INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS

2001 EDITION

ENVIRONMENT, SAFETY, AND HEALTH

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SCOPE

BACKGROUND

The semiconductor industry views responsible performance in environment, safety and health (ESH) as critical to success. Continued ESH improvement is a major consideration for semiconductor manufacturers, whose business approach to ESH employs strategies that are integrated with manufacturing technologies, products, and services. This approach is structured around the belief that good business stewardship includes an active awareness and commitment to responsible environmental, safety, and health practices. Addressing these areas aggressively has resulted in the industry being an ESH leader as well as a technology leader. This roadmap identifies R&D challenges that may impact ESH as new technology requirements are identified.

EXPECTATIONS

For both engineers and research scientists, this roadmap identifies ESH R&D challenges that occur as new wafer processing and assembly technologies are designed and created. Technology requirements are listed in Tables 82–87. It also proposes possible technology and management solutions to meet the challenges, as illustrated in Figures 53–54.

By giving direction to research centers, suppliers and semiconductor manufacturers, this roadmap focuses the search for solutions. ESH integration into manufacturing and business practices is clearly a priority. A high expectation of success and improvement requires that ESH must be integral to the thoughts and actions of process, equipment, and facilities engineers, and to university researchers. Improvements must meet local, national, and international needs, with positive impact on cost, technical performance and product timing. They must also minimize risk, public and employee health effects, and environmental impact. Solutions must be timely, yet far reaching, to assure long-term success. Integration of international initiatives and other notable ESH-focused entities sponsored by the semiconductor industry, universities and government have made the ESH objectives of this roadmap truly international.

DIFFICULT CHALLENGES

Five global ESH challenges essential to a synergistic ESH strategy and ones that must be integrated into the technical thrust areas are: *Chemicals, Materials, and Equipment Management, Resource Conservation, Workplace Protection, Climate Change Mitigation, and Design for Environmental, Safety, and Health (DFESH). Chemicals, Materials, and Equipment Management* must provide timely ESH information to equipment design engineers and equipment users regarding the environmental, safety and health characteristics of potential new process chemicals and materials. This information is essential to the selection of optimal chemicals and materials for function and ESH impact with respect to reaction product emissions, health and safety properties, materials compatibility with both equipment and other chemical components, flammability and reactivity while minimizing unnecessary business impact after processes are developed and in production. *Resource Conservation* (water, energy, chemicals, and materials) will grow in importance with respect to availability, cost reduction, manufacturing location, sustainability, and waste disposal. *Workplace Protection* is always among the top priorities for our industry. As more is known about potential work environment impacts on health and safety, technology improvements need to be made in facilities, equipment, personal protective equipment, and training. *Climate Change Mitigation* is a major consideration because it potentially could limit the use of energy and chemicals essential to the manufacturing process. To address the above issues in a cost-effective and timely way, *Design for Environmental, Safety, and Health (DFESH)* minimizes ESH impacts by systematically considering them in the design process as an integral part of management decision-making.

Table 82 ESH Difficult Challenges

Five Difficult Challenges ≥ 65 nm / Through 2007	*Summary of Issues / Needs*
Chemicals, Materials and Equipment Management	*New Chemical Assessment* Need for quality rapid assessment methodologies to ensure that new chemicals can be utilized in manufacturing, while protecting human health, safety, and the environment without delaying process implementation. Chemicals in existing uses require reassessment when new chemical restrictions are identified. *Chemical Data Collection* Need to document and make available environment, safety, and health characteristics of chemicals. *Chemical Reduction* Need to develop processes that meet technology demands while reducing impact on human health, safety and the environment, both through replacement of hazardous materials with materials that are more benign, and by reducing chemical quantity requirements through more efficient and cost-effective process management. *Environment Management* Need to develop effective management systems to address issues related to disposal of equipment, and hazardous and non-hazardous residue from the manufacturing process.
Resource Conservation	*Natural Resource Conservation (Energy, Water)* Need to design more energy and water efficient processing equipment. *Chemicals and Materials Use* Need more efficient utilization of chemicals and materials. *Resource Recycling* Increase resource reuse and recycling.
Workplace Protection	*Equipment Safety* Need to design ergonomically correct and safe equipment. *Chemical Exposure Protection* Increase knowledge base on health and safety characteristics of chemicals and materials used in the manufacturing and maintenance processes, and of the process byproducts; and implement safeguards to protect the users of the equipment and facility.
Climate Change Mitigation	*Reduce Energy Use Of Process Equipment* Need to design energy efficient larger wafer size processing equipment. *Reduce Energy Use Of The Manufacturing Facility* Need to design energy efficient facilities to offset the increasing energy requirements of higher class clean rooms. *Reduce High Global Warming Potential (GWP) Chemicals Emission* Need ongoing improvement in methods that reduce emissions from processes using GWP chemicals.
Design for Environmental, Safety, and Health (DFESH)	*Evaluate and Quantify ESH Impact* Need integrated way to evaluate and quantify ESH impact of process, chemicals, and process equipment, and to make ESH a design parameter in development procedures for new equipment and processes.

Table 82 ESH Difficult Challenges (continued)

FIVE DIFFICULT CHALLENGES < 65 NM / BEYOND 2007	SUMMARY OF ISSUES / NEEDS
Chemicals, Materials and Equipment Management	*Chemical Use Information* Rapid introduction of chemicals and materials into new process requires the understanding of process fundamentals in order to reduce ESH impacts.
Resource Conservation	*Reduce Water, Energy, Chemicals And Materials Use* Need resource efficient processing and facility support equipment and improved water reclaim and recycling methods. Emphasis on resource sustainability will grow.
Workplace Protection	*Equipment Safety* Need ergonomic principles integrated into the processing and wafer moving equipment for both operation and maintenance aspects, and into the overall manufacturing facility.
Climate Change Mitigation	*Reduce Energy Use* The importance of reducing energy use to minimize/slow climate change will grow. *Reduce High GWP Chemicals Emissions* The international pressures to reduce emissions of GWP chemicals will continue.
Design for Environmental, Safety, and Health (DFESH)	*Evaluate and Quantify ESH Impact* Need integrated ESH design in development of new equipment and processes.

ESH TECHNOLOGY REQUIREMENTS AND POTENTIAL SOLUTIONS

ESH INTRINSIC REQUIREMENTS

ESH-based technology requirements, require an explicit set of analysis methodologies, data sets and implementation methods to enable scientists and engineers who are responsible for making the technology decisions. The 2001 ITRS introduces a new table for “ESH Intrinsic Requirements,” Table 83, that defines those needs. The ESH intrinsic requirements are met in parallel to, but independent of the mainstream technology objectives.

One important element of measurement and evaluation methods is risk assessment. As an example, the results of chemical industry investigations can be applied to the semiconductor industry with appropriate modification. A standardized methodology to identify, access, and accept risk is needed.

A methodology to determine the lowest ESH impact of materials and processes needs to be developed. Measurement and evaluation methods must be easy to use and reliable. Their meaning lessens if their content is not updated in response to new semiconductor technologies and other technical developments. A design algorithm to conduct environmentally-conscious design during the device/process design stage is needed.

Process analysis is another evaluation element. Process by-products, for example from plasma processes, are an important issue. The elementary chemical reactions in each process must be understood, and new measurement and evaluation methods must be implemented for developing processes that have the lowest ESH impact. For material balance, it may be advantageous to apply the results of pollutant release and transfer disclosure (PRTR) programs.

Database establishment—A database is necessary to store the information for accurately conducting risk assessment on the materials and chemicals used. The database should contain information such as safety data, environmental load/impact data, process data, emission distribution factor (dispersion model) and emission treatment methods to use the material, and conditions regulated by law. At present, the general database for chemical materials is generated by the chemical material industry, but the data are not sufficient, especially on the process used or the distribution factor (dispersion model) of the chemical material to the environment.

Water—Process simulation and cost optimization tools are required to determine the optimum balance of high efficiency rinse processes; recycling of higher quality water process applications; and reuse of lower quality water for nonprocess applications at different factories and different locations.

CHEMICALS, MATERIALS AND EQUIPMENT MANAGEMENT

Risk assessment—Prior to employing a new chemical material, it is necessary to accurately and quickly evaluate the safety, health danger and environmental load/impact. A decision is then made whether to employ the chemical, based on the quantity to be used, the method to be employed and the risk assessment. Operator and maintenance worker exposure to the chemical material must be reduced for safety and health reasons, and emissions must be controlled to minimize environmental load/impact.

Safety and environmental load/impact evaluation of new materials and new chemicals—The safety, health hazards, and environmental load/impact of new materials and chemicals must be evaluated.

It is necessary to identify the path by which the environmental load/impact material is emitted (including the control of waste material), to find alternative materials, or to develop recovery/treatment technology.

Reduction of environmental load/impact materials and chemicals—Efforts have been made to find alternative materials, especially for greenhouse gases and ozone-depleting substances. Alternative materials for bromine and antimony used as fire resistant materials in plastic packages, and lead used for soldering and tinning, are being developed.

Environment management—It is necessary to control the chemicals and materials in each plant to reduce the quantity used and their emissions. Therefore, a material balance control system is needed. A system for automatically collecting data will be needed as the number of target chemicals and materials expands. Life Cycle Analysis (LCA) on materials is currently performed using manual data collection and reporting. An automatic data collection system should be established.

CLIMATE CHANGE MITIGATION

Energy consumption has increased owing to the increased energy consumption of the manufacturing equipment for more complex semiconductors, larger wafer diameter, and the increase of air conditioning energy consumption for higher cleanliness of the cleanroom. Changes in areas such as cleanroom design, equipment design, and wafer transfer/storage methods are needed. In addition to the energy saving of the semiconductor manufacturing equipment, it is necessary to reduce the elements that increase the heat load/impact to the cleanroom. Potential solutions for energy are shown in Figure 51.

Global climate change concerns are driving international efforts to reduce emissions of greenhouse gases, such as PFCs used in semiconductor manufacturing.

WORKPLACE PROTECTION

For equipment, processes, maintenance, factory design, and factory integration, the industry must accept and fully employ standard protocol for hazard control utilizing the following ranking for solutions: a) hazard elimination, b) engineering controls, c) administrative controls, and d) personal protective equipment (PPE).

Increases in wafer size and throughput will require wafer handling systems that may increase worker risk during operation and maintenance. The movement of automated system- and people-guided wafer transport systems and their interface with manufacturing equipment are potentially dangerous to nearby workers. Design controls and procedures comprehending ergonomics and robotics to improve equipment operability and prevent incorrect operation need to be established.

An industry need exists for safe, cost-effective materials of construction. Fire-resistant, process-compatible materials that meet the needs of manufacturing and the expectations of insurers are necessary.

Electromagnetic waves exhibit various wavelength-dependent characteristics. When the wavelength used for pattern exposure is shortened to the X-ray region, the health effects must be evaluated.

RESOURCE CONSERVATION

The increase in wafer size and process steps and the need for higher purity water and chemicals indicates a potential trend for higher resource (water, energy, and chemicals) usage per wafer. This trend can be reversed by development of higher efficiency processes and tools and by a combination of strategies including recycling for process applications and reuse for non-process applications, especially for water and waste Resource usage efficiency in semiconductor tools can be greatly improved. The photolithography process is an example where large amounts of chemicals are used, but most materials are removed from the wafer and become (industrial) waste.

*Wate*r—Water used in semiconductor manufacture is mostly ultrapure water (UPW). Since UPW manufacturing requires large quantities of chemicals, the increase in UPW consumption and quality has accelerated chemical consumption (and the cost of ultrapure water manufacturing). Reduction of UPW consumption and manufacturing will result in reduced environmental effects caused by the chemicals and reduced manufacturing costs. Recycling of higher quality water for process applications and reuse of lower quality water for non-process applications is important. In areas where water is sufficient, wastewater recycling should be implemented after reviewing the local water reuse and associated recycling costs.

*Energ*y—Limits on sources of energy could potentially limit industry's ability to expand existing factories or build new ones. While the semiconductor manufacturers have demonstrated improved energy efficiencies over the past decade, potential resource limitations require the industry to continue the trend.

Chemicals—New chemicals and materials will be used and their usage will be rapidly increased with introductions and development of new technologies to satisfy technology requirements. On the other hand people are more sensitive to environmental pollution caused by industrial activities. Though total quantity of chemicals and materials usage in semiconductor industry is quite small compared to other industries, resource efficient processing and production equipment should be needed

No waste—In consideration of the above situations the semiconductor manufacturers should aim at realizing “no waste” plant like other industries. To achieve that objective the waste recycle rate must be improved and cooperation with the recycling industry and governments will be necessary.

DESIGN FOR ENVIRONMENTAL, SAFETY, AND HEALTH (DFESH)

Design for Environment, Health and Safety (DFESH) is the term applied to the integration and proliferation of EHS improvements as part of manufacturing technology design. It allows for the early evaluation of EHS issues related to critical technology developments and serves to enable technology development by ensuring the solutions do not include any EHS-related “showstoppers”. It requires a comprehensive understanding of tools and materials development, facility design, waste and resource management-and the way they affect EHS results. DFESH allows us to build EHS improvements into the way products are manufactured, while maintaining desirable product price/performance and quality characteristics.

Table 83a ESH Intrinsic Requirements—Near-term

Year of Production	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*Driver*
DRAM 1/2 Pitch (nm)	*130*	*115*	*100*	*90*	*80*	*70*	*65*	
Chemicals, Materials, and Equipment Management Technology Requirements								
Assessment of Chemical and By-product Properties								
Data accumulation Existing chemicals (include by-product materials)	**Design of Data Base**		**50% of the data/chemical**		**100% of the data/chemical**			*New Restrictions*
New chemicals (include by-product materials)					**100% after 2 years of market introduction**			*New Processes*
Resource Conservation Technology Requirements								
Energy Consumption								*Sustainable Growth*
Overall fab equipment (KWh/cm2)	**0.5-0.7**		**0.4-0.5**		**0.3-0.4**			
Fab facility (kWh/cm2)	**0.5-0.7**		**0.4-0.5**		**0.3-0.4**			
Tool energy usage per wafer pass (300mm versus 200mm); baseline 1999	**1.5**				**1.0**			
Water Consumption								*Cost and Sustainable Growth*
Net feed water use (Liters/cm2)	**5.9**		**3.5**		**3.5**			
Fab UPW use (Liters/cm2)	**6 - 8**	**5 - 7**			**4 - 6**			
Tool UPW Use (Liters/cm2, per wafer pass)	**0.15**	**0.075**		**0.06**				
Chemical Consumption & Waste Reduction								*Environmental Stewardship*
Chemical Use (liters/cm2/mask layer)	**Reduced 5% per year**					**Reduced 5% per year**		
Recycle/Reuse Systems	**Infrastructure improvement**	**Thorough recycle/reuse system**			**Innovative recycling technologies**			
Waste recycle rate (%)	**60%**	**65%**			**70%**			
Climate Change Mitigation Technology Requirements								
Reduce PFC emission	**10% absolute reduction from 1995 baseline by 2010 as agreed to by the WSC**							*Voluntary Agreement*
Workplace Protection Technology Requirement								
Equipment safety, gases and chemical leaks, and equipment stability during an earthquake	**Conformance to S2 Safety Guidelines and S8 Ergonomic/Human Factor Guidelines**			**Conformance to revisions of S2 Safety Guidelines and S8 Ergonomic/Human Factor Guidelines**				
Safe Interface of Automated Material Handling Systems (AMHS) and manufacturing equipment			**Standardized control features and procedures**					
Safe Robotics			**Standardized control features and procedures**					
Comprehensive exposure data	**Data collection**		**Comprehensive industrial hygiene(IH) exposure data for operations and maintenance**					
	Collaboration among government, industry, academia, and companies regarding new exposure data							
Personal protection equipment (PPE)	**Investigation of PPE**		**Test and rate PPE**					
Material Safety Data Sheets (MSDS)	**Employee awareness for new technologies**		**Comprehensive data**					
Equipment Risk Assessment (Health and Safety)	**Case Study**		**Common Algorithm**			**Common Application**		
Reduced chemical exposure	**Workers isolated from chemicals and by-product for non-routine operation and maintenance**							
Ergonomic Improvement	**Basic Study for 300mm**		**Minimized/eliminated physiological stresses**					
Design for ESH (DFESH)								
Environmental load/impact assessment (LCA)	**Case Study**		**Common Algorithm to identify, access, and accept risk**			**Common Algorithm to identify, access, and accept risk**		
Chemical Risk Assessment (Health and Safety)	**Case Study**		**Common Algorithm to identify, access, and accept risk**			**Common Algorithm to identify, access, and accept risk**		
Material Balance	**Pollutant release, and transfer disclosure (PRTR)**				**PRTR data acquisition system**			*New Materials and Restrictions*
	Common Test Methods, Protocol, and Application							
Regulatory Requirements	**Collection of requirements, guidelines, policy trends, and others**							

Table 83b ESH Intrinsic Requirements—Long-term

Year of Production	*2010*	*2013*	*2016*	*Driver*
DRAM 1/2 Pitch (nm)	*45*	*32*	*22*	
Chemicals, Materials, and Equipment Management Technology Requirements				
Assessment of Chemical and By-product Properties				
Data accumulation				*New restrictions*
Existing chemicals (including by-product materials)	**100% after 2 years of market production**			
New chemicals (including by-product materials)	**100% after 2 years of market production**			
Resource Conservation Technology Requirements				
Energy Consumption				
Overall fab equipment (KWh/cm2)	**0.3-0.4**			
Fab facility (kWh/cm2)	**0.3-0.4**			
Tool energy usage per wafer pass (300mm versus 200mm); baseline 1999	**0.8**			
Water Consumption				*Cost and sustainable growth*
Net feed water use (Liters/cm2)	**3.5**			
Fab UPW use (Liters/cm2)	**3 - 5**			
Tool UPW Use (Liters/cm2, per wafer pass)	**0.05**			
Chemical Consumption & Waste Reduction				*Environmental stewardship*
Chemical Use (liters/cm2/mask layer)	**Reduced 5% per year**			
Recycle/Reuse Systems	**Innovative recycling technologies**			
Waste recycle rate (%)	**80%**	**90%**		
Climate Change Mitigation Technology Requirements				
Reduce PFC emission	**10% absolute reduction from 1995 baseline by 2010 as agreed to by the WSC**			*Voluntary agreement*
Workplace Protection Technology Requirement				
Equipment safety, gases and chemical leaks, and equipment stability during an earthquake	**Conformance to revisions of S2 Safety Guidelines and S8 Ergonomic/Human Factor Guidelines**			
Safe Interface of Automated Material Handling Systems (AMHS) and manufacturing equipment	**Standardized control features and procedures**			
Safe Robotics	**Standardized control features and procedures**			
Comprehensive exposure data	**Industry database of IH exposure data**			
	Collaboration among government, industry, academia, and companies regarding new exposure data			
Personal protection equipment (PPE)	**Test and rate PPE for new materials**			
Material Safety Data Sheets (MSDS)	**Comprehensive data**			
Equipment Risk Assessment (Health and Safety)	**Common Application for new equipment**			
Reduced chemical exposure	**Workers isolated from chemicals and by-product for non-routine operation and maintenance**			
Ergonomic Improvement	**Minimized/eliminated physiological stresses for new equipment**			
Design for ESH (DFESH)				
Environmental load/impact assessment (LCA)	**Lowest environmental load/impact materials in production**			
Chemical Risk Assessment (Health and Safety)	**Lowest chemical risk (health & safety) materials in production**			
Material Balance				*New materials and restrictions*
Regulatory Requirements	**Collection of requirements, guidelines, policy trends, and others**			

Table 84a Chemicals, Materials and Equipment Management Technology Requirements—Near-term

Year of Production	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*Driver*
DRAM ½ Pitch (nm)	*130*	*115*	*100*	*90*	*80*	*70*	*65*	
Interconnect								
Low κ materials – spin on and CVD	**Lowest ESH impact solvents/ CVD precursors**		**Emissions modeled**		**ESH benign processes**			*Speed, signal loss*
Copper processes	**Lowest ESH impact plating chemistries**		**Plating bath recycle**		**ESH benign processes**			*Speed, reliability*
Advanced metallization	**Lowest ESH impact processes/ emissions characterization**				**ESH benign processes**			
Planarization	**Slurry minimization**		**Slurry recycling**		**Slurry-less planarization**			*Planarity*
Plasma processes	**Etch abatement**		**Alternative etch chemistries**			**Lowest ESH impact etch chemistries**		*Etch/clean*
	Characterization of plasma by-products				**Lowest ESH impact etch chemistries**			
Front end Processes								
High κ materials	**Characterization of high κ precursor materials**		**Lowest ESH impact high κ materials**			**ESH benign processes**		*Transistor performance*
	Characterization of low-hazard deposition methods			**Low-hazard deposition methods**	**ESH benign processes**			*Transistor performance and device development*
				High κ materials without potentially toxic/bioaccumulative metals (Pb, Ni)	**Lowest hazard metal compounds**			*Device development*
Doping	**Sub-atmospheric delivery system**				**Lowest hazard dopant materials and processes**			
Surface preparation	**Fundamental research on surface/interface science**		**Ongoing research and integration of solutions**		**Optimized surface preparation processes**			
	Alternative wafer rinse methods			**Incorporation into new rinse/clean tools**				
	Characterization of alternative cleaning methods			**Incorporation into new clean tools**		**ESH benign cleans**		
	Elimination of sulfuric acid							
Front end etch	**Characterization of plasma by-products**				**Plasma process simulation-optimized processes for by-product destruction**			

Table 84a Chemicals, Materials and Equipment Management Technology Requirements— Near-term (continued)

YEAR OF PRODUCTION	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*DRIVER*
DRAM ½ PITCH (nm)	*130*	*115*	*100*	*90*	*80*	*70*	*65*	
Lithography								
New Equipment								*REDUCED FEATURE SIZE*
Optical			**Characterization of ESH Impacts**		**Minimal ESH Impact for hazardous chemicals and material compatibility**			*NEXT GENERATION LITHOGRAPHY*
e-Beam			**Characterization of ESH Impacts**		**Minimal ESH Impact for ionizing radiation, ergonomics, chemical consumption, and disposal**			
EUV			**Characterization of ESH Impacts**		**Minimal ESH Impact for non-ionizing radiation, ergonomics, chemical consumption, and disposal**			
Radiation	**Fundamental research on X-ray exposure**		**Requirements for x-ray exposure PPE and/or equipment defined**					
New Materials			**Characterization of ESH Impacts**		**Minimal ESH Impact for new chemicals, purification requirements, wastes, and emissions**			*REDUCED FEATURE SIZE*
	Identification of PFOS applications				**PFOS Alternatives**			

Table 84b Chemicals, Materials, and Equipment Management Technology Requirements—Long-term

Year of Production	*2010*	*2013*	*2016*	*Driver*
DRAM ½ Pitch (nm)	*45*	*32*	*22*	
Interconnect				
Low κ materials – spin on and CVD	**ESH benign processes**			*Speed, signal loss*
Copper processes	**ESH benign processes**			*Speed, reliability*
Advanced metallization	**ESH benign processes**			
Planarization	**Slurry-less planarization**			*Planarity*
Plasma processes	**Lowest ESH impact etch chemistries**			*Etch/clean*
	Lowest ESH impact etch chemistries			
Front end Processes				
High κ materials	**ESH benign processes**			*Transistor performance*
				Transistor performance and device development
	Lowest hazard metal compounds			*Device development*
Doping	**Lowest hazard dopant materials and processes**			
	Self-cleaning dopant tools (*in situ* clean)			
Surface preparation	**ESH benign cleans**			
Front end etch	**ESH benign processes, including high κ etch**			
Lithography				
New Equipment				*Reduced feature size*
Optical				*Next generation lithography*
e-Beam	**Minimal ESH Impact for ionizing radiation, ergonomics, chemical consumption, and disposal**			
EUV	**Minimal ESH Impact for non-ionizing radiation, ergonomics, chemical consumption, and disposal**			
Radiation				
New Materials	**Minimal ESH Impact for new chemicals, purification requirements, wastes, and emissions**			*Reduced feature size*

Table 85a Climate Change Mitigation Technology Requirements—Near-term

Year of Production	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*
DRAM ½ Pitch (nm)	*130*	*115*	*100*	*90*	*80*	*70*	*65*
Interconnect							
Reduce PFC emissions for CVD equipment	**Optimized chamber clean processes, alternative chemistries, and cost-effective abatement**			**Optimized chamber clean processes, alternative chemistries, and cost-effective abatement for new technologies**			
Chamber Clean Gas Utilization*	**85%**		**90%**		**95%**		
Front End Processes							
Reduce PFC emissions (etch)	**Develop optimized etch processes and cost-effective abatement**			**Develop optimized etch processes and cost-effective abatement for new technologies**			
					Alternative etch chemistries identified		

Table 85b Climate Change Mitigation Technology Requirements—Long-term

Year of Production	*2010*	*2013*	*2016*
DRAM ½ Pitch (nm)	*45*	*32*	*22*
Interconnect			
Reduce PFC emissions for CVD equipment	**Optimized chamber clean processes, alternative chemistries, and cost-effective abatement for new technologies**		
Chamber Clean Gas Utilization*	**>95%**		
Front End Processes			
Reduce PFC emissions (etch)	**Develop optimized etch processes and cost-effective abatement for new technologies**		

**Utilization = (PFCin-PFCout)/PFCin*100*

Table 86a Resource Conservation Technology Requirements—Near-term

Year of Production	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*Driver*
DRAM ½ Pitch (nm)	*130*	*115*	*10*	*90*	*80*	*70*	*65*	
Interconnect								
Copper processes	**Minimum rinse water and chemical consumption**							*Increasing number of interlayers*
Planarization	**Reduced water consumption**			**Water recycle**				
Plasma processing	**Measured and optimized energy use**			**Reduced tool/system energy requirements**				
Front End Processes								
High κ			**Energy-efficient deposition processes**			**Precise uniform thermal processes with minimal energy consumption**		
Doping			**Minimum energy use for future doping technologies**		**Energy efficient processes**			
Surface preparation	**Quantified energy use**		**Energy efficient clean processes**					
	Incorporation of novel rinse methodologies in wet tools			**Novel water reduction techniques derived from surface/interface science**				
Front end etch	**Measured and optimized energy use**		**More energy efficient plasma processes**					
Starting Materials			**Quantified energy/water reduction from SOI-based process flows**					
Lithography								
Equipment resource consumption: optical, e-beam, and EUV			**Optimized energy consumption, equipment related chemicals/ gases/materials, and water consumption**					*Reduced feature size*
Factory Integration								
Net feed water use (Liters/cm2)	**5.9**		**3.5**		**3.5**			
Fab UPW use (Liters/cm2)	**6–8**	**5–7**			**4–6**			
Tool UPW Use (Liters/cm2, per wafer pass)	**0.15**	**0.075**		**0.06**				
Assembly & Packaging								
Eliminate waste from molding process			**Newly developed molding technologies**					
Reduce water use	**0.8X (X = 1999 baseline)**							
Reduce chemical use and consumption	**0.8X (X = 1999 baseline)**							

Definitions:

Net feed water use—Source water consumed in support of the operation of the wafer fabrication facility, including sanitary, irrigation, and facilities infrastructure. Net feed water may be obtained from a city supply, surface or ground water body.

UPW use—Water used in wafer contact processes, including water recovered from any source.

Tool UPW use reduction—A percentage reduction versus 200 mm UPW usage. The baseline value is set at (0.83 gal per in^2 per mask layer).

Table 86b Resource Conservation Technology Requirements—Long-term

Year of Production	*2010*	*2013*	*2016*	*Driver*
DRAM ½ Pitch (nm)	*45*	*32*	*22*	
Interconnect				
Copper processes				*Increasing number of interlayers*
Planarization	**Water recycle**			
Plasma processing	**Reduced tool/system energy requirements**			
Front End Processes				
High κ	**Precise uniform thermal processes with minimal energy consumption**			
Doping	**Energy efficient processes**			
Surface preparation	**Energy efficient clean processes** **Novel water reduction techniques derived from surface/interface science**			
Front end etch	**More energy efficient plasma processes**			
Starting Materials	**Quantified energy/water reduction from SOI-based process flows**			
Lithography				
Equipment resource consumption: optical, e-beam, and EUV	**Optimized energy consumption, equipment related chemicals/ gases/materials, and water consumption**			*Reduced feature size*
Factory Integration				
Net feed water use (Liters/cm2)	**3.5**			
Fab UPW use (Liters/cm2)	**3 – 5**			
Tool UPW Use (Liters/cm2, per wafer pass)	**0.05**			
Assembly & Packaging				
Eliminate waste from molding process	**Newly developed molding technologies**			
Reduce water use	**0.5X**			
Reduce chemical use and consumption	**0.5X**			

Table 87 Design for Environmental, Safety, and Health Technology Requirements

Year of Production	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*
DRAM ½ Pitch (nm)	*130*	*115*	*100*	*90*	*80*	*70*	*65*
Factory Integration							
Improved factory design and equipment integration for ESH	**Case Study** **Consensus designs for chemical delivery and by-product management** **Consensus design for equipment factory interface**		**ESH Design guidelines, methodology, and criteria defined**		**Safe, "Green" Fab Built**		

ESH INTRINSIC REQUIREMENTS

Technology developers [scientists and engineers] have been historically dependent upon their own ESH instincts or supporting ESH professionals, to make technical decisions for meeting ESH requirements. ESH goals, which are often generated by the need to meet policy and regulatory objectives, do not provide the specificity for technical decision-making in many cases. ESH INTRINSIC REQUIREMENTS define, for the professional ESH community, analysis methodologies, data sets and implementation methods that enable scientists and engineers to make those decisions. Included in these are subjects such as Chemical and by-product property assessment, Chemical consumption and waste reduction, and workplace protection.

One important element of measurement and evaluation methods is risk assessment. As an example, the results of chemical industry investigations can be applied to the semiconductor industry with appropriate modification. A standardized methodology to identify, access, and accept risk is needed.

A methodology to determine the lowest ESH impact of materials and processes needs to be developed. Measurement and evaluation methods must be easy to use and reliable. Their meaning lessens if their content is not updated in response to new semiconductor technologies and other technical developments. A design algorithm to conduct environmentally-conscious design during the device/process design stage is needed.

Process analysis is another evaluation element. Process by-products, for example from plasma processes, are an important issue. The elementary chemical reactions in each process must be understood, and new measurement and evaluation methods must be implemented for developing processes that have the lowest ESH impact. For material balance, it may be advantageous to apply the results of pollutant release and transfer disclosure (PRTR) programs.

Database establishment—A database is necessary to store the information for accurately conducting risk assessment on the materials and chemicals used. The database should contain information such as safety data, environmental load/impact data, process data, emission distribution factor (dispersion model) and emission treatment methods to use the material, and conditions regulated by law. At present, the general database for chemical materials is generated by the chemical material industry, but the data are not sufficient, especially on the process used or the distribution factor (dispersion model) of the chemical material to the environment.

Water—Process simulation and cost optimization tools are required to determine the optimum balance of high efficiency rinse processes; recycling of higher quality water process applications; and reuse of lower quality water for nonprocess applications at different factories and different locations.

Table 83a and b also provides numerical goals for broadly applicable areas such as energy and water conservation and PFC emission reduction, from which individual thrust requirements can be derived.

INTERCONNECT

The interconnect area poses several unique environment, safety, and health (ESH) challenges. Because of the new processes being developed to meet the technology demands, the industry is evaluating new materials in the area of advanced metallization, low κ, high κ, CMP, and optical interconnect. The ESH impacts of these new materials, processes, and subsequent reaction by-products must be determined as early as possible, ideally in the university and early supplier research stages, to ensure that the ESH information is available to the users. This will allow selection of optimal process materials based on both function and lowest ESH impact with respect to reaction product emissions, health and safety properties, materials compatibility with both equipment and other chemical components, flammability and reactivity. This will minimize the unnecessary business impact after processes are developed and in production. The short term technology requirements for Chemicals, Materials, and Equipment Management (Table 84a) include the development of the lowest impact materials and processes for all areas of interconnect. This includes solvents and polymers for spin-on processes, CVD precursors, planarization chemistries, and etch chemistries. It also calls for reduced chemical requirements and reduced waste in these areas, which may be achieved by increasing chemical utilization efficiency in CVD processes; extending bath life or recycling in copper plating; and decreasing slurry requirements or recycling slurry in CMP. The long term technology requirements (Table 84b) include zero-waste deposition processes for both dielectrics and metals and non-chemical consuming processes for planarization.

Global warming has been identified as one of the possible phenomena of climate change. Perfluorocompounds (PFCs), one type of high global warming potential chemicals, are used almost exclusively in interconnect. Both the short and long term technology requirements for Climate Change Mitigation (Table 85) are for a 10% absolute reduction of PFC emissions from the 1995 baseline, the goal established internationally by the semiconductor industry. To achieve this aggressive goal and to ensure that these chemicals remain available for industry use, the industry must strive to reduce emissions of PFCs compounds via process optimization, alternative chemistries, recycle, and/or abatement. The development of new materials results in the implementation of new etch chemistries; the lowest ESH impact etch processes should be developed that do not emit high global warming potential by-products. This concept also applies to CVD chamber cleaning.

The increased requirement for CMP will result in interconnect becoming a major user by volume of both chemicals and water. As indicated in the short term technology requirements for Resource Conservation (Table 86a), efforts must be made to develop the lowest ESH impact CMP and post-CMP clean chemistries while reducing overall water requirements. Rinse water minimization in copper electroplating and post-CMP cleaning is necessary. Water recycle and reclaim for CMP and post CMP cleans is also a potential solution for water use reduction. With increased focus on energy conservation, the power requirements of plasma processing and CMP tools and related infrastructure must be minimized. RF generators are energy-intensive. Coupled with the process chemistry efficiencies (30–70% dissociation of F ions), plasma processes are not energy-efficient. Some installed base tools can be monitored and optimized for reduction in electricity consumption especially in the idle stages or better end point detectors for chamber cleaning. Waste heat from the plasma systems could be recovered for reuse. Future generation tools would require R&D in low-energy consuming plasma systems. Etchers and CVD tools use point-of-use (POU) chillers and heat exchangers to maintain wafer and chamber temperatures in a vacuum. More efficient heating and cooling control systems could help decrease energy use. New research is needed for improved heat transfer in vacuum systems.

The short term technology requirements for Workplace Protection (Table 83a) call for the development of tools with reduced employee exposure. This applies to the development of new copper plating tools as well as tools that may be developed for optical interconnect in the long term.

FRONT END PROCESSING

Key ESH concerns for Front End Processes center on development of new materials for gate dielectrics and electrodes; natural resources use (especially water); management of potential physical and chemical hazards to ensure worker protection; and optimization of processes to reduce chemical use and generation of wastes requiring abatement. New materials for 100 nm technologies and beyond (and corresponding precursors, clean techniques and etch gases) will require thorough ESH review.

The global EHS challenges affect all areas of Front End Processes. The primary chemical management strategy should be to optimize processes to maximize chemical use efficiency, including consideration of chemical throughput, waste generation, recovery of hazardous materials, and tool utilization factors. On-demand/*in situ* chemical generation can contribute to improved efficiency. Energy needs (tool and facility systems) must be evaluated for new technologies. Worker protection measures should address potential physical (such as thermal, non-ionizing radiation, laser and robotics hazards) as well as chemical hazards, especially during equipment maintenance. Factory planning should identify ergonomic design criteria for wafer handling (especially for 300–450 mm wafers), tools, and factory layout. EHS Cost-of-Ownership (CoO) and risk assessment tools should be utilized to evaluate process improvements and identify potential risks of new materials.

In addition, key ESH issues apply to specific areas of Front End Processes:

Surface preparation—ESH concerns for surface preparation focus on new clean techniques, chemical use efficiency, and consumption of water and energy. Surface preparation methods will undergo fundamental changes to accommodate new materials after the 2005 timeframe for expected adoption of new gate dielectrics and electrodes. There is a need for improved understanding of surface and interface science with the potential for significant reductions in chemical or water use.

Chemical use optimization should be applied to conventional and alternate clean processes. Among the areas being addressed by FEP are post etch via and metal cleans—solvent free dry cleaning; copper cleaning (including post CMP clean)—wet cleans and dry cleans; polymer/residue removal nitride strip by gas phase etching and cleaning; and metal and particle performance-simplified chemical sequences; dilute chemistries; and use of chelating agents. Several alternate clean processes have potential for significant chemical use reduction (cryogenic, supercritical fluids, dilute chemistries, sonic solvent cleans, simplified process flows, O_3 cleans, alternate BEOL cleans, cleans for copper and new low κ materials). Fluid flow optimization and sensor-based process control should be evaluated. Potential increased use of anhydrous gases (HF/HCl and alternatives) should be reviewed through process hazards analysis.

Sustainable, optimized water use strategies utilizing improved UPW production efficiency, reduced tool consumption, and efficient rinsing are being developed. However, the energy-use impact of alternate clean methods (such as cryogenic wafer and parts cleaning and hot-UPW wafer cleaning) or UPW production methods (such as continuous electrolytic ion-exchange) needs to be considered. Alternative solvent-based cleans need development. Development of reliable sensors to speciate low-level organics is needed to mitigate the process risk of UPW recycling. The optimization of test wafer usage can reduce chemical, water, and energy consumption. Wet-tool designs should continue to incorporate enclosed processes, ergonomic principles, and robotics safety.

Starting materials—Current materials are primarily Czochralski (CZ) polished silicon wafers with epitaxial (Epi) silicon. Silicon-on-insulator (SOI) materials expected in conjunction with the 130 nm node may offer ESH advantages of fewer process steps—less chemicals and less energy than other materials. Larger wafers from 300–450 mm will require more chemicals, energy, and water although industry initiatives have been advanced to hold usage flat.

Thermal/thin films—The evaluation of alternative higher-κ materials must include thorough assessment of potential process hazards associated with both the materials and associated deposition processes. Alternate silicides (such as Co, Ni, others) present potential hazards requiring mitigation through engineering controls and appropriate personal protective equipment. Chemical use efficiency can be optimized through improved delivery systems and tool designs (such as small batch furnaces, single-wafer tools). Energy use, for diffusion and implant tools and associated facility systems (exhaust) should be evaluated and optimized.

A wide variety of organic ligands (potentially including halogens) are proposed as high κ precursors. The resulting metallorganic compounds may pose potential toxicity or flammability hazards. There is work on termanires like BST (barium strontium titanate, $BaSrTiO_3$), and $PbLaTiO_3$. More complex dielectrics include ZrSnTiO compositions, SrBiTaO compositions, PbZrTiO compositions and other ferro, piezo compounds. Anneals are probably necessary, utilizing N_2, FNO_2, O_2, NH_3, H_2 (forming gas).

Various metals and sources (gas phase, solution and solid) are being considered for gate electrodes. Gate metals will range from doped-polysilicon to metals (Ta, Ti, Nb, Al, Mo, Zr, V, Co W, Ru, Rh, Ni, Re, Ir, Pt) and various silicides and nitrides. Most CVD precursors will be organometallics, but they may be dissolved in a matrix solution with stabilizers, and carrier liquid that will be injected as a liquid.

Doping—The potential physical and chemical hazards of alternate technologies (a variety of new techniques are being considered) need to be evaluated and mitigated. Process hazards analysis tools will assist in managing hydrides (SiH_4, B_2H_6, PH_3, SbH_3, AsH_3, possibly others), metal alkyls and laser sources. Sub-atmospheric delivery stems should be developed for a wider variety of dopant materials.

Front end plasma etch—Continued use of PFCs will necessitate near-term process optimization/increased gas utilization (conversion efficiency within the process). Over the longer term, alternative chemistries for PFCs that do not emit PFCs as by-products need to be developed. Changes in gate dielectric materials will drive corollary changes in etch chemistries, necessitating review of potential ESH impacts. High κ materials will require an anisotropic selective etch over doped Si. The chemistry for these etches have not been determined but most likely a Cl-based chemistry will be used**.**

LITHOGRAPHY

From the perspective of ESH, lithography is represented by four subject areas. These are lithography and mask manufacturing chemicals (photoresists, thinners, developers, rinses, and strippers); processing equipment (spinners, vapor-phase deposition systems, and silylation ovens); exposure equipment (DUV, E-beam, X-ray, and ion beam); and equipment cleaning. Of critical concern with respect to these areas and the implementation of new lithography technologies is the avoidance of showstopper problems. In particular, issues such as new process chemicals evaluation, compliance with environmental regulations, equipment safety, and worker protection must be considered before changes are made.

Photolithography and mask manufacture chemicals—The first critical need in this category is the need for information related to properties and availability of new chemicals used in photolithography and mask manufacture. Among the information required are chemical toxicity, risk assessment data, status under TSCA, ability to monitor potential exposures, process emissions (HAPs and VOCs) including etch, strip, etc. The second critical need is for better materials management. This would include integration of new materials into patterning, maintaining performance and cost while, at the same time, promoting recycling and minimum use.

Potential solutions for these critical needs include preparation of a list of acceptable lithography chemicals based on evaluation of TSCA conformance, development of analytical protocols that enable monitoring of new chemicals, robust chemical selection criteria, risk assessment, and the use of pollution prevention principles. Additional potential solutions include alternate materials and chemistries, life cycle analysis of new materials and chemistries, use of additive technologies, and use of benign materials.

Processing equipment—Critical needs for processing equipment include understanding potential exposure to toxic materials, emission of HAPs and VOCs, hazardous waste disposal, cost of ownership, and energy consumption. Additional needs are ergonomic design of equipment, controlling emissions from PFC usage, and plasma byproducts.

Lastly, there is a need to minimize waste, for example, waste resulting from spin-on processes and assorted “wet” processes.

Among the potential solutions are effective point-of-use abatement, optimization of tool exhaust, use of pollution prevention and DFESH principles, and supplier use of S2 and S8 standards. Further potential solutions include deployment of zero impact processes, elimination of the need for materials with significant global warming potentials, and utilization of DFESH tools in design for manufacture of new equipment.

Exposure equipment—Critical needs with respect to new exposure equipment include understanding toxicity of required chemicals, control of potential exposure to radiation, risk assessment, cost-of-ownership, hazardous energies, and beam shielding.

Potential Solutions include performing risk assessments, analysis of cost-of-ownership and establishing radiation protection programs as necessary.

Equipment cleaning—Critical needs relate to understanding solvent usage, emission of HAPs and VOCs, hazardous waste disposal, and required personal protective equipment. It will also be important to understand the proper selection of cleaners and cleaning methodologies.

Potential solutions include cryogenic cleaning, solvent-free cleaning, dry resist technology, point-of-use abatement, pollution prevention, and optimization of tool design. Additionally, redesign of processes and equipment to achieve minimal environmental impact will be required.

FACTORY INTEGRATION

Responsible safety, health, and environmental performance for the SC industry begins with factory pre-design (training and planning), design and construction. Standardization of safety and environmental systems, apparatus, procedures, and methodologies when applicable, will prove to be an efficient and cost effective approach. Sharing of these practices can reduce start up schedules and will result in greater cooperation by equipment suppliers for interfacing their products into factories. Factory design, manufacturing equipment, the interface between these elements and their interaction with the people who work in this environment strongly influence ESH performance for the industry.

Early comprehension of safe and environmentally responsible design coupled with an understanding of code and regulatory requirements is essential for designers to develop factories that meet ESH expectations, reduce start up schedules and avoid costly retrofits and changes.

Accepted protocol and order of selection for risk management are hazard elimination, design controls (isolation or engineering design), administrative controls (procedural), and personal protective equipment.

One opportunity for greater standardization exists with manufacturing and assembly/test equipment. Standardization in ESH aspects of equipment design, design verification, ESH qualification and signoff will greatly improve ESH performance, start up efficiency, and cost. Additionally, standardization of ESH practices in equipment maintenance, modification, migration, decommissioning, and final disposition will also reap substantial performance improvements in ESH and cost over the life of equipment and factories.

Standardization of building safety systems and interface to tools will improve safety and also increase efficiency of installations and reduce start-up times. This would include but is not limited to fire detection and suppression systems and their monitoring interface, gas detection systems, electrical and chemical isolation devices, emergency shut off systems, and safety related alarms. These include building systems as well as those that are integral to manufacturing and assembly/test equipment.

Additionally, the careful selection of process and maintenance chemicals addressed in other sections of this roadmap should be complemented by designs that serve to isolate personnel from equipment and product during operation and maintenance of equipment and systems.

The safety issues associated with factory processing support systems must also be aggressively improved in future factories. As more is known about potential impacts of the work environment on health and safety, worker protection improvements must be incorporated into factory systems. Improved risk assessment methodologies and their consistent utilization during the design phase will enhance this effort.

A thorough understanding of the potential safety risks associated with automated equipment will drive development of standards that assure safe working conditions for both people and product. These standards and guidelines must be directed at the integrity of the automated systems, the tools with which they interface, and the interface as well.

The industry faces increasing permit, code, and emissions limitations. Planning for future factories and modifications to existing factories should involve cooperative efforts with code entities and government bodies to ensure that advancements in technology of tools and factories are comprehended and utilized in new regulations and amendments. These actions must be driven on a global level. The SC industry should move to establish basic ESH specifications that apply to all equipment and factory practices that are recognized around the world.

Factory design defines the systems that deliver process materials to tools, manage by-products, and control work place environments. Future factory design must employ balanced programs, resource conservation, reduction, and management. These conservation and reduction programs are driven by increasing competition for limited water and energy resources, pollution concerns, and industry consumption.

ESH standardization and design improvements for factories and equipment can be greatly enhanced through training programs established for and by the industry. Technology now allows for computer based training (CBT) programs to be developed to address all of the design and procedural challenges noted in this section.

While much of the responsibility for reduction in use of limited resources and waste minimization rests with the tool suppliers and process technologists, application of advanced resource management programs to factory systems will have a significant impact. The goal of these future programs is to build factories that minimize resource consumption and reuse, recycle, or reclaim by-products to produce near-zero effluent factories. Key factory-related ESH programs require water reuse in process and non-process applications, energy efficient facilities equipment, improved facilities system design, and new facilities operating strategies.

ASSEMBLY & PACKAGING

The drive towards flip-chip and chip-scale packaging will change the ESH needs for assembly and packaging eventually completely, as these technologies eliminate the application of leadframes, conventional molding and substrates.

However, the application of environmentally hazardous materials, such as lead, chromium, beryllium, antimony and brominated flame retardants is under increasing international regulatory pressure. Restrictions on the use of these materials are expected by the year 2004 for products on the European market.

Lead (Pb) gets special attention as the alternative soldering processes will cause numerous problems in the electronics industry, where the current process is widely used and integrated in equipment assembly lines. *Alternatives may cause a technology problem, as the soldering temperature of semiconductors has to be increased, leading to reduction of lifetime and quality.*

For power devices, an additional complication is the use of a lead-containing alloy to attach the chip to the leadframe.

The energy consumption needs to be reduced because of the need to reduce the emissions of global warming gasses, as well as from a resource point of view.

The needs for assembly and packaging are not tied to the nodes of the wafer production, but to the requirements and technologies of our customers. However, to maintain the roadmap format, the same tables have been used.

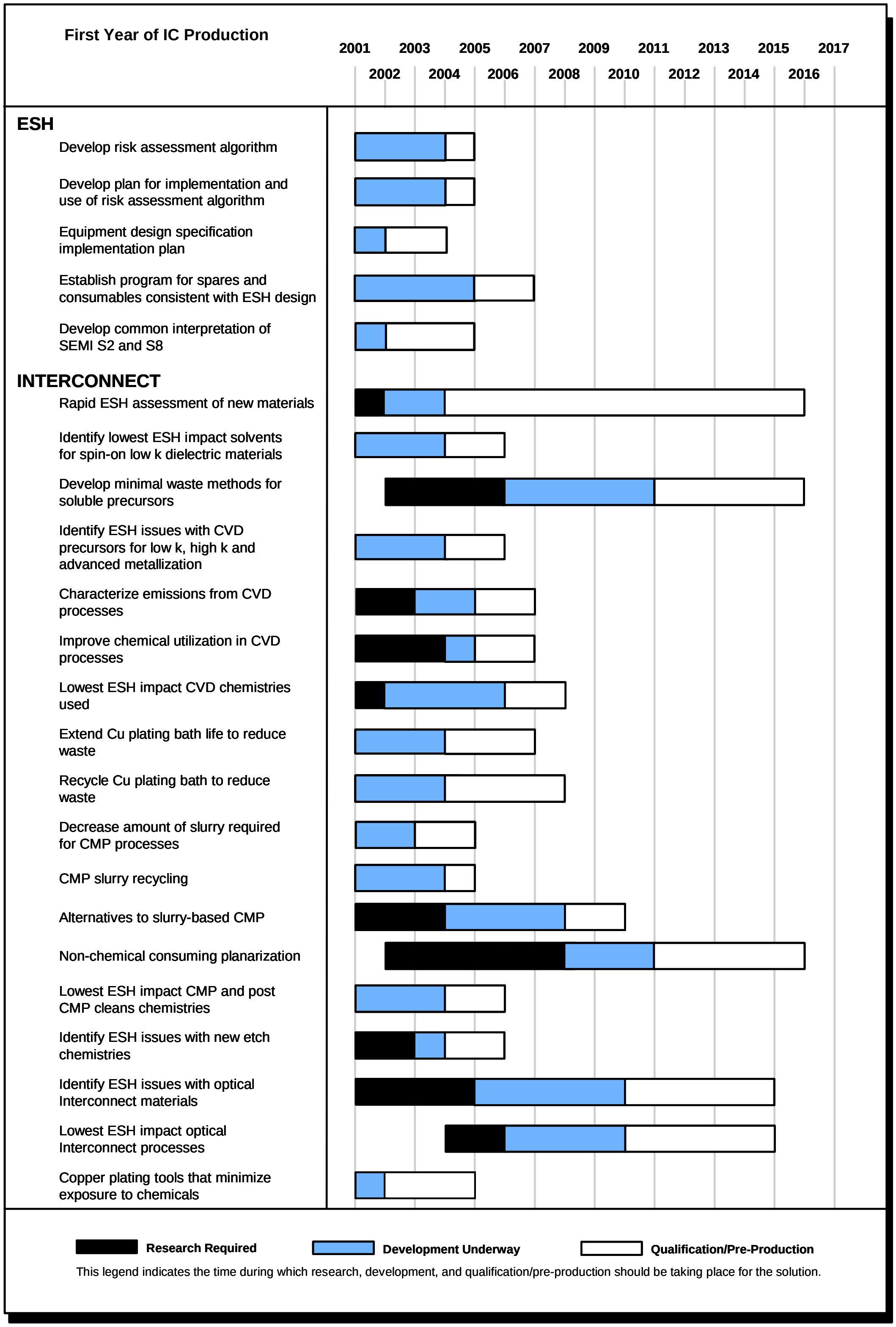

Figure 53 Potential Solutions for ESH: Chemicals, Materials, and Equipment, and Worker Protection

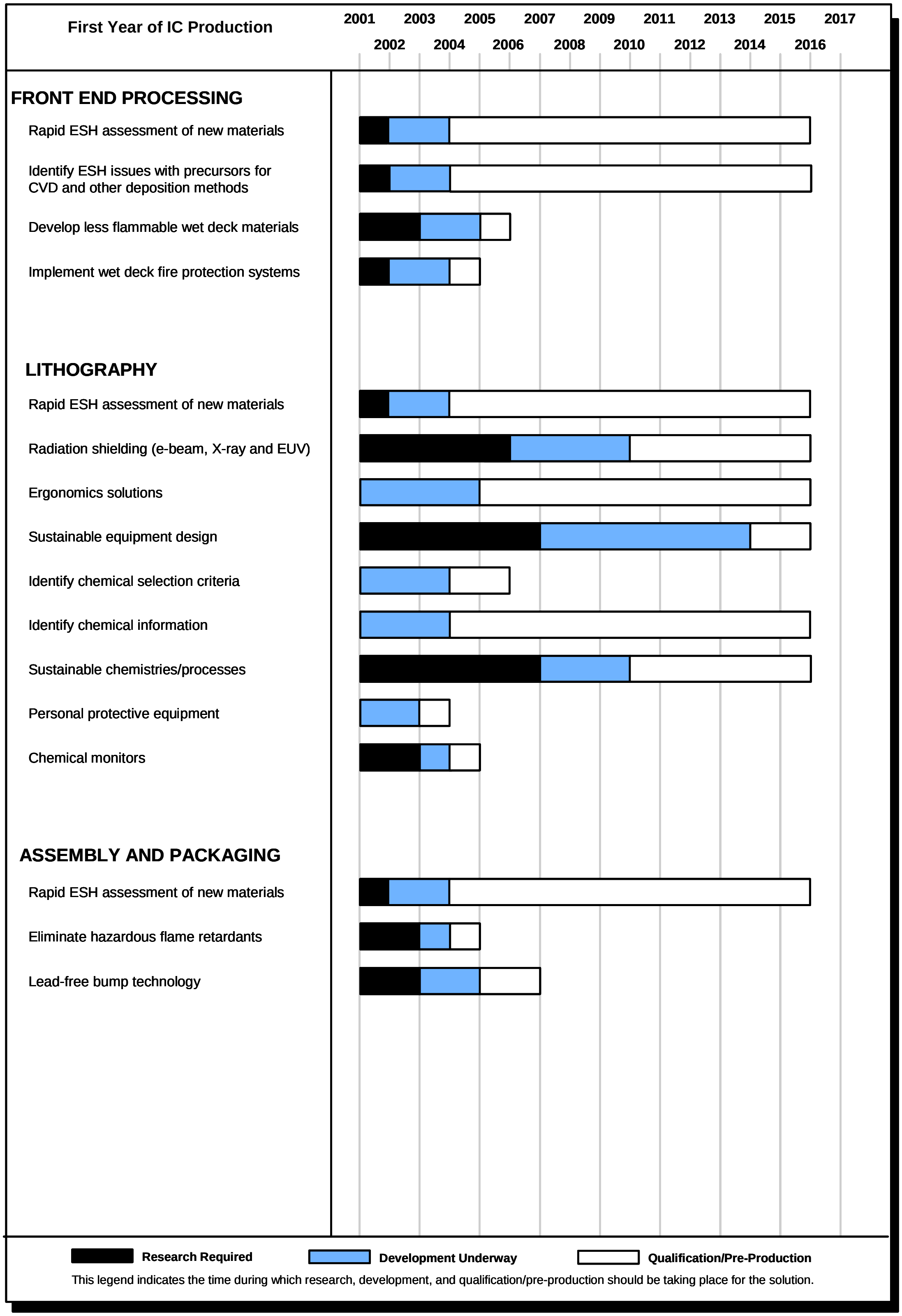

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Figure 53 Potential Solutions for ESH: Chemicals, Materials, and Equipment and Worker Protection (continued)

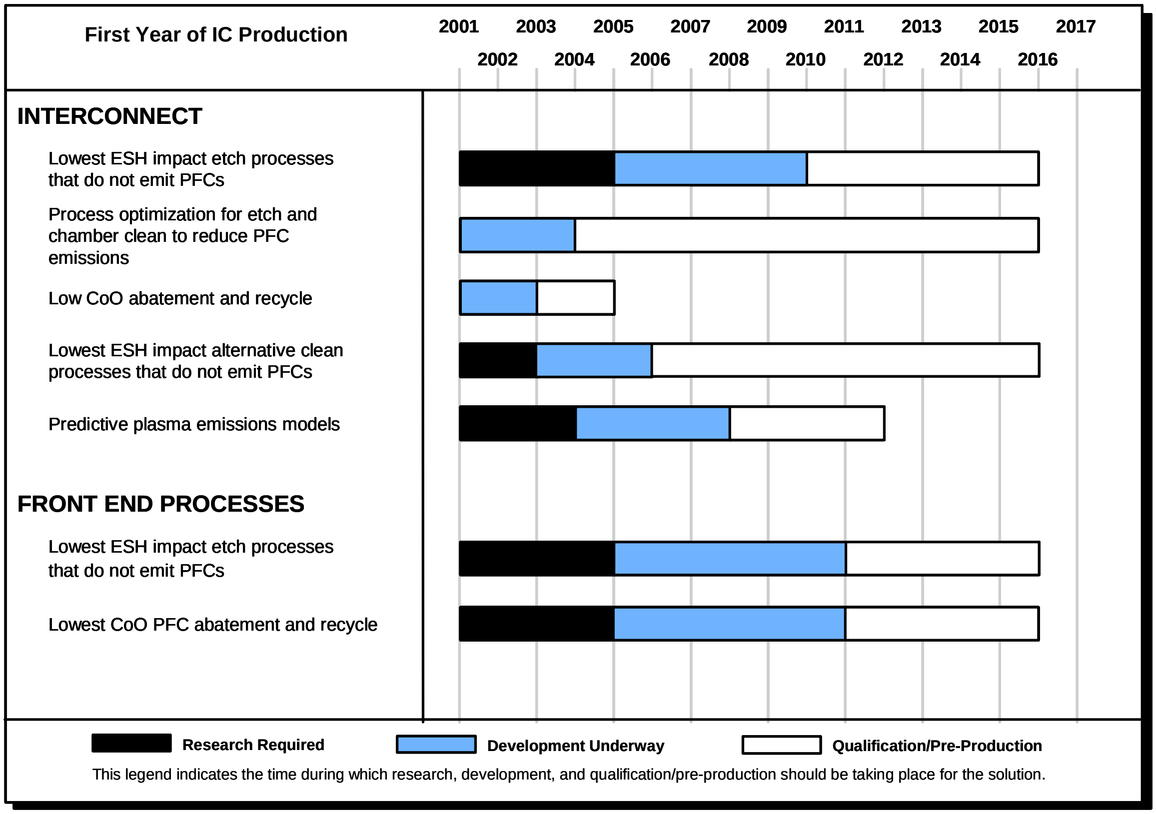


Figure 54 Potential Solutions for ESH: Climate Change Mitigation

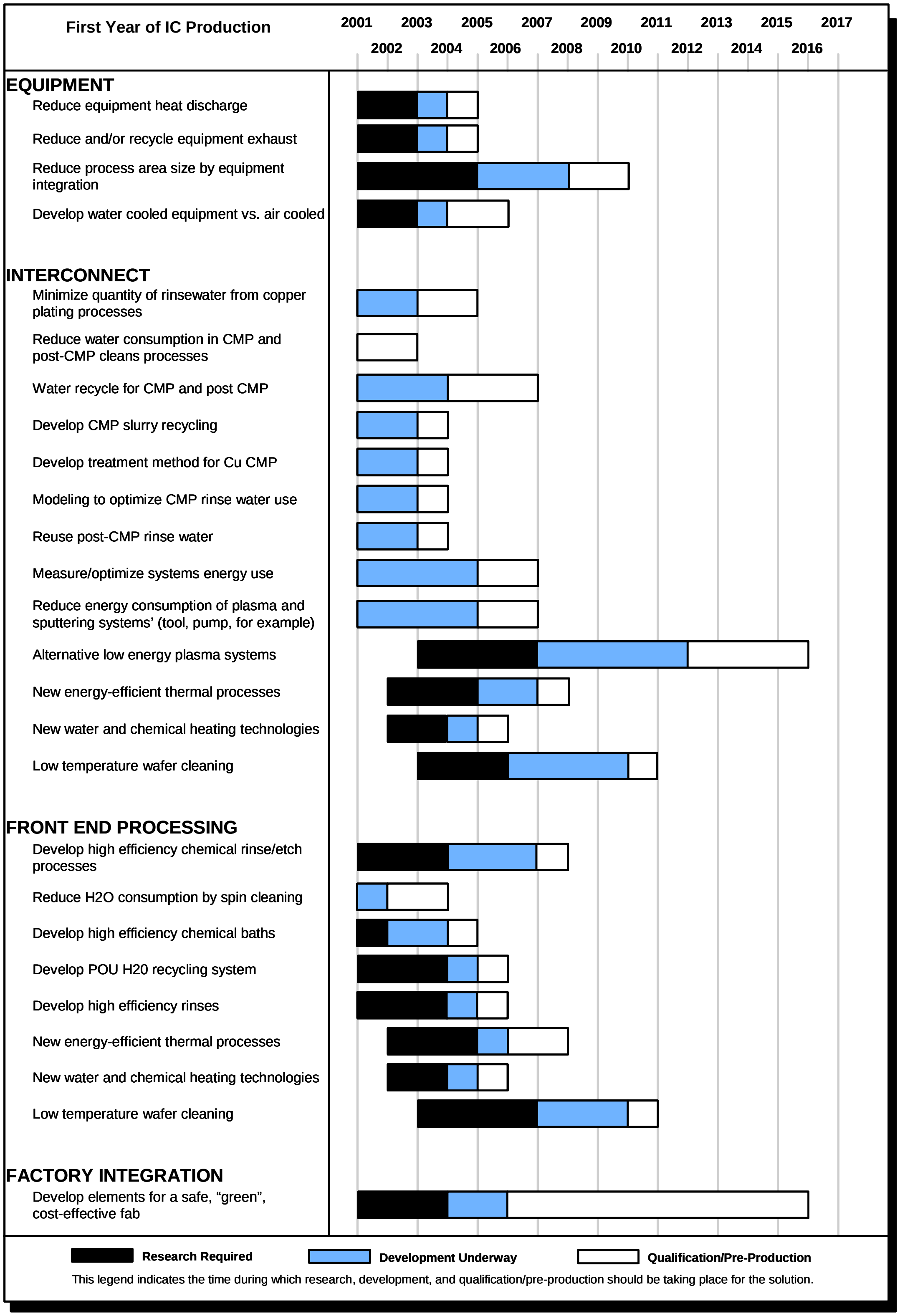


Figure 55 Potential Solutions for ESH: Resource Conservation

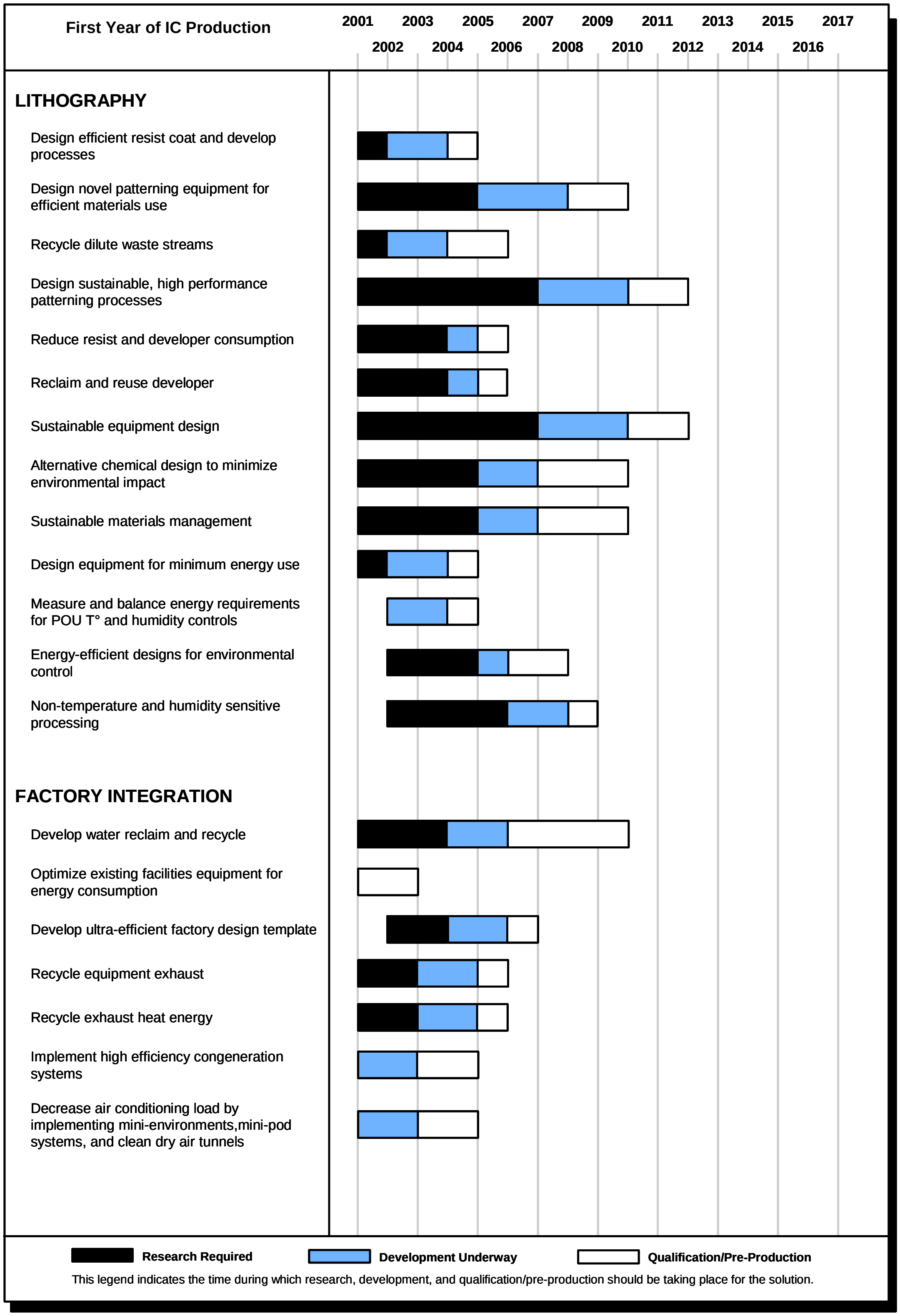
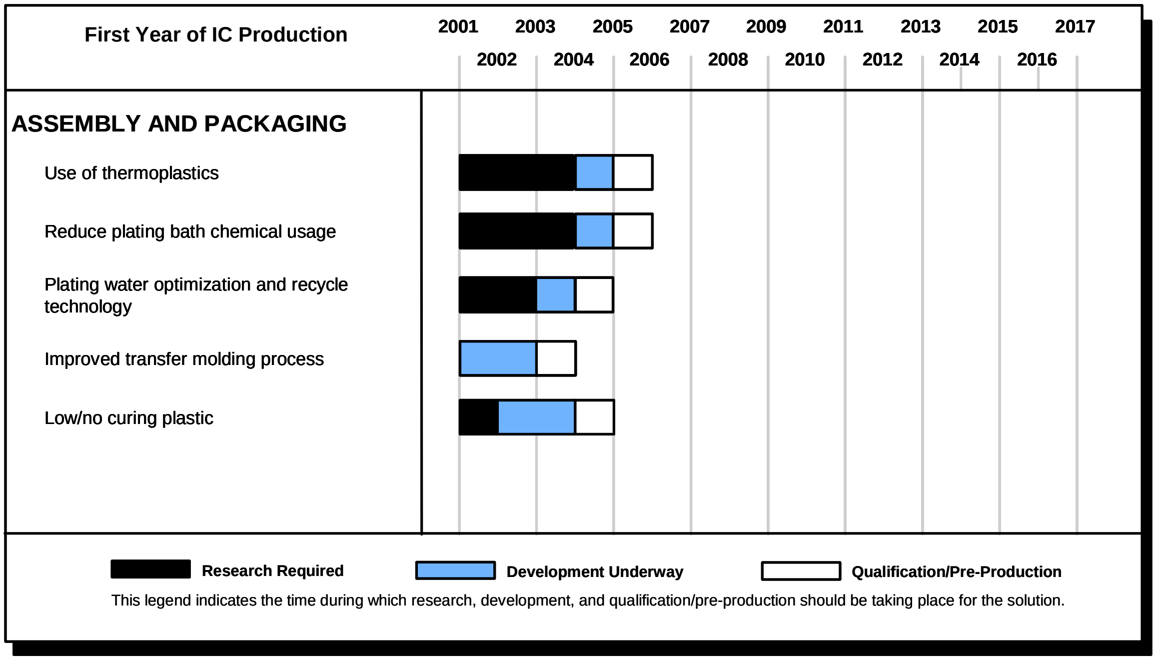


Figure 55 Potential Solutions for ESH: Resource Conservation (continued)



This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

Figure 55 Potential Solutions for ESH: Resource Conservation (continued)