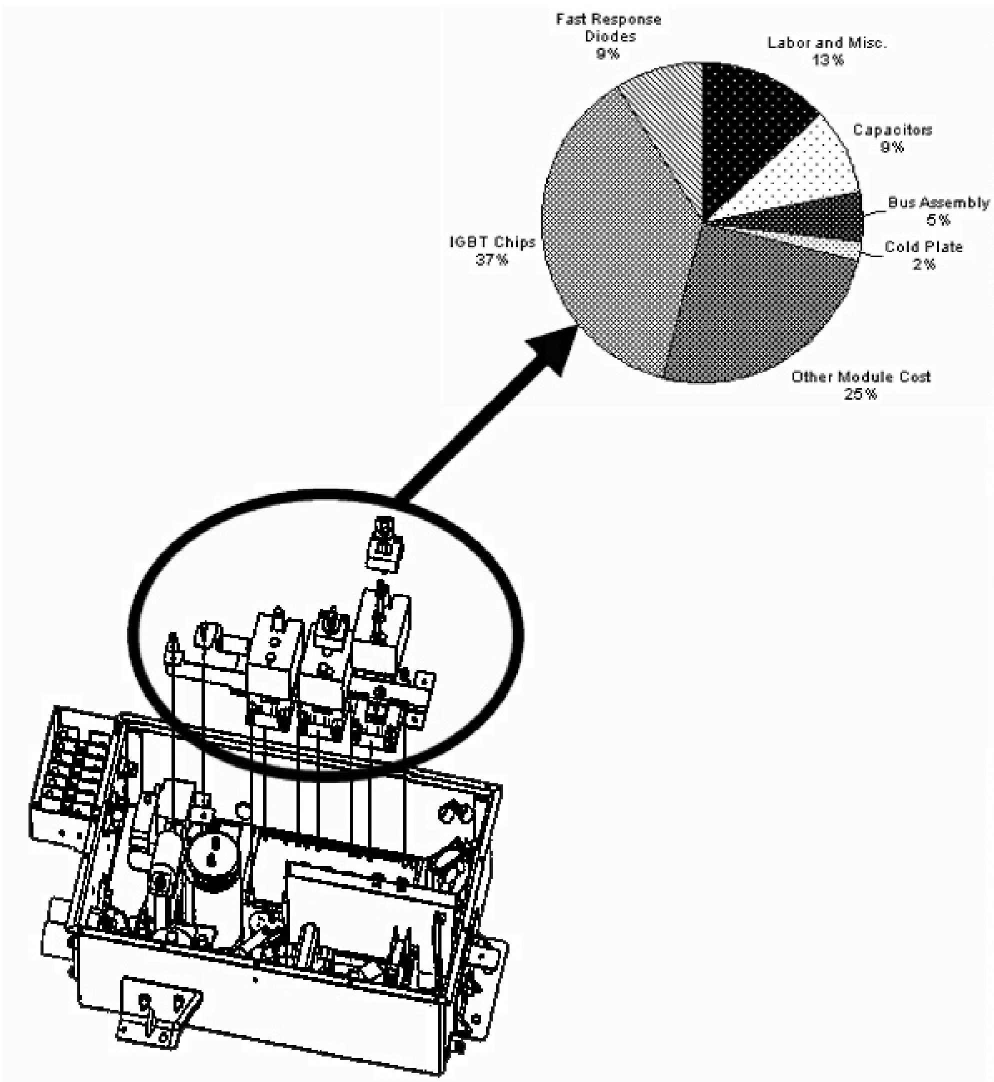

Figure 9 – Existing Power Block Cost

Cost Issues?

Who Drives The Power Electronics Development?

Power Electronics Application Conflicting Requirements Power and Voltage Ratings				
Requirement	**Utility**	**Traction**	**Industrial**	**Shipboard**
Power (MVA)	10 - 250	2 – 5	2 – 10	5 – 25
Voltage (kV)	6 - 34	.5 – 2	.5 – 6	.5 – 1 (12?)

Figure 10 – Power Electronics Application Conflicting Requirements