

99-3 Planning Report

Benefit Analysis of IGBT Power Device Simulation Modeling

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Benefit Analysis of IGBT Power Device Simulation Modeling

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Executive Summary

NIST's contributions to the development of simulation modeling tools for IGBT power devices have led to significant economic benefits primarily through increased R&D efficiency and increased product quality.

The National Institute of Standards and Technology's Electronic and Electrical Engineering Laboratory (NIST/EEEL) program supports the development of mathematical models for several classes of semiconductor devices. This study presents the results from a microeconomic impact assessment of the development of mathematical models for the design of insulated-gate bipolar transistor (IGBT) semiconductor power devices. NIST/EEEL's IGBT mathematical modeling program (referred to as the NIST IGBT modeling program) has led to significant economic benefits. These benefits include

- improvements in R&D efficiency,
- decreases in transaction costs,
- decreases in production costs, and
- improvements in product quality.

NIST's activities have affected software companies, IGBT device manufacturers, and manufacturers of products that employ IGBTs (referred to as applications manufacturers). Software companies have incorporated NIST's mathematical models into their commercial simulation modeling software. Device manufacturers, such as Harris Semiconductors and International Rectifier, and applications manufacturers, such as Ford Motor Company and General Electric, use this software to design electrical systems employing IGBTs. IGBTs are used in a wide range of applications, such as automotive ignition systems and adjustable speed drives. In the absence of NIST's activities, industry experts stated that the availability of IGBT simulation modeling software "would have been delayed, and the modeling software developed would not have been as accurate."

This study quantifies the economic benefits associated with improvements in R&D efficiency and reductions in transaction costs. In addition, the study identifies and qualitatively describes the impact of the NIST IGBT modeling program on production costs and quality and performance of final products employing IGBTs.

Table ES-1 presents several measures of social return to NIST’s investment in mathematical models of IGBTs. A range of social returns to NIST’s investment is presented, reflecting the difficulties in quantifying the quality and timing of the development of IGBT modeling in the absence of NIST’s contributions.

Table ES-1. Measures of Economic Benefits from the NIST Program
The benefits of the NIST IGBT modeling program are at least 15 times the cost.

Measure	Estimate	Range
Benefit-cost ratio	23.2	±7.7
Social rate of return	76.5%	±9.1%
Net present value (\$thousands, 1998)	\$9,954	±3,467

The returns in Table ES-1 are based on the value of improvements in R&D efficiency, the savings to industry from decreased transaction costs, and the NIST IGBT modeling program expenditures. Actual economic impacts associated with NIST’s contributions are likely to be larger than the estimates presented in Table ES-1 because they do not include the economic impacts of reduced production costs and improved product quality. Although industry experts indicated that manufacturing costs and product quality benefits do result from using simulation modeling in designing IGBT systems, they were not able to quantify these impacts.

ES.1 NIST’S ROLE AND MARKET BARRIERS TO SOFTWARE DEVELOPMENT

In 1985 NIST’s Electronic and Electrical Engineering Laboratory (EEEL) program initiated a project to support and promote semiconductor power-device modeling. One of the main outputs from the NIST Program was the development of mathematical models for IGBT devices that simulate their performance. Several

NIST's mathematical models for IGBT devices were introduced into commercial simulation software products in 1990.

industry experts and academics stated that NIST's model is the "universal standard for IGBT modeling."

NIST's mathematical models for IGBT devices were introduced into commercial simulation software products in 1990. The automotive industry was one of the first industries to integrate IGBT simulation modeling into their design process, using it in the design of electronic ignition systems and electronic vehicles. By late 1990s these software products were widely used by IGBT device manufacturers and by applications manufacturers producing motor control, lighting, power control, and automotive products. Figure ES-1 illustrates the path through which NIST's mathematical models have affected industry and end users of products employing IGBT devices.

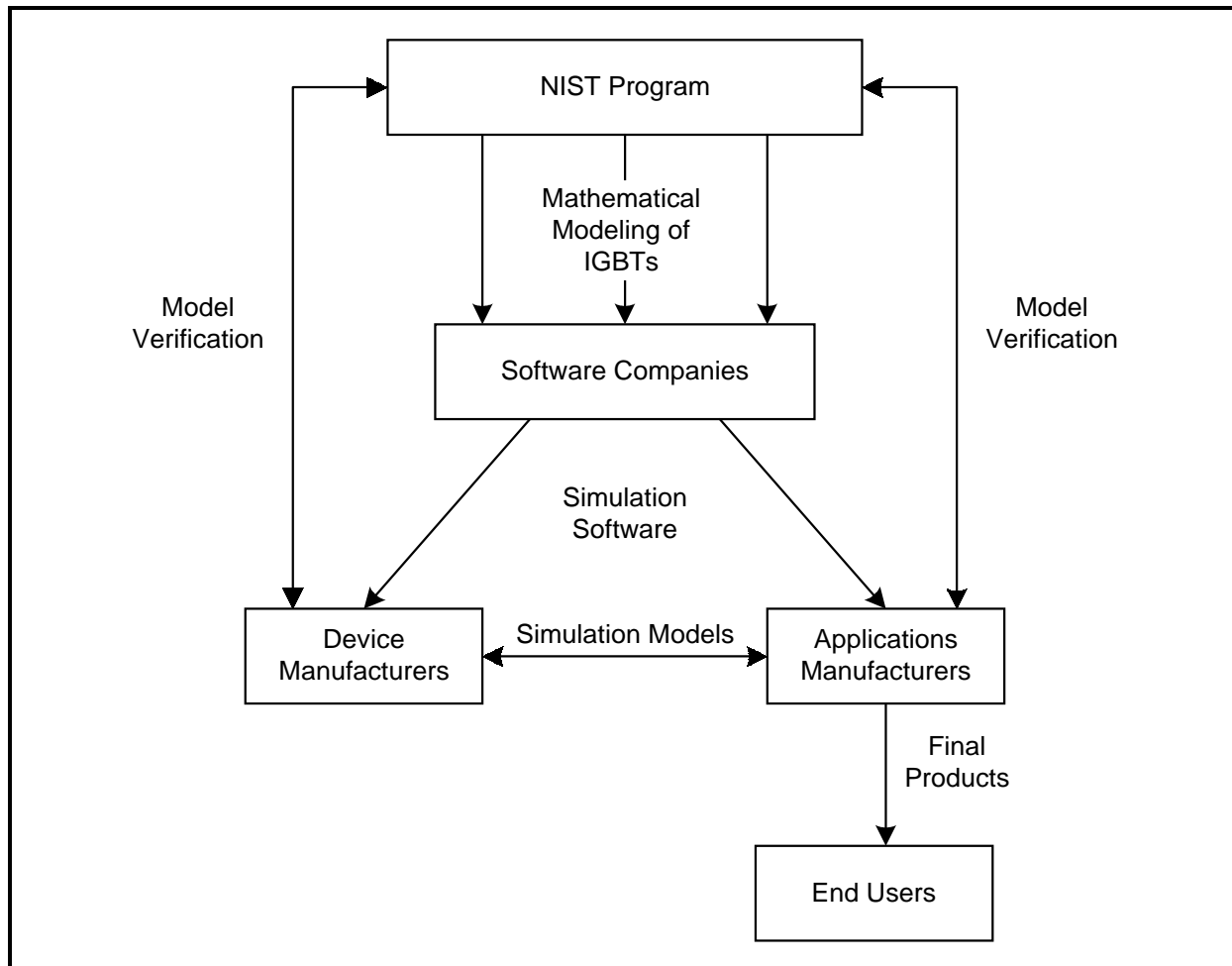
The development and verification of IGBT simulation modeling software currently used by industry resulted from the combined efforts of NIST, software companies, and device and applications manufacturers. For example, Ford Motor Company and its device supplier Motorola made important contributions to verifying and incorporating NIST's mathematical models into Analog's software product SABER. In the process they generated significant technology spillovers by making IGBT simulation tools available to other applications manufacturers, such as manufacturers of motor controls or power control equipment.

Industry experts indicated that NIST had a "significant" impact on the development and use of IGBT simulation modeling tools. The general consensus was that software for IGBT simulation modeling may have been developed in the absence of NIST's efforts; however, industry experts acknowledge that NIST's efforts in developing and promoting the use of simulation modeling of IGBTs have

- increased the accuracy of simulation models for IGBTs used in software products, such as SABER and PSPICE;
- accelerated the adoption of simulation models and virtual prototyping by system designers and device manufacturers; and
- lowered the cost of software development for simulation software companies such as Analog and Orcad.

Figure ES-1. Industry Relationships and NIST's Role in Developing Simulation Modeling Tools for IGBTs

NIST collaborated with members of the semiconductor industry supply chain to develop and verify IGBT simulation modeling software.



Market barriers contributed to the delay in the development of IGBT capabilities in simulation modeling software. Two of the main barriers are the following:

- Software companies do not have the technology base to develop, verify, and implement the required mathematical algorithms.
- Applications manufacturers that have the required technical expertise are not able to appropriate the returns to these R&D activities.

NIST's role in the development and incorporation of IGBT modeling capabilities into software products such as SABER was motivated by these market barriers.

ES.2 IMPACT CATEGORIES AND ANALYSIS RESULTS

The net present value (NPV) of the NIST program expenditures related to the development and promotion of simulation modeling for IGBT power devices is presented in Table ES-2. Program expenditures began in 1985 and are projected to continue through the year 2000 at current expenditure levels (Hefner, 1998). Labor costs account for the largest share of program costs.

Table ES-2. NIST Program Expenditures
The NPV of NIST's IGBT program expenditures from 1985 to 2000 is \$477,000.

Categories	Expenditures NPV (thousands, \$1998)
Labor	363.4
Equipment	61.1
Miscellaneous costs	22.5
Total	477.0

As shown in Figure ES-1, NIST's contributions to the development of simulation modeling tools have generated benefits for several sectors of the economy, including software companies, device manufacturers, applications manufacturers, and end users of products employing IGBT devices. Table ES-3 relates benefit categories with associated economic sectors.

Table ES-3. Economic Sectors and Related Benefit Categories
NIST's IGBT modeling program generated different benefits to each member of the supply chain.

Sectors	R&D Efficiency	Transaction Costs	Production Costs	Product Quality
Software companies	✓			
Device manufacturers		✓		
Applications manufacturers	✓	✓	✓	
End users				✓

Software companies benefited from the development of NIST's mathematical models of IGBT performance and from NIST's model verification activities with applications and device manufacturers. These activities lowered the R&D costs for incorporating IGBT simulation modeling capabilities into their software products.

Device manufacturers use NIST's models to develop product datasheets for the IGBT devices they manufacture. The datasheets provide performance information to applications manufacturers and support the comparison of competing IGBT devices. The use of NIST's model for developing datasheets reduces transaction costs by increasing the quantity and quality of information available to applications manufacturers and by lowering the cost for device manufacturers to generate the information.

Applications manufacturers use simulation software incorporating NIST's model in the design of electrical systems employing IGBTs. Simulation models are used to develop *virtual* prototypes that reduce the R&D cycle design time, lower labor cost, and reduce material costs associated with developing physical prototypes.

The end users of products that employ IGBTs benefit from NIST's models because their use in the systems design process also increases the quality of final products employing IGBTs. For example, the use of simulation modeling for designing ignition switches increased the fuel efficiency of automobiles, and the use of simulation modeling for designing adjustable speed drives (ASDs) decreased energy consumption of electric motors. The potential benefits to society from increased product quality are very large.

The quantitative analysis of the economic benefits from the NIST IGBT modeling program focused on changes in R&D efficiency for applications manufacturers and transaction costs for device manufacturers. Table ES-4 presents the NPV of benefits to these industry sectors in 1998 dollars. The table includes aggregated benefits from 1990 to 2003. The design of motor controls, such as ASDs account for 63 percent of quantified benefits.

The quantitative analysis does not include benefits due to reduced production costs and improved product quality. However, we did conduct a qualitative analysis of these benefit categories. All of the modeling and design engineers interviewed said that simulation modeling leads to improved performance of the final product

The quantitative analysis of the economic benefits from the NIST IGBT modeling program focused on changes in R&D efficiency for applications manufacturers and transaction costs for device manufacturers.

Table ES-4. The NPV to Industry of Quantified Benefits from Simulation Modeling of IGBTs (thousands, \$1998)

These benefits include projected benefits through the year 2003 and are presented in 1998 dollars.

Industry Segment	R&D Efficiency	Transaction Costs	Quantified Benefits
Device manufacturers		1,301	1,301
Applications manufacturers			
Automotive ignition systems	1,547		1,547
Automotive electric vehicles	588		588
Motor controls	10,859		10,859
Lighting	363		363
Power control	8,673		2,675
Sum	16,033	1,301	17,334

employing the IGBT device. However, no one was able to provide an accurate estimate of the magnitude of these impacts. In addition, most contacts said that the use of simulation modeling leads to material savings in the production process. However, they could not quantify these savings either.

In several instances, we assessed the potential magnitude of benefits associated with product quality improvements by developing example product improvement scenarios. For example, industry experts indicated that simulation modeling of IGBTs could increase the efficiency of automobile ignition systems, potentially leading to a 0.05 percent increase in automobile fuel efficiency. Based on current automobile fuel consumption, a 0.05 percent increase in fuel efficiency would decrease fuel expenditures by \$33.5 million per year.

ES.3 FUTURE TRENDS AND BARRIERS TO ADOPTION

The use of IGBT simulation modeling is still gaining momentum and will continue to expand into new product areas. Many applications manufacturers are in the process of adopting IGBT simulation modeling, and the benefits will be realized in the near future. Future penetration of IGBT simulation modeling will be

driven by factors such as the increasing complexity of electrical systems and the spread of IGBTs into lower voltage applications.

All industry experts interviewed as part of this study acknowledged the “potential” benefits associated with simulation modeling of IGBTs in the design process; however, they also indicated that certain factors are limiting widespread adoption of IGBT simulation modeling. The most commonly mentioned barriers to the adoption of IGBT simulation modeling were

- overhead costs associated with purchasing and maintaining software and staff training,
- effort and expense required to characterize IGBT models,
- modeling limitations and related costs associated with confidential information,
- weak models for non-IGBT components, and
- missing complementary analysis capabilities in simulation software.

Future activities NIST may want to consider to promote the adoption of IGBT simulation modeling and enhance its benefits are

- identifying weak links in the simulation modeling chain and supporting model development,
- supporting a standardized modeling language,
- supporting development of capabilities to model the distribution of failures resulting from variability in parts, and
- enhancing systems for patenting semiconductor device characteristics.

1

Introduction

The field of power electronics has experienced substantial growth in recent years due to the introduction of and improvements in controllable switches. Controllable switches can significantly enhance the performance of products because they have the capability to sense voltages, currents, and temperatures and to provide functions such as load diagnostics and short-circuit protection. Insulated-gate bipolar transistors (IGBT) semiconductor devices are the dominant controllable switches for devices ranging from 200 to 1,500 volts.

The increased performance requirements and general technical sophistication of end products employing IGBTs have led to the need for advanced modeling tools to support the custom design of IGBT power devices. However, the technical infrastructure necessary to support custom design of IGBTs systems has not developed as rapidly as the demand for products using IGBTs. In particular, the development and commercialization of mathematical models of IGBTs have been slow because of the infrastructure-type market failures associated with design tools.

The National Institute of Standards and Technology (NIST) provides measurement infrastructure support to U.S.-based industries for the purpose of promoting economic growth. The broad, economy-wide portfolio of technologies for which these infratechnologies are provided creates a demanding strategic planning challenge for NIST. In response, NIST requires economic assessments of technologies, industries, and market structure to

- project or document the returns from NIST's laboratory research programs and
- provide information that NIST can use to improve the selection and management of its portfolio of projects.

This project furthers NIST's objectives for economic analysis by examining NIST's contributions to the mathematical modeling of insulated-gate bipolar transistor (IGBT) power devices.

This project furthers NIST's objectives for economic analysis by examining NIST's contributions to the mathematical modeling of IGBT power devices. Mathematical modeling of IGBTs (also referred to as simulation modeling) allows designers to use "virtual" prototypes when designing electrical systems that incorporate IGBT power devices. In the past, IGBT system designs relied primarily on constructing physical test circuitry and failing (destroying) the circuitry to analyze extreme conditions. In comparison, using mathematical modeling to develop virtual prototypes is faster and less expensive and leads to superior designs.

This section introduces the project by outlining its objectives, discussing the motivation for NIST's involvement, summarizing NIST's contributions to the development of IGBT mathematical models and software tools, and presenting an overview of the analysis approach. Section 2 provides background information on IGBT power devices, product applications, and manufacturers in the supply chain. Sections 3 and 4 describe the technical impacts associated with using simulation modeling of IGBTs in the system design process and our methodology for estimating economic impacts. Analysis results are presented in Section 5, and market barriers to the development and adoption of IGBT simulation modeling are discussed in Section 6 along with potential future roles for NIST.

1.1 PROJECT OBJECTIVES

The objective of this project was to conduct a microeconomic impact assessment of NIST's contributions to mathematical modeling of IGBT power devices. The focus of the analysis was to evaluate the social benefits from incorporating NIST's mathematical modeling capabilities for IGBTs into commercially available simulation software products. The analysis included

- a quantitative analysis of the impact of IGBT simulation modeling on applications manufacturers' R&D efficiency and on device manufacturers' transactions costs and,

The focus of the analysis was to evaluate the social benefits from incorporating NIST's mathematical modeling capabilities for IGBTs into commercially available simulation software products.

- a qualitative analysis of IGBT simulation modeling's impact on changes in production costs and on increased product quality and performance of final products employing IGBT devices.

This study includes both retrospective and prospective analyses of NIST's contributions to date on existing products employing IGBTs. In addition, we identify NIST's impact on future products employing IGBTs, such as electric cars and advanced medical applications.

1.2 MOTIVATION FOR NIST'S INVOLVEMENT

The potential benefits to society from the use of simulation modeling in the design of products employing IGBT power devices are large. Industry benefits from increased R&D efficiency, reduced transaction costs, and decreased production costs. Consumers benefit from increased product quality at decreased prices. In addition, environment benefits are generated from the increased energy efficiency of products employing IGBTs.

The versatility of IGBT devices places increased demand on designers to modify devices to meet the specific technical requirements of each new application. The technical infrastructure necessary to support efficient custom design includes technology tools such as

- mathematical models, test methods, and standards for simulating device performance;
- component libraries containing scientific and engineering data that specify design parameters; and
- model verification parameters and techniques to provide measurements, comparisons, and test circuits for verifying that device models are performing properly.

These tools have infratechnology characteristics because they improve the efficiency of R&D and advance industry's technological opportunities. Mathematical models, test methods, and standards allow researchers to build on previous work using terminology and measurements common to their colleagues. In addition, the replication and verification of research results are essential to building component libraries and to verifying models. These infratechnologies in the semiconductor power-device industry also enhance the efficiency of the production process and

the characteristics of products by providing tools for quality assurance and process control.

Because modeling capabilities possess many of the characteristics of public goods, social returns on investments in infratechnologies, such as mathematical modeling, are often greater than private returns. In the instances where private returns are not large enough to stimulate investment (i.e., the private return is not greater than industries' hurdle rate of return), this leads to a market failure and underinvestment by the private sector.¹

1.3 NIST'S CONTRIBUTIONS TO MATHEMATICAL MODELING OF IGBT POWER DEVICES

In 1985 NIST's Electronic and Electrical Engineering Laboratory (EEEL) program initiated a project to support and promote IGBT semiconductor power-device modeling (referred to as the NIST IGBT modeling program). Dr. Allen Hefner at NIST is the project manager and the principal scientist. To date, NIST's contributions in the field of IGBT power-device modeling have led to advances in

- mathematical modeling,
- device design,
- model parameter extraction,
- circuit utilization, and
- model validation.

Mathematical modeling, model parameter extraction, and model validation are all infratechnologies that stimulate R&D, improve the efficiency of R&D, advance industry's technological opportunities, and promote technology adoption. The term "simulation modeling" is used to refer to this group of design activities.

NIST's core contribution has been the development of a physics-based mathematical model (commonly referred to as the NIST model or as Dr. Hefner's model) that accurately predicts behavioral parameters of IGBT power devices. The academic community recognizes Dr. Hefner's model as a "significant professional

The NIST model is internationally accepted as the standard by which other IGBT models are compared.

¹Nelson (1959) and Arrow (1962) provided the earliest and most influential discussions of market failure in the production of knowledge. Many authors have clarified this view, and Tasse (1997) has discussed market failure in the context of infratechnologies.

contribution.” The model is internationally accepted as the standard to which other IGBT models are compared.

NIST has collaborated with Analogly, Inc., to incorporate Hefner’s Model into Analogly’s design software SABER. Components of Hefner’s Model have also been incorporated into other simulation models such as OrCad’s software PSPICE. Industry experts acknowledge that NIST’s efforts in developing and promoting the use of simulation modeling of IGBTs have

- increased the accuracy of simulation models for IGBTs used in software products, such as SABER and PSPICE;
- accelerated the adoption of simulation models and virtual prototyping by system designers and device manufacturers; and
- lowered the cost of software development for simulation software companies such as Analogly and Orcad.

NIST has had a “significant” impact on the development and use of simulation modeling using mathematical models.

Several contacts from device manufacturers and applications manufacturers stated that NIST has had a “significant” impact on the development and use of simulation modeling using mathematical models. The general consensus is that software for simulation modeling would have been developed in the absence of NIST’s efforts. However, the models would not have been as accurate and hence would not have penetrated the market as quickly as the products using NIST’s mathematical models.

NIST’s contribution to infratechnologies has also leveraged related private-sector investment. Software companies that develop, refine, or market device models and component libraries build on NIST’s contributions to mathematical modeling. Device manufacturers and applications manufacturers use NIST technology to simulate IGBT device performance and thus can provide higher-quality/lower-cost devices and system designs.

1.4 OVERVIEW OF ANALYSIS APPROACH

Our approach to estimating the economic impact of NIST’s contribution to IGBT semiconductor power-device modeling required two main steps:

- Identifying the impacts associated with the simulation modeling of IGBTs. This step included estimating benefits associated with currently affected markets and projecting

potential impacts of existing modeling capabilities into the near future.

- Assessing NIST’s impact on developing and adopting simulation modeling of IGBTs. NIST’s contribution to social welfare is a portion of the total net benefit to society from simulation modeling of IGBTs.

Sectors affected by the use of simulation modeling are software companies, device manufacturers, applications manufacturers, and end users of products employing IGBT devices. Table 1-1 relates benefit categories with associated economic sectors.

Table 1-1. Economic Sectors and Related Benefit Categories

The categories identified with an X were included in the quantitative analysis. The categories identified with a ✓ were evaluated qualitatively.

Sectors	R&D Efficiency	Transaction Costs	Production Costs	Product Quality
Software companies	✓			
Device manufacturers		X		
Applications manufacturers	X	✓	✓	
End users				✓

As shown in Table 1-1, the analysis quantifies the value of the impacts associated with changes in applications manufacturers’ R&D efficiency and device manufacturers’ transaction costs. The remaining economic sectors and benefit categories were evaluated qualitatively.²

²For the categories evaluated qualitatively, technical and economic benefits associated with simulation modeling of IGBTs were identified, but industry contacts could not reliably quantify the magnitude of the benefits.

2

The IGBT Supply Chain

IGBT power devices are controllable switches and are used in a wide range of products for motor and power control. IGBTs currently dominate the medium- to high-voltage applications markets, devices ranging from 200 to 1,500 volts. However, as technology advances decrease the cost of IGBTs, they are expected to penetrate the market for low-voltage controllable switches, such as household appliances.

This section provides background information on IGBT power devices and their current and future applications in final products. We then describe the three major segments of the IGBT simulation modeling supply chain: software companies, device manufacturers, and application manufacturers.

2.1 IGBT POWER DEVICES

The IGBT is a hybrid of two transistors: the bipolar transistor and the metal-oxide-semiconductor field effect transistor (MOSFET). The technical advantages from joining these two devices are threefold:

- First, the IGBT's MOSFET is typically controlled by 10 volts, but the whole unit can control nearly 1,500 volts and 100 amperes.
- Second, the IGBT has a higher operating current density than its components.
- Third, when switched on, the IGBT has very low electrical resistance between the collector and the emitter (Baliga, 1997).

The smoother sine wave keeps the motors controlled by the IGBT from generating excessive harmonics. Harmonics create heat and waste energy and can also lead to significant damage to the device and power quality problems.

These three attributes allow IGBTs to be smaller, more efficient, and less expensive to produce compared to alternative controllable switches in their voltage range, such as the Darlington transistor. The smoother sine wave keeps the motors controlled by the IGBT from generating excessive harmonics. Harmonics create heat and waste energy and can also lead to significant damage to the device and power quality problems. In addition, the IGBT's high switching frequencies exceed humans' detection range, making the applications employing IGBTs quieter and more suitable for commercial and household applications.

MOSFETs are currently used for lower voltage controllable switch applications. MOSFETs are less expensive than IGBTs and can be switched on and off at incredibly high speeds. The main limitation of MOSFETs is their inability to handle high voltages. MOSFETs lose their ability to efficiently control power at voltages of 100 volts or greater.

Appendix A contains a brief history of the development of semiconductor power devices and a more detailed description of the technical characteristics of IGBTs.

2.2 END-USE APPLICATIONS

End-use applications for IGBTs are concentrated in the automotive, motor control, power control, and lighting markets. The use of IGBTs is anticipated to expand rapidly in the future as the cost of manufacturing them decreases and environmental concerns place efficient power control systems high on the list of priorities for manufacturers and regulators (Baliga, 1997).

2.2.1 Automotive Applications

IGBTs are used in automobiles for ignition systems and motor controllers in electric vehicles.

Automotive applications of IGBTs are currently limited to ignition systems and motor controllers in electric vehicles. These applications are ideal for IGBT devices because they require high-voltage switching capabilities. The remaining electronic systems in automobiles requiring power devices, such as power accessories and fuel injection systems, use standard 12 volt systems and are more efficiently controlled by power MOSFETs.

Ignition Systems

Ignition systems ignite the air/fuel combination that powers engines in motor vehicles. In the 1970s, electronic (or distributorless) ignition systems were developed that would eventually replace the 50-year old Kettering breaker-point ignition system, which had used a distributor along with manifolds and valves to control spark timing. The advantages of electronic ignition systems include

- ▶ reduced emissions,
- ▶ increased fuel efficiency, and
- ▶ increased reliability

All American and European automobile manufacturers had introduced electronic ignition systems by the early 1990s. Japanese auto makers introduced electronic ignition systems in the 1995 model year.

Originally, electronic ignitions were controlled by devices known as Darlington transistors, but those transistors were replaced by IGBTs beginning in 1992. The Darlington transistor controlled spark timing but needed a high drive current, sapping power in the driver integrated circuit (IC). IGBTs improved ignition designs by reducing the number of protective devices required, simplifying the controlling circuit, and allowing the IGBT to be driven directly from a low current microprocessor output port.

IGBTs' seemingly late adoption by the automotive industry was because of device-design issues that made IGBTs unsuitable for automotive applications. Semiconductor manufacturers had experimented with automotive IGBTs since the early 1980s, but IGBTs' high saturation voltage (more than 2 volts) and need for high gate potential (more than 12 volts) prevented them from being used. By 1990, researchers resolved these problems. Designers optimized the current gain of the device's structure, which reduced the saturation voltage to acceptable levels. To drop the gate potential from 12 to below 2 volts, designers used a thinner oxide layer. Currently, a second generation of ignition IGBTs is being designed that meets ignition system requirements while using 40 percent less silicon than the previous generation of IGBTs (Mamileti et al., 1996).

Electric Vehicles

Electric vehicles have been introduced as an environmentally responsible alternative to traditional vehicles that consume fossil fuels. General Motors, among other manufacturers, began producing electric vehicles for niche markets, such as California and Arizona, where air quality is a pressing concern. In addition, numerous manufacturers are experimenting with hybrid gasoline and electric automobiles, but none are currently commercially available.

IGBT-based systems are used in the power control modules of electric vehicles to turn energy from fuel cells and batteries into alternating current (AC) to drive the engine.

IGBT-based systems are used in the power control modules of electric vehicles to turn energy from fuel cells and batteries into alternating current (AC) to drive the engine. When the vehicle operator presses or eases off the accelerator to vary speed, a signal is sent to the power control module, or controller. The controller monitors and directs a number of power modules containing an array of IGBTs that distribute the battery voltage and current to the motor in amounts proportional to the pressure applied to the accelerator. In this way the IGBTs control the flow of electricity from the batteries to the motor. They also switch the electricity from the batteries' direct current (DC) to the AC the motor uses. General Motors' EV1 contains six arrays of six IGBTs (for a total of 36) that distribute power to the motor.

Electric automobiles' market penetration has been limited because their lead-acid battery packs can go no farther than 100 miles per charge. However, new technologies such as nickel-metal-hydride packs will allow electric automobiles to travel much farther than 100 miles per charge. A recent prototype pack allowed an electric car to travel 375 miles on one charge. The prototype pack contained batteries that cost over \$35,000; however, it is estimated that the pack's cost will drop to \$5,000 and last for 100,000 miles (Electric Auto Association, 1998).

2.2.2 Motor Controls

IGBTs are the key component of adjustable speed drives (ASDs) that enable motor controls to vary output speed. ASDs make more efficient use of electricity by providing only the necessary amount of power to accomplish a task. ASDs also provide more accurate control of precision equipment such as robotic machinery and x-ray machines.

IGBTs provide adjustable speed drives the ability to regulate input current more precisely than their predecessors.

IGBTs provide the ability to regulate input current more precisely than their predecessors. During the early to mid-1990s ASD manufacturers migrated from bipolar junction transistor (BJT) semiconductors to IGBTs as the preferred output switching device (Skibinski, Maslowski, and Pankau, 1997). The technical advantage of IGBTs over BJTs is that device rise and fall time switching capability is five to ten times faster. Faster switching time generates smoother sine waves, leading to more efficient and precise drive control.

Industrial motors are commonly outfitted with ASDs to provide speed control for a variety of factory machinery, equipment, and robotic systems. ASDs in industrial motors reduce electricity consumption by varying output power. Motors with ASDs are significantly more energy efficient than constant speed motors for applications that operate a large portion of the time at partial loads.

One of the largest applications of ASDs is heating, ventilation, and air conditioning (HVAC) systems. ASDs enable air ventilation systems to run more efficiently at part loads. For example, an air conditioning unit traditionally had one speed, “on.” The compressor ran at full power to cool a room. With an ASD controlling the fan, the system can run continuously at 25 percent as opposed to off and on at 100 percent. Running at part load reduces the amount of energy needed to meet the same cooling requirements.

2.2.3 Power Control Equipment

Power control is a broad applications category that includes power conditioning, power correction, and industrial electrotechnologies. IGBT-based systems are used to “clean” and regulate power flows for these applications.

Power conditioners primarily regulate voltage surges and overvoltage and brownouts and handle isolation problems such as noise and grounding issues. Fluctuations in voltage are typically caused by severe weather, such as lightning, and generator or transmission faults and can lead to damaged equipment, false or lost data, and data transmission disruptions.

The high speed switching capability of IGBTs increases the efficiency of power correction equipment and reduces the capacitor and resistor component costs.

IGBTs are used in power factor correction equipment to switch banks of capacitors on- and off-line to maintain a high power factor. The high-speed switching capabilities of IGBTs increase the efficiency of the equipment and reduce the capacitor and resistor component costs required to meet a specific level of performance (power factor improvement).

Power factor correction equipment is used to improve power factors at large industrial plants by regulating reactive power.¹ A power factor is the ratio of active power to total power and quantifies the portion of power used by a facility that does electrically useful work. A power factor of 90 percent implies that 10 percent of the total power is being lost. Large contributors to poor power factors are motors operating at part load and motors with frequent start-up and shut-down schedules.

Power companies generally charge an additional fee to facilities having power factors less than 85 to 95 percent to capture generating costs not reflected in their electric energy (kWh) meter. Additional benefits from power factors close to 100 percent are better voltage regulation and released system capacity.

IGBTs are also used in industrial electrotechnologies, such as high frequency welding, electroplating, and induction heating. For example, the availability of IGBTs has resulted in the development of high-frequency (>20 kHz) welding power supplies. IGBT's increased switching frequency leads to the following benefits:

- reduced size and weight, and hence cost;
- improved welding performance; and
- reduced noise (Theron et al., 1993).

Additional high-voltage supply applications that use IGBTs include highly specialized equipment for military and public utility applications. Examples of these applications are electrical power distribution and transmission equipment and locomotive drives for electric trains.

¹Inductive devices, such as inductive motors, magnetic ballasts, and transformers require two types of power to operate—active and reactive power. Active power (also called real power) produces work or heat and is expressed in terms of kilowatts (kW). Reactive power does not perform useful work but is used by inductive devices to generate magnetic fields. Reactive power is expressed in terms of kilovolt-amps (kVARs). Total power (also referred to as apparent power) is the vector sum of active and reactive power.

2.2.4 Lighting

Twenty to 30 percent of the electricity consumed in the U.S. is for lighting purposes. By expanding the use of electronic ballasts that incorporate IGBTs in lighting, experts estimate that energy consumption for lighting could be reduced by one-third (Jednacz, 1991a).

IGBTs and power MOSFETs are used in electronic lamp ballasts to control current for lighting applications. Electronic lamp ballasts (ELBs) that incorporate power semiconductors provide a variety of benefits. First, they are more energy efficient. Second, they reduce the amount of harmonics sent back on the wire, improving overall power quality for the commercial or industrial facility. Finally, they eliminate the stroboscopic effect, or flicker, associated with fluorescent lighting.

Currently IGBTs are used primarily in the electronic lamp ballasts of compact fluorescent lights. However, it is anticipated that in the near future IGBTs will penetrate the larger market of electronic ballasts for fluorescent lamps used in commercial buildings.

2.2.5 Future Trends and Applications

The growth in IGBT usage in the medium-power control market is expected to continue; no substitute products are anticipated in the foreseeable future. The IGBT currently dominates the market for medium-power control devices between 200 and 1,500 volts. In the near future IGBTs are expected to make inroads in the lower-voltage power-device applications, replacing power MOSFETs (Baliga, 1998).

For large power control devices (greater than 3,000 volts), the thyristor continues to be the dominant device. Thyristors are capable of controlling high voltage levels on the order of 6,000 volts or more and can carry 1,000 amperes. Even though they are relatively small devices, they require huge control circuits, have slower switching capabilities, and are much noisier. Some Japanese corporations are experimenting with high-voltage applications using groups of IGBTs.

Table 2-1 presents future applications for IGBTs. Automobile electronics are projected to be the largest user of IGBTs in the near future.

Table 2-1. Projected Applications for IGBTs by the Year 2000
Automobile electronics, telecommunications, and smart homes are projected to be the largest users of IGBTs in the near future.

Application	Projected Market
Display drives	\$2 billion
Computer power supplies	\$3 billion
Adjustable speed drives	\$1 billion
Factory automation	\$1 billion
Telecommunications	\$5 billion
Appliance controls	\$3 billion
Consumer electronics	\$2 billion
Lighting ballasts	\$3 billion
Smart homes	\$5 billion
Air-craft electronics	\$5 billion
Automobile electronics	\$10 billion

Source: Baliga, Jayant. 1997. "How the Super-transistor Works." *Scientific American* 8(1):34-41.

IGBTs are just beginning to be used in household applications, and this market is expected to be a significant growth area for the use of IGBTs. In the average household in a developed country, there are 40 electric motors in everything from blenders to compressors (Baliga, 1997). The number of those devices controlled by IGBTs will increase as their usage spreads into smaller devices. For example, Maytag has recently introduced ASDs incorporating IGBTs produced by Emerson Electronics into their top-of-the-line washing machines. High-end refrigerators are also being fitted with ASDs incorporating IGBTs. In addition to the advantage of reduced energy consumption, the IGBTs enable silent compressors, eliminating background noise (hum) because their switching speeds generate pulses that have a frequency range that is above human hearing.

2.3 IGBT SIMULATION MODELING SUPPLY CHAIN

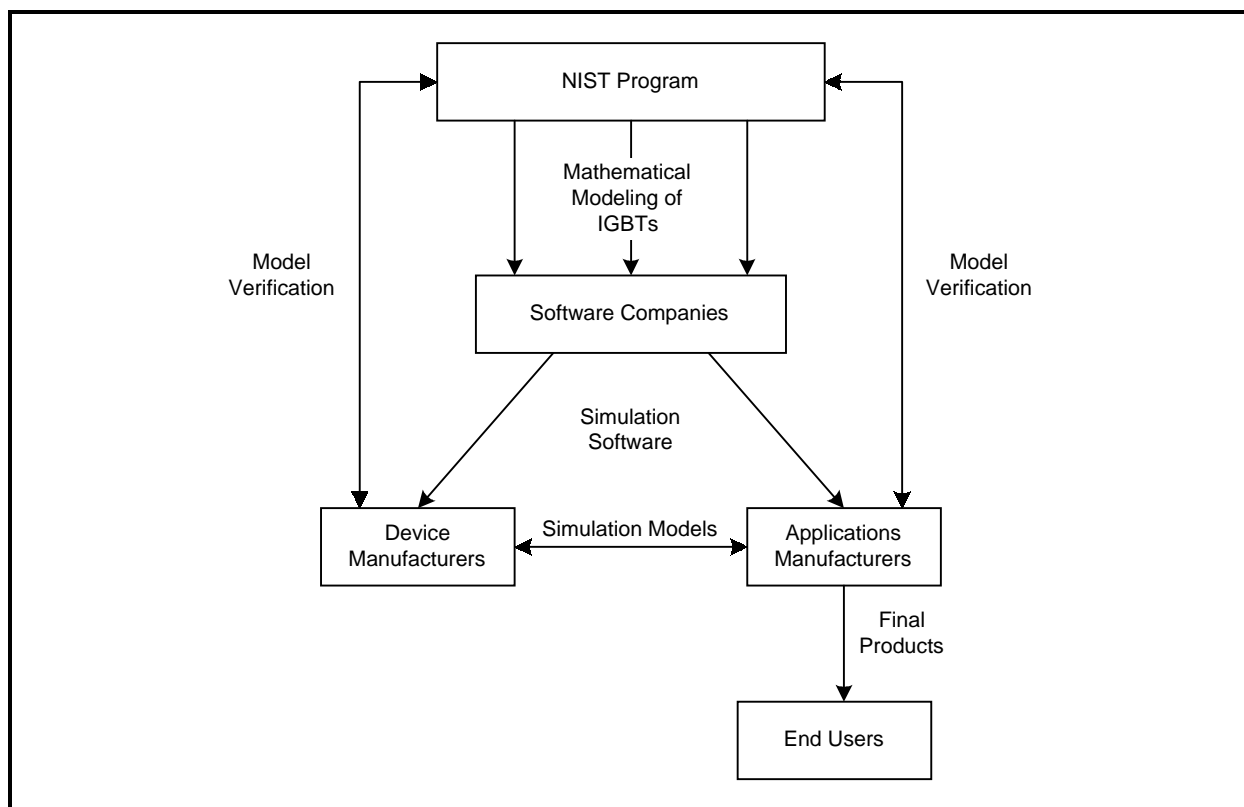
The IGBT simulation modeling supply chain is shown in Figure 2-1 and includes software companies, device manufacturers, and applications manufacturers. Software companies supply simulation tools to both device and applications manufacturers. Device and

applications manufacturers use the simulation tools to integrate IGBT devices in electrical systems. Device and applications manufacturers typically work closely together in an iterative process during the electrical system design.

As shown in Figure 2-1 there is significant feedback from device and applications manufacturers to support the development and verification of mathematical algorithms. NIST has played a leading role in coordinating this feedback to support the development and verification of mathematical models for IGBTs. This subsection discusses the major companies involved in the IGBT simulation modeling supply chain.

Figure 2-1. Industry Relationships and NIST's Role in Developing Simulation Modeling Tools for IGBTs

Mathematical modeling of IGBT devices involves many members of the supply chain.



2.3.1 Software Companies

Analogy, Inc., and OrCAD, Inc., are the two major manufacturers in the U.S. producing modeling software for power electronics applications. Analogy produces SABER and OrCAD produces PSPICE (originally developed by MicroSim). These two companies' software products support virtually all the simulation modeling of IGBTs (Benjakowski, 1997). The only known foreign competitor that produces IGBT modeling software is the University of Zurich, Switzerland; several European companies use this software for IGBT design (Clemente, 1997).

Analogy worked directly with NIST to include Hefner's mathematical models in SABER. By 1991, IGBT modeling was available in SABER.

Analogy, Inc., is a relatively small company in terms of sales and employment and specializes in software development and support of simulation modeling of electrical devices and systems. As of March 1997, the company reported \$25.8 million in revenue and 218 employees (Analogy, 1998). Analogy worked directly with NIST to include Hefner's mathematical models in SABER. By 1991, IGBT modeling was available in SABER. SABER is generally viewed by device and applications manufacturers as the most accurate modeling tool available. However, it is also more costly and technologically demanding to use compared to alternative models such as PSPICE (Benjakowski, 1997).

MicroSim incorporated NIST's mathematical modeling algorithms in its software product PSPICE in the early 1990s. The NIST IGBT Model was integrated into PSPICE through the combined efforts of MicroSim, NIST, SRC, and the University of Florida (Shen, 1997). MicroSim merged with OrCAD in 1997. OrCAD is a leading supplier of electronic design automation (EDA) software and services to engineering firms developing products on the Intel/Microsoft platform (OrCAD, 1998). In 1997, OrCAD (including MicroSim) had revenues of \$44 million.

2.3.2 Device Manufacturers

U.S. device manufacturers have focused on IGBT devices with current capacities from 10 to 50 amperes. These devices employ a single silicon chip. Table 2-2 provides information on the major U.S. manufacturers of IGBT devices. Of these companies,

Table 2-2. Company-Level Data for Major U.S. Manufacturers of IGBT Devices
 Delco Electronics, Harris Corporation, International Rectifier, and Motorola use SABER for IGBT modeling.

Name	Parent Company	Organization Type	Sales ^a (\$million)	Employment	Fiscal Year Ended	End-Use Applications
Advanced Power Technology	—	NA	NA	NA	NA	Automotive electronics, consumer audio systems, factory automation, computers and telecommunications uninterruptible power supplies, sonar and radar systems
Delphi Delco Electronics	Delphi Automotive Systems	Public Subsidiary	\$5,560	31,000	12/31/95	Automotive electronics for General Motors automobiles
Harris Semiconductor	Harris Corporation	Public Subsidiary	\$637	8,489	06/30/95	Motor controllers and power supplies, automotive electronic systems, communications systems, military and aerospace applications
International Rectifier	—	Public	\$486	4,385	06/30/97	Automobile electronic systems, computer applications, consumer electronics, lighting applications, industrial applications, government and aerospace applications
IXYS Corporation	—	Private	\$55	NA	03/31/97	Automotive, industrial, and power conversion applications
Motorola Incorporated	—	Public	\$27,973	139,000	12/31/95	Communications, automotive, industrial, consumer electronics and computer applications

NA = Not available.

^aSales include all products, including non-IGBT products.

Sources: Information Access Corporation. 1998. Business Index [computer file]. Foster City, CA: Information Access Corporation.

Advanced Power Technology (APT). World Wide Web Site:

<http://www.advancedpower.com/Co_Over/BackeG_96.html. Last updated December 16, 1996.

General Motors Corporation. March 20, 1997. 10-K for year ended December 31, 1996. EDGAR Database:

<<http://www.edgar-online.com/pointcast/gdoc/?choice=2-616283&nad=0>>. Bethesda, MD: Lexis/Nexis.

Harris Corporation. August 29, 1997. 10-K405 for year ended June 27, 1997. EDGAR Database:

<<http://www.sec.gov/Archives/edgar/data/202058/0000950152-97-006326.txt>>. Bethesda, MD: Lexis/Nexis.

International Rectifier Corporation. September 26, 1997. 10-K405 for year ended June 30, 1997. EDGAR Database:

<<http://www.sec.gov/Archives/edgar/data/316793/0000912057-97-031847.txt>>. Bethesda, MD: Lexis/Nexis.

Motorola Incorporated. March 31, 1997. 10-K/A for year ended December 31, 1996. EDGAR Database:

<<http://www.sec.gov/Archives/edgar/data/68505/0000950131-97-003500.txt>>. Bethesda, MD: Lexis/Nexis.

Delphi Delco Electronics, Harris Corporation, International Rectifier, and Motorola Incorporated hold SABER licenses.

Delphi Delco Electronics manufactures IGBT devices that are used in the electrical systems of GM automobiles. Delco's power MOSFET and IGBT devices are included in GM automobile systems such as ignition systems, antilock brakes and traction controllers, air bag deployment, and audio and security systems.

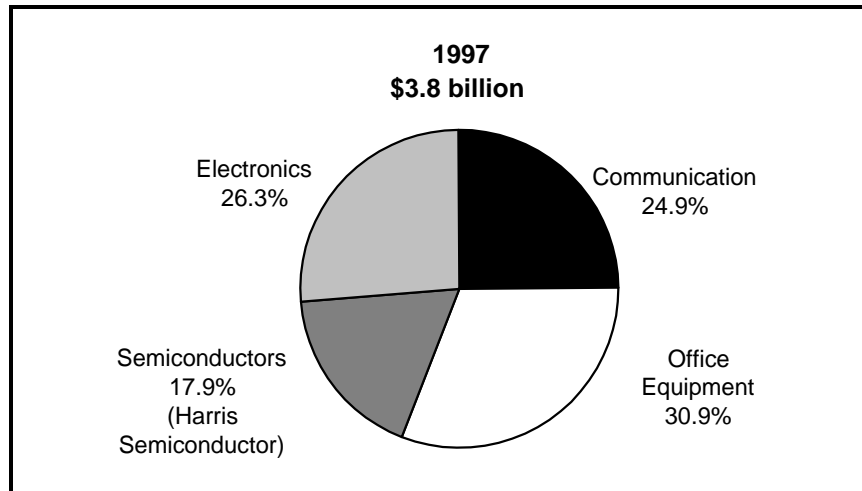
Harris Semiconductor, a subsidiary of Harris Corporation, produces custom integrated circuits (ICs) and discrete devices that are used in a variety of products such as automotive systems, wireless communications, telecommunications, video and imaging systems, multimedia, industrial equipment, computer peripherals, and military and aerospace systems. As shown in Figure 2-2, semiconductor sales accounted for 17.9 percent of Harris Corporation's total revenues in 1997 (Harris, 1997). Harris Corporation's communications segment (24.9 percent), office equipment segment (30.9 percent), and electronics segment (26.3 percent) accounted for the majority of the company's revenues. The Harris Corporation is vertically integrated to the extent that its communications equipment, office business equipment, and electronic systems incorporate IGBTs and other semiconductors produced by Harris Semiconductor.

International Rectifier is a worldwide supplier of power semiconductors and a leader in the power MOSFET segment. The company's devices are incorporated in subsystems and end products manufactured by companies that are not part of its corporate structure. As shown in Figure 2-3, the company's power MOSFET products and IGBT transistors accounted for approximately 70 percent of fiscal 1997 sales. The remaining 30 percent resulted from sales of high-voltage control ICs, high-performance diodes, and high-power rectifiers and thyristors.

Motorola Incorporated's semiconductor segment designs, manufactures, and distributes discrete semiconductors and ICs. Semiconductor sales accounted for 27 percent of Motorola's total revenue. Motorola produces a wide range of final products that use

Figure 2-2. Distribution of Harris Corporation Sales by Segment: 1997^a

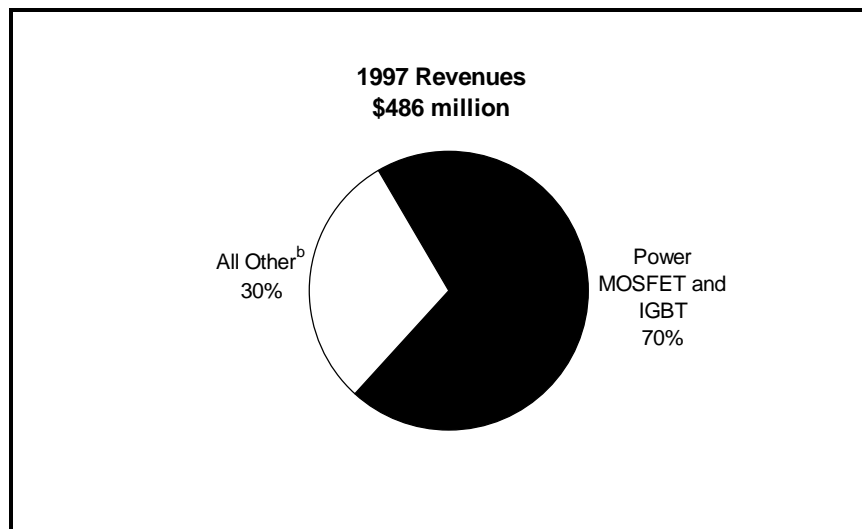
Harris Semiconductor accounts for about 18 percent of the revenues of the Harris Corporation.



^aFiscal year ended June 27, 1997.

Source: Harris Corporation. August 29, 1997. 10-K405 for year ended June 27, 1997. EDGAR database: <<http://www.sec.gov/Archives/edgar/data/202038/0000950152-97-006326.txt>>. Bethesda, MD: Lexis/Nexis.

Figure 2-3. Distribution of International Rectifier Sales by Product: 1997^a
Seventy percent of International Rectifier's sales are from power MOSFET and IGBT devices.



^aFiscal year ended June 30, 1997.

^bAll other including high-power voltage controls, diodes, rectifiers, and thyristors.
Source: International Rectifier Corporation. September 26, 1997. 10-K405 for year ended June 30, 1997. EDGAR database: <<http://www.sec.gov/Archives/edgar/data/316793/0000912057-97-031847.txt>>. Bethesda, MD: Lexis/Nexis.

power devices (MOSFETs and IGBTs) such as cellular phones, portable radios, and modems. Motorola is vertically integrated to the extent that it incorporates these IGBTs as an input in its

production of other products. In addition, Motorola sells semiconductors directly to other customers.

Foreign Device Manufacturers

Japan is the leading foreign country manufacturing IGBT devices. Most Japanese companies focus on devices with high current capacity (200 to 1,000 amperes), and Japan is the predominant world supplier of devices within this range. These devices are hybrid in nature; that is, they contain multiple IGBT chips in parallel. For example, an IGBT device with a capacity of 400 amperes may employ three IGBT chips in parallel. The following Japanese firms manufacture IGBTs:

- Fuji Electric (Japan)
- Mitsubishi Electric (Japan)
- Hitachi (Japan)
- Toshiba (Japan)
- ABB (Switzerland)
- Siemens (Germany)
- Samsung (Korea)

2.3.3 Applications Manufacturers

The majority of IGBTs are used in automobile and motor controls, power controls, and lighting applications. These groups of applications manufacturers are also the main users of simulation modeling for IGBT design. Of these groups, the automotive and motor control industries have the highest penetration of simulation modeling for the design of IGBT systems.

All of the main device manufacturers that supply IGBTs to the auto industry hold SABER licenses.

Table 2-3 identifies the main device manufacturers that supply IGBTs to the three major U.S. automotive manufacturers. Many electrical system designs, such as ignition system design, are typically contracted out or conducted by subsidiaries of the major automobile manufacturing companies. For example, Delco produces all of GM's electronic systems. In contrast, basic research on electric vehicles is conducted at the major automobile companies' laboratories. All the companies listed in Table 2-3 hold SABER licenses.

Table 2-3. U.S. Automobile Manufacturers and Their Primary Device Supplier
The three major U.S. auto manufacturers each obtain their IGBT devices from a different supplier.

Automotive Company	Main Supplier of IGBT Devices
Ford Motor Company	Motorola
General Motors	Delco Electronics
Chrysler Corporation	Harris Corporation

Most motor control manufacturers are large multinational conglomerates with diverse business interests; smaller firms tend not to have the capital resources to compete against the larger firms. Table 2-4 presents the major manufacturers of motor controls and indicates which companies have SABER licenses and are likely to be using simulation modeling in the design of their motor control systems.

Table 2-4. Major U.S. Motor Control Manufacturers
Only five of the 13 manufacturers hold SABER licenses.

Company	Currently Hold SABER License
Allen Bradley	Yes
Eaton	Yes
Micro Linear	No
Reliance	Yes
General Electric	Yes
Warner Electric	No
Renold Power Transmission	No
Baldor	No
AMK	No
Transcoil	No
Sprint Electric	No
Rockwell International	Yes

Sources: Analogy Inc.

A sample of major power control manufacturers is presented in Table 2-5. Power control manufacturers are segmented into four categories: welding, power correction, power conditioning, and induction heating. Of the major companies in these categories, only General Electric and Rochester Instrument Systems hold SABER licenses.

Table 2-5. Selected Power Control Manufacturers Most power control manufacturers do not use SABER for simulation modeling.

Company	Currently Hold SABER License
Welding	
ESAB	No
Lincoln Electric	No
Weltronic/Technitron Corp	No
Weldlogic, Inc.	No
Unitrol Electronics	No
Thermadyne	No
RoMan Manufacturing	No
Robotron Corporation	No
Polaris Electronics	No
Miller Electric	No
LaseRevolution Inc	No
ITW Dynatec	No
Power Correction and Power Conditioning	
Northeast Power Systems	No
Thunderbyrd Power Systems	No
Phaseco, Inc	No
Correction Controls	No
Commonwealth Sprague	No
Steelman Industries	No
General Electric	Yes
Arco Electric	No
Chloride Power electronics	No
Online Power	No
MCG Surge Protection	No
Oneac	No
EFI Electronics	No
PowerSmiths	No
Rochester Instrument Systems	Yes
Pribusin	No
Induction Heating	
Zion Industries	No
Michigan Induction	No
Lepel	No
Inductotherm Industries	No
EYE-HS USA	No

Source: Analogy, Inc.

Major U.S. manufacturers of compact fluorescents are presented in Table 2-6. General Electric is the only manufacturer of compact fluorescents identified that holds a SABER license.

Table 2-6. U.S. Manufacturers of Compact Fluorescents
General Electric is the only lighting manufacturer that holds a SABER license.

Companies	Currently Hold SABER License
OSRAM Sylvania	No
Advance Transformer Company	No
Advanced Lighting Technologies	No
General Electric	Yes
Genlyte	No
Lights of America	No
Howard Industries	No
Renova	No

Source: Analogy, Inc.

3

Technical Impacts of Simulation Modeling of IGBT Devices

Simulation modeling of IGBT devices has had a significant impact on the system design process and final performance of products employing IGBTs. Modeling allows engineers to determine the best design characteristics before physical prototypes are produced, saving both time and money in the design process. A model can improve product performance by determining the performance range of a device and allowing an engineer to explore alternative design scenarios in a more timely and efficient manner than if (s)he had produced a physical prototype.

This section describes the technical impacts associated with using mathematical modeling of IGBT devices. Table 3-1 summarizes the technical impacts and categorizes them as impacts on R&D efficiency, transaction costs, production costs, and final product quality and performance. These technical impacts are described in detail in this section.

3.1 IMPACTS ON R&D EFFICIENCY

Software incorporating NIST's mathematical models is primarily used for integrating the IGBT device into the electrical system of the final product. We refer to this as the use of simulation modeling in the system design process. Figure 3-1 shows the interaction

Table 3-1. Technical Impacts of Simulation Modeling of IGBT Devices

The use of simulation modeling of IGBT devices affects the design process, reduces the materials required for manufacturing, improves the manufacturing process, and improves product quality and performance.

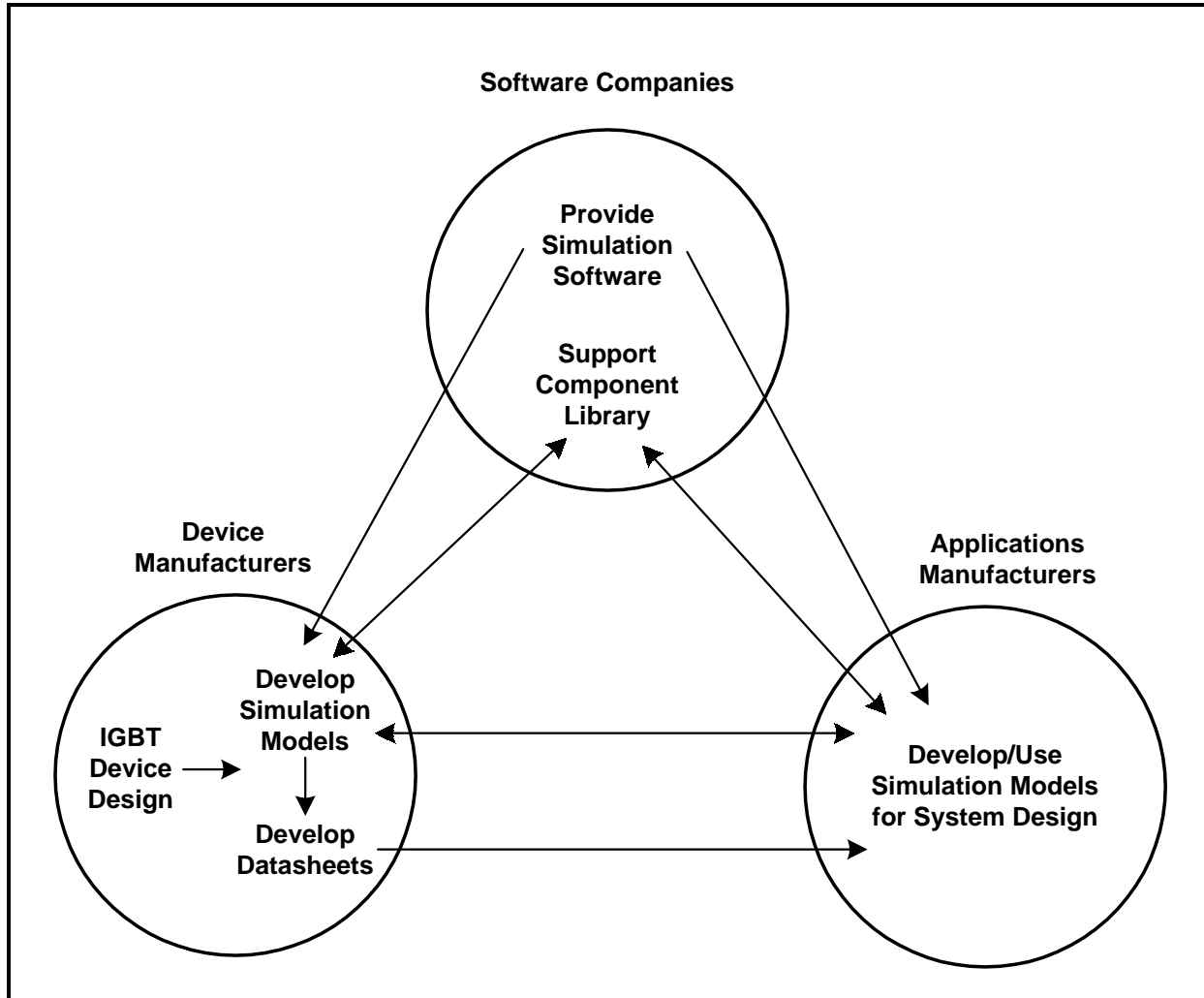
Benefit Categories	Description of Technical Impact
R&D Efficiency	<ul style="list-style-type: none"> ➤ Supports mathematical representation of the physical behavior of IGBT devices' complex electrical characteristics in the silicon and enables analysis of how the IGBT device interfaces with the electrical system design. ➤ Allows IGBT device designers to gain an understanding of their design without physically procuring materials and building a prototype. ➤ Reduces the number of design iterations needed to develop a new product, reducing labor and material inputs. ➤ Enables concurrent design of IGBT devices and applications employing the device for optimal performance of application. ➤ Reduces R&D cycle design time. However, reduction in R&D design time is typically not large enough to affect total product cycle design time.
Transaction Costs	<ul style="list-style-type: none"> ➤ Reduces the cost of developing datasheets that provide information on device performance over a range of operating conditions. ➤ Enables more detailed datasheets allowing purchases of IGBTs to compare products across different device suppliers.
Production Costs	<ul style="list-style-type: none"> ➤ Reduces material needs associated with packaging the IGBT-based electrical system in the final product. ➤ Increases design precision, which enables lower tolerances and safety margins, reduces size of capacitors and heat sinks needed. ➤ Reduces final product defect rates.
Final product quality and performance	<ul style="list-style-type: none"> ➤ Enables cost-effective analysis of alternative design scenarios—analysis of multiple “what-if” scenarios helps optimize system design and increase performance. ➤ Provides more accurate information about the performance range of the IGBT device—leads to increased product efficiency and improved product characteristics.

As shown in Figure 3-1, software incorporating NIST’s mathematical models is not typically used to design IGBT power devices. Device engineers use finite element and two-dimensional models to develop the physical parameters of the IGBT devices.

between applications manufacturers, device manufacturers, and software companies that support the system design process.

Software companies license simulation software to both applications and device manufacturers. Device and applications manufacturers typically work closely together in the system design process, exchanging software models and device information in an iterative process. Device manufacturers use SABER to develop software models for new

Figure 3-1. The Interaction of Design Activities Among Members of the Supply Chain
 Designing electrical systems incorporating IGBTs requires interaction among the software companies, the device manufacturers, and the applications manufacturers.



IGBT devices to support applications manufacturers' system design activities. Device manufacturers also use SABER's simulation capabilities to develop IGBT device datasheets.

Datasheets provide information on static device performance so that applications manufacturers can compare IGBT devices from different vendors over a variety of operating conditions.

Only large applications manufacturers develop their own IGBT simulation models. Most applications manufacturers use either models provided by device manufacturers or models contained in component libraries supported by software companies. Once a

model has been developed, it is usually placed in the public domain (on the Internet) or included in the component library.

Identifying the steps conducted in a typical system design process is difficult because the activities required vary greatly across end-use applications (Clemente, 1997). Some of the factors that influence system design activities are

- the size (voltage) and complexity of the electrical system,
- the interaction of the IGBT-based components with other components in the system,
- whether “off the shelf” IGBT component models are available or if a new simulation model must be developed, and
- whether the design is for a new system or is a re-design of an existing system.

The following is a description of a typical system design process without and with simulation modeling.

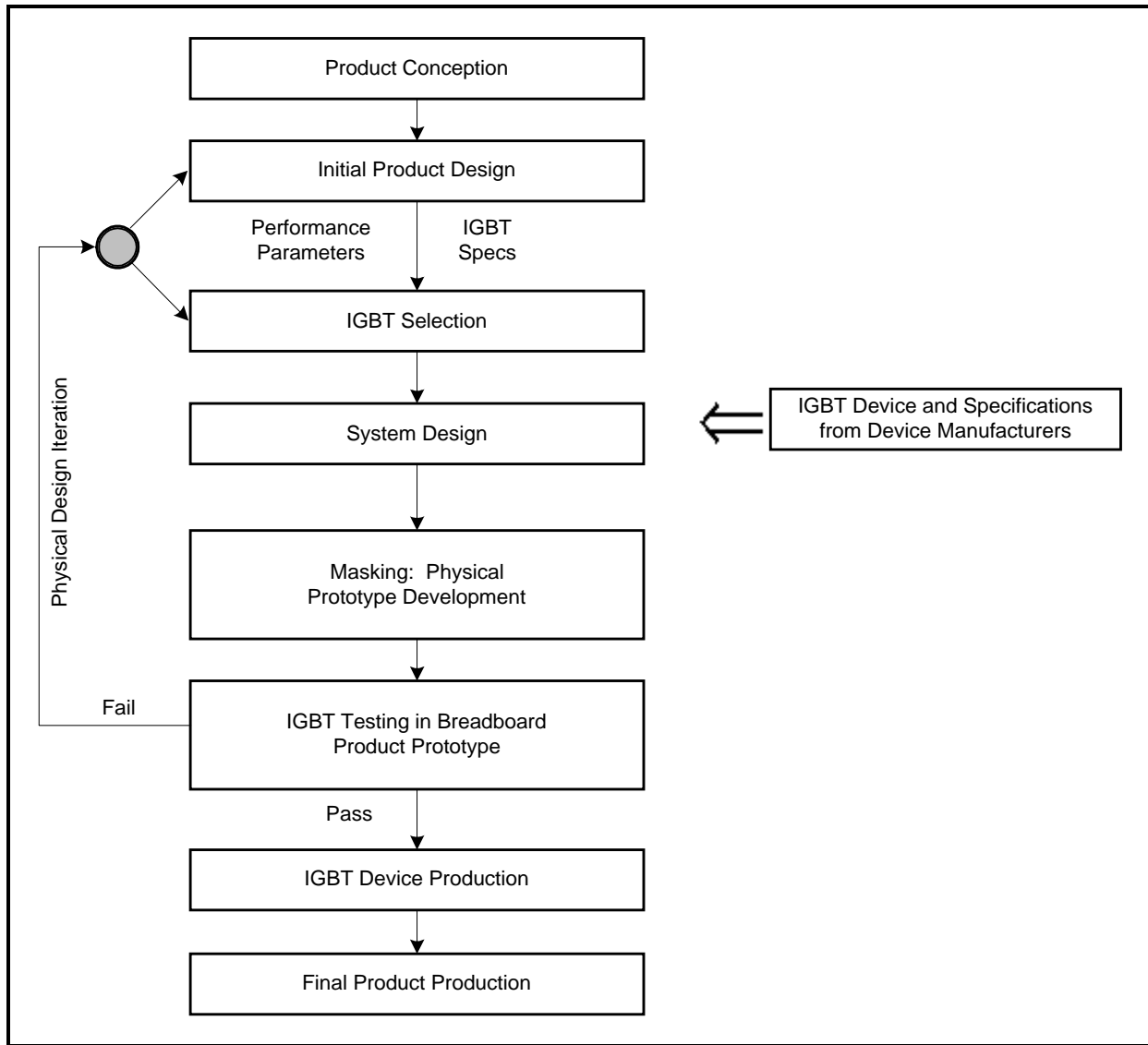
3.1.1 Description of the System Design Process *Without* Simulation Modeling

Figure 3-2 illustrates the flow of a “typical” system design process without simulation modeling. After the initial product conception and product design, system performance parameters and IGBT device specifications are determined and an IGBT device is selected. During the system design process, the IGBT device is integrated into the electrical system and a physical prototype (also referred to as a mask) is developed and tested in a breadboard configuration. One of the main purposes of the breadboard testing is to determine the performance range of the device.

In most cases a system designer physically “fails” the device and the prototype is destroyed. In these situations the system designer will then work very closely with the device manufacturer to re-design the device to meet the desired power requirement. This is commonly referred to as a physical design iteration. It is not uncommon for the system design to entail five to six design iterations. Each design iteration typically takes several weeks and requires the construction of a new physical prototype.

Figure 3-2. System Design Process Without Simulation Modeling

In the absence of simulation modeling, the design sometimes requires as many as six physical design iterations before passing.

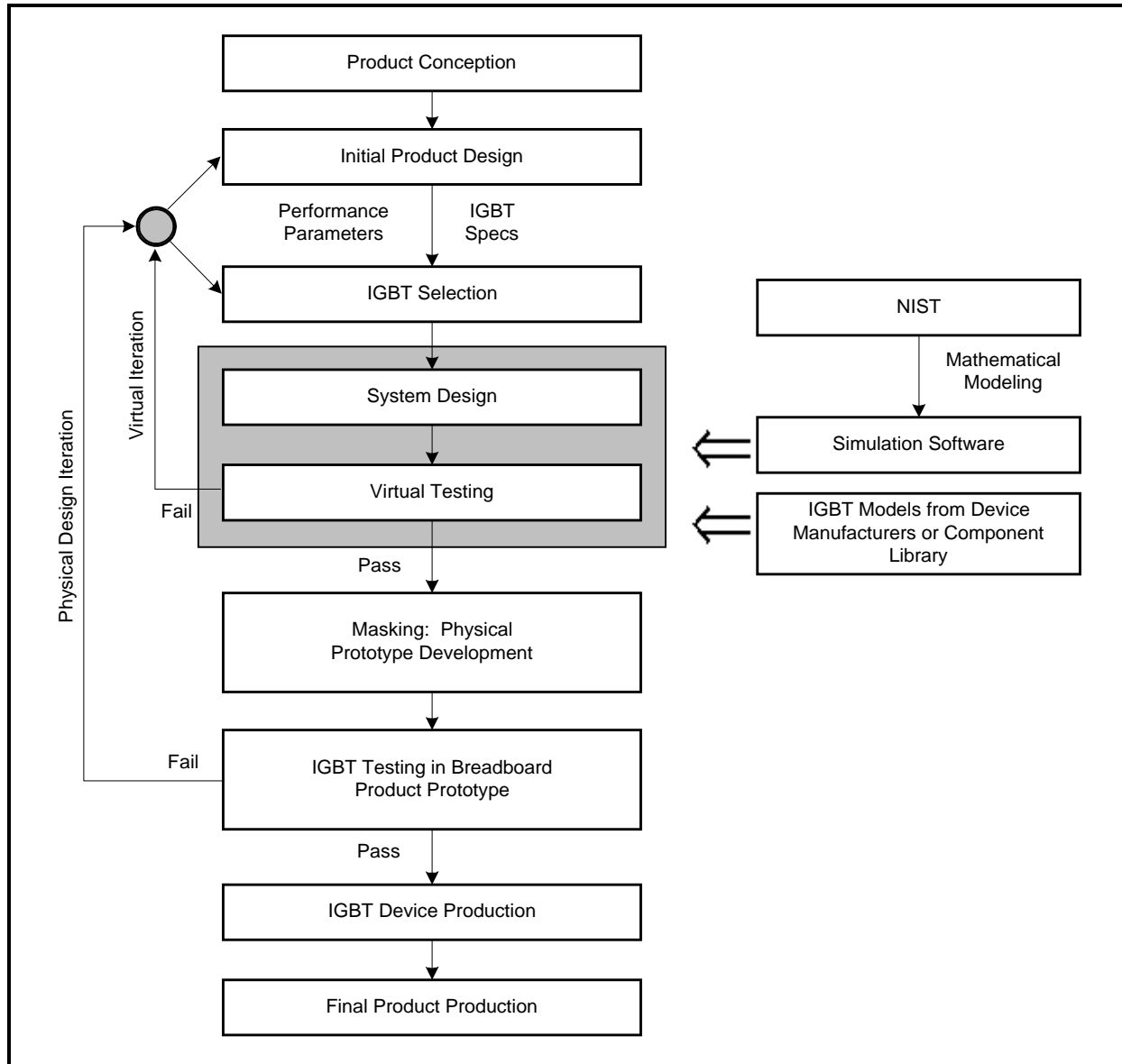


Once the IGBT device prototype passes the breadboard test, the device specifications and performance parameters are passed on to production or the next design tier.

3.1.2 Description of the System Design Process *With* Simulation Modeling

Figure 3-3 illustrates the system design process using simulation modeling of IGBTs. The main advantage of using simulation modeling in system design is that it enables virtual testing of

Figure 3-3. System Design Process with Simulation Modeling
 With simulation modeling, the design often passes with fewer iterations.



alternative designs before the development of physical prototypes (virtual iteration). Because simulation models can accurately predict device performance, they enable the simulation of “what if” scenarios.

By investigating alternative design scenarios in a virtual environment, the number of physical iterations required to “pass” a device can be significantly reduced. The use of simulation modeling will almost always eliminate one physical iteration from

the design process and frequently will eliminate three to four physical iterations (Benjakowski, 1998).

3.1.3 Summary of the Technical Impacts of Simulation Modeling on System Design Process

Simulation modeling based on mathematical models of IGBTs enables virtual testing of systems. Virtual testing affects the design process in the following ways:

The use of simulation modeling enables representation of the physical behavior of IGBTs' complex electrical characteristics in the silicon and how the device interfaces with the system design.

- The use of simulation modeling enables representation of the physical behavior of IGBTs' complex electrical characteristics in the silicon and how the device interfaces with the system design.
- IGBT designers gain an understanding of their design without physically procuring materials and building a prototype.
- With simulation modeling, a design may require only one to two iterations. Historically, IGBT design would require three to four iterations.
- The use of simulation modeling enables concurrent design of IGBT systems and applications employing the device, minimizing overall R&D cycle design time and improving performance of the application.
- Having fewer redesign iterations leads to reductions in labor and materials. Reductions are generally proportional to the number of iterations reduced.
- Mathematical models of IGBTs also affect the performance range of the system devices. Mathematical modeling enables designers to test their systems at all ranges to determine if a given IGBT design will meet multiple design and performance requirements.
- Simulation modeling increases the fixed design costs of purchasing and maintaining the required software and hardware and training designers to use them.

3.2 IMPACT ON TRANSACTION COSTS

Device manufacturers use simulation modeling of IGBTs to generate datasheets for each new family of IGBTs developed. Datasheets provide information on static performance so that buyers can compare IGBT devices from different vendors over a variety of operating conditions.

The use of simulation modeling significantly reduces the cost of developing a datasheet for a new device. Without simulation

modeling, device design engineers need to conduct hundreds of measurement tests per datasheet to manually plot out behavioral curves. With simulation modeling, they can map IGBT device behavior using only a few physical test points to verify the simulated behavioral curves.

Using simulation modeling to develop datasheets also increases the range and quantity of information that can be cost effectively provided on datasheets. This reduces search costs for purchasers of IGBTs by enabling them to more efficiently compare device performance across different suppliers.

3.3 IMPACT ON PRODUCTION COSTS

The use of simulation models in the system design process may also affect material costs and manufacturing costs. Simulation modeling enables the reduction in engineering safety margins for system components and packaging, which in turn reduces the cost of manufacturing. The superior predictive capabilities of IGBT simulation models can be used by product design engineers and module engineers minimize the use of materials (such as silicon).

For example, the use of IGBT simulation models can reduce the number and size of capacitors and heat sinks used in a system, resulting in a reduction of the dimensions and weight of some systems by about 20 to 30 percent (Et-Info, 1997). In addition, the IGBT's smaller size also lowers integration costs, reduces complexity, and increases reliability of the component, thus leading to fewer defective parts.

3.4 IMPACT ON PRODUCT QUALITY AND PERFORMANCE

Simulation modeling also leads to increased performance of products employing IGBTs. Concurrent design and more accurate information on the performance range of the IGBT generated by NIST's mathematical models enables designers to increase the efficiency of their final products. Increased fuel efficiency was one of the main motivating factors in the automotive industries' decision to adopt simulation modeling for the design of ignition systems.

Additional examples of potential product quality and performance improvements resulting from the use of simulation modeling of IGBTs include

- ▶ increased accuracy of roboting equipment,
- ▶ decreased electricity consumption of ASDs in industrial and HVAC applications,
- ▶ increased lighting quality, and
- ▶ decreased noise (hum) of electrical equipment.

4

Methodology for Estimating Economic Impacts

The methodology used in the quantitative analysis provides reliable and conservative (lower-bound) estimates of the social benefits associated with NIST's contributions to the simulation modeling of IGBTs. Our approach is to include in the quantitative analysis only impacts that have been explicitly identified *and* quantified by industry experts. For many of the impacts described in this section, industry experts identified impact areas but were not able to quantify the impacts in terms of technical or economic metrics. These hard-to-quantify impacts are not included in the benefits estimates but instead are discussed qualitatively with examples that illustrate the potential magnitude of economic benefits.

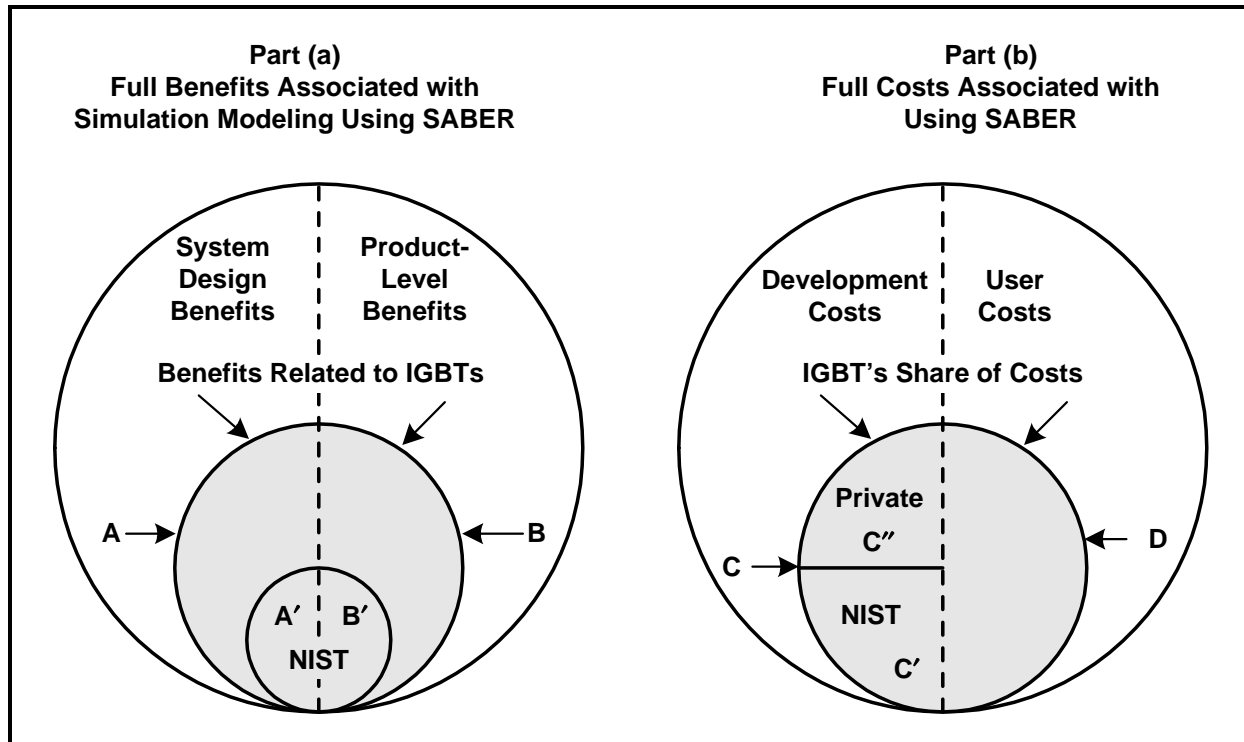
This section begins with a graphical presentation of our methodology to estimate economic benefits. This is followed by the definition of benefit and cost categories and the technical and economic metrics used to quantify impacts associated with these benefit and cost categories. The section concludes with an overview of the data collection process.

4.1 ECONOMIC MODEL

Figure 4-1 illustrates the conceptual framework and associated taxonomy used in the quantitative analysis. The framework defines the benefit and cost categories used in the analysis and helps ensure that all impacts are accounted for and that benefits or costs are not double-counted.

Figure 4-1. Defining Benefits and Costs

The total benefits of the use of simulation modeling of IGBTs is represented by areas A and B. The total costs are represented by areas C and D.



As discussed in the following section, our quantitative analysis focuses on the use of Analog's software product SABER for simulation modeling of IGBTs. However, because IGBT modeling is only one small component of SABER's modeling capabilities we begin by looking at the larger picture of the full benefits and costs associated with using SABER.

Part (a) of Figure 4-1 represents the full social benefits associated with simulation modeling using SABER. Benefits are segmented into two categories:

- benefits realized during the system design process, such as decreased labor costs or decreased material costs for physical prototypes, and
- product-level benefits, such as decreased manufacturing costs and improved product performance.

The benefits associated with simulation modeling of IGBTs are a subset of the full benefits of using SABER. These are represented by the shaded area in Part (a) of Figure 4-1 (Area A and Area B).

The inner area in the benefits figure is the portion of benefits attributed to NIST’s contributions to the development and promotion of IGBT simulation modeling.¹ NIST-related benefits are a subset of the benefits associated with simulation modeling of IGBTs. As shown in the figure, NIST’s contributions have generated benefits in both the system design category (area A’) and in the product-level category (Area B’).

Software costs are actually transfer payments between the developer and user of the simulation modeling software. They do not affect the size of net benefits. We have included software costs on the user side because it is difficult to quantify private R&D (C’). Our modeling approach is to assume that private R&D costs net of software revenue is approximately zero (i.e., software company profit from developing IGBT modeling ≈ 0). In this way we minimize the impact of not being able to quantify private R&D expenditures.

Part (b) of Figure 4-1 represents the full social costs of using SABER for simulation modeling. Costs are also segmented into two categories: development costs and user costs. Development costs are the R&D costs associated with SABER development and promotion that are not captured in SABER licenses, maintenance fees, or component library lease fees. User costs are the costs device and applications manufacturers incur for adopting SABER for simulation modeling. User costs include software costs, such as software licenses, maintenance fees, component library lease fees, and training costs for staff to learn how to use SABER.

The shaded areas in Part (b) of Figure 4-1 (Area C and Area D) represent the portion of costs associated with simulation modeling of IGBTs. This includes both development costs (Area C) and user costs (Area D). Development costs associated with simulation modeling of IGBTs are further subdivided into NIST simulation modeling program expenditures (area C’) and private expenditures (Area C’).

4.1.1 Net Benefits from Simulation Modeling of IGBTs

Based on the areas in Figure 4-1, the net benefits to society associated with the simulation modeling of IGBTs are defined as the design process benefits and product-level benefits, less the development costs and user costs:

$$\begin{aligned} \text{Net Benefits to Society} &= (\text{Area A} + \text{Area B}) \\ &\quad - (\text{Area C} + \text{Area D}). \end{aligned} \tag{4.1}$$

The net benefits are based on the counterfactual of IGBT simulation modeling capabilities not being available to device and application

¹Areas A’ and B’ in Figure 4-1 represent the benefits that would not have occurred in the absence of the NIST simulation modeling program. Industry stated that IGBT mathematical models would not have been as accurate and would not have been incorporated into SABER as quickly without NIST’s contributions.

manufacturers. Thus, the size of areas A and B are determined by comparing the current situation (with simulation modeling) with the counterfactual situation in which all products using IGBTs are design without simulation modeling.

4.1.2 Net Benefits from NIST's Contributions to Simulation Modeling of IGBTs

To estimate the net benefits associated with NIST's expenditures, we need to know NIST's share of development costs (area C') and the share of benefits attributable to NIST's contributions (Area A' + Area B'). With this information, the net benefits from NIST's expenditures could be expressed as

$$\text{NIST Net Benefits} = (\text{Area A}' + \text{Area B}') - (\text{Area C}') \quad (4.2)$$

NIST's share of costs is theoretically simple to calculate; Area C' is NIST's simulation modeling program expenditures. However, NIST's share of benefits is much more difficult to estimate. NIST's share of IGBT simulation modeling benefits is measured relative to the counterfactual that reflects IGBT simulation modeling development and adoption in the absence of the NIST simulation modeling program.

As discussed in the following section, industry experts confirmed that NIST has made a "significant" contribution to the development and adoption of simulation modeling of IGBTs. However, none of the industry experts could provide adequate information for the development of a "without"-NIST counterfactual baseline.

In the absence of a without-NIST counterfactual baseline, the net benefits associated with NIST's contributions are defined in terms of a NIST impact coefficient (IC) and the net benefits to industry. The NIST impact coefficient is defined as a fraction between zero and one that represents NIST's relative contribution to the development and adoption of simulation modeling. The advantage of using a single impact coefficient is that sensitivity tests can be conducted for estimated values of NIST's impact.

Net benefits associated with the NIST simulation modeling program, defined in terms of the NIST impact coefficient and the net benefits to industry and are expressed as²

$$\text{Net Benefits to Industry} = (\text{Area A} + \text{Area B}) - (\text{Area C}'' + \text{Area D})$$

$$\text{NIST Net Benefits} = \text{NIST's Impact Factor} * [\text{net benefits to industry} - \text{NIST Expenditures}]$$

The NIST benefit-cost ratio is similarly defined as NIST's share of net benefits to industry divided by the NIST simulation modeling program expenditures.

$$\text{NIST Benefit-Cost Ratio} = \frac{\text{NIST Impact Factor} * \text{Net Benefit to Industry}}{\text{NIST Expenditures}}$$

4.2 CALCULATING BENEFIT AND COST CATEGORIES

The benefit and cost categories in Figure 4-1 represent flows of benefits and costs over time. The net present value (NPV) of these benefit and cost flows are calculated by adjusting for inflation and by discounting using the social (real) discount factor of 7 percent (OMB, 1995).

4.2.1 Benefits Categories

Benefits are divided into design-level benefits and product-level benefits. This distinction is important because for design-level impacts the unit of analysis is the number of times a design process is conducted and for product-level benefits the unit of analysis is the number of products sold.

For example, the use of IGBT simulation modeling can reduce the number of design iterations needed to develop a new product (or redesign an existing product). These cost reductions occur each time a system design process is conducted and are a portion of fixed costs in that they are independent of the number of units

²Alternatively, we could have defined NIST net benefits as

$$\text{NIST Net Benefits} = [\text{IC} * (\text{Area A} + \text{Area B})] - \text{Area C}'.$$

However, this definition does not incorporate information on SABER user costs and in effect assumes that NIST has no impact on user costs. Our approach assumes that IC affects all these things equally.

produced. In contrast, the unit of analysis for changes in manufacturing costs and improvements in product quality is the number of units produced and sold.

Design-Level Benefits

Simulation modeling decreased the cost of designing an IGBT system. These cost savings occur each time a new IGBT system is designed. In some cases, the system is custom designed for a narrowly defined product, such as an ASD for a specialized motor application; in other cases, the system is designed to be used in an entire class of products, such as an ignition system for an entire line of automobiles.

The system design process is defined as all steps leading up to and including the successful testing (“passing”) of the IGBT device in the breadboard (physical) product prototype.³ Benefits are generated primarily from reducing the number of physical design iterations.

Reducing the number of physical design iterations may lead to both direct and indirect benefits. Direct benefits include material cost savings from fewer physical prototypes and labor cost savings from reduced R&D design cycle time.

Indirect benefits may occur if the reduction of physical design iterations reduces coordination costs or leads to a reduction in the overall product design cycle.

Indirect benefits may occur if the reduction of physical design iterations reduces coordination costs or leads to a reduction in the overall product design cycle. Coordination costs result from idle resources or missed delivery dates due to bottlenecks in the product design process. For example, a supplier may not meet his or her delivery date if an unexpectedly large number of physical iterations are required during the system design process. In addition, reducing the overall product design cycle may generate benefits by accelerating the introduction of new products.⁴

Our approach for estimating design-level benefits is to estimate incremental impacts for “typical” design processes and then to weight them by the average number of design processes conducted per year. A series of “typical” application design processes are

³See Section 3.1 for a detailed description of the IGBT system design process.

⁴See Appendix B for a discussion of the benefits from accelerating the introduction of new product.

modeled, such as automotive ignition systems, ASDs, and compact fluorescent lamp ballasts.

The system design benefits for an application i in year t are expressed as

$$\text{System Design Benefits}_{it} = (\Delta\text{material costs}_i + \Delta\text{labor costs}_i + \Delta\text{coord costs}_i + \text{accel benefits}_i) * D_{it}$$

where

$\Delta\text{material costs}_i$ = change in the material costs for a system design for application i ,

$\Delta\text{labor costs}_i$ = change in the labor costs for a system design for application i ,

$\Delta\text{coord costs}_i$ = increased coordination costs associated with reduced overall product design time,

accel benefits_i = benefits from accelerating the introduction of a new product in application i , and

D_{it} = the number of system designs conducted in year t for application i .

Product-Level Benefits

In addition to the flow of benefits being generated over time as products are produced and sold, product quality improvements have a second time dimension because benefits accrue to individual units over their life time.

The use of IGBT simulation models in the system design process can also affect production costs and product quality and performance. Both of these are product-level benefit categories that depend on the number of units produced and sold over time. As described in Section 3, simulation modeling of IGBT devices can affect the cost of production by reducing material costs associated with heat sinks and packaging. In addition, simulation modeling can lead to improvements in product quality and performance, such as increased fuel efficiency, decreased maintenance, and decreased operating noise (hum).

Individual product-level benefits for each applications in year t are weighted by the number of units sold each year:

$$\text{Product-level Benefits}_{it} = [\Delta\text{production costs}_i + \Delta\text{product quality}_i] * Q_{it}$$

where

- Δ production costs_{*i*} = change in material costs per unit for application *i*,
- Δ product quality_{*i*} = NPV of product quality and performance improvements over the life time of the product for application *i*, and
- Q_{it} = number of units produced and sold in year *t* of application *i*.

The above approach to estimating product-level benefits is frequently referred to as a bottom-up approach—impacts per unit are estimated and then weighted by the number of units sold. Alternatively, a top-down approach could be used. In the top-down approach aggregate national statistics are typically used as the starting point for the analysis. For example, to calculate the product quality benefits from simulation modeling of automobile ignition systems, the analysis would multiply the total annual gasoline consumption in the U.S. by an estimate of the relative (percentage) impact IGBT simulation modeling has had on overall fuel efficiency. A top-down approach has the advantage of providing an upper-bound estimate of benefits (total gasoline consumption) and is useful for gaining insight into the potential range of benefits when detailed product-level information is not available.

In Section 5 we use the top-down approach to develop estimates of the potential magnitude of benefits. These product-level benefits estimates are not included in the quantified benefit estimates because of uncertainty in measuring the underlying impact metrics.

4.2.2 Cost Categories

The cost to society from using IGBT simulation models in the system design process includes both the development costs and user costs associated with SABER. NIST simulation modeling program expenditures are included in development costs.

Development Costs

Development costs include the basic development of IGBT mathematical models, verification of the models, and incorporation of the models into the SABER software. NIST made significant

contributions in all three of these design areas. NIST developed the basic mathematical models, worked with device and applications manufacturers to verify the models, and worked with Analogy to incorporate the mathematical models into SABER.

As illustrated in Figure 4-1, our modeling approach segments development costs into NIST expenditures and private expenditures. Development costs occur over time and are expressed as

$$\text{Design Costs}_t = \text{NIST exp}_t + \text{Private exp}_t$$

where

- NIST exp_t = NIST simulation modeling program expenditures in year t,
- Private exp_t = device manufacturers, applications manufacturers, and software company (Analogy) expenditures in year t (net of revenue from user costs).

User Costs

User costs include expenditures by device and applications manufacturers to purchase, support, and integrate SABER’s IGBT simulation modeling capabilities into their design activities. User costs include the fixed (one-time costs) of purchasing the SABER software and variable (annual) costs of maintenance fees, component library fees, and staff training.

The user cost information collected during the interviews with industry experts reflects expenditures and training associated with all SABER activities. However, because SABER is used for many design activities not involving IGBT systems, these total SABER costs are scaled by the percentage of time SABER is used for IGBT-related design activities.

User costs are developed for a series of typical research facilities, representing the different end-use applications employing IGBTs. Typical research facility user costs are expressed as

$$\text{User Costs}_i = [\text{Fixed Costs}_i + \sum (\text{Variable Costs}_{it})] * \text{IGBT Share}_i$$

where

- fixed costs_i = cost of purchasing SABER licenses for facility type i,
- variable costs_{it} = annual SABER maintenance fees, component library fees, and staff training for facility type i in year t, and
- IGBT share_i = percentage of SABER activities involving IGBT design for facility type i.

4.3 AGGREGATING ECONOMIC IMPACTS

To aggregate economic impacts, benefits and costs are grouped into two categories: net benefits to industry and NIST simulation modeling program expenditures. Benefit and cost flows over time are adjusted to 1998 dollars and then discounted by the social discount rate of 7 percent to obtain the NPV of the net benefits to industry (NPV industry) and NPV of NIST expenditures (NPV NIST exp).

Figure 4-1 graphically illustrates the relationship between the net benefits to industry and NIST expenditures. The benefit and cost areas in Figure 4-1 represent the NPV of the benefits and costs from the beginning of the NIST simulation modeling program (1985) through the competitive life of the IGBT mathematical models incorporated into SABER. Industry experts indicated that the current version of IGBT simulation modeling in SABER is expected to remain the dominant IGBT software model for at least the next 5 years. Thus, for the purpose of this study, we have projected benefits and costs through the year 2003.

The quantitative analysis presented in Section 5 includes all benefits and costs discussed in Section 4.1 and Section 4.2, with the exception of

- ▶ product-level benefits and
- ▶ private design costs.

As discussed in detail in the following section, industry experts were not able to provide sufficient information to reliably quantify product-level benefits and private design costs associated with IGBT simulation modeling.

As a result, the economic impact estimates presented in Section 5 are estimated as follows. The NPV of net benefits to a typical research facility in applications industry i is defined as

$$\text{NPV Net Benefits}_i = \sum_{j=0}^n \frac{\text{Benefits}_{i,t+j} - \text{Variant}_{i,t+j} \text{ IGBT Share}_i}{(1+r)^j} - \frac{\text{Fixed Costs}_i * \text{IGBT Share}_i}{(1+r)^{(t-t^*)}}$$

where

- r = social discount rate of 7 percent,
- t = base year of 1984,
- j = 0 corresponds to the beginning of 1985
- j = 1 corresponds to the end of 1985
- t^* = year in which fixed costs occurred, and
- n = 18 (year 2003).

All benefits and costs are expressed in 1998 dollars.

Typical research facility-level net benefits are weighted by the number of research facilities in each applications industry that hold SABER licenses. And all applications industries are summed to obtain the NPV to industry:

$$\text{NPV to Industry} = \sum_i (\text{NPV Net Benefits}_i * n_i)$$

where

- n_i = the number of research facilities in applications industry i with SABER licenses.

The NPV of NIST simulation modeling program expenditures is expressed as

$$\text{NPV NIST exp} = \sum_{j=0}^n \frac{C_{t+j}}{(1+r)^j}$$

where

- C = real expenditures in 1998 dollars in year t , including labor, equipment, and miscellaneous costs;
- r = social discount rate of 7 percent;
- t = base year of 1984; and
- j = 0 corresponds to the beginning of 1985

j = 1 corresponds to the end of 1985

n = 18 (year 2003).

4.3.1 Measures of Social Return to NIST Expenditures

The NPV of the NIST simulation modeling program is defined as

$$\text{NPV NIST} = (\text{NPV to Industry} * \text{NIST Impact Factor}) - \text{NPV NIST Expenditures.}$$

The benefit to cost ratio of the NIST simulation modeling program is defined as

$$\text{Benefit-to-Cost} = (\text{NPV to Industry} * \text{NIST Impact Factor}) / \text{NPV NIST Expenditures.}$$

Finally, the social rate of return of the NIST simulation modeling program is the social discount rate that equates the NPV of the NIST simulation modeling program to zero.

4.4 IMPACT MEASURES

To operationalize our modeling approach, we collected information on technical and economic impact metrics. *Technical impact metrics* describe the effects of mathematical modeling on the design and manufacturing process and on the final product employing the IGBT device. *Economic impact metrics* describe how the technical impacts translate into changes in design and manufacturing costs and into changes in consumers' valuation.

Table 4-1 summarizes the technical and economic impact metrics used to support the estimation of the economic benefits from IGBT simulation modeling. The information contained in Table 4-1 was collected through interviews with applications, device, and software manufacturers and developed from secondary data sources.

4.5 DATA COLLECTION PROCEDURES

Surveys of applications, device, and software manufacturers and secondary data sources were used to support the estimation of economic impacts. The survey instruments for the three groups are contained in Appendixes C, D, and E.

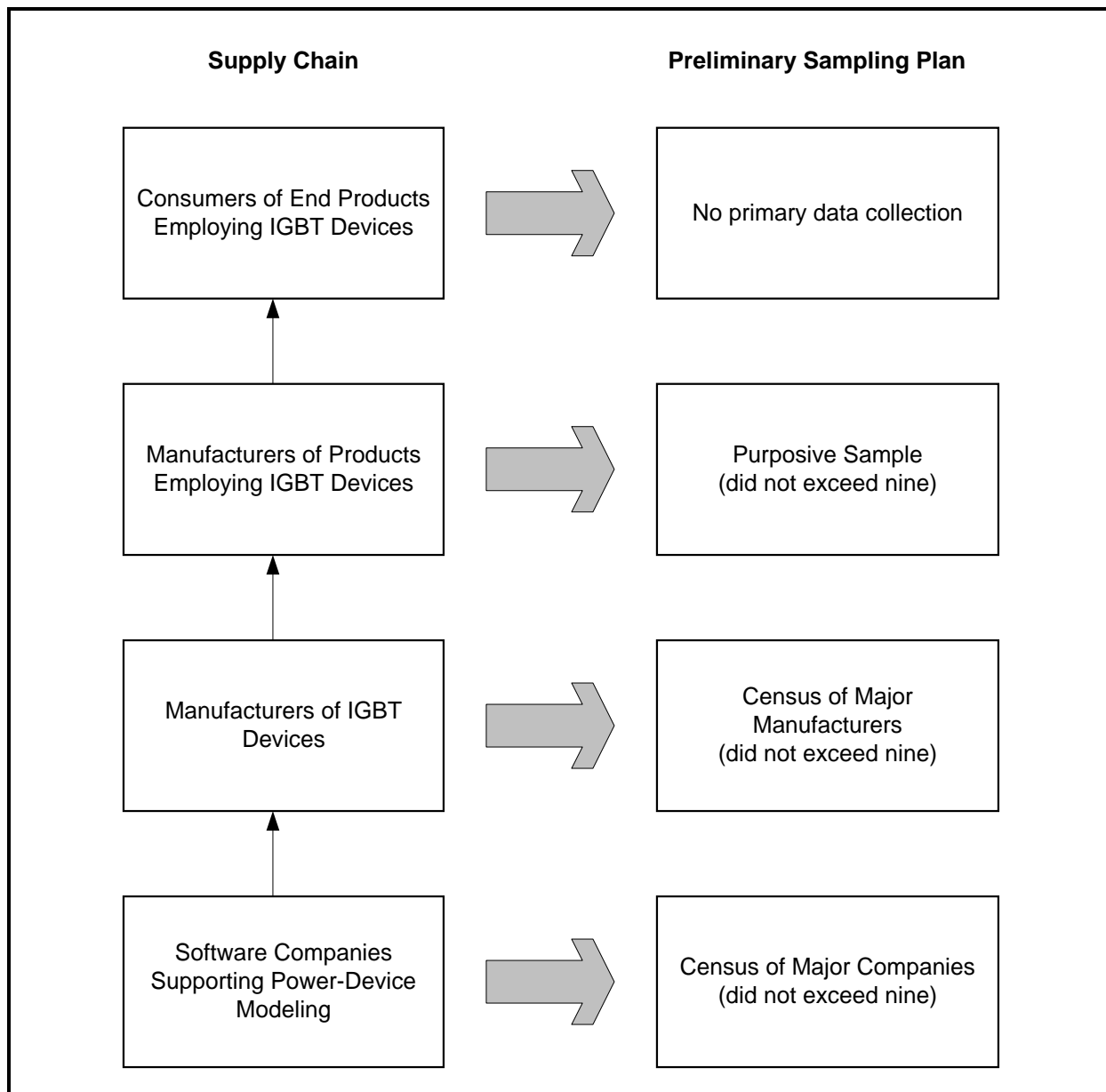
Table 4-1. Metrics for Estimating Economic Benefits
 These metrics were used to support the estimation of the economic benefits.

Impact Category	Components	Technical Metric	Economic Metric
Design-Level Benefits	Δ labor costs _j	Decreased labor hours per system design	(Number of labor hours per iteration) X (Labor cost per hour [or average wage rate])
	Δ material costs _j	Decreased materials inputs system design	(Material costs for physical prototype) X (The reduction in the number of iterations)
	Coordination costs _j	Decrease in the number of weeks for total product design cycle	(Length of delay) X (The opportunity cost of idle resources per period of delay)
	Acceleration benefits _j	Length of time product availability is advanced	Increased valuation of new product compared to old product
Product-Level Benefits	Δ production costs _j	Change in manufacturing equipment, raw materials, or labor used in the production process	(Number of units produced) X (Cost savings per unit)
		Change in the number of defective units	(Change in number of defects) X (The cost per defect)
	Δ product quality _j	Increased energy efficiency, such as energy-efficiency rating (EER) or fuel consumption	(Energy savings) X (Fuel price) X (The number of units sold)
		Changes in maintenance requirements	(Cost per maintenance or service call) X (The average reduction in calls) X (The number of units sold)
Development Costs	NIST expenditures _t	Labor hours of NIST staff to support program	(Number of labor hours) X (Wage rate)
		Equipment to support program	Equipment expenditures
	Private expenditures _t	Private labor hours to support model testing and verification	(Number of labor hours) X (Wage rate)
		Equipment to support model testing and verification	Equipment expenditures
User Costs	Fixed costs _j	Software and the number of licenses	License costs for SABER
	Variable costs _j _t	Software maintenance	(Initial software cost) X (Percentage maintenance fee)
		Component library fee	Rental free for component library
		Labor hours devoted to training	(Number of hours) X (Labor cost per hour [or average wage rate])

Figure 4-2 illustrates the sampling strategy for the surveys. A purposive sample of nine applications manufacturers was used to identify benefits and costs in the automotive, motor control, power control, and lighting industries. Applications manufacturers were the primary source of information for research facility-level impacts associated with simulation modeling.

Figure 4-2. Sampling Plan for Surveys

We conducted interviews with software and manufacturing companies in the semiconductor power-device supply chain.



Surveys of the device and software manufacturers (not exceeding nine in either group) were conducted to investigate the impact NIST's contributions have had on the development and adoption of mathematical modeling in the design process. This information was used to identify the portion of economic benefits associated with mathematical modeling that can be attributed to NIST's efforts. In addition, information from the software and device manufacturers' surveys was used to develop weights to expand research facility-level economic impacts to industry- and national-level impacts.

Secondary data were used to develop the quantity of units sold over time and to supplement information on the change in product quality and performance. For example, in the absence of survey information, the change in unit efficiency was used to calculate energy savings as a proxy.

5

Analysis Results

NIST's contributions to the development of simulation modeling tools for IGBT power devices have led to significant economic benefits through reduced design costs and improved performance of products employing IGBTs. Estimated benefit-cost ratios from the NIST program range from 15.5 to 31.0 and estimates of the social rates of return to NIST simulation modeling program expenditures range from 67.4 percent to 85.6 percent. In this section we present the information and procedures used to calculate economic impacts.

The actual economic impact from the NIST program is likely to be larger than the estimates presented in this section because improved product performance was not included in the quantified benefits estimates. In most instances, industry experts could not quantify the benefits of simulation modeling on final product performance. As a result, the benefit and cost estimates presented in this section are based primarily on reduced labor costs in the design process and the user costs associated with adopting simulation modeling tools, respectively.

This section begins with an overview of the methodology and taxonomy used in the quantitative analysis and a summary of the findings from the interviews with industry experts. Then we present the estimation procedure used to quantify NIST's contributions, which consisted of five steps:

- ▶ Estimate laboratory-level benefits and costs and calculate net benefits

- Weight laboratory-level net benefits to obtain national net benefits to industry.
 - Estimate NIST's share of net benefits to industry.
 - Calculate NIST simulation model program expenditures.
 - Calculate benefit-cost ratios, social rate of return, and NPV associated with the NIST simulation modeling program.
-

5.1 OVERVIEW OF METHODOLOGY AND TAXONOMY

In terms of the conceptual framework presented in Section 4, our method for quantifying the economic impact of the NIST program is summarized below.

Benefits

- Use technical interviews with industry experts to identify the system design and product-level benefits associated with simulation modeling of IGBTs.
- Quantify the system design benefits (product-level benefits will be included in the qualitative analysis).
- Identify NIST's share of benefits.

Costs

- Use technical interviews with industry experts to quantify user costs associated with SABER modeling.
- Identify the percentage of SABER activities associated with simulation modeling of IGBTs and use this percentage to estimate IGBT user costs.
- Estimate the NIST simulation modeling program expenditures.

Based on the categories described above, the net benefit to industry is defined as system design benefits less IGBT user costs associated with the simulation modeling of IGBTs.

To estimate the benefit-cost ratio and the social rate of return from the NIST program we need NIST's program expenditures and NIST's share of net benefits to industry. The share of net benefits to industry attributed to the NIST program is determined through the technical and scoping interviews with industry experts.

$$\text{NIST Benefit-Cost Ratio} = \frac{\text{Net Benefits to Industry} \times \text{NIST's Share}}{\text{NIST's Program Expenditure}}$$

5.2 SUMMARY OF INTERVIEWS

To gather data for the analysis, four sets of telephone interviews were conducted with industry representatives from the major segments of the IGBT modeling supply chain, software companies, device manufacturers, applications manufacturers, and academic institutions. Table 5-1 shows the number of technical and scoping interviews conducted for each of the four surveys. Appendix F contains the list of respondents and their company/university affiliation.

Table 5-1. Number of Interviews by Type and Sector

Our interviews included the two major software companies, the three major device manufacturers, and selected applications manufacturers in the automotive and motor control, power control, and lighting industries.

Interview Group	Number of Technical Interviews	Number of Scoping Interviews
Software companies	2	2
Device manufacturers	3	3
Applications manufacturers	7	1
Academic institutions		4

The technical interviews were the primary source of detailed technical and economic data used to quantify the benefit and cost estimates that follow in this section. These interviews were conducted mostly with design and modeling engineers. Technical interviews with applications manufacturers targeted automotive manufacturers and industrial manufacturers of motor control, power control, and lighting systems. Industry experts indicated that these were the major end-use application groups using IGBTs in their electrical systems.

The scoping interviews were primarily used to identify penetration and adoption issues associated with using simulation modeling and to identify the industries that are using (and the industries not using) simulation modeling for the design of IGBTs. In addition, these interviews were used to gather information about design practices outside of the study's four application focus areas. The scoping interviews were conducted with both engineers and upper

management personnel and also included representatives from the academic sector.

5.3 TECHNICAL AND ECONOMIC IMPACTS OF IGBT SIMULATION MODELING

The technical and economic impacts presented in this subsection are based on the technical interviews conducted with industry representatives. Impacts are divided into R&D efficiency impacts, transaction cost impacts, and production and product quality/performance impacts.

5.3.1 R&D Efficiency Impacts

Simulation modeling of IGBTs affects the system design process by reducing the number of physical design iterations and reducing labor costs. Most modeling and design engineers did not think there were material cost savings (in the systems design process) associated with simulation modeling.

NIST's model is primarily used for integrating the IGBT device into the electrical system of the final product. We refer to this as the use of simulation modeling in the system design process. All of the benefits and costs associated with simulation modeling of IGBTs are based on the use of SABER. Thus, the terms "simulation modeling of IGBTs" and the use of "SABER to model IGBTs" are used interchangeably.

Typically the device and applications manufacturers work closely together in the system design process, and simulation modeling leads to fewer labor hours for both parties. Because the number of labor hours reduced varies by end-use application, in our discussion and calculation of benefits below we have grouped the system design process impacts for device and applications manufacturers together and presented them by end-use application (e.g., automotive, motor control).

Benefits and costs associated with the impacts on the system design process were estimated at the research facility level. A large company may have several research facilities (or divisions) conducting simulation modeling, with each research facility purchasing its own software licenses and providing its own modeling support staff in-house. When appropriate, design

activities within a research facility were segmented by product type, such as small versus large drive design, to capture variations in design complexity.

Design benefits and user costs are discussed below segmented into three application categories: automobiles, motor controls, and additional applications.

Applications Manufacturers

Automotive Industry. Ford uses SABER to conduct simulation modeling in the design of electronic ignition systems for all their vehicles and in the design of power drives for electric cars. Detailed telephone interviews were conducted with design engineers at Ford Motor Company and Visteon Electronics Division (a fully owned subsidiary of Ford).

Ford estimates that using simulation modeling for ignition system redesign leads to a reduction of one iteration in the redesign process and that each iteration requires 40 percent of four design engineers' time over a 2.5-month period.

Ford was actively involved in developing and testing the final IGBT models that were incorporated into SABER (see Donnelly and Gauen, 1994). Ford first began using simulation modeling of IGBTs in their ignition system design process in 1991. At that time the basic ignition system design had been completed; thus, the primary use of simulation modeling for ignition systems to date has been in the redesign process.¹ Redesigns are required in response to the continuing “shrinkage” of Motorola’s IGBT devices, advances in ignition coil technology, and increased performance specifications to meet government fuel efficiency mandates (Kirksey, 1998).

A summary of the benefits associated with the simulation modeling of IGBTs for ignition systems is presented in Table 5-2. Ford conducts on average two ignition system redesigns per year that involve IGBT modeling. The same basic system design is used in all of Ford’s combustion vehicles; thus, separate ignition system design processes are not required for each make and model. Ford estimates that using simulation modeling for ignition system redesign leads to a reduction of one iteration in the redesign process and that each iteration requires 40 percent of four design engineers’ time over a 2.5-month period.

¹The use of simulation modeling in the redesign process leads to “continuous” incremental improvements in product performance. Incremental benefits are not realized once, but are continually realized each time the system is redesigned.

Table 5-2. Benefits—IGBT Modeling Cost Reductions for Automotive Design Application
R&D cycle time is reduced by 1 to 2.5 months.

Product Segment	Year First Used	Number of IGBT Modeling Activities per Year	Reduced R&D Cycle Time per Modeling Activity	Number of Engineers (and share of time) Involved in the Design Task	Material Savings per Design Activity
Automobile (Ford) ignition systems	1991	Two redesigns	2.5 months	4 engineers (40%)	Negligible because used for redesign activities
Automobile (Ford) electric vehicles	1993	1	1 month	3 engineers (100%)	Negligible

Because simulation modeling has been used for redesign (as opposed to initial design) Ford said that material cost savings in the system design process have been negligible. However, if simulation modeling had been available for basic design development of the electronic ignition system, this would have led to significant material cost savings through reductions in the number of physical prototypes constructed.

Even though simulation modeling reduces R&D cycle time, Ford said that it is not likely to result in an acceleration of product development. Product development cycle time is primarily driven by retooling production lines to meet new engine design specifications.

Ford began using SABER in its electric vehicle research in 1993 and estimates that it reduces a typical 8-month, three-person IGBT modeling task by about 1 month.

Ford's electric vehicle research division also uses simulation modeling of IGBTs as part of its design process. A summary of the benefits associated with the simulation modeling of IGBTs for electric vehicles is also presented in Table 5-2. Ford began using SABER in its electric vehicle research in 1993 and estimates that it reduces a typical 8-month, three-person IGBT modeling task by about 1 month.

However, Ford's electric vehicle research division did not think that using simulation modeling led to material cost savings through fewer prototypes. Because the models they are working with are not available in component libraries, Ford must develop experimental models that require verification by physical prototypes. In the future, as component libraries expand, material cost savings in the design process may be realized.

Ford's ignition system and electric vehicle research are conducted in separate divisions and have independent overhead modeling costs. Both divisions indicated that fixed overhead costs associated with simulation modeling are large. Table 5-3 shows a summary of overhead costs to support simulation modeling. These costs include SABER licenses, annual software maintenance fees per license, component library lease fees, and employee training. However, Ford's electric vehicle division indicated that they do not have any full-time SABER support staff.

Table 5-3. Research Facility-Level Modeling User Costs for the Automobile Design Application
Companies typically maintain several SABER licenses; however, only 5 percent of SABER activities are related to IGBT modeling.

Product Segment	Year Purchased Software	Number of SABER Licenses	Training for Engineers	SABER Support Staff	Percent of SABER Activities Related to IGBT Modeling
Automobiles ignition systems	1991	6	2 modeling engineers per year attending 5-day course	2.5 full-time staff	5 percent
Automobiles electric vehicles	1993	3	2 modeling engineers 5 days per year (no formal course)	None	5 percent

SABER is used throughout the automobile design process, and Ford estimates that only 5 percent of SABER activities are related to IGBT modeling. Thus, annual IGBT modeling user costs are assumed to be only 5 percent of the total modeling user costs associated with supporting SABER.

Motor Controls. Motor controls are used primarily in ASDs for industry, HVAC applications, and switching components that are used in industrial programmable logic controllers (PLCs). PLCs are used to control robotic assembly lines and other mechanical processes driven by electronic feedback from sensors.

We conducted technical interviews with modeling engineers at General Electric, Rockwell Automation/Allen Bradley Company, and Eton Electronics. Three of the four motor control modeling engineers interviewed indicated that they use simulation modeling of IGBTs in designing their ASDs and that SABER was the primary

modeling software they use. One engineer indicated that they also use PSPICE for some simple or quick-turnaround design tasks.

The fourth motor control modeling engineer interviewed indicated that they did not use simulation modeling at their laboratory, but that SABER is being used for IGBT modeling in a different division within their company. He indicated that their division had considered purchasing SABER a few years ago. However, the company decided that the benefits of simulation modeling did not justify the large software and training costs. This facility uses about 20 different IGBT devices in their ASDs. As an alternative to simulation modeling, they conduct physical measurements of switching rates and use these in designing their electronic systems. They do use PSPICE to model some system parameters, such as turnoff voltage spikes. However, at this point they have not used PSPICE's IGBT modeling capabilities.

The motor control companies that do use SABER for system design typically do not develop the IGBT models themselves. They rely on device manufacturers to supply the models, or they obtain them from component libraries provided by Analogly (see Figure 3-1). The models are then incorporated into the system simulation that is conducted using SABER.² If the IGBT modeling task is beyond what is contained in Analogly's component library, then they contract modeling out to a modeling consultant, such as Sandia Labs. Analogly provides a list of modeling consultants who support SABER on their web site.

In general, any time simulation modeling is used in designing motor controls, respondents said that at least one design iteration can be eliminated.

In general, any time simulation modeling is used in designing motor controls, respondents said that at least one design iteration can be eliminated. In some instances multiple iterations can be eliminated. However, the use of simulation does add an additional step early in the design process; thus, there is no significant change in total product development cycle time.

Table 5-4 summarizes the benefits associated with using SABER to model IGBTs as part of the new product design process for a typical research facility. Benefits are identified separately for large and small drive design activities. All the benefits identified during the

²SABER models the entire system, including FET, resistors, etc. The IGBT model is frequently a small part of the total system simulation model.

Table 5-4. Benefits—IGBT Modeling Cost Reductions for Motor Control Applications (typical research facility)
SABER was first used for motor control applications in 1993.

Product Segment	Year First Used	Number of IGBT Modeling Activities per Year	Reduced R&D Cycle Time per Modeling Activity	Number of Engineers (and Share of Time) Involved in the Design Task	Material Savings per Design Activity
Small drives	1993	2	4.5 months	1.5 engineers (100%)	Could not estimate
Large drives	1993	1	9 months	2.3 engineers (100%)	Could not estimate

interviews were from reductions in the number of labor hours required to conduct the design process. Reductions in design time ranged from 4.5 to 9 months, for two to three full-time engineers, depending on the size of the drive. Most interviewees also indicated that there were material savings from building fewer physical prototypes, but that they could not estimate these cost savings. As a result we have not included material costs savings from the design process in our quantitative analysis.

An additional benefit mentioned during the interviews with motor control modeling engineers is the reduction in the time and cost required for final product testing in the simulation laboratory. Simulation models allow engineers to conduct product debugging in a virtual environment, thus reducing expensive simulation laboratory time. However, respondents were not able to provide information on associated cost savings or on the potential impact on total product development cycle time.

The user costs associated with simulation modeling for a typical large research facility are shown in Table 5-5. As with other applications manufacturers, the primary costs are for the SABER

Table 5-5. IGBT Modeling User Costs for Motor Control Applications (typical research facility)
Fifty percent of SABER activities are related to IGBT modeling.

Product Segment	Year Purchased Software	Number of SABER Licenses	Training for Engineers	SABER Support Staff	Percent of SABER Activities Related to IGBT Modeling
Drives (large and small)	1993	6	2 modeling engineers per year attending 5-day course	0.25 full-time modeler	50%

license, maintenance, and component libraries and for the time required to develop the modeling skills to use SABER. User costs include support for both large and small drive design activities.

Additional Applications

Simulation modeling of IGBTs is also used in designing products such as compact fluorescent lights, power control equipment, and electrotechnology equipment. The roles of IGBTs in these applications are discussed in Section 2. As part of our discussions with General Electric, we obtained information on the benefits and costs of using simulation modeling in systems design for these applications. General Electric indicated that in addition to using SABER to conduct two to three motor control system designs per years, they also typically use SABER to design one compact fluorescent lighting system and one power control or electrotechnology system per year. The benefits and costs associated with these applications are presented in Tables 5-6 and 5-7, respectively.

Table 5-6. Benefits—IGBT Modeling User Cost Reductions for Additional Applications
Design engineers could not estimate material cost savings.

Product Segment	Year First Used	Number of IGBT Modeling Activities per Year	Reduced Time per Modeling Activity	Number of Engineers (and Share of Time) Involved in the Design Task	Material Savings per Iteration
Compact fluorescent lights	1993	1	4.5 months	1.5 engineers (100%)	Could not estimate
Power control/ electrotechnology	1993	1	9 months	2.3 engineers (100%)	Could not estimate

General Electric indicated that approximately two SABER licenses were dedicated to lighting applications and two SABER licenses were dedicated to power control/electrotechnology applications. In both cases IGBT simulation modeling accounted for about 50 percent of SABER activities.

Table 5-7. IGBT Modeling Overhead Costs for Additional Applications
About 50 percent of SABER activities are related to IGBT modeling.

Product Segment	Year Purchased Software	Number of SABER Licenses	Training for Engineers	SABER Support Staff	Percent of SABER Activities Related to IGBT Modeling
Compact fluorescent lights	1993	2	1 modeling engineer per year attending 5-day course	0.25 full-time modeler	50%
Power control/electrotechnology	1993	2	1 modeling engineer per year attending 5-day course	0.25 full-time modeler	50%

5.3.2 Transaction Cost Impacts

SABER is also used by device manufacturers to generate datasheets for each new family of IGBTs developed. Datasheets provide information to applications manufacturers on the performance of individual devices. Datasheets enable the comparison of similar devices across device manufacturers and make publicly available device characteristics needed to support simulation modeling.

The use of SABER for simulation modeling of IGBTs reduces the time needed to develop product datasheets from about 1 month to 1 week (for one full-time design engineer). Without simulation modeling, design engineers would have to conduct hundreds of measurement tests per datasheet to manually plot out behavioral curves. Now they use simulation modeling to predict IGBT device behavior and only need to test a few points to verify the simulated behavioral curves. Harris Semiconductors indicated that they typically introduce one to two new families of IGBTs per year. Each family typically contains six device sizes, two switching speeds, and three package configurations, resulting in 36 different devices (6x2x3). For each of these 36 devices, separate datasheets are developed.

International Rectifier (IR) plans to begin using SABER for generating datasheets in 1999. IR typically generates about 30 datasheets per year. Tables 5-8 and 5-9 provide a summary of benefits and costs, respectively, for Harris Semiconductors and IR.

Both Harris Semiconductors and IR indicated that the overhead costs associated with SABER were large. These costs include

The use of SABER for simulation modeling of IGBTs reduces the time needed to develop product datasheets from about 1 month to 1 week.

Table 5-8. Benefits for Device Manufacturers
Three weeks of person hours are saved for each datasheet.

Device Manufacture	Year First Used	Number of Data Sheets per Year	Time Reduction per Datasheet	Number of Engineers (and Share of Time) Involved
Harris Semiconductors	1998	36	3 weeks	1 engineer (100%)
IR	1999	30	3 weeks	1 engineer (100%)

Table 5-9. Overhead Costs for Device Manufacturers
SABER was not used to develop datasheets until 1998.

Device Manufacture	Year Purchased Software	Number of SABER Licenses	Training for Engineers	SABER Support Staff	Percent of SABER Activities Related to IGBT Modeling
Harris Semiconductors	1997	4	2 modeling engineers per year attending 5-day course	1 half-time staff	100%—1 license 25%—3 licenses
IR	1998	1	1 modeling engineer attending 5-day course	1—25% of time	100%

software license costs, maintenance fees, component library fees, and staff training costs.

Harris Semiconductors maintains four SABER licenses. One model is used full time by one IGBT modeling specialist who provides modeling support. The other three licenses are used approximately 25 percent of the time for IGBT-related modeling activities by design engineers. IR maintains one SABER license and uses it exclusively for simulation modeling of IGBTs. The percentage of SABER activities related to IGBT modeling will be used to estimate Area D' in part (b) of Figure 4-1.

5.3.3 Production Costs and Product Quality/Performance Impacts

All of the modeling and design engineers interviewed said that simulation modeling leads to improved performance of the final product employing the IGBT device. However, no one was able to

provide an accurate estimate of the magnitude of these impacts. In addition, most contacts said that the use of simulation modeling leads to material savings in the production process. However, they also could not quantify these savings.

Automotive Industry

Ford engineers indicated that IGBT simulation modeling in the ignition system has had an impact on automobile manufacturing costs and performance. One modeling engineer stated that the main benefit from IGBT simulation modeling was an increase in system reliability. Decreasing defective components can lead to substantial savings given production levels of 20 to 40 million units per year. Defect screening is conducted during the manufacturing process. Simulation modeling allows most reliability issues to be addressed before components go to manufacturing. However, respondents were not able to provide estimates of changes in defect rates due to simulation modeling.

In addition, Hefner's model can be used by product design engineers to minimize the use of materials (such as silicon) given the model's superior predictive capabilities. However, respondents were skeptical if this was actually being done because design engineers typically use preset performance specifications for the system including the IGBT.

Ford modeling engineers also stated that simulation modeling of the ignition system can have a significant impact on automobile fuel efficiency. It is commonly agreed that the introduction of the electronic ignition system increased fuel efficiency by about 5 percent (Liu, 1998). Ford modeling engineers said that simulation models of the ignition system can affect the performance of electronic ignition systems by an additional 20 percent. IGBT modeling accounts for approximately 5 percent of ignition system modeling activities. Based on this information, one estimate of

The potential economic impact from very small changes in automobile fuel efficiency is large.

Typically systems are “over designed,” providing a safety factor to account for uncertainties in the design process. The increased precision of simulation modeling enables designers to reduce safety factors.

simulation modeling of IGBTs’ potential impact is a 0.05 percent increase in fuel efficiency.³

The potential economic impact from very small changes in automobile fuel efficiency is large. National Highway Statistics from the Department of Transportation indicate that fuel expenditures for cars and motorcycles in 1995 were approximately \$67 billion (DOT, 1998). If we assume that IGBT modeling has a 0.05 percent impact on fuel efficiency, we estimate an annual reduction in fuel expenditures of \$33.5 million. This impact should be viewed as an upper-bound estimate of the fuel efficiency benefits from IGBT simulation modeling because the modeling engineers interviewed at Ford were uncertain about the extent to which simulation modeling results were being used throughout the design process.⁴

For electric vehicles, Ford engineers indicated that simulation modeling of IGBTs has led to significant decreases in engine costs. The precision of Hefner’s Model allows designers to lower safety factors, sometimes from 20 to 50 percent. This safety factor reduction decreases material costs for silicon and heat sinks and has resulted in a 10 percent reduction in the cost of inverters for electric engine drives. Inverter costs for electric engines typically range from \$500 to \$1,000. Thus, simulation modeling of IGBTs has led to a \$50 to \$100 materials cost reduction per vehicle. At the current production rates of only a few hundred vehicles per year, the aggregate savings is relatively small. But as electric vehicles move to mass production the aggregate economic benefit could potentially be significant.

³The example of 0.05 percent increase in fuel efficiency is based on information provided by Ford, assuming simulation modeling is used to its full advantage throughout the design process. If electronic ignition systems increased fuel efficiency by 5 percent, simulation modeling increases the performance of the ignition system by an additional 20 percent, and IGBT modeling accounts for approximately 5 percent of simulation activities, then multiplying these percentages together yields a 0.05 percent impact on fuel efficiency.

⁴Ford modeling engineers said that, if used properly, simulation models can lead to significant design improvements. However, the impact of simulation modeling on fuel efficiency depends on how the design engineer uses the modeling results. It is suspected that some downstream design engineers do not use the “simulation” capabilities of the model in the overall ignition system design. They either ignore the model and just make a few modifications to previous component designs, or they conform strictly to the simulated performance parameters and do not take advantage of alternative design options.

Motor Controls

Our technical interviews indicate that simulation modeling of IGBTs in the system design of motor controls has led to increased product performance for industrial and HVAC drive applications. However, none of the modeling engineers involved in drive design that we interviewed could quantify these benefits. Because drives are used in such a wide range of products, such as compressors for air conditioners, air circulation systems, industrial conveyer belts, and controls for robotics, modeling engineers could not assess the impact that increased drive performance would have on metrics such as energy consumption.

All of the modeling engineers interviewed said that using simulation modeling increases the switching efficiency of the drive, which leads to more precise motor control.

All of the modeling engineers interviewed said that using simulation modeling increases the switching efficiency of the drive, which leads to more precise motor control. In addition, modeling engineers indicated that using simulation modeling reduces waste heat generated by the drive. This lowers the energy consumption of the drive itself and reduces material costs associated with heat sinks used to dissipate waste heat.

Even though the incremental impact of simulation modeling of drive performance may be small, the economic benefits associated with these small increases in drive performance are potentially very large. Table 5-10 lists major motor-driven end uses, estimates of their share of national electrical energy consumption, and the potential energy savings associated with motor controls. Electrical energy consumption in 1996 was 3,114,894 MWhs, representing expenditures of approximately \$214 billion (DOE, 1997). Assuming that the penetration of ASDs has reached approximately half of its potential identified in Table 5-10, energy savings associated with ASDs is \$11.6 billion. Then, for example, if using simulation modeling led to a 0.05 percent increase in efficiency, the annual economic benefit to society would be \$5.8 million.⁵

⁵\$214 billion x 57.1 percent x (1/2) percent x 0.05 percent = \$5.8 million. The 0.05 percent increase in efficiency is provided as an example; this value is not based on information collected during the surveys of motor control applications manufacturers.

Table 5-10. Estimated Motor Electricity Usage and Potential ASD Savings

The end uses shown in this table account for 57.1 percent of total electrical energy usage in the U.S. The use of ASDs could potentially reduce usage associated with these end uses by 19 percent. For example, refrigeration consumes 6.9 percent of electricity usage in the U.S. The use of ASDs can reduce refrigeration energy usage by 20 percent.

Sector	End-Use	Electrical Usage as a Percent of Total U.S. Usage for Selected End Uses	Potential ASD Savings in Terms of Reduction in Energy Usage by End-Use Percent
Residential	Refrigeration	6.9	20
	Space Heating	1.4	25
	Air Conditioning	3.8	20
	Other	0.9	0
	Residential Total	13.1	19
Commercial	Air Conditioning	7.5	15
	Ventilation	2.2	25
	Refrigeration	1.3	25
	Other	0.1	20
	Commercial Total	11.3	18
Industrial	Pumps	7.7	25
	Blowers and Fans	4.5	25
	Compressors	3.9	25
	Machine Tools	2.1	10
	Other Integral HP	2.8	0
	DC Drives	2.5	15
	Fractional HP	1.1	0
	HVAC	0.6	15
	Industrial Total	25.4	18
Public and miscellaneous	Municipal Water Works	1.7	15
	Electric Utilities	5.4	25
	Other	0.2	0
	Public and Miscellaneous Total	7.3	22
Totals		57.1	19

Source: de Almeida, Anibal T., Steve Greenberg, and Carl Blumstein. 1990. "Demand-Side Management Opportunities through the Use of Energy-Efficiency Motor Systems." *IEEE Transactions on Power Systems* 5(3):852-861.

The use of high efficiency ballasts in compact fluorescent lamps has the potential to reduce total annual U.S. electrical energy consumption by approximately 0.75 percent, or \$1.6 billion.

Additional Applications

As with automobile and motor control applications, industry experts indicated that simulation modeling of IGBTs in the system design process can lead to increased product performance for compact fluorescent lighting, power control, and electrotechnology applications. Even though the industry experts interviewed could not quantify the increased product performance, the following examples provide insight into the potential magnitude of these benefits.

IGBTs are used in high-efficiency electronic ballasts in compact fluorescent lamps. The use of high efficiency ballasts in compact fluorescent lamps has the potential to reduce total annual U.S. electrical energy consumption by approximately 0.75 percent, or \$1.6 billion. These reduction estimates are based on the following information:

- total annual U.S. electrical energy expenditures in 1996 = \$216 billion (DOE, 1997)
- lighting accounts for approximately 25 percent of energy consumption (Jednacz, 1991b)
- compact fluorescents have the potential to account for 20 percent of lighting applications (Mitchell, 1998)
- high-efficiency electronic ballasts in compact fluorescents can reduce energy consumption by 15 percent (compared to incandescent lamps) (Nielsen, 1993).
- percent reduction = 25 percent x 20 percent x 15 percent = 0.75 percent
- energy expenditure reduction = \$212 billion x 0.75 percent = \$1.6 billion.

Thus, if using simulation modeling in designing electronic ballasts leads to, for example, a 0.01 percent increase in ballast performance, this could result in a \$0.16 million reduction in annual energy expenditures.

As a second example, several industry experts indicated that simulation modeling of IGBTs in the system design process leads to a reduction in the size and number of capacitors needed for power conditioning equipment. Power conditioning equipment is a major end user of capacitors, and annual sales of capacitors in 1994 were \$1.9 billion (1996 Electronic Market Data Book). As a result, small

changes in the size and number of capacitors needed for power conditioning applications can lead to significant economic benefits.

5.4 AGGREGATE DESIGN IMPACTS

Our approach to estimating benefits is to include only clearly identifiable and quantifiable impacts in the quantitative analysis. Table 5-11 shows the benefit categories included in the quantitative analysis.

Table 5-11. Economic Sectors and Related Benefit Categories

The categories identified with an X were included in the quantitative analysis. The categories identified with a ✓ were evaluated qualitatively.

Sectors	R&D Efficiency	Transaction Costs	Production Costs	Product Quality
Software companies	✓			
Device manufacturers		X		
Applications manufacturers	X	✓	✓	
End users				✓

Quantified benefits are derived from the use of SABER by device manufacturers to generate datasheets and by applications manufacturers to simulate IGBTs in the system design process. Benefits are defined as the difference between labor savings from using simulation modeling of IGBTs and user costs to support SABER activities related to IGBTs.

The impacts described in Section 5.3.1 provide the basis for estimating research facility-level benefits and costs associated with simulation modeling of IGBTs. Research facility-level benefits and costs are used to calculate net research facility-level benefits (benefits net of user costs). Net research facility-level benefits are then weighted to obtain national benefits.

As indicated in Table 5-11, we have not quantitatively included benefits from improved product performance in our estimate of total benefits. As described in Section 5.3, the impact of simulation modeling in this area has potentially generated significant benefits to society. However, because of difficulty in obtaining reliable

information on the magnitude of these impacts we have not included these potential benefit in the estimate of total benefits calculated below or in the benefit-cost ratio or social rate of return to the NIST program presented in Section 5.6. Thus, our economic impact estimate associated with NIST's contributions may be considered a conservative estimate.

In addition, R&D efficiency gains to software companies were not directly quantified. NIST's contributions to IGBT simulation modeling lowered R&D costs for software companies, leading potentially to

- ▶ increased profits for software companies and
- ▶ lower software prices for device and applications manufacturers.

Benefits associated with lower software prices are captured in our quantitative analysis through lower user costs for device and applications manufacturers. However, increased profits to software companies are not included in the quantitative analysis.

5.4.1 Research Facility-Level Benefits

Research facility-level benefits associated with simulation modeling include the decrease in R&D labor costs, less the user costs to support modeling software. Material cost reductions in the system design process (such as fewer physical prototypes) are not included in benefits estimates because modeling engineers either indicated that there were no material costs savings or that the savings could not be identified.

The benefits and costs included in the quantitative analysis are based on the use of Analog's software product SABER. All of the benefits and costs identified by the modeling engineers in the technical interviews were directly related to using SABER for simulating IGBTs' behavior. Whereas some engineers said they do occasionally use PSPICE for simple or quick-turnaround modeling activities, they did not think that the benefits of Hefner's Model were realized during the use of PSPICE.

The following economic information was obtained during the technical interviews and used in the calculation of research facility-level benefits:

- ▶ Initial SABER license is \$50,000.

- Each additional SABER license is \$30,000.
- Annual maintenance fee is 12 percent of total license costs.
- Annual lease fee for components library is \$5,000.
- SABER prices (nominal) have remained constant over the past 8 years.
- Design engineer's fully loaded (including fringe benefits plus overhead) salary is \$100/hr (1998 dollars).
- SABER modeling engineer's (modeling support staff's) fully loaded salary plus fringe benefits is \$125/hr (1998 dollars).

A spreadsheet model was used to calculate the NPV of benefits and costs. A real social discount factor of 7 percent was used to discount cash flows (OMB, 1995). Because the social discount factor of 7 percent is a real discount factor, all benefits and costs were adjusted to 1998 dollars prior to discounting. Benefits and costs were projected through the year 2003.⁶

For applications manufacturers, benefits and costs were calculated at the research-facility level using the information on typical research facilities presented in Section 5.3. For device manufacturers, benefits per datasheet were estimated and scaled to represent a typical device manufacturer. From surveys and company web sites, the typical number of datasheets generated annually by a device manufacturer was estimated to be 20.25.⁷

Research facility-level labor savings, SABER user costs, and net benefits estimates are shown in Table 5-12. Estimates are presented by industry segment and represent impacts for a typical research facility. Both the labor savings and SABER overhead costs are largest for a typical drive research facility because of the large

⁶Projecting benefits 5 years into the future will provide a conservative (lower-bound) estimate of total benefits. Professor Peter Lauritzen (1998) indicated that during the 1990s Hefner's model has been widely accepted as the standard for IGBT modeling and that it is currently at its peak of "significance." He noted that enhanced models (still based on NIST's core algorithm) are currently being developed. However, it is likely to take several years for new models to be verified and incorporated into commercially available software packages, implying that NIST's existing models in SABER will continue to represent significant advantages over alternative design processes for several years in the future.

⁷Included were Harris Corporation (36 IGBT datasheets per year), IR (30 IGBT datasheets per year), Motorola Incorporated (10 IGBT datasheets per year), and Delco (5 IGBT datasheets per year). The number of IGBT datasheets per year was obtained through the technical interviews with modeling engineers for Harris Corporation and IR and was estimated from product offerings for Motorola Incorporated and Delco.

Table 5-12. Estimated Benefits and Costs to Industry from Simulation Modeling of IGBTs in the System Design Process
 Motor control applications account for 63 percent of estimated benefits.

Industry Segment	Research Facility-Level Labor Savings (thousands, \$1998)	Research Facility-Level SABER User Costs (thousands, \$1998)	Net Research Facility-Level Benefits (thousands, \$1998)	Weight to Obtain National Benefits	National Benefits (thousands, \$1998)
Device manufacturers	438	112	325	4	1,301
Automotive ignition systems	713	197	516	3	1,547
Automotive electric vehicles	209	13	196	3	588
Motor control	2,388	216	2,172	5	10,859
Lighting	471	108	363	1	363
Power control	1,445	108	1,337	2	2,675
Benefits					17,334

number of design activities conducted annually at these laboratories that involve IGBT simulation modeling.

5.4.2 Weighting Research Facility-Level Benefits to National Benefits

We used weights to scale research facility-level benefits to obtain national-level benefits. Weights were developed separately for different industry segments. The weights are based on the number of research facilities that were identified to be using SABER for IGBT modeling.⁸

For the automotive industry, Ford's research facility-level benefits were multiplied by three because Ford indicated that both GM and Chrysler were also using SABER to conduct simulation modeling of IGBTs in the design of their ignition systems and electric vehicles and that their benefits and costs would be similar.

⁸These weights are likely to be conservative because it is possible that additional companies within these industries are using SABER for IGBT modeling. However, we included in the weights only companies verified during our telephone surveys.

The weight for device manufacturers was developed based on the number of U.S. companies using SABER to generate datasheets. Analogy identified four U.S. device manufacturers that use SABER: Harris Corporation, IR, Motorola Incorporated, and Delco Electronics.

Weights for motor control, lighting, and power conditioning applications manufacturers' research facility-level benefits were developed with the help of Analogy. As shown in Tables 2-4 through 2-6, five motor control, two power control, and one lighting research facility hold SABER licenses.

5.4.3 Net Benefits to Industry

Table 5-12 also presents national benefit estimates. The net benefits to industry associated with IGBT simulation modeling are estimated to be approximately \$17 million. Seventeen million dollars reflects the sum of the discounted flow of benefit net of cost from 1985 to 2003, presented in 1998 dollars. Benefits and costs by year are presented in Table 5-13.

The most influential factors in determining the magnitude of benefits and costs are highlighted below:

- The reduced design time and the number of modeling and design engineers involved in the task were important determinants of benefits. This provided the basic building block for estimating benefits.
- The number of activities conducted per year (new product designs or datasheet development) was also an important determinant of benefits. In particular, for device manufacturers, the large number of datasheets developed per year lead to large benefits even though the time savings per datasheet were relatively small.
- The number of full-time support staff for SABER modeling was the largest contributor to user costs. The main distinction between costs for automobile ignition systems and electric vehicles is that Ford's ignition system division reported having 2.5 full-time SABER modelers to assist design engineers, whereas Ford's electrical vehicle division said they had no SABER modeling support.
- The percentage of SABER activities related to IGBT simulation modeling greatly influenced overhead cost estimates. Total software and modeling support staff costs associated with SABER were typically quite large. However, because IGBT simulation is just one of SABER's many simulation components, only a fraction of SABER

Table 5-13. Net Benefits Generated by Industry—by Industry Group and Year (\$thousand 1998)
 For most companies benefits were not generated in the year in which SABER was purchased. Thus, the net benefits generated by industries in the initial year are negative.

Year	Auto— Ignition Systems	Auto— Electric Vehicles	Drives (GE)	Device Manufacturers	Lighting	Power Controls	Total Net Benefits to Industry
1985 (beginning)	0	0	0	0	0	0	0
1985 (end)	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0
1990	-130	0	0	0	0	0	-130
1991	293	0	0	0	0	0	293
1992	293	-26	-645	0	-65	-129	-571
1993	293	138	2,567	0	91	629	3,718
1994	293	138	2,569	0	91	629	3,720
1995	293	138	2,571	0	91	629	3,723
1996	293	138	2,572	0	92	630	3,725
1997	294	138	2,574	-163	92	630	3,565
1998	294	138	2,576	286	92	630	4,016
1999	294	138	2,577	790	92	631	4,522
2000	294	138	2,579	791	92	631	4,525
2001	294	139	2,580	791	92	631	4,528
2002	294	139	2,582	792	93	632	4,530
2003	294	139	2,583	793	93	632	4,533
NPV	1,547	588	10,859	1,301	363	2,675	17,334

t=0 1985 beginning
t=1 1985 end

overhead costs were attributed to simulation modeling of IGBTs. For example, Ford modeling engineers (both in ignition systems and electric vehicles) said that the share of SABER modeling activities involving IGBT simulation was 5 percent. When this is applied to total SABER overheads, costs are significantly reduced.

5.5 INDUSTRIES' ASSESSMENT OF NIST'S CONTRIBUTIONS AND NIST'S SHARE OF TOTAL BENEFITS

To estimate benefit-cost ratios or the social rate of return to the NIST program, we need to determine what share of the total benefits estimated in Section 5.3 should be attributed to NIST's contributions. Although NIST was the sole developer of the mathematical modeling algorithms, several parties were involved in model verification and incorporating the model into SABER to make it available to device and applications manufacturers. The primary parties involved were NIST, Analog, industry end-users such as Ford, and device manufacturers such as Harris Semiconductors and Motorola.

Because of the importance and uncertainty of NIST's share of total benefits, we present a range of benefit-cost ratios and social rate of returns to the NIST program, varying NIST's share of total benefits from 40 percent to 80 percent.

For example, NIST and Ford Motor Company worked together closely for several years to verify the mathematical models and support Analog's efforts to incorporate these models into SABER. In addition, NIST participated in a Cooperative Research and Development Agreement (CRDA) with Ford, Motorola, and Harris Semiconductor to transfer parameter extraction technology to private industry. The extraction hardware and procedures developed by NIST are an essential part of simulation modeling because they are used to generate the input parameters for the SABER simulations.

Ford may have pursued the development of IGBT simulation capabilities (including parameter extraction) in the absence of NIST, possibly developing in-house models. However, the resulting models would not have been as accurate, leading to lower benefits, and hence would not have penetrated the market as quickly as the simulation software using NIST's mathematical models (Perry, 1998).

To reflect contributions from Ford and other industry end users of simulation modeling, it is likely that NIST's share of total benefits estimated in Section 5.3 is approximately 60 percent. This estimated percentage is based on discussions with technical experts in the industries involved in the collaborations. However, because of the importance (and uncertainty) of this percentage, we present a range of benefit-cost ratios and social rate of returns to the NIST program, varying NIST's share of total benefits from 40 percent to 80 percent. Again, based on discussions with industry experts, it

was determined that NIST's share of benefits was probably not greater than 80 percent or less than 40 percent. For example, one industry expert stated that NIST has had "a significant impact" and credited NIST with "accelerating the development of SABER for IGBTs." Upper-level management at Analogly stated that "without NIST's contributions Analogly would have developed an IGBT model, but it would not have been nearly as good." However, a few industry experts were sensitive about giving NIST the majority of the credit, pointing out that many other device and applications manufacturers "contributed to getting the model up and running."

5.6 NIST'S PROGRAM COSTS

In 1985 NIST began development of a mathematical model for IGBT devices that simulates their performance. This model was introduced in commercial simulation software packages in 1990. Tables 5-14a and 5-14b show actual and inflation adjusted annual NIST program expenditures related to developing and promoting simulation modeling for IGBT power devices. Future program costs are expected to continue through the year 2000 at current expenditure levels (Hefner, 1998).

The NPV of NIST's program expenditures in 1998 dollars is \$447,000. Labor costs are fully loaded and include fringe benefits and overhead costs. Discounted program expenditures are given by

$$\text{Discounted Expenditures} = \sum_{i=0}^n \frac{C_{t+i}}{(1+r)^i} \quad (5.1)$$

where

- C = real (\$1998) expenditures in year (t+i), including labor, equipment and miscellaneous costs
- r = real social discount rate of 7 percent
- t = base year 1984
- i = 0 corresponds to the beginning of 1985
- i = 1 corresponds to the end of 1985 (expenditures occurred from 1/85 to 12/85)
- n = 19 (through year 2003)

Table 5-14a. Actual NIST Program (Nominal) Expenditures by Year
 Labor accounted for the majority of NIST's expenditures.

Fiscal Year	Labor (\$thousands)	Equipment (\$thousands)	Misc. Costs (\$thousands)	Total (\$thousands)
1985 (beginning)	0	0	0	0
1985 (end)	5	0	1	6
1986	9	0	1	10
1987	10	0	1	11
1988	24	0	2	26
1989	35	0	2	37
1990	47	0	3	50
1991	96	16	5	115
1992	68	25	3	96
1993	69	17	3	89
1994	32	25	2	89
1995	32	13	2	50
1996	16	0	1	17
1997	19	0	1	20
1998	20	0	1	21
1999	20	0	1	21
2000	20	0	1	21
2001	0	0	0	0
2002	0	0	0	0
2003	0	0	0	0

Table 5-14b. Inflation Adjusted NIST Program (Real) Expenditures by Year (\$thousands 1998)
 Labor accounted for the majority of NIST's expenditures.

Fiscal Year	Inflation Index (CPI)	Labor	Equipment	Misc. Costs	Total
1985 (beginning)	0.647	0	0	0	0
1985 (end)	0.647	8	0	2	9
1986	0.659	14	0	2	15
1987	0.683	15	0	1	16
1988	0.711	34	0	3	37
1989	0.745	46	0	3	49
1990	0.785	60	0	4	64
1991	0.819	117	20	6	143
1992	0.843	80	30	4	113
1993	0.868	79	20	3	102
1994	0.891	35	28	2	66
1995	0.916	35	14	2	51
1996	0.943	17	0	1	18
1997	0.971	20	0	1	21
1998	1.000	20	0	1	21
1999	1.030	19	0	1	20
2000	1.061	18	0	1	19
2001	1.093	0	0	0	0
2002	1.126	0	0	0	0
2003	1.159	0	0	0	0
NPV		363	61	23	447

t=0 1985 beginning
t=1 1985 end

5.7 BENEFIT-COST RATIO AND SOCIAL RATE OF RETURN FROM THE NIST PROGRAM

We used the NPV estimates of total benefits attributable to NIST and NIST's program expenditures to develop three measures of economic return from the NIST program—the NPV, the benefit-cost ratio, and the social rate of return.

The NPV of the NIST simulation modeling program is given by

$$\text{NIST NPV} = \left[\left(\begin{array}{c} \text{Discounted} \\ \text{Benefits to} \\ \text{Industry} \end{array} \right) \times \left(\begin{array}{c} \text{NIST's} \\ \text{Share} \end{array} \right) \right] - \begin{array}{c} \text{Discounted} \\ \text{NIST} \\ \text{Expenditures} \end{array} \quad (5.2)$$

$$6.5 = 17.3 \times 0.4 - 0.45$$

$$13.4 = 17.3 \times 0.8 - 0.45$$

NIST NPV ranges from \$6.5 million to \$13.4 million (1998 dollars).

The benefit-cost ratio is given by

$$\text{Benefit-Cost Ratio} = \frac{\begin{array}{c} \text{Discounted Benefits to} \\ \text{Industry x NIST's Share} \end{array}}{\text{Discounted NIST Expenditures}} \quad (5.3)$$

$$15.5 = \frac{17.3 \times 0.4}{0.45}$$

$$31.0 = \frac{17.3 \times 0.8}{0.45}$$

The estimated benefit-cost ratio for the NIST program ranges from 15.5 to 31.0 for the two scenarios of NIST's share of benefits being 40 percent and 80 percent. The social rate of return is the discount rate where the NIST NPV equals zero. Thus, r is determined by solving the following equation for r .

$$\sum_{i=0}^n \left[\frac{B_{(t+i)}}{(1+r)^i} \right] \times \text{NIST's Share} - \sum_{i=0}^n \left[\frac{C_{t+i}}{(1+r)^i} \right] = 0 \quad (5.4)$$

The estimated social rate of return for the NIST program is 67.4 percent for the scenario where NIST's share of total benefits is 40 percent. For the scenario where NIST's share of benefits is 80 percent, the social rate of return is 85.6 percent.

6

Market Barriers and the Role of NIST

NIST's contributions have helped lower market barriers to the development and adoption of IGBT simulation modeling software and have led to significant social benefits.

NIST's contributions have helped lower market barriers to the development and adoption of IGBT simulation modeling software and have led to significant social benefits. IGBT simulation modeling advances initiated by NIST and private industry primarily for modeling automobile ignition systems have generated significant spillovers in applications such as motor controls, power conditioning equipment, electrotechnologies, and lighting. These benefits flow to society through improved performance of final products employing IGBTs and through lower R&D costs.

The use of IGBT simulation modeling is still gaining momentum and will continue to expand into new product areas. Many applications manufacturers are in the process of adopting IGBT simulation modeling, and these additional benefits will be realized in the near future. Future penetration of IGBT simulation modeling will be driven by factors such as the increasing complexity of electrical systems and the spread of IGBTs into lower voltage applications.

However, several barriers are limiting the adoption of and the benefits generated from the use of IGBT simulation modeling. Some of these barriers, such as software and training costs (pull costs), are natural market factors that affect the evolution of most new products. But other barriers seem to represent persistent market failures and hence potential roles for the NIST program. For example,

- software companies do not have the technology base to design full-function models and it is not in their strategic market focus to develop these capabilities;

- spillovers occur in the form of technology's use by firms or industries that did not fund the underlying R&D, but are still able to appropriate at least some of the resulting benefits;
- network externalities are created as increasing numbers of companies along the supply chain assimilate IGBT modeling into their design process; and
- network externalities are created as additional component models (such as diodes) are added to simulation software.

This section focuses on barriers to the realization of economic benefits from IGBT simulation modeling. Some of these barriers are market failures that limit the development of modeling techniques and software and the adoption of IGBT simulation modeling by device and applications manufacturers. This section also describes how NIST's activities in this area have addressed these barriers and how ongoing and potential future activities might lead to greater economic benefits. The information presented in this section reflects comments provided by industry experts during the interviews.

6.1 BARRIERS TO THE DEVELOPMENT OF SIMULATION MODELING SOFTWARE PRODUCTS

Several barriers are limiting the adoption of and the benefits generated from the use of IGBT simulation modeling.

Software companies and device and applications manufacturers each cited unique factors that represented barriers to the development of IGBT performance simulation modeling software products. These factors include market barriers such as nonappropriability and the cost of assembling multidisciplinary teams to address the broad range of technical issues. Interviewees also suggested that similar barriers affect the development of non-IGBT modeling components and that enhancements to non-IGBT modeling components would increase the overall effectiveness of simulation modeling in the system design process.

6.1.1 Barriers to the Development and Incorporation of IGBT Modeling Capabilities into Simulation Software

Market barriers have contributed to the delay in the development of IGBT capabilities in simulation modeling software. Different barriers affect different segments of the IGBT simulation modeling supply chain. For example, software companies, such as Analog, do not have the technology base to develop, verify, and implement

the required mathematical algorithms. Device manufacturers do not have the in-house expertise to model how their devices will interact with the systems in which they are incorporated. Applications manufacturers in many instances have the technical expertise to develop the mathematical algorithms and system interactions, but they do not have the marketing infrastructure to be able to appropriate the returns to these R&D activities. In general, each segment of the chain possesses a subset of the capabilities required to research, commercialize, and support IGBT simulation modeling, but it is not in their strategic market focus to internally develop the full spectrum of capabilities.

Analogy is a relatively small software company with limited resources. It is not their strategic market focus to specialize in theoretical modeling for the wide range of electrical components supported by SABER. As a result, most simulation modeling enhancements are initiated and supported by applications manufacturers. However, it is difficult for individual (or groups of) applications manufacturers to appropriate the returns to their investments in simulation modeling capabilities because the algorithms and techniques they develop will be widely used by many other firms in many different industries. Because of the presence of large spillover benefits, many simulation modeling software enhancements that are in the best interest of society are not pursued. Only the “killer applications” for which the returns to individual software companies or device or applications manufacturers (without appropriating spillovers) are sufficiently large are developed and incorporated in the simulation modeling software.

The “killer application” motivating the development of IGBT modeling capabilities was the introduction of IGBTs in electronic ignition systems.

The development of commercially available software packages such as SABER that incorporate IGBT simulation modeling capabilities was largely driven by NIST and the automobile industry. In this case, the “killer application” was the use of IGBT modeling to support the design of electronic ignition systems. Advances in ignition coils and federal mandates to increase fuel efficiency provided the financial incentives for the automobile industry to pursue the development of IGBT simulation modeling capabilities.

Ford Motor Company and its device supplier Motorola made important contributions to verifying and incorporating NIST’s

mathematical models into SABER. In the process they generated significant technology spillovers by making IGBT simulation tools available to other applications manufacturers, such as manufacturers of motor controls or power control equipment.

However, even with these relatively large financial incentives, Ford and Analogix representatives indicated that without NIST's contributions the development of IGBT simulation modeling would have been delayed or may not have been pursued after all. The barriers to Analogix were the costs of assembling the multidisciplinary team needed to develop and verify the models. Barriers for Ford and Motorola were their inability to appropriate the full returns from their R&D efforts because they did not have (or desire to develop) the needed software marketing distribution capabilities.

Both Ford and Analogix indicated that SABER's IGBT modeling components would not have been as accurate without NIST's contributions.

In addition, both Ford and Analogix indicated that SABER's IGBT modeling components would not have been as accurate without NIST's contributions. As a result, without NIST, the returns to private investment would have been lower, and IGBT simulation modeling capabilities might not have been developed.

NIST's role in the development and incorporation of IGBT simulation modeling capabilities into SABER was motivated by the market barriers described above.

In addition, during interviews with applications manufacturers, we identified a second example supporting the presence of barriers in the software development area. Incorporating dynamic thermal modeling capabilities into simulation modeling software was cited as one of the most important issues facing modelers. Ford and Motorola had been pursuing a joint venture to expand IGBT dynamic thermal modeling beyond ignition components, which are the existing capabilities in SABER. However, the joint venture, which was estimated to be a relatively modest project with a \$10,000 budget, has failed to proceed because the individual benefits to Ford or Motorola are relatively small, in part because these modeling benefits would also be realized by other automobile manufacturers also using SABER. Total benefits to society, however, would be large because of significant spillover benefits.

The barriers described above also affect the development of non-IGBT component models. Industry experts emphasized that IGBT

modeling is just one of many interrelated components used in the overall simulation design process (Ford stated that only 5 percent of SABER activities were associated with IGBT modeling). As a result, network externalities are generated when IGBT and non-IGBT modeling components are improved.

Several interviews indicated that existing simulation software packages require enhancement of their non-IGBT component models to fully realize the benefits of NIST's mathematical models. However, industry experts were not optimistic that these enhancements would be incorporated in the near future if the market is left to its own forces, again implying that market failures were delaying incorporation of these enhancements. Section 6.2 discusses this issue in greater detail.

6.1.2 Competition in the IGBT Simulation Modeling Software Market

Lack of competition in the simulation modeling software market was mentioned by applications manufacturers as a potential barrier limiting the incorporation of software enhancements. NIST's mathematical models are available in the public domain. However, it is costly for software companies to incorporate these mathematical models into their software products. Analogly and OrCAD (formerly MicroSim) currently offer software products that have incorporated NIST's mathematical modeling—SABER and PSPICE, respectively. Other simulation software suppliers, such as Mentor Graphics, Intusoft, and Cadence, do not have IGBT modeling capabilities.

Although SABER and PSPICE compete in the market for design tools used in the design of products employing IGBTs, their competition is limited because their markets are differentiated. SABER is widely acknowledged as having superior IGBT modeling capabilities and is the dominant software package used for detailed simulation modeling of IGBTs. However, assimilation costs associated with SABER are significant. For example, SABER is significantly more expensive to purchase, learn, and support compared to PSPICE. Many companies we spoke with indicated that they had full-time programming staff dedicated to supporting SABER modeling.

Although SABER and PSPICE compete in the market for design tools used in the design of products employing IGBTs, their competition is limited because their markets are differentiated.

In contrast, many versions of PSPICE are publicly available on the Internet. PSPICE is simple to learn and is used by universities in power electronic courses; thus, most design engineers have been exposed to PSPICE as part of their academic education. As a result, SABER and PSPICE each serve their respective niche markets and compete only in the instances where device and applications manufacturers are willing to sacrifice modeling capabilities for lower modeling costs.

SABER's near dominance in the market for advanced IGBT simulation software does not necessarily indicate a market failure. Alternatives to the use of SABER, such as the use of physical prototypes in the design process, limit Analog's ability to extract monopoly profits. In addition, given the relatively limited size of the existing market for advanced IGBT simulation capabilities and the cost of developing simulation software, it is unclear if the market could support competing advanced simulation software products. Also, in the future as IGBT applications expand into lower voltage applications, it is likely that increased demand for advanced IGBT modeling capabilities will stimulate entries into the advanced simulation modeling software market.

However, some applications manufacturers thought that Analog's use of a propriety modeling language for SABER limited competition and hence increased Analog's software prices. Device and applications manufacturers said that after developing a new IGBT behavioral model they typically make the model publicly available by either posting it on the Internet or including it in Analog's component library. However, because the model has been developed in MAST (SABER's propriety underlying language), it cannot be integrated into competing simulation packages such as PSPICE.

IEEE has formed a committee to develop and promote a standardized modeling language to make simulation modeling component libraries more interoperable. However, at this point the language is not advanced enough to accommodate many simulation modeling activities. In addition, some applications manufacturers indicated that this effort has received little support from simulation software companies with strong market positions. As a result, they were not optimistic that a standardized modeling

language would be available in the near future. This represents a potential new research area for NIST.

6.2 BARRIERS TO THE ADOPTION OF SIMULATION MODELING

Many industries, such as the aircraft industry, that include IGBTs in their system design, have not adopted simulation modeling in their design process.

Simulation modeling of IGBT devices has made its greatest penetration in the design of automobile ignition systems, electric vehicles, motor controls, power conditioning equipment, electrotechnologies, and lighting. However, many industries, such as the aircraft industry, that include IGBTs in their system design, have not adopted simulation modeling in their design process. In addition, the manufacturers that currently use products, such as SABER or PSPICE, typically use mathematical modeling for only selected design activities.

Almost all industry experts interviewed acknowledged the “potential” benefits associated with simulation modeling of IGBTs in the design process; however, they also indicated that certain factors are limiting widespread adoption of IGBT simulation modeling. The most commonly mentioned barriers to the adoption of IGBT simulation modeling were

- assimilation and overhead costs,
- effort and expense required to characterize IGBT models,
- modeling limitations and costs associated with confidential information,
- weak models for non-IGBT components, and
- missing complementary analysis capabilities in simulation software.

These barriers are discussed below.

6.2.1 Assimilation and Overhead Costs

The most commonly mentioned factor limiting penetration of IGBT simulation modeling (and simulation modeling in general) was the cost and complexity of learning and supporting existing simulation software. Most of the comments were related to SABER.

Assimilation and overhead costs associated with purchasing and supporting SABER are quantified in Section 5. These costs include initial software purchase price, maintenance fees, component library fees, formal staff training, and in-house SABER support staff.

One modeling engineer said that a 6-month learning curve was needed to effectively use SABER's capabilities.

The largest component of overhead costs is typically maintaining in-house SABER support.

One modeling engineer said that a 6-month learning curve was needed to effectively use of SABER's capabilities. This type of investment can be risky if staff turnover is high. In addition, applications manufacturers stated that SABER support staff and ongoing training were needed because as IGBT devices evolve, parameter extraction techniques and modeling practices continue to change. Thus, the assimilation of simulation modeling capabilities is an ongoing activity.

Some motor control applications manufacturers indicated that they limit the level of in-house expertise required by using consultants to develop the IGBT models or by relying on component libraries. However, many of the design benefits come from being able to "tweak" the IGBT models when they are incorporated into the system simulation. Thus, there is a tradeoff between the benefits gained through simulation modeling and the level and cost of in-house expertise needed. This decision is influenced by the volume of IGBT design activities and the extent to which SABER is used for other modeling activities.

6.2.2 Effort and Expense Required to Characterize IGBT Models

Several modeling engineers indicated that IGBT simulation modeling is useful, but difficulties in characterizing the models are limiting the use of simulation modeling. Characterizing (also referred to as parameterizing) simulation models adds an additional step early in the design process, and several modeling engineers said that upper management was often reluctant to add any new steps to the design process, given the importance of quickly introducing new products.

Applications manufacturers indicated that they need more information from device manufacturers to characterize models. Currently, device manufacturers do not provide applications manufacturers all of the structural information and performance parameters required to characterize the models because of confidentiality issues. Applications manufacturers frequently take a

device to the lab and make the measurements themselves to obtain the needed information to develop the IGBT model.

The step adds time and cost to IGBT simulation modeling, thus limiting its use by applications manufacturers. In addition, it is not socially efficient for multiple applications manufacturers to be replicating this measurement activity.

6.2.3 Modeling Limitations Associated with Confidential Information

Efforts by device manufacturers to protect confidential information not only increase applications manufacturers' time and costs associated with characterizing IGBT models, but also affect the productivity of the simulation process. Applications manufacturers said that because of gaps in data they need for characterization, they were sometimes constrained in their ability to use simulation for custom applications or investigate new system configurations that might lead to enhanced system performance.

The software company Anology provides a component library that includes many of the off-the-shelf IGBT models that have been provided by device manufacturers, but these models are encrypted. As a result there are limits to the type of “what-if” scenarios that can be performed by application manufacturers during the system design. In PSPICE, models are not encrypted, but they are less detailed and not as accurate. If applications manufacturers were able to access the underlying code, this would increase the penetration of IGBT simulation modeling into additional applications.

Advances in the patent systems may help applications manufacturers access proprietary software code and device characteristics while still allowing device manufacturers to appropriate returns for R&D investments. This would stimulate R&D activity for device manufacturers and increase design efficiency of applications manufacturers.

6.2.4 Weak Models for Non-IGBT Components

Simulation is only as strong as the weakest link: if not all components can be accurately represented because of data gaps, the ability of the simulation to investigate design alternatives is limited.

The overall accuracy of simulation modeling was also identified as a factor limiting the adoption of IGBT simulation modeling. Accuracy issues, however, are not related to the core IGBT model; NIST's model accurately predicts IGBT behavior. The issue is that IGBTs are only one of many components in their systems that need to be modeled to conduct simulation. FETs and transistors, for example, also need to be modeled accurately. Simulation is only as strong as the weakest link: if not all components can be accurately represented because of data gaps, the ability of the simulation to investigate design alternatives is limited.

Diodes are the most commonly mentioned "weak link" in the simulation modeling chain. Diodes are simpler than IGBTs, and their basic structure has not changed in several decades. Because they were introduced prior to the use of simulation modeling, there was no need for accurate models at the time of their design. Other components needing improved modeling accuracy that were identified during the interviews are transistors and resistors.

The barriers to filling in the data gaps for poorly modeled (non-IGBT) components are the same as those discussed in Section 6.1. Software companies do not have the technical expertise to develop the theoretical models, and applications manufacturers are not able to appropriate the return from R&D investment and model verification.

6.2.5 Missing Analysis Capabilities in Simulation Software

In addition to upgrading specific non-IGBT components, modeling engineers indicated that adding several important capabilities to existing simulation software would increase the usefulness of IGBT modeling and, hence, increase the impact of NIST's model. Additional capabilities identified during the interviews are the following:

- Current simulation software has difficulty modeling IGBT devices in a predictive manner. Underlying models do not have the capability to incorporate how variations (and uncertainties) in IGBT parameters affect the behavioral distribution of the system. Currently, multiple testing of physical prototypes and "over-engineering" of design parameters are used in the absence of these modeling capabilities.

- Applications manufacturers need the ability to address variability in parts. There is always some variability in manufactured parts (e.g., resistors, capacitors). Industry would like to be able to incorporate Monte Carlo simulations into the system design process to address reliability and performance over a distribution of product specifications. Currently there is no good approach for this.
- Applications manufacturers indicated that they need simulation software that includes the capability to conduct dynamic thermal modeling. The core issue is that too much voltage burns out IGBT devices; simulating thermal behavior could increase product reliability. NIST's models have the potential to support dynamic thermal modeling; however, these capabilities have not been incorporated into SABER at this time. Ford and Motorola were going to begin development of this modeling capability through a joint venture, but the project did not proceed. NIST has expertise in this area and is currently pursuing the development of these capabilities.
- For high-voltage applications, component libraries often do not have the appropriate models so custom models must be developed. This increases the cost of using simulation modeling.

As before, the barriers to integrating these capabilities into simulation software typically stem from a combination of

- proprietary information issues,
- the fact that the required technology base is outside software companies' expertise, and
- applications manufacturers are not able to appropriate all the returns to the required R&D investments.

6.3 FUTURE ADOPTION TRENDS AND ISSUES

Most of the applications manufacturers we interviewed plan to increase their use of IGBT simulation modeling in the near future. Future adoption of simulation modeling of IGBTs in the system design process will be driven by several factors, including

- the increased complexity of electrical systems,
- the decreased life expectancy of new products,
- the spread of IGBTs into additional applications,
- software interoperability, and
- labor mobility.

The increasing complexity of electrical systems will increase the use of simulation modeling (including non-IGBT applications).

Simulation modeling of electrical systems requires the integration of multiple separate components. It is becoming increasingly costly to use physical simulation laboratories to evaluate how IGBTs interact with the overall system under a range of operating scenarios. Virtual simulation for product testing will be an important pull factor in using IGBT simulation modeling.

The decreased life expectancy of new products will increase the adoption of simulation modeling. Industry experts indicated that currently the decreased IGBT system design time (also referred to as R&D cycle time) has not translated into a decrease in the overall product development cycle time. However, as product development cycle time becomes an increasingly large part of the product life cycle, manufacturers will look to exploit the design time reduction offered by simulation modeling.

New applications will also be a primary driver for the increased use of IGBT simulation modeling. The adoption of IGBT simulation modeling in the system design process will parallel the penetration of IGBT devices into some markets currently dominated by MOSFETs. MOSFETs are currently cheaper than IGBTs, but they have larger voltage losses. Thus, MOSFETs currently dominate lower voltage applications where the product material costs are more important than energy usage (e.g., household appliances less than 10 kW). However, the price of IGBTs (relative to MOSFETs) is steadily decreasing, and IGBTs are projected to penetrate some of the lower voltage applications' market.

Advances in IGBT modeling software capabilities will likely be driven by the next big "killer" IGBT application. Simulation modeling capabilities commercially available in software packages today have been largely driven by the automobile industry to support the design of ignition systems and motor control applications for the design of ASDs. The growth in the use of IGBTs in consumer electronics and industrial equipment will influence the use of simulation software in the future.

IGBTs will be incorporated in consumer electronics ranging from toasters to refrigerators. In most instances component libraries will provide off-the-shelf IGBT models that will be cost effectively integrated into the simulation of the electrical system.

A wide variety of industrial equipment is incorporating IGBTs for power correction and this will increase the demand for IGBT simulation modeling. The trend for industrial electrical equipment is for individual units to build in their own power correction components, as opposed to having a single bank of capacitors sitting outside the plant where the plant interconnects with the grid. This practice is very common already in Europe where it is regulated as part of safety guidelines.

The interoperability of simulation software packages with different levels of modeling complexity will lower overhead costs associated with simulation modeling. Harris Semiconductors is currently developing a new set of “more accurate tools” that will support applications manufacturers that do not have SABER. Harris is developing models of IGBTs in SABER and using them to generate IGBT models that can then be plugged into PSPICE or other simulation tools such as MathCad. After being developed, many of these models are placed on the Internet and become publicly available. As a result, non-SABER users will have a high-quality (but not as good as SABER), low-cost system simulation tool. These tools will be targeted to smaller companies with only a few engineers that cannot support the overhead costs associated with SABER.

Labor mobility will play a large role in spreading the use of IGBT simulation modeling. As a core of modeling experience and expertise grows, their knowledge will diffuse throughout the industry as modeling engineers move from company to company and take their knowledge capital with them.

6.4 FUTURE ROLES FOR NIST

The NIST program has contributed to lowering market barriers associated with the development and adoption of IGBT simulation modeling. Our interviews with industry experts indicate that the private sector did not have the market incentives to fully pursue the development of these IGBT modeling capabilities on their own. In the absence of NIST’s contributions the development of IGBT simulation modeling would likely have been delayed and the models eventually implemented would not have been as accurate.

However, industry experts indicated that there are additional areas where NIST's involvement could significantly increase current benefits associated with using IGBT simulation modeling. In particular, supporting enhancements to simulation software and increasing data availability could significantly increase the benefits estimated in Section 5.

NIST is currently engaging in activities to address several of these issues. The economic impacts of these ongoing NIST activities are not included in the benefits and costs estimated in Section 5.

NIST's current work in model compartmentalization may alleviate one of the most important barriers to the widespread use of IGBT simulation modeling.

NIST is currently working with Analog on developing an extraction tool/procedure so that modeling engineers can extract needed parameters for simulation without the device manufacturer having to reveal specific structural information about the device. This is sometimes referred to as model compartmentalization. By protecting the device manufacturer's intellectual property, the extraction tool would alleviate one of the most important barriers to widespread use of IGBT simulation modeling. However, a limitation of the extraction procedure currently being developed is that it is very complex. As a result, it is likely that only a handful of large companies will be able to support the overhead training costs needed to use the procedure. The primary users will probably be the major device manufacturers and one or two major applications manufacturers (Hefner, 1998).

Future activities NIST may want to consider to promote the adoption of IGBT simulation modeling and enhance its benefits are

- identifying and addressing weak links in the simulation modeling chain, such as supporting model development for other classes of devices;
- supporting a standardized modeling language to promote interoperability;
- supporting analysis needed to address the impact of variability in part on system performance and reliability; and
- enhancing systems for patenting device characteristics.

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Appendix A:
Background
Information on IGBTs

A.1 HISTORY OF SEMICONDUCTOR POWER DEVICES

In 1948, American physicists John Bardeen, Walter H. Brattain, and William Shockley of Bell Telephone Laboratories invented the transistor, a device at the heart of modern power electronics. The transistor is a small electronic unit consisting of semiconductor materials (impure germanium and silicon) used as a voltage and current amplifier in electrical machinery and equipment. Nearly 50 years after its invention, the bipolar transistor has developed to such an extent that millions of transistors can occupy a fingernail-sized sliver of silicon (Baliga, 1997).

A transistor is designed to operate switches and block or permit the flow of electric current. Transistors are distinguished by the amount of power they control, which is determined, in turn, by the individual unit's maximum operating voltage and current-handling capability. When the transistor is switched on, either with voltage or current depending on the type, electric current is allowed to pass through the device. When the transistor is switched off, electric current is blocked from coursing through the transistor. At the same time, the transistor maintains its support of the voltage on the wire.

Soon after its discovery at Bell Labs, the transistor technology was applied to all forms of electric devices. Two trends quickly developed: one towards miniaturization, the other towards the grandiose (Baliga, 1997). For products ranging from radios to the earliest computers, the transistor was shrunk to fit in all manners of microapplications, ushering in the age of electronics. For other applications, the transistor was enlarged and built to withstand and conduct massive amounts of power on command for generators and in power conditioners.

The complementary metal oxide semiconductor (CMOS) was an improvement on the bipolar transistor and was developed in the early 1970s. The introduction of the CMOS allowed greater power gain and control, but it was subject to destructive failures, necessitating the use of protective circuits. CMOSs were originally developed for microelectronic applications but have since become the basic building block of silicon integrated circuits.

A descendant of the CMOS, the metal oxide semiconductor field effect transistor (MOSFET) switches on and off faster and does not require the cumbersome protection circuits that bipolar transistors need. It switches on and off with voltage, not current. Current flow is limited to short bursts whenever the MOSFET is turned off or on. Although the MOSFET's ability to manage low voltages is well documented, its current-handling capability is less effective when operated at more than 100 volts. MOSFETs are found in consumer electronics, personal computers, automotive systems, and other low-power applications; it is currently known as the every-day transistor.

In the late 1970s, experiments with MOSFET/bipolar transistor combinations led to MOSFETs that could be used to control a bipolar transistor. These devices can be switched by a small voltage, while still operating at high amperes. This discovery, known as a MOS-gated thyristor, led to RCA's 1982 discovery of the IGBT. IGBT semiconductors are about the size of a postage stamp and can be grouped together to switch up to 1,000 amperes of electric current at voltages of up to several thousand volts.

Currently power electronics devices control an estimated 50 to 60 percent of the electric power generated in developed countries (Baliga, 1997). They are used in products as varied as car ignitions, electric bullet trains, blenders, fluorescent light ballasts, and computers. Table A-1 presents the power transistor market by product.

Table A-1. North American Power Transistor Market: 1993

Product	Revenues (%)
Bipolar	60
MOSFET	30
IGBT	10

Source: Profound. 1997. "North American Power Semiconductor Markets— Introduction, Total Market, Power Transistor, and Rectifier Market." <<http://www.profound.com/htbin/>>.

A.2 TECHNICAL CHARACTERISTICS OF IGBTs

The IGBT is a hybrid of two transistors: the bipolar transistor and the MOSFET. The simple bipolar transistor consists of three layers:

the top (the emitter), the middle (the base), and the bottom (the collector). The three layers alternate conductivity type. The areas between the conductivity types are called p-n junctions. Electrons pass through these junctions to move from one layer to another. If the electric potential or voltage on the segments is properly determined, a small current between the emitter and base connections generates a large current between the emitter and collector connections, thereby producing current and amplification (Columbia Encyclopedia, 1998).

Base bipolar transistors and MOSFETs are the two types of transistors used in IGBTs. Bipolar transistors are simple in design and rugged in performance. They effectively control large amounts of power and can be switched at high speeds. The main drawback, however, is that the amount of power they consume is directly related to the amount of power they control and conduct. In other words, bipolar transistors require a large current flow to control a larger current (Baliga, 1997).

The base bipolar transistor used in IGBTs is the p-n-p transistor. This transistor is the inverse of the standard n-p-n bipolar. The standard bipolar has a narrow base region and a lightly doped, thick collector. In contrast, the IGBT's base is thick and lightly doped and the collector is thin and highly doped. The advantage of the transistor's inverse properties is that they enable it to support high voltages across its output terminals, emitter, and collector when it is turned off. This had been previously accomplished by making the collector thick and lightly doped, but in an IGBT this is accomplished using thinner layers (Baliga, 1997).

MOSFETs are the other type of transistor used in IGBTs. MOSFETs evolved from the CMOS that had been developed during the 1970s for microelectronics. The n-p-n MOSFET, or n-channel MOSFET, has two n-type regions, the source and drain, that play the same roles as the collector and emitter in the bipolar transistor. The base in the MOSFET is known as the substrate, the p-type region. The top of the substrate is a metal gate that allows an electrical field to be created in the substrate when a positive voltage is applied to it. The field forces positively charged holes (electron deficiencies) from the substrate through the gate while attracting electrons toward the substrate surface. The moving electrons allow the current to flow through the substrate. From the perspective of an

IGBT, the key attribute of the MOSFET is that it is switched on and off with voltage, not current.

MOSFETs cannot control large amounts of power, but they can be switched on and off at incredibly high speeds. In addition, they do not require the protective circuits of their predecessor, the CMOS. The main limitation of MOSFETs is in their ability to efficiently handle high-voltage currents. As a MOSFET controls voltages of 100 volts or more, it loses its ability to control that power efficiently.

The inefficiency of MOSFETs at high power led to the development of the IGBT for controlling medium-power devices in the 1980s. In an IGBT, the MOSFET provides the control current to the bipolar transistor. To create an IGBT, the bipolar transistor and the MOSFET are joined so that the channel current flowing in the substrate of the MOSFET is also the current that is applied to the base of the bipolar transistor. The technical advantages from joining these two devices are threefold (Baliga, 1997). First, the IGBT's MOSFET is typically controlled by 10 volts, but the whole unit can control nearly 1,500 volts and 100 amperes. This equates to a possible power gain of 10 million or more. The high power gain allows the unit to be controlled by delicate integrated circuits but requires the use of protective circuits to prevent destructive failure.

Second, the IGBT has a higher operating current density than its components. The electrical current flowing through the IGBT's MOSFET is the control current for the bipolar transistor. The bipolar transistor's emitter-collector current joins the MOSFET's channel current to produce the IGBT's total output current. The two currents from the IGBT's components are equal; therefore, the IGBT's output current is double that of either of its components.

Third, when switched on, the IGBT has very low electrical resistance between the collector and the emitter. Because so many electrons and holes flow through the bipolar's base region from the emitter and collector, the base's conductivity increases 1,000 times. The improved conductivity keeps power loss at a minimum, especially when compared to the MOSFET and bipolar transistor alone. These three attributes allow IGBTs to be smaller, more efficient, and less expensive to produce for the manufacturer.

Appendix B: Acceleration Effect

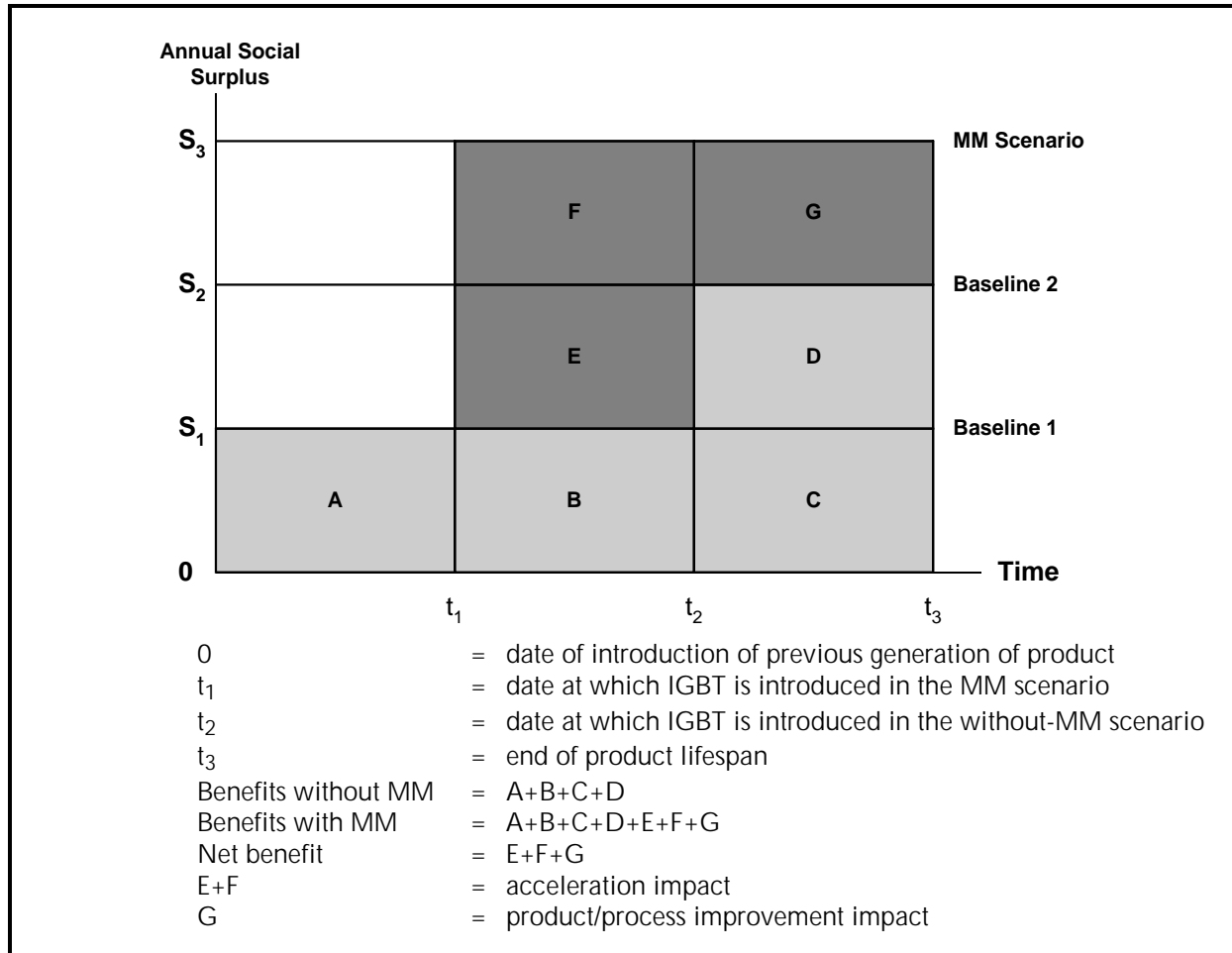
Mathematical modeling of IGBT devices can accelerate product availability, improve the value of products, and reduce the cost of designing and manufacturing products containing IGBT devices. The acceleration of new product introduction creates an important temporal element for the impact analysis. Over time, the relevant baseline for estimating the effects of mathematical modeling changes. Thus, we need three scenarios to model the economic impact of mathematical modeling: two baseline scenarios and one mathematical modeling (or MM) scenario. We define the scenarios as follows:

- Baseline 1: product does not contain an IGBT device
- Baseline 2: product contains an IGBT device but is not designed with mathematical modeling
- MM scenario: product contains an IGBT device and is designed with mathematical modeling

Over the lifetime of a product, the relevant baseline for measuring the impact of mathematical modeling will change. Figure B-1 illustrates how the baseline changes over time and how this affects our measurement of the net social surplus associated with mathematical modeling. Suppose that S_1 represents the net social surplus of a product without an IGBT device (Baseline 1). S_2 represents the social value of a product with an IGBT device that is not designed and produced using mathematical modeling (Baseline 2). S_3 represents the social value of a device with an IGBT that was produced with mathematical modeling. t_1 represents the time at which the product with the IGBT device is introduced if mathematical modeling is used; t_2 is the time at which this product would be introduced in the absence of mathematical modeling; and t_3 represents the end of the product's life cycle.

The net impact of mathematical modeling is equal to areas E+F+G. In the absence of mathematical modeling, the social surplus associated with the product over its entire life cycle is equal to areas A+B+C+D. Until t_2 , the product does not contain an IGBT, and its social surplus is equal to S_1 . At t_2 , the product's value increases to S_2 . However, if mathematical modeling is used to design and produce the product, the IGBT is introduced sooner, at t_1 rather than t_2 . Furthermore, rather than S_2 , the product's value is S_3 ; mathematical modeling has increased its performance relative

Figure B-1. The Timeline of Benefits from Mathematical Modeling of IGBT Devices
 The baseline needed to construct the counterfactual scenario changes over time.



to a product with an IGBT that is not designed with mathematical modeling. Thus, the product's social surplus in the mathematical modeling scenario is equal to areas $A+B+C+D+E+F+G$. We call areas $E + F$ the acceleration impact; area G is the product/process improvement impact.

Appendix C:
Survey Instrument:
Applications
Manufacturers

Questionnaire Applications Manufacturers

Introduction

On behalf of the National Institute of Standards and Technology (NIST), Research Triangle Institute (RTI) is conducting an evaluation of NIST's contributions to the development of simulation modeling techniques used for the simulation of semiconductor power devices. As part of this evaluation, we are investigating the benefits and costs of using simulation software in the system design of products employing insulated-gate bipolar transistors (IGBTs).

In general, we are interested in measuring the value of having simulation models for IGBTs available for use in system design. Specific issues of interest to NIST are

- the cost and time savings associated with using simulation software such as SABER and PSPICE;
- the limitations of simulation modeling of IGBT designs;
- enhancements that accelerated the adoption of simulation modeling techniques;
- the impact of simulation modeling on companies' decisions to incorporate IGBTs into their new products or redesigned existing products;
- improvements in the efficiency of end products employing IGBTs resulting from simulation modeling techniques; and
- impacts on production, such as material costs, yield, or time to market improvements resulting from using simulation techniques.

Our study would benefit a great deal from your input. Please read and consider the enclosed questions as they relate to your company's products. We encourage you to collaborate with your colleagues when answering these questions, because several questions span a variety of aspects of the product design and development process.

Any information you provide will remain strictly confidential. Only national-level cost and benefits impacts will be published in our study. Product- and company-level information will be used to estimate national-level impacts, but will not be included in any intermediate or final reports.

A staff member from RTI will contact you in the next few days to answer any questions you may have. At that time you may respond to these questions over the phone or make an appointment to do so at a later date. Alternatively you may complete the questionnaire and e-mail or fax it to us at mpg@rti.org or (919) 541-6683. At any time, if you have any questions, please feel free to contact Mike Gallaher at (919) 541-5935 or Alan O'Connor at (919) 541-7186. Thank you for your input to our study.

1. Company Identification

Company Name: _____
Mailing Address: _____
Contact Name: _____
Title: _____
Phone Number: _____

2. Product Information

- 2.1 In the table below, please identify the product lines your company manufactures that incorporate IGBT power devices. For each product line, provide the unit size ranges manufactured and the number of different circuit architecture designs. In particular, we are interested in the number of circuit architectures used in the product line employing different IGBT system designs. In addition, provide the approximate number of units sold in the previous fiscal year and indicate the year IGBTs were first incorporated into this product line.

Table 1. Product Lines Incorporating IGBTs

Product Line Description	Size Range	Number of Different Circuit Architecture (IGBT System) Designs	Number of Units Sold Per Year	Year IGBTs First Used
<i>Example: Ignition switches for trucks</i>	<i>All</i>	<i>one for small trucks one for large trucks</i>	<i>100,000</i>	<i>1992</i>

2.2 For the product lines listed in Table 1, please indicate the benefits and costs associated with incorporating IGBTs into the product, relative to the alternative device (MOSFET or other controllable switching system).

Table 2. Benefits and Costs of Using IGBTs

Product Line	Alternative Device	Percent Increase in Efficiency ^a	Percent Reduction in Manufacturing Costs ^b	Percent Decrease (Increase) in Design Costs
<i>Example: Ignition switch for trucks</i>	<i>MOSFET</i>	<i>No impact on fuel efficiency</i>	<i>0.5% of total cost of truck</i>	<i>20% decrease</i>

^aPlease provide a percentage change in efficiency of final product. If efficiency change is for a subcomponent please describe the subcomponent.

^bPlease provide per-unit percentage change in manufacturing costs for the final product.

3. General Information on IGBT Power-Device System Design

3.1 Approximately how many times per year does your company conduct a system design process that incorporates IGBT power devices?

3.2 When new or updated products are developed, does this generally require a revision of the electronics system containing IGBT power devices? Please explain.

3.3 Is a separate system design process required for each product? Please explain.

3.4 Do you use simulation modeling as part of your system design process for products incorporating IGBTs?

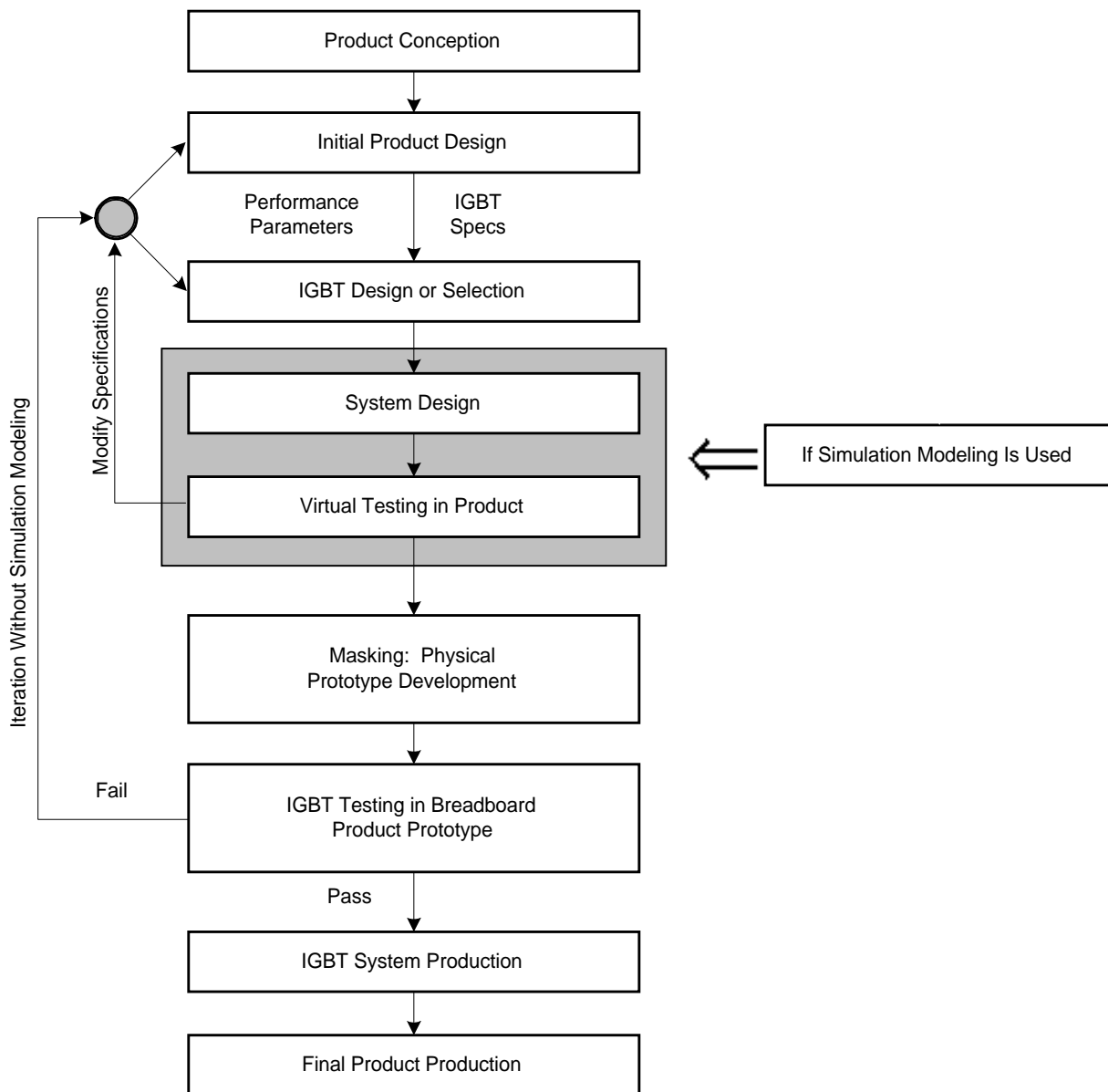
- Yes *Continue to Question 3.5*
- No

If no, answer the following questions in the space below and skip the remainder of the questions in this survey. Thank you for your input.

- a. Please explain why simulation modeling is not used.
- b. What are its shortcomings relative to the design of your products?
- c. Do you plan to use simulation modeling in the future?
- d. What are you using in place of simulation modeling to verify the design (e.g., prototypes in hardware)?

3.5 Figure 1 contains a flow chart of the design process for systems incorporating IGBT power devices. Does the process flow in this figure accurately represent the typical system design process with and without simulation modeling? Please elaborate.

Figure 1. Design Process



3.6 Using the list of products you provided in Table 1 indicate whether simulation modeling is used in the design process and when your company began using simulation modeling. Also indicate the frequency of product design processes per year and the specific software used (e.g., SABER, PSPICE).

Table 3. Use of Simulation Modeling

Product Line	Simulation Modeling Used in Design Process (Y/N)	Year First Used	Software Used

3.7 In Table 4, provide the overhead costs associated with each simulation software product that you use.

Table 4. Overhead Costs

Software	Number of Licenses	Cost per License	Labor Hours for Training (per year) to Support Software
SABER			
PSPICE			
others			

3.8 What is the average hourly wage of design engineers employing the software programs listed in Table 4? _____ per hour.

What is their fringe benefit rate? _____ %

4. Impact of Simulation Modeling on the System Design Process

Our preliminary interviews have suggested that simulation modeling provides an understanding of the IGBT system design without physically procuring materials and building a prototype. Thus, simulation modeling reduces the number of design iterations, saving time and design labor hours. Please answer the questions below to help us determine the extent of resource savings from simulation modeling.

An example framework for providing this information is provided below. However, if this is not applicable, please use any framework that may be appropriate.

Example:

Simulation modeling provides an understanding of the IGBT system design without physically procuring materials and building a prototype. Each time an IGBT design is modified (referred to as an iteration, see Figure 1), an estimated \$\$ is spent for new mask sets, and there can be a delay of X weeks. Historically, IGBT design required Y iterations. With simulation modeling, a design may require only Z iterations.

- 4.1 Describe in general how using these simulation software products influences your design activities. Describe the alternative design process without simulation modeling of IGBTs.

- 4.2 Considering the products listed in Table 1, how many iterations, on the average, were required to complete an IGBT design before you started using simulation modeling? _____ iterations

- 4.3 How many are required now, with the use of simulation modeling? _____ iterations

- 4.4 On the average, what is the cost of developing new mask sets and other materials required for each iteration? \$_____/iteration

- 4.5 How many hours of labor are required per design iteration? \$_____/iteration

4.6 Has simulation modeling accelerated the design process?

Yes

No

If yes, by how many weeks or months? _____ weeks/months

4.7 Has this accelerated the introduction of new products?

Yes

No

If yes, by how many weeks or months? _____ weeks/months

5. Impact of Simulation Modeling on the Manufacturing Process

Some system designers have indicated that using simulation modeling reduces the cost of production for products with IGBT devices because it improves the predictability of the products' performance. Please answer the following questions in general with respect to the products your company produces that employ IGBT devices:

5.1 Does simulation modeling reduce the cost of materials required to produce these products?

Yes

No

If yes, what would you estimate to be the percentage change in materials costs for these products from the use of simulation modeling? _____%

What percentage of TOTAL production costs is attributable to materials costs?
_____%

5.2 Does simulation modeling affect the manufacturing defect rate?

Yes

No

If yes, please indicate, on average, the defect rate with and without simulation modeling.

Without simulation modeling: _____ per thousand

With simulation modeling: _____ per thousand

6.2 Please use Tables 5 and 6 to provide specific information on increased final product quality for each product line. Please separate the impact of including an IGBT in the product design from the impact of using simulation modeling in the design process.

Table 5. Increased Final Product Quality from IGBTs' Simulation Modeling

Product Line (Keep same order as in Table 1)	Brief Technical Description of Impact on Product Quality/Reliability/Weight, etc.	
	Impact of IGBTs	Impact of Simulation Modeling

Table 6. Impact of IGBTs and Simulation Modeling on Energy Consumption and Maintenance Requirements

Product Line (keep same order as in Table 1)	Impact on Energy Consumption (For Example, Percentage Change in Efficiency) ^a		Impact on Maintenance Requirements (For Example, Percentage Change in Costs)	
	Impact of IGBTs	Impact of Simulation Modeling	Impact of IGBTs	Impact of Simulation Modeling

^aFor example, if a unit had an energy efficiency rating (EER) of 92 percent before IGBTs were incorporated and an EER of 95 percent after IGBTs were incorporated, the increase in efficiency would be 3 percentage points. Or, if a line of air conditioning units went from 10.5 SEER to 12.5 SEER, this represents a $\frac{12.5 - 10.5}{10.5} = 19$ percent increase in efficiency. If efficiency change is for a subcomponent please describe the subcomponent and its share of energy usage in the final product.

Appendix D:
Survey Instrument:
Device
Manufacturers

Questionnaire Device Manufacturers

Introduction

On behalf of the National Institute of Standards and Technology (NIST), Research Triangle Institute (RTI) is conducting an evaluation of NIST's contributions to the development of simulation modeling techniques used for the simulation of semiconductor power devices. As part of this evaluation, we are investigating the benefits and costs of using simulation software in the design of products employing insulated-gate bipolar transistors (IGBTs).

In general, we are interested in measuring the value of having simulation models for IGBTs available for use in device and system design. Specific issues of interest to NIST are

- the cost and time savings associated with using simulation software such as SABER and PSPICE;
- the limitations of simulation modeling of IGBT designs;
- enhancements that accelerated the adoption of simulation modeling techniques;
- the impact of simulation modeling on companies' decisions to incorporate IGBTs into their new products or redesigned existing products;
- improvements in the efficiency of end products employing IGBTs resulting from simulation modeling techniques; and
- impacts on production, such as material costs, yield, or time to market improvements resulting from using simulation techniques.

Our study would benefit a great deal from your input. Please read and consider the enclosed questions as they relate to your company's activities and clients. We encourage you to collaborate with your colleagues when answering these questions, because several questions span a variety of aspects of the product design and development process.

Any information you provide will remain strictly confidential. Only national-level cost and benefits impacts will be published in our study. Product- and company-level information will be used to estimate national-level impacts, but will not be included in any intermediate or final reports.

A staff member from RTI will contact you in the next few days to answer any questions you may have. At that time you may respond to these questions over the phone or make an appointment to do so at a later date. Alternatively you may complete the questionnaire and e-mail or fax it to us at mpg@rti.org or (919) 541-6683. At any time, if you have any questions, please feel free to contact Mike Gallaher at (919) 541-5935 or Alan O'Connor at (919) 541-7186. Thank you for your input to our study.

1. Company Identification

Company Name: _____
Mailing Address: _____
Contact Name: _____
Title: _____
Phone Number: _____

2. Products Employing IGBTs

2.1 In the table below, please identify the major systems manufacturers that your company has worked with in designing IGBT power device systems. For each systems manufacturer, list their product lines that incorporate IGBTs. We are also interested in the number of circuit architectures used in each product line employing different IGBT system designs. For example, if manufacturer X produces a line of air conditioners that incorporate IGBTs, how many different IGBT system designs are needed to support their line of air conditioners? In addition, indicate the year IGBTs were first incorporated into each product line.

Table 1. Product Lines Incorporating IGBTs

Major Manufacturers	Products	Number of Different Circuit Architecture (IGBT System) Designs	Year IGBTs First Used
<i>Example: Manufacturer X</i>	<i>Product A</i> <i>Product B</i> <i>Product C</i>	<i>3</i> <i>1</i> <i>2</i>	<i>1994</i> <i>1992</i> <i>1997</i>

2.2 For the systems manufacturers and product lines listed in Table 1, please indicate the benefits and costs associated with incorporating IGBTs into the product, relative to the alternative device (MOSFET or other controllable switching system).

Table 2. Benefits and Costs of Using IGBTs

Manufacturer/ Product Line	Alternative Device	Increase in Operating Efficiency ^a	Percent Decrease (Increase) in Design Costs
<i>Example: Manufacturer X:</i> <i>-Product A</i> <i>-Product B</i> <i>-Product C</i>	<i>MOSFET</i> <i>None</i> <i>MOSFET</i>	<i>2%</i> <i>1%</i> <i>None</i>	<i>30%</i> <i>30%</i> <i>20%</i>

^aFor example, if a unit had an energy efficiency rating (EER) of 92 percent before IGBTs were incorporated and an EER of 95 percent after IGBTs were incorporated, the increase in efficiency would be 3 percentage points. Or, if a line of air conditioning units went from 10.5 SEER to 12.5 SEER, this represents a $\frac{12.5 - 10.5}{10.5} = 19$ percent increase in efficiency. If efficiency change is for a subcomponent please describe the subcomponent and its share of energy usage in the final product.

2.3 Please describe other benefits or costs (not listed in Table 2) associated with incorporating IGBTs, such as changes in product reliability, maintenance costs, etc.

3. IGBT Power-Device Design

3.1 Approximately how many new or modified IGBT power devices does your company design per year?

3.2 When new or updated products are developed, does this generally require the development of a new IGBT power device? Please explain.

3.3 Please describe your IGBT device design process.

3.4 Do you use simulation modeling as part of your IGBT device design process for products incorporating IGBTs?

Yes *Continue to Question 3.5*

No

If no, answer the following questions in the space below and skip the remainder of the questions in this survey. Thank you for your input.

- a. Please explain why simulation modeling is not used.
- b. What are its shortcomings?
- c. Do you plan to use simulation modeling in the future?

- 3.5 Using the list of systems manufacturers and product lines you provided in Table 1 indicate whether simulation modeling is used in the design process and approximately what year simulation modeling was first used in each product line. Also indicate the specific software used (e.g., SABER, PSPICE).

Table 3. Use of Simulation Modeling

Product Line	Simulation Modeling Used in Design Process (Y/N)	Year First Used	Software Used
<i>Example: Manufacturer X:</i> <i>-Product A</i> <i>-Product B</i> <i>-Product C</i>	<i>Y</i> <i>Y</i> <i>N</i>	<i>1993</i> <i>1993</i> <i>NA</i>	<i>SABER</i> <i>PSPICE</i> <i>NA</i>

3.6 In Table 4, provide the overhead costs associated with each simulation software product that you use (e.g., SABER, PSPICE).

Table 4. Overhead Costs

Software	Number of Licenses	Original Purchase Cost per License (and year of purchase)	Additional Annual Maintenance or Update Costs	Labor Hours for Training (per year) to Support Software
<i>Example: SABER</i>	<i>3</i>	<i>\$XXX.00 (1992)</i>	<i>\$XX.00/yr</i>	<i>2 staff members 50 hours each</i>

3.8 What is the average hourly wage of design engineers employing the software programs listed in Table 4? _____ per hour.

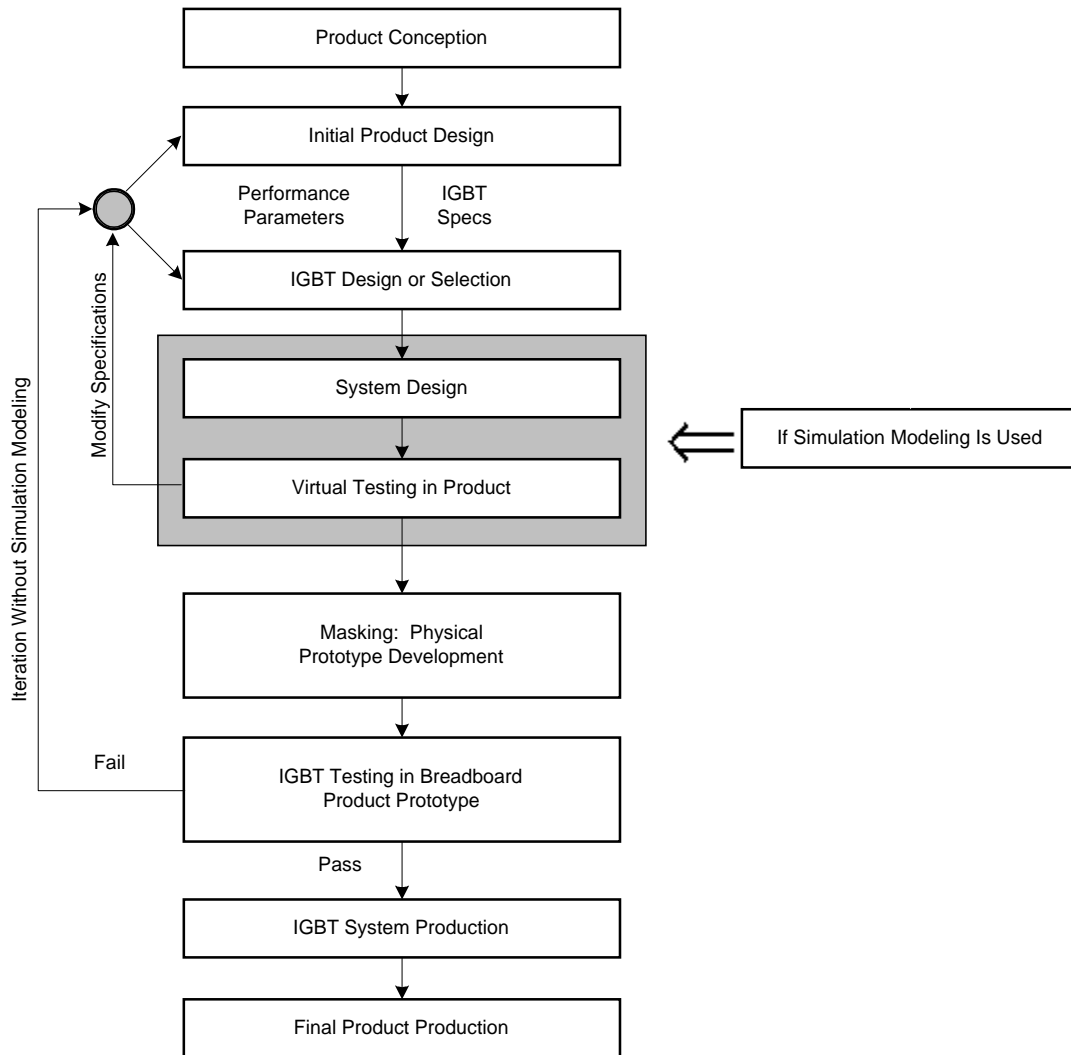
What is their fringe benefit rate? _____ %

4. Impact of Simulation Modeling on the System Design Process

Our preliminary interviews have suggested that simulation modeling provides an understanding of the IGBT system design without physically procuring materials and building a prototype.

4.1 Figure 1 contains a flow chart of the design process for systems incorporating IGBT power devices. Does the process flow in this figure accurately represent the typical system design process with and without simulation modeling? Please elaborate.

Figure 1. Design Process



We are interested in how simulation modeling affects the number of design iterations, saving time and design labor hours. Please answer the questions below to help us determine the extent of resource savings from simulation modeling.

An example framework for providing this information is provided below. However, if this is not applicable, please use any framework that may be appropriate.

Example:

Simulation modeling provides an understanding of the IGBT system design without physically procuring materials and building a prototype. Each time an IGBT design is modified (referred to as an iteration, see Figure 1), an estimated \$\$ is spent for new mask sets, and there can be a delay of X weeks. Historically, IGBT design required Y iterations. With simulation modeling, a design may require only Z iterations.

4.2 Describe in general how using these simulation software products influences your design activities. Describe the alternative design process without simulation modeling of IGBTs.

4.3 Considering the products listed in Table 1, how many iterations, on average, were required to complete an IGBT design before you started using simulation modeling? _____ iterations

4.4 How many are required now, with the use of simulation modeling? _____ iterations

4.5 On the average, what is the cost of developing new mask sets and other materials required for each iteration? \$_____/iteration

4.6 On average, how many hours of labor are required per design iteration? \$_____/iteration

4.7 Has simulation modeling accelerated the design process?

Yes

No

If yes, by how many weeks or months? _____ weeks/months on average

4.8 Has this accelerated the introduction of new products?

Yes

No

If yes, by how many weeks or months? _____ weeks/months on average

5. Impact of Simulation Modeling on Final Product Performance

We know that using IGBTs has important effects on the performance of many products. Some system designers have indicated that using simulation modeling in designing IGBT systems improves predictive accuracy and expands the performance range of the IGBT component system, resulting in increased quality of final products employing IGBTs.

5.1 Does the use of simulation modeling further improve the product over and above the product improvements described in Section 2 (i.e., we are interested in the benefits from simulation modeling of IGBTs separate from the benefits of IGBTs over alternative, controllable switching technologies)?

Yes

No

If yes, please explain.

5.2 Please use Table 5 to provide specific information on increased final product quality for each product line. Please separate the impact of including an IGBT in the product design from the impact of using simulation modeling in the design process.

Table 5. Increased Final Product Quality from IGBTs' Simulation Modeling

Product Line (Keep same order as in Table 1)	Brief Technical Description of Impact on Product Quality/Reliability/Weight, etc. ^a	
	Impact of IGBTs	Impact of Simulation Modeling

^aPlease provide quantitative impact estimates if possible.

Appendix E:
Survey Instrument:
Software Developers

Questionnaire Software Developers

Introduction

On behalf of the National Institute of Standards and Technology (NIST), Research Triangle Institute (RTI) is conducting an evaluation of NIST's contributions to the development of mathematical modeling techniques used for the simulation of semiconductor power devices. As part of this evaluation, we are investigating the benefits and costs of using simulation software in the system design of products employing insulated-gate bipolar transistors (IGBTs).

The issues of particular interest to NIST include

- ▶ the penetration of simulation modeling of IGBT system design in new products or the redesign of existing products,
- ▶ the limitations of simulation modeling of IGBTs,
- ▶ enhancements that would accelerate the adoption of simulation modeling techniques, and
- ▶ NIST's contribution to the development of simulation software products.

Our study would benefit a great deal from your input. Please read and consider the enclosed questions as they relate to your company's software products. We encourage you to collaborate with your colleagues when answering these questions, because several questions span a variety of aspects of the product design and development process.

Any information you provide will remain strictly confidential. Only national-level cost and benefits impacts will be published in our study. Product- and company-level information will be used to estimate national-level impacts, but will not be included in any intermediate or final reports.

A staff member from RTI will contact you in the next few days to answer any questions you may have. At that time you may respond to these questions over the phone or make an appointment to do so at a later date. Alternatively you may complete the questionnaire and fax it to us at 919-541-6683. At any time, if you have any questions, please feel free to contact Mike Gallaher at 919-541-5935 or Alan O'Connor at 919-541-7186. Thank you for your input to our study.

1. Company Identification

Company Name: _____
Mailing Address: _____
Contact Name: _____
Title: _____
Phone Number: _____

Section 1. Market Penetration of Simulation Modeling

- 1.1 Please describe your company's software products that support simulation modeling of IGBTs.

- 1.2 Are your IGBT simulation components stand alone products or are they modules in a large simulation package?

- 1.3 Please describe how your simulation software product is used by device manufacturers and system designers.

1.4 In Table 1, please list the major products that employ IGBTs. For each product, estimate the percentage of existing IGBT products that have been designed using simulation modeling and how this percentage is likely to change over the next 5 years.

Table 1. Products Incorporating IGBTs

Product Line Description	% of Existing IGBT Products Designed Using Simulation Modeling	% Designed Using Simulation Modeling in 2003
<i>Example: Air Conditioners</i>	70%	95%

1.5 In Table 2, please identify additional products for which simulation modeling of IGBTs will likely be used in the future.

Table 2. Products Likely to Incorporate IGBTs in the Future

Product Description	Time Horizon for Product Introduction

1.6 What are some of the limitations of existing simulation modeling techniques?

1.7 What model enhancements would accelerate the adoption of simulation modeling techniques?

Section 2. Software Development

As part of our evaluation of the benefits of simulation modeling in the design of IGBT systems, we need to estimate the cost of developing the software tools used by device manufacturers and system designers.

- 2.1 When did your company first introduce IGBT modeling capabilities into your software products?

- 2.2 What was your company's investment in the development of the software components that support the simulation of IGBT systems?

Length of time to develop (months) _____

Cost of development (\$\$) _____

- 2.3 If the software development was a joint venture with other companies or educational or government agencies (other than NIST), please estimate their total expenditures in Table 3.

Table 3. Software Development Expenditures by Other Organizations

Company or Agency Name	Total Expenditures

Section 3. NIST's Contribution to the Development and Adoption of Simulation Modeling of IGBT Power Devices

Over the past 8 years Dr. Allen Hefner, Project Leader, Semiconductor Electronics Division at NIST, has contributed to the development of mathematical models that predict device performance of IGBTs.

- 3.1 Please comment on the impact NIST has had in the development of your company's simulation modeling software for IGBT power devices.

- 3.2 Without NIST's contribution to the development of mathematical models, would your company have developed the modeling techniques?

Yes

No

Please explain the factors that would have influenced your decision to either proceed or not proceed with development on your own.

3.3 If you would have developed the modeling techniques yourself,

- would you have developed them in the same time frame? When do you predict you would have introduced a software product with comparable capabilities?

- do you think your simulation models would have been as accurate as the existing models based on NIST's algorithms? Please explain.

3.4 Do you think that NIST's involvement in this area has

- accelerated the adoption of circuit simulation models and virtual prototyping by system designers and device manufacturers? Please explain.

- lowered the cost of using simulation software by reducing license fees or increasing user friendliness? Please explain.

Thank you for your assistance.

Appendix F: Completed Interviews

F.1 TECHNICAL INTERVIEWS

The number of persons interviewed at each organization is shown in parentheses.

F.1.1 Software Companies

Analogy Inc. (2)

F.1.2 Device Manufacturers

Harris Semiconductor (2)

International Rectifier (1)

F.1.3 Applications Manufacturers

Rockwell Automation/Allen-Bradley (2)

Visteon Electronics Division (3)
(Fully owned subsidiary of Ford)

Ford Electric Vehicle Division (1)

General Electric Company-CRD (1)

F.2 SCOPING INTERVIEWS

F.2.1 Academics

University of Colorado (1)

University of Washington (1)

Virginia Tech (1)

University of Tennessee (1)

F.2.2 Software Companies

Analogy Inc. (1)

MicroSim Corp (1)

F.2.3 Device Manufacturers

Consultant to Harris Semiconductor (1)

International Rectifier (1)

Harris Semiconductor (1)

F.2.4 Applications Manufacturers

General Electric (1)