WELDING TECHNOLOGY ROADMAP

Final Draft

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Prepared for:

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The American Welding Society

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1 Introduction

The recently published *Welding Industry Vision Workshop Results* describes the issues and opportunities facing the U.S. welding industry (users as well as suppliers of welding equipment, materials, processes, and support services) through the next twenty years. The strategic goals outlined in the *Vision* (see box) are ambitious and will require hard work and commitment by the industry, but expectations are high for maintaining a competitive worldwide position for welding well into the new century.

Although end-user manufacturers would not typically consider themselves as part of the welding industry, advanced joining technologies allow manufacturers to use the latest materials and designs to enhance their products' performance, reduce manufacturing costs, and decrease life-cycle costs. Because the established distribution system sometimes places a barrier or "filter" between the manufacturers of welding products and the end users, it is sometimes difficult for these manufacturers to learn what the users think of their products, and what their long-term needs (and opportunities) really are. The joining needs of each industry vary, depending on the demands placed upon its products, and the pressures for more cost-effective productivity.

Welding Industry Strategic Goals (2020)

Cost/Productivity/Market Growth
- Reduce the average cost of welding by one-third
- Increase the use of welding by 25%

Process Technology
- Enhance the use of welding in manufacturing and construction operations by integrating welding at all levels with other manufacturing and construction disciplines

Materials Technology
- Develop new welding technology along with new materials so that practical fabrication methods are available for all engineering applications

Quality Technology
- Assure that welding can be part of a six-sigma quality environment

Education and Training
- Increase the knowledge base of people employed at all levels of the welding industry

Energy and Environment
- Reduce energy use by 50% through productivity improvements

Virtually every construction and manufacturing industry uses some type of welding, whether during manufacturing or while in the repair and maintenance of products or process equipment. Four industry segments (described in their relative sections of this report) that rely heavily on welding and represent the overall needs of industry are covered in this roadmap:

- heavy industry
- aerospace
- petroleum/energy
- automotive

The *Vision* identified the key challenges facing the welding industry as materials development, manufacturing integration, workforce integrity, and product quality. This *Welding Technology Roadmap* addresses these hurdles by articulating an industry-defined strategy for ensuring the weldability of new alloys and materials; integrating welding into the entire product design and manufacturing process; maintaining a skilled, educated workforce; and eliminating the image of the welded joint as the weakest link in any structure. The transition of welding over the coming decades to a rigorous science based on detailed physical data will contribute greatly to the industry's success in achieving its vision.

The roadmap is based on input provided by representatives from the industry segments at workshops held in Chicago in October 1999 and Houston in March 2000 (see Appendix for a listing of workshop participants). Input for the automotive section was extracted from previously developed roadmaps prepared in collaboration with the Edison Welding Institute.

The following chapters discuss research needs in the four industry segments listed above. A synthesis of research needs applicable to the entire industry is contained in the summary section of the roadmap.

2 Heavy Industry

Welding has a long-standing tradition as the joining process of choice for the manufacture and maintenance of transportation and farming equipment (such as ships, trains, and construction equipment and farm vehicles) and machinery and process equipment for manufacturing and mining industries. Heavy industry also incorporates those who build large structures such as oil platforms, petrochemical plants, bridges, buildings, and similar structures. These may be more commonly called construction companies rather than manufacturers. Advances to welding processes for these applications have not always kept pace with other technological developments. Research to develop new welding processes, better measurement techniques, and integrated manufacturing systems will go far to improve the cost effectiveness and cost of welding. Attracting top-quality personnel and maintaining its corporate core competency are also equally important.

R&D Challenges

The R&D challenges (or needs) identified for the heavy industry market are organized into nine areas, as shown in Exhibit 2-1. The exhibit also outlines the strategic goals that each area of R&D will impact.

The "R&D challenge" shown for each area summarizes the desired objectives and accomplishments in that area. In the materials area, for example, the challenge is to integrate weldability with materials development (including development of new alloys, filler metals, and consumables) and product design.

Exhibit 2-2 presents the detailed list of R&D activities needed to improve welding in heavy industry applications. Within each category, the R&D activities are listed according to the time frame in which useable results would be available if work on the activity began immediately.

Analysis of Highest-Priority R&D Needs

A subset of the R&D activities in Exhibit 2-2 are considered key to the industry's strategic goals. These high-priority R&D needs and an indication of their expected impact on key goals are discussed in more detail below.

Exhibit 2.1. R&D Challenges for Welding in Heavy Industry

R&D Category	Strategic Goals	Challenge
Quality	Quality	Increase the quality of welded products through development of sensors and controls, inspection devices, and real-time data acquisition
Processes	Cost, Markets, Processes	Reduce the cost and expand the use of welding by employing non-traditional processes, alternative energy sources, automation/robotics, and reduced post-weld processing
Design and Modeling	Cost, Markets, Quality	Develop models and user-friendly interfaces to reduce costs, increase quality, and expand the use of welding
Automation	Cost, Productivity, Quality	Increase the use of automation/robotics to reduce costs and improve productivity
Sensors and Monitors	Quality, Productivity	Develop new sensors, monitors, automatic inspection devices to improve welding quality and productivity
Materials	Materials, Cost, Environment	Promote alloy/filler metals development and integrate structural design, materials development, and fabricability
Education	Education/Training	Change the negative perception of welding, attract younger workforce, and maintain consistent skill levels globally
Environment	Environment	Minimize the impact of welding on natural resources through reduced materials and energy consumption; make the workplace more attractive by eliminating fumes, noise, and radiation
Strategic Issues	Cost, Quality, Education/Training	Develop knowledge management systems, benchmark technologies, use metrics to measure progress in achieving strategic goals, create a forum to develop and conduct tasks, and support a high level of global technological awareness

Exhibit 2-2. Heavy Industry Welding R&D Needs by Time Frame of Expected Results

R&D Legend: ✪ - Top Priority; ● - Very High Priority; ○ - High Priority

2000	2010	2020
QUALITY		
	○ Real-time quality systems Standards based on fitness for service Simplified weld qualifying procedure	
PROCESSES		
Strengthening and repairing, along with validation of ultrasound impact treatments	○ Evaluation of laser technologies for process monitoring (e.g. heat input, metal melted) for construction/heavy industry ○ Increase in solid state welding for heavy industries	○ Full exploration of alternative energy sources, including but not limited to laser and electron beam ○ Elimination of distortion and residual stresses in weldments Ripple-free (smooth) welds for better properties and appearance Non-thermal (metallurgical) method of post-weld heat treating Solar-powered welding systems
DESIGN AND MODELING		
● Computer integration of manufacturing (CIM)/automation and automated testing Design guidelines for details; constructability, economical fabrication (details) emphasis for both designer and fabricator	● Concurrent product/process simulation and development	
AUTOMATION		
● Integration of precision measurement techniques and sensors with automatic cutting and welding systems	○ Robots that are easy to program, flexible, agile, autonomous, and designed for welding	
SENSORS AND MONITORS		
○ Improved dimension measurement and evaluation of existing measuring technologies In-situ recording of welding conditions in real time	Feedback controls that include artificial intelligence for welding large/thick/irregular weld joints More user-friendly, laser-based seam tracking systems	○ Real-time defect sensing techniques Material-based (embedded sensors/intelligent weldments), non-destructive evaluation – validates original processing – determines fitness-for-service

○ Hand-held equipment for residual stress and stress concentration measurements around the weld area

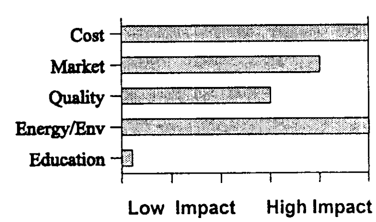
Exhibit 2-2. Heavy Industry Welding R&D Needs by Time Frame of Expected Results

2000 → 2010 → 2020

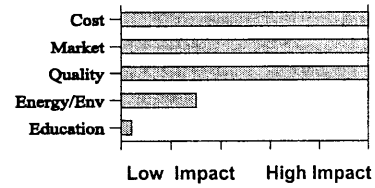
R&D Legend: ✪ - Top Priority; ● - Very High Priority; ○ - High Priority

2000	2010	2020
MATERIALS		
○ Process control and filler metals for new materials, new alloys More alloy development in general	○ Longer term, more focused understanding of post-weld heat treatment requirements (e.g. microstructure) ○ Research on extended weld life assessment, including non-destructive evaluation	✪ Welding processes and filler metals to improve productivity while reducing heat, sound, smoke, etc. ○ Improvements in dissimilar materials joining ○ Basic research on materials to replace Cr and Ni Materials and/or process developments to enable aluminum alloys to be welded with minimal material property degradation
✪ Inclusion of weldability and manufacturability in new material development		
EDUCATION		
Hands-on learning tools for users	○ Government/industry cost-shared apprenticeship program	
Development and implementation of a virtual curriculum to integrate welding with other engineering areas		
ENVIRONMENT		
	On-demand (on/off) energy-efficient welding systems	○ Elimination of welding fumes
STRATEGIC ISSUES		
● Better forum to identify research needs Promotion of high-level awareness of welding techniques used worldwide Measurement of performance targets for particular applications	Knowledge management system for welding techniques and manufacturing system techniques for heavy industry Partnership with firms outside the welding industry to develop other joining methods	

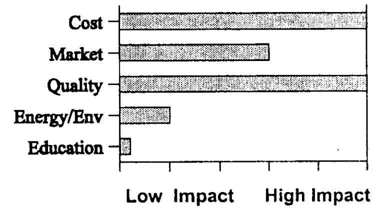
New Welding Processes and Filler Metals must improve productivity while at the same time reducing emissions of toxic fumes and other pollutants. Such developments will yield the combined benefits of reduced production costs and improved environment (including a safer working environment for welders). Improving the cost effectiveness of welding will lead to significant market growth.



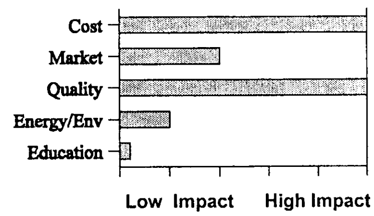
Weldability and Manufacturability is a major issue in the development of new materials. New products made from design-to-be-welded materials should cost less, have higher quality, and create opportunities for application in new markets.



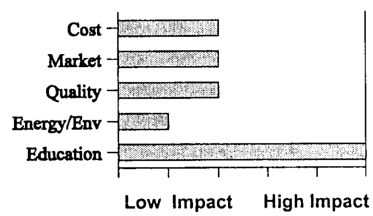
Computer-Integrated Manufacturing/Automation and ***Concurrent Product/Process Development*** will further integrate the design/manufacturing/welding process. Engineers will possess the ability to design a product and its manufacturing process on the computer before production even begins. Optimization of this process should lower the production costs and lead times associated with the development of new products. Because these two R&D activities involve advanced computer and software technology, they should also help attract more computer-knowledgeable workers to the industry.



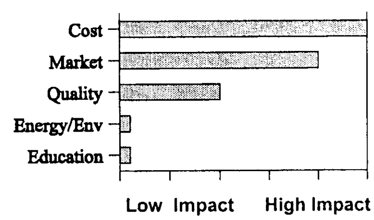
Integration of Precision Measurement Techniques/Sensors with Automatic Cutting/Welding will improve weld quality and reduce the amount of product that must be reworked, leading to higher output and lower costs. This technology will also enhance the agility of welding in manufacturing processes.



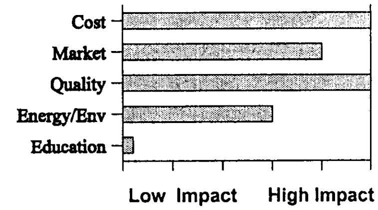
A Better Forum to Identify Research Needs and ***Benchmark Today's Heavy Industry Technologies*** will help establish a baseline of knowledge for welding in heavy industry and set clear directions for future research. There should be wide availability of established procedures and quick dissemination of new findings. Future developments in information technology could help attract higher-quality students to the welding industry.



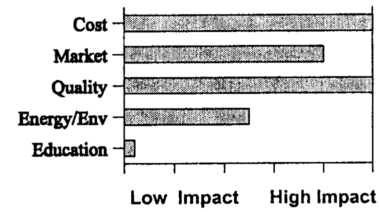
Dissimilar Materials Joining, which has been widely used in aerospace and automotive industries, can provide opportunities in construction and other heavy industries. Breakthroughs in the technology for joining dissimilar materials could lead to new manufacturing strategies that could reduce costs, improve productivity, and open up new markets for welded structures and components.



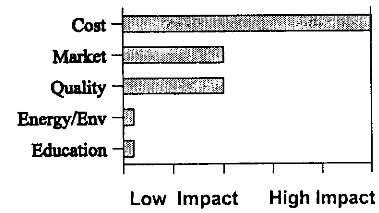
Improved Knowledge of Process Control and Filler Metals as Applied to New Materials and Alloys are companions to the development of new materials for use in welded applications. Welding and materials engineers must work in cooperation to develop techniques that ensure the weldability of new materials. Anticipated benefits include higher quality welds, improved productivity (a result of fewer rejects) and lower costs, and potential expansion into new markets for welded products.



Reduction/Elimination of Distortion and Residual Stresses in Weld Zones will have a major impact on the quality and performance of welds, leading to corresponding savings in productivity and production costs. Worker safety will be enhanced by the elimination of finishing equipment containing moving parts.



Standard Architecture for Robotic Systems (including control procedures) commonly used in welding is another component of an agile manufacturing process. Reduction of the lead time associated with setting up robotic systems will improve throughput and reduce costs.



R&D Linkages

The *Vision* states that welding operations must be more completely integrated into agile manufacturing processes. Many of the R&D activities identified here emphasize the need to integrate the different components of the design/development/production cycle and to further automate the manufacturing/welding process. Welding and weld filler metals must be considerations early in the development of new materials, new products, and new manufacturing strategies.

The drive for integration will pave the way for increased automation and computerization of welding processes in the form of concurrent product/process development, computer-integrated manufacturing and automated testing, in-situ recording of weld conditions, feedback controls employing artificial intelligence technology, real-time defect sensing, and other real-time quality systems. Knowledge management systems will merge welding requirements and welding knowledge in industry-accessible databases to support integrated welding across the entire manufacturing cycle.

3 Aerospace

The aerospace industry is a technologically sophisticated designer, producer, and end-user of welded components such as aircraft, engines, missiles, and rockets. Manufacturers of aerospace products face tough pressure for new products to be more affordable, both in initial production costs and overall life-cycle costs. Safety considerations, however, mandate that this cost-effectiveness be achieved without compromising product quality. The welding supply industry wants to ensure that welding is preserved and expanded as the preferred method of joining by integrated aerospace product developments teams. The integration of weldability into the development of new, lighter alloys will be a key component of this success. Educating aerospace users about the impact of welding on the overall process and its value to product manufacturing should facilitate the introduction of a new generation of improved, high-value-added products.

R&D Challenges

The R&D challenges identified for the aerospace industry are categorized into six areas as shown in Exhibit 3-1. The strategic goals from the welding industry vision that are most closely aligned with these areas are also listed. The industry's major goals and objectives have been condensed into a challenge for each area.

Exhibit 3-2 presents the R&D activities identified for achieving the strategic goals for welding in aerospace applications. Within each area, the R&D activities are listed according to the time frame in which useable results would be available if work on the activity were to begin today.

Analysis of Highest-Priority R&D Needs

How meeting the challenges, shown in Exhibit 3-1, will impact industry's strategic targets is discussed below.

Process Understanding must improve both process and product quality to the six-sigma level, thereby removing any reservations about the quality of welded joints. Welding costs should drop considerably because of the high dependency of cost on quality. A related high-priority need, ***Improving Existing Processes to the Six-Sigma Level,*** would similarly lead to quality and cost benefits as well as product confidence and market expansion, especially for critical components and products.

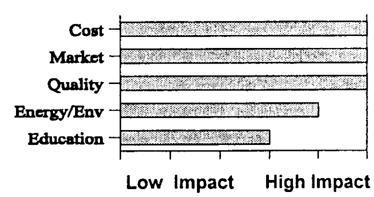


Exhibit 3-1. R&D Challenges for Welding in the Aerospace Industry

R&D Category	Strategic Goals	Challenge
Design	**Cost, Markets, Quality**	Provide better process capability data and modeling tools to allow design engineers to incorporate the latest welding technology into their designs
Modeling	**Cost, Markets, Quality, Education/Training**	Develop the capability to simulate thermal, mechanical, and metallurgical changes caused by welding and integrate information with overall system models; develop models for feedback control systems
Quality	**Quality, Cost, Markets**	Develop process understanding that enables inclusion of welding into any six-sigma process
Inspection Processes	**Quality**	Develop economical, reliable inspection technologies that do not constrain design, fabrication, and process flow
Materials	**Materials, Quality**	Promote weldability as a key characteristic of engineering structural materials
Welding Processes	**Cost, Markets, Processes, Quality**	Develop better, faster ways of implementing new joining technologies into the aerospace industry; improve existing process that allows inclusion of welding into any six-sigma process

Informing/Training of Entire Welding-Related Workforce must include not just welders but also managers, design engineers, metallurgists, and other decision-makers involved in the development and production lines of a welded product. Designers and manufacturing engineers need to know the full potential of available welding processes so they can select the best manufacturing method for a given product. Through the development of a ***Business Case for Welding***, and a ***Better Understanding of the Relative Value and Costs of Welding***, businesses will make informed decisions on equipment purchases, process selection, and product development. This training could rely in part on a ***Coupling of the Capabilities of Distributed Resources to Develop a Virtual Welding Scientific Community***. Through the use of information technology, new findings could be disseminated quickly and accurately to others in the industry.

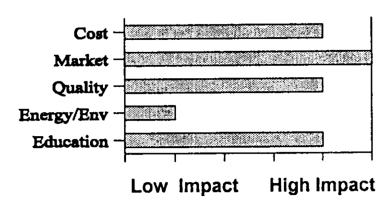


Exhibit 3-2. Aerospace Welding R&D Needs by Time Frame of Expected Results

R&D Legend: ✪ - Top Priority; ● - Very High Priority; ❍ - High Priority

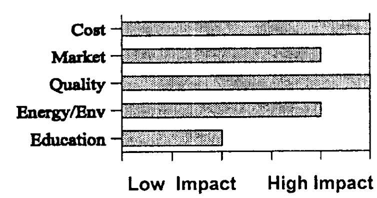
2000	2010	2020
DESIGN		
	❍ Internationally agreed-upon standards ❍ Examination of combinations of fabrication processes to improve materials utilization efficiency ❍ Near net shape welding ❍ Rethinking of the aerospace design process to incorporate weldments into aerospace structures	
MODELING		
	✪ More comprehensive mathematic/scientific understanding and modeling of welding ✪ Capability to predict distortion and understand effect of residual stresses	Study of welders' hand motions as basis for computer models/machine controls Automated troubleshooting process that incorporates skilled welder knowledge Better understanding of the problems faced by welders
QUALITY		
	✪ Strategies/techniques to assure quality in processing to eliminate inspection ✪ Tools to address root cause of process unreliability in aerospace welding ✪ New generation of statistical process control for weld processing applications	
MATERIALS		
		Better filler metals Use of modeling coupled with scientific understanding to encourage alloy development for weldability Incorporation of welding as part of a group of disciplines to figure out composites joining – non-metallics, electronic materials

Exhibit 3-2. Aerospace Welding R&D Needs by Time Frame of Expected Results

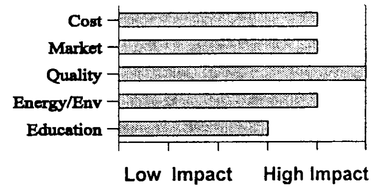
R&D Legend: ✪ - Top Priority; ● - Very High Priority; ❍ - High Priority

2000	2010	2020
INSPECTION PROCESSES		
	Techniques to make NDI easier on a small scale of production	
	Cheaper inspection methods for complex parts	
WELDING PROCESSES		
	● Methods of producing welds with minimal distortion for near-net welding	❍ Direct manufacturing (make a part atom-by-atom)
	● Application of six-sigma concepts to fusion welding processes	
	● Simulation tools to help the welding engineer better control the process	
	❍ Expanded use of friction-stir welding and friction surfacing	
	❍ Affordable, modular welding equipment responsive to single piece flow and work cells	
	❍ Wider use of laser technology for surface modification and forming	
	❍ Methods to develop atomic-scale ultra-clean surface to facilitate bonding	

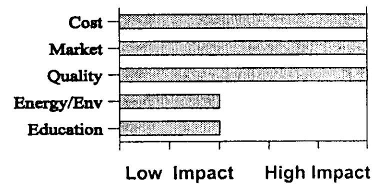
Welding Simulation Capabilities and Integration With System Models can compress the time needed between the design phase and production start-up. The capability to simulate thermal, mechanical, and metallurgical changes caused by welding and to predict distortion and residual stress will help product development teams select the best welding option and better predict weld lifetime and performance. Benefits include reduced production costs, reduced reworking requirements and otherwise improved weld quality, lower energy consumption, and market growth.



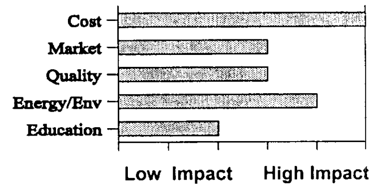
Improving the Image of Welding will attract the best and brightest students. The industry needs a public information effort that will reveal welding as a desirable, high-tech career, providing bright students with plenty of opportunities for upward mobility. Having corporate managers who are knowledgeable about welding presents an excellent marketing opportunity for the industry. The industry should also enlist government agencies and other stakeholders in welding to join them in providing ***Infrastructure Support to Improve The Welding Workforce.***



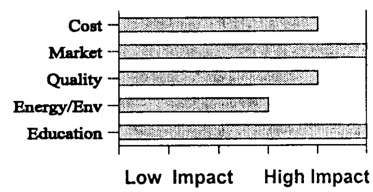
Better Ways to Implement New Joining Technologies More Swiftly will improve product quality and performance. More demonstrations, partnerships, case studies, and other technology transfer activities will speed the adoption of advanced technologies.



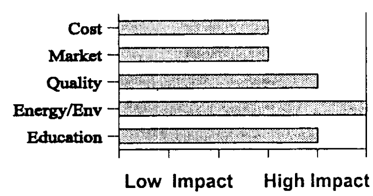
Better Process Capability Data and Modeling Tools for Design Engineers will support the cost-effective use of welding. Enabling design engineers to incorporate the latest welding technologies into their designs should yield sizable benefits in almost every strategic goal area.



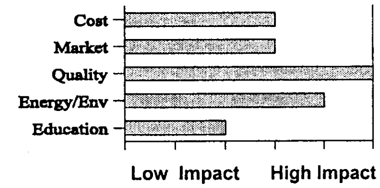
Industry-Accessible Aerospace Engineering Database should contain data on the properties and characteristics of welding materials and welds and a history of past solutions. Wide availability of materials data and established procedures will help designers and welders compare material and manufacturing processes and select the best options for their particular application.



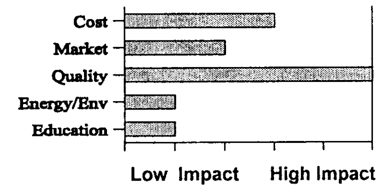
The Promotion of Welding as a Key Characteristic of Engineering Structural Materials would allow the industry to remain competitive against alternative processes and combinations of technologies. The idea of promoting welding for use in more aggressive engineering structural materials is considered high risk because of the aerospace industry's perception that its products operate in extreme environments. The likelihood of dramatically improving weldability in this industry is limited by the performance characteristics of the materials used. It is also why six-sigma quality standards must be met by welding methods to assure product integrity. If this effort were successful, however, the impact on cost, market growth, and quality could be tremendous.



Models That Provides Basis for Feedback Control System must be honed. Although feedback control is not a new concept, more work is needed to improve the technology so that it provides real-time control. The largest impact would be on quality, as any necessary adjustments are made early in the welding process.



Economical, Reliable Inspection Technologies that do not constrain product design, fabrication, and process flow could help ensure the quality of welded structures without increasing delivery time or final cost. Welding and the inspection of those welds will likely be integrated into one operation.



R&D Linkages

Many research components feed into the development and implementation of improved welding processes and practices for the aerospace market. These include

- a comprehensive scientific understanding of the welding process, which will be incorporated into industry-accessible models
- simulation tools to predict material response to both the welding process and the conditions the weld will face in various applications
- artificial intelligence systems that incorporate the knowledge and skill of experienced welders
- a rethinking of the whole aerospace design process that better integrates welding

Materials research on new filler metals and more weldable alloys will also facilitate new welding processes and applications.

Research to improve the quality of welding through better understanding of the process also relies on the development of materials property data and models.

4 Petrochemical/Energy

The extraction of oil and gas and the refining of petroleum rely on welded equipment ranging from pipes and tanks to offshore drilling structures. Increasing emphasis on offshore, and in particular deep-water, applications will require technologically advanced welding techniques suitable for use with advanced alloys in extreme environments. Weld quality and performance will be critical in these applications. The welding users in this industry must partner with metal producers on the development of new alloys to ensure their weldability. Better data on weld performance, along with new integrity assessment techniques and updated integrity standards, will reduce maintenance requirements and improve the cost-effectiveness of welded structures.

R&D Challenges

The R&D challenges identified for the petrochemical/energy markets are categorized into nine areas, as shown in Exhibit 4-1. Also shown are the strategic goals for each area.

The "challenge" for each of the nine areas in Exhibit 4-1 outlines the welding industry's main research objectives. In Sensing and Measurement Techniques and Process Control, for example, the challenge is to "advance sensing technologies and control techniques to completely characterize and control weld quality during the welding process." The R&D activities identified in this category ranges from computerized welding equipment and model-based process control to real-time quality assessment tools and 3-D imaging technology.

Exhibit 4-2 presents a comprehensive list of R&D activities identified for achieving the strategic goals for welding applications in the petrochemical/energy industries. Within each category, the R&D activities are listed according to the time frame in which the activity would be expected to yield positive benefits.

Analysis of Highest-Priority R&D Needs

Several of the R&D activities listed in Exhibit 4-2 are considered critical to achieving the strategic goals in the petrochemical and energy market. These high-priority R&D needs and their expected impact on the strategic targets are discussed in more detail below.

Exhibit 4-1. R&D Challenges for Welding in Petrochemicals/Energy

R&D Category	Strategic Goals	Challenge
Weld Properties and Data	**Cost, Quality**	Establish a comprehensive framework for collecting and organizing weld properties and data to support modeling, integration, sensors, integrity, and standards
Modeling	**Cost, Markets, Quality, Education/Training**	Develop the capability to simulate thermal, mechanical, and metallurgical change and integrate into product life cycle
Sensing and Measurement Techniques and Process Control	**Cost, Quality, Markets, Energy, Environment**	Advance sensing techniques to completely characterize and control weld quality during welding process
Integrity Assessment	**Cost, Quality**	Improve integrity assessment techniques to better assess weld fitness-for-service and life expectancy
New Welding Processes	**Cost, Markets, Processes**	Improve current processes and develop new processes that target quality, performance, cost, markets, and environmental performance
Manufacturing Integration	**Markets, Quality, Education/Training**	Develop and implement more effective techniques for demonstrating benefits of new technologies and transferring them to industry
Repair Techniques	**Cost, Education, Training**	Characterize the degrading effects of time, service, and environment; develop relevant repair technologies; create accessible base of repair information
Standards	**Quality**	Ensure the consistency and reasonableness of welding standards
Materials	**Materials, Cost, Quality**	Maintain weldability as an important characteristic in development of materials for applications requiring improved performance; develop smart materials that can communicate their conditions
Education/ Human Resources	**Education/Training, Markets, Cost**	Assess the current and future changing workforce and develop innovative, education and training infrastructure to support future needs

Exhibit 4-2. Petrochemical/Energy Industry Welding R&D Needs by Time Frame of Expected Results

2000 → 2010 → 2020

R&D Legend: ✪ - Top Priority; ● - Very High Priority; ○ - High Priority

WELD PROPERTIES AND DATA

2000	2010	2020
	✪ Development of relationships between material anomalies and physical and chemical properties (e.g., grain size, porosity, inclusions) for use in realistic integrity standards ○ Fitness-for-service and weldability data (e.g., thermal fatigue) to use in tools	○ National repository for weld knowledge

● Welding solution database that contains particulars rather than ranges

MODELING

2000	2010	2020
Understanding of the mechanism of post-weld heat treatment in order to reduce time from hours to minutes	✪ Weld process and product modeling techniques ● Ability to model residual stresses and distortion in very complex structures ● Development of interface between model and design to use in concurrent engineering ○ Prediction of dilution characteristics performance of dissimilar welds	

SENSING AND MEASUREMENT TECHNIQUES AND PROCESS CONTROL

2000	2010	2020
○ Automated information on the volume, mass, and heat deposited on a pass Adaptive welding involving feedback between weld itself and welding technique	✪ Smarter welding equipment through computerization ● Real-time, practical quality assessment tools ● Model-based process control ○ Adaptive welding techniques with the sense to avoid bad welds Wireless way to feed end-process welding data back to the central engineering office	● Transient thermal or electrical energy that scans the image of a weld (similar to MRI) ● Technology that allows inspection (3D image) using only "special glasses" ("Superman vision") ○ 3-D imaging technology that captures all observable defects ○ Real-time, adaptive technology to determine weld soundness, properties ○ All-optical, portable sensing system to feed display capturing welder's skill

Exhibit 4-2. Petrochemical/Energy Industry Welding R&D Needs by Time Frame of Expected Results

R&D Legend: ✪ - Top Priority; ● - Very High Priority; ○ - High Priority

2000	2010	2020
INTEGRITY ASSESSMENT		
● Better technologies for in-service life assessments	● Linking of integrity standards to realistic fitness-for-service information	○ Method using other technologies to improve welding industry (e.g. internal friction)
Improved integrity assessment tools for welding materials	○ Non-destructive yet field-applicable residual stress measurement techniques	Wear markers for welds
NEW WELDING PROCESSES		
Cost-effective weld overlay technologies	○ Cost-effective elimination of manual welding	○ Advanced concepts to promote wetting during welding
High-speed welding techniques for pipe welding	Non-fusion techniques for high-strength welding	○ Welding technique that does not create a heat-affected zone
	Examination of solid state processes such as inertia and friction-stir welding	○ Techniques to weld non-metallics for high-temperature environments
	"Cold-spray" technologies for joining dissimilar materials	Fume-free fusion welding
		High-efficiency (>50%) laser welding
		Joining at cryogenic temperatures
		100% energy-efficient fusion welding processes for extreme environments
MANUFACTURING INTEGRATION		
○ Robust welding procedures that allow operation to be adjusted in real-time	Welding design to minimize redundancy, especially in off-shore structures	
Increased efficiency of power supplies for weld systems	"Plug-and-play" welding machines that divorce procedure detail from welding equipment	
Methods to ensure use of latest welding technology in power plant maintenance	Portable, cheap, reliable, small, flexible robotic systems	
Better contact tip to ensure process consistency		
REPAIR TECHNIQUES		
	○ More efficient methods for inspection and repair of aging pipeline network	○ Non-intrusive weld-repair technology
	Repair technique for age-embrittled material	

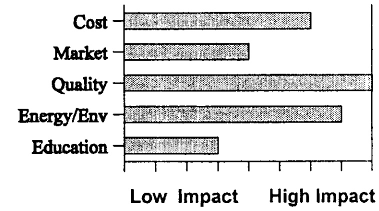
Exhibit 4-2. Petrochemical/Energy Industry Welding R&D Needs by Time Frame of Expected Results

R&D Legend: ✪ - Top Priority; ● - Very High Priority; ○ - High Priority

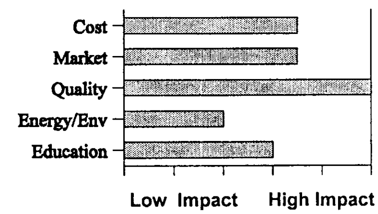
2000	2010	2020
STANDARDS		
Definition of six-sigma applicable to the petrochemical/energy industries	○ Universal manufacturing data interface from planning to production	
MATERIALS		
Weldable materials sustainable of higher temperatures	○ Development of engineered materials, including parts made from weld metal with desired composition and structure Methodologies to deal with composition-sensitive materials	● Weldable alloys that reduce need for pre and post heat treatment ○ Smart materials that tell when and where weld is failing, corroding, etc. Magnetostrictive weld materials Materials for extreme environments (e.g., underwater) that can be fabricated and repaired in place Materials for use in seeding a weld to help determine quality upon post-weld examination (e.g., piezo quartz)
EDUCATION/HUMAN RESOURCES		
● Better understanding of current make-up of human resources: who staffs petrochemical and energy companies, projected make-up in 2020	● Increase in the number of fabrication/ welding courses for mechanical and other design engineers Virtual reality training stations that simulate real working environments	

● Development of more weldable corrosion-resistant materials

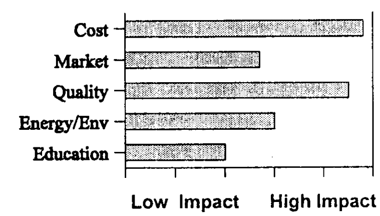
Smarter Welding Equipment has two main drivers: quality and cost. The move to greater use of welding processes based on rigorous modeling and analysis is to produce higher-quality welds that have fewer defects and last longer. Reducing defects conserves the energy and other resources required for reworking. Smarter welding equipment would positively impact market growth in two ways: improved weld quality will create new opportunities for welded components, and increase the output and quality of product without requiring increase in labor force skills.



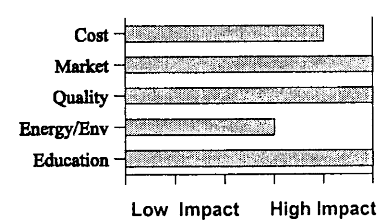
Weld Process and Product Modeling Techniques should help designers and welding engineers relate weld microstructure and related properties to specific welding processes. These techniques will reduce production lead times while ensuring weld quality. Combining data on materials characteristics with information derived from past failures will improve the design of welded products. These data can also be incorporated into ***Model-Based Process Control*** tools that will facilitate selection of optimal process conditions through increased understanding of the welding process. The benefits will include the ability to weld materials previously not used, an increase in the knowledge base, better quality and lower costs, and reduced energy use.



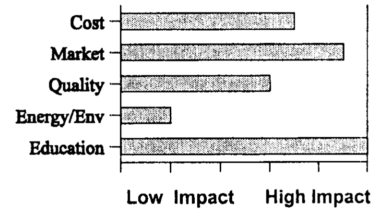
An Understanding of How to Link Material Anomalies to Material Properties, while it does not provide much benefit on its own, becomes a powerful tool when combined with other R&D needs, such as an integrity assessment model. The anomaly/property linkage will also feed into ***Linking Integrity Standards to Realistic Fitness-for-Service Information***. Although every product may have some defects or discontinuities, the challenge is gauging the level that produces the desired performance of the product. Once again, cost and quality issues are the driving goals, with improved weld quality leading to lower costs and higher productivity. Successful completion of the ***Real-Time Practical Quality Assessment Tool*** is anticipated to have similar benefits.



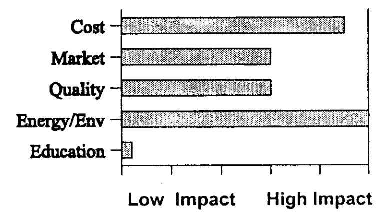
Increased Fabrication/Welding Courses for Engineering Students should cultivate a new generation of design and manufacturing engineers who integrate welding across the entire manufacturing cycle. This integrated approach will be a primary contributor to the superior quality and cost-effectiveness of welded products. Confidence in welding will rise, spurring market growth.



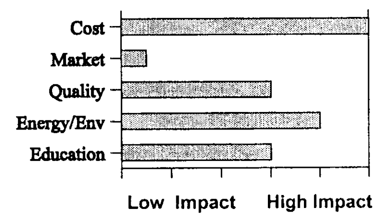
Understanding of the Workforce in the Petrochemical/Energy Industries will help the industry develop strategies to deal with mid- and long-range workforce deficiencies. Once these deficiencies are addressed through recruiting and training, increased automation, or both, there should be strong positive impacts on the cost, productivity, market, and education/training goals.



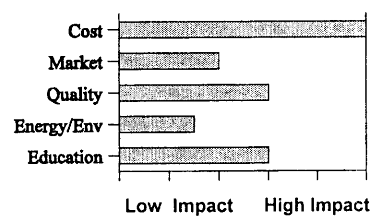
Weldable Alloys that Reduce the Need for Pre- and Post-Heat Treatment could simplify the types of welding processes typically used in the petrochemical and energy industries. In addition to directly addressing the strategic goal for new materials, this R&D activity should increase manufacturing productivity (thereby reducing costs) and save considerable amounts of energy by reducing or eliminating pre- and post-heat treatment processes.



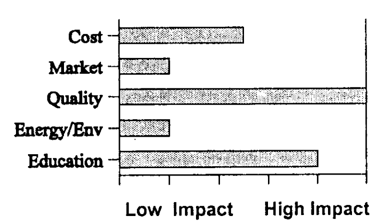
Technologies for In-Service Life Assessment extend the life of a weld and thereby reduce product life-cycle costs. The ability to better predict in-service life may reduce the need for replacement welds, as well as increase the application of welding because of improved economics and higher confidence levels in welding. Improved life assessment technologies will generate data on weld quality over time, leading to further improvements in quality and material selection. Better performance over the lifetime of the weld will reduce overall energy consumption, while more accurate lifetime prediction will eliminate the downtime associated with weld failure.



The Ability to Model Residual Stresses and Distortion in Complex Structures should reduce the time needed to fabricate and test these structures and result in substantial cost savings. In some cases, the number of welds may actually be reduced. Behavior modeling should help designers select the optimal fabrication method for a welded structure, improving quality and performance. Market growth both domestically and internationally could occur as a result of lower costs and shorter fabrication times.



Innovation in Weld Imaging based on the use of transient thermal or electrical energy, similar to the MRI technique used in medicine, could significantly improve weld quality, particularly in more critical applications. Productivity could also be enhanced as false indications are reduced. The development of this type of imaging tool may allow the use of new materials in welded applications.



R&D Linkages

Many of the R&D needs identified for the petrochemical/energy markets are interdependent. Process/product integration is a driving force behind many of the needs. Data must be gathered and fed into models that cover all aspects of design and production. New sensing/measurement techniques will be integrated with models to provide real-time control during the welding process. Integrated assessment tools will incorporate data from both the models and the actual weldment itself.

Modeling activities may include residual stresses and distortion in very complex structures, prediction of dilution characteristics and performance of dissimilar welds, and weld microstructure modeling. The types of data needed to support the modeling include fundamental data on high-temperature materials and understanding of weld metallurgy and relationships between material anomalies and material properties.

Integrity assessments will also be fed by data on weld properties as well as historical failure data. Better fitness-for-service data will be developed for use in these assessments. Eventually, integrity standards should be linked to realistic fitness-for-service information.

The petrochemical and energy segments of the welding industry place particular emphasis on integrity assessments as a component of the industry's quality goal. Integrity standards for the design process and the joining/welding process should be linked. Current standards should be revised and updated; by reducing or eliminating the arbitrary components of integrity standards, the industry can realize substantial financial and energy savings by eliminating unnecessary repairs.

5 Automotive

The automotive industry sector includes all on-road and light versions of off-road motor vehicles. Companies within this sector include the original equipment manufacturers (OEMs) and their tiered supplier base. In the United States, several OEMs operate facilities (including "transplant") with thousands of companies supplying components to typically numerous OEMs or other suppliers. Outsourcing of components has been the trend with OEMs over the past decade. This trend is expected to continue, creating a larger, more sophisticated tier-1 and tier-2 supplier base. Therefore, the R&D trends in this industry must be directed towards both OEMs and their suppliers, who have taken over design authority and will eventually be (or already are) responsible for component warranty.

R&D Challenges

The R&D challenges identified for the automotive industry are categorized into six areas, as shown in Exhibit 5-1. The exhibit also outlines the strategic goals that each area of R&D will impact. The "R&D challenge" shown for each area summarizes the desired objectives and accomplishments in that area.

Exhibit 5-2 presents the R&D activities identified for achieving the strategic goals for welding in applications within the automotive industry. Time frames for completion of these activities have not yet been determined.

Analysis of Highest-Priority R&D Needs

The highest priority welding R&D needs for the automotive market and their expected impact on the strategic targets are discussed in more detail below.

Welding Processes for Lightweight Alloys must reliably and economically join both ferrous (e.g., high-strength steels, HSS) and non-ferrous alloys (e.g., aluminum and magnesium). Existing processes usually have numerous disadvantages that undermine their benefits. Reducing the weight of vehicles can improve fuel efficiency, reduce emissions and improve driving performance.

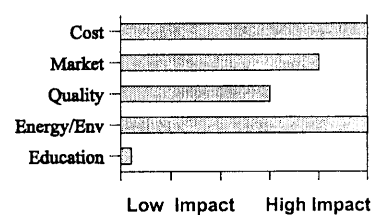


Exhibit 5-1. R&D Challenges for Welding in the Automotive Industry

R&D Category	Strategic Goals	Challenge
Design	**Cost, Markets, Quality**	Develop design tools that will allow engineers to predict the performance of welded components, subassemblies, and structures
Modeling	**Cost, Markets, Quality**	Develop the capability to simulate thermal, mechanical, and metallurgical changes caused by welding and interface with existing modeling software
Welding/Joining Processes	**Costs, Markets, Processes, Quality**	Develop new or refine existing processes that join coated mild and high-strength steels, non-ferrous alloys (e.g., aluminum and magnesium), and future generation polymers for high-volume applications such as welding, adhesive bonding, mechanical fastening, and combinations of the aforementioned processes (e.g., weld bonding)
Inspection Processes	**Quality**	Develop non-destructive inspection processes that require low operator skill and are inexpensive, easily integrated, dependable and robust, and capable of detecting defects in arc and resistance welds on various metals (e.g., aluminum, coated steel, HSS)
Materials	**Materials, Markets, Quality**	Develop weldable, cost-effective materials that offer significant performance advantages (e.g., strength-to-weight, corrosion resistance, high-temperature strength) over currently used materials (both metals and polymers)
Environment	**Environment**	Design and manufacture vehicles that have lower overall weight, improved engine/power plant designs, and more efficient exhaust systems to reduce emissions
Strategic Issues	**Costs, Markets**	Reduce manufacturing costs to enhance competitiveness without compromising quality, and develop strategies to address recent consolidation of global suppliers

Exhibit 5-2. Automotive Welding R&D Needs

R&D Legend: ✪ - Top Priority; ● - Very High Priority; ○ - High Priority

DESIGN

- ✪ Predictive tools/software for welded structures
  - impact or crash performance
  - static and fatigue performance
  - structural rigidity/stiffness
  - fatigue as it relates to managing high-mileage vehicles
  - modular automotive designs (complete chassis, cockpits, drivetrains, etc. from suppliers)
- Increased design authority for tier-1 suppliers
- Emphasis on reducing weight and emissions

MODELING

- ✪ Capability to accurately predict changes due to thermal, mechanical, and metallurgical effects of welding
- ● FEM tools designed for welded structures
  - high confidence levels (close match between model output and attribute data)
  - easily integrated with standard FEM software packages
- ● Models that accurately predict weld joint performance
- ● Rapid integration from concept-to-prototype-to-production

WELDING/JOINING PROCESSES

- ✪ Processes to economically join coated mild and high-strength steels, non-ferrous alloys, and future generation polymers
- ● Welding processes for tubular structures
- ✪ Process for speciality materials used in high-volume applications
- ● Joining processes for dissimilar materials

INSPECTION PROCESSES

- ✪ Economic, robust non-destructive inspection processes for automotive, high volume applications
  - for a variety of materials
  - do not require high operator skill level
  - effective on both arc and resistance welds

MATERIALS

- ✪ Weldable, cost-effective materials that met performance requirements of future automotive structures
  - good strength-to-weight ratios, corrosion resistance, and/or high-temperature strength
- Speciality automotive materials (e.g., composites, ceramics, and high-temperature alloys) for specific applications

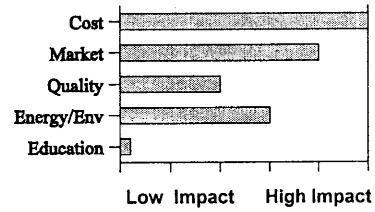
ENVIRONMENT

- ✪ Welding of lighter-weight materials used in low-emission vehicles
- ● Environmentally friendly welding processes
- ● Welding processes and filler materials that do not hamper the ability to recycle automotive components

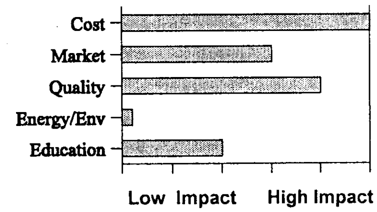
STRATEGIC ISSUES

- ● Standardization of global welding practices
- ● Continuous improvement strategies

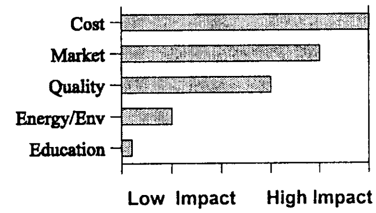
Joining Processes for Dissimilar Materials increase flexibility in automotive designs and can lead to lower costs and improved component performance, crashworthiness, and NVH (noise, vibration, and harshness).



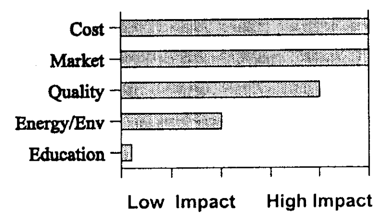
The use of ***Predictive Tools for Welded Structures*** and ***Models that Accurately Predict Weld Joint Performance*** will enable designers to predict weld/bond integrity and performance based on historical weld quality data. In-process data acquisition is an existing technology. However, automakers must use more sophisticated, non-destructive methods for evaluating weld integrity versus the currently used chisel-and-pry test or destructive testing on a sampling basis.



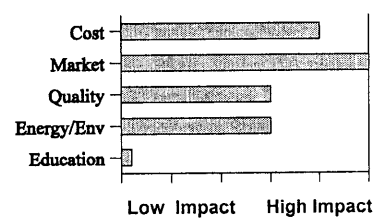
Economical Joining Technologies that reduce manufacturing costs must be further developed for joining future automotive structures. The development of resistance welding electrodes that have greater life and reduced piece cost over current designs is one example.



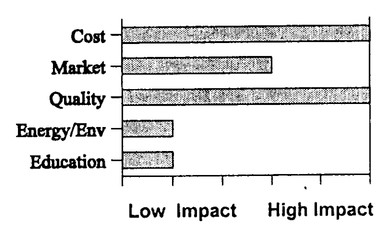
New Automotive-Grade Materials must be developed for specific automotive applications. The large automotive market represents a significant economic driver for development and production of improved materials. Example materials include: high-strength steels with improved weldability and lower cost; aluminum alloys that have high-strength-to-weight ratios and are weldable, formable, and cost-effective for numerous applications; and polymers that have user-friendly automotive characteristics, such as good UV resistance and low gas permeability, ready weldability, good impact resistance, and cost effectiveness.



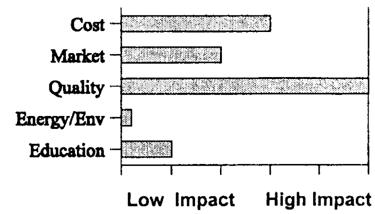
Welding Processes for Tubular Structures may reduce weight and increase the stiffness of vehicles. Cost-effective joining techniques need to be developed to cope with the numerous joint configurations that will result from new tubular frames and monocoque designs.



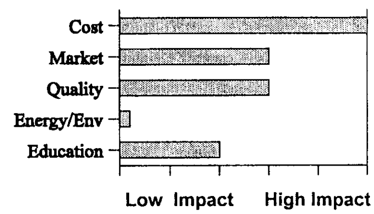
Integrated Joint/Component Design will significantly improve product quality. The concept of concurrent engineering has existed for several years. For weld joints, the integration of desired performance and practical joint design rarely occurs. The joining of two components to meet structural performance and cost requirements will necessitate the participation of various functional groups early in the design phase.



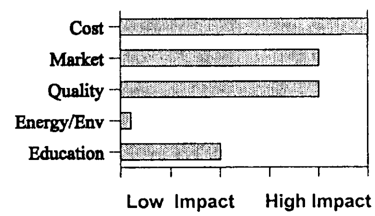
New Non-Destructive Evaluations (NDE) Processes must be developed for high-volume resistance and arc weld structures. Chisel-and-pry testing is the current NDE technique used to assure resistance weld integrity for body-in-white fabrications. Welds on high-strength steels and non-ferrous alloys cannot be reliably tested using this method. New NDE techniques must be easily integrated and cost effective and must accommodate low-level operator skills.



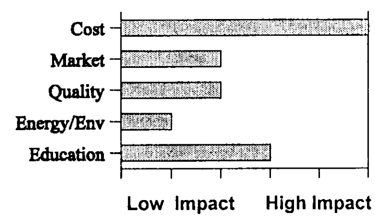
High Confidence Modeling Tools must take into account the mechanical and metallurgical changes that occur with resistance and arc welds. These welding specific tools must easily integrate with existing, widely used modeling systems and packages. The input data for the models should be readily available (various databases for specific material and joint combinations) or collectable (simple, standardized welding trials).



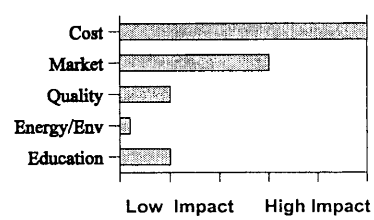
Reliability and Performance Tools will help design engineers to predict performance and reliability of welded components. Finite element modeling (FEM) will play an even larger role in the design of future vehicles. The ability to predict the performance characteristics and reliability of specific designs ad materials is a major competitive advantage to OEMs. Performance characteristics include impact or crashworthiness, fatigue life, and vehicle stiffness.



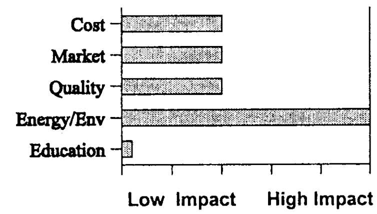
Standardization of Global Welding Practices is necessary due to the recent consolidation of global suppliers (via mergers, acquisitions, or strategic alliances). A welding cell/system designed for a specific product must be implemented at a variety of locations.



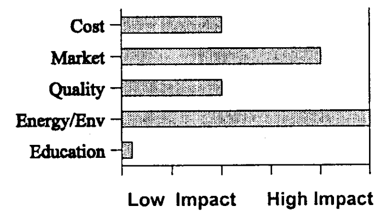
Continuous Improvement Strategies, the automakers' buzz phrase of the '80s, is now a reality, particularly for suppliers, who are constantly faced with the need to reduce manufacturing costs in order to secure long-term contracts. Welding/joining processes will be targeted for annual cost reductions along with the other manufacturing technologies being utilized to fabricate assemblies.



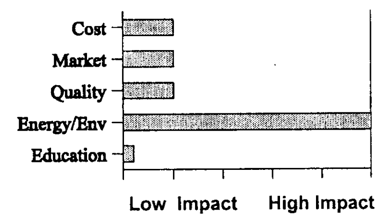
Weld Joints that are Recyclable must be developed to meet anticipated future mandates. The ability to strip-out unwanted materials (e.g., remove copper wiring) will be come a key issue. Welding filler materials must comply with future environmental regulations.



Environmentally Friendly Vehicles will require automakers to improve fuel efficiency and tailpipe emissions. Reducing overall vehicle weight and improving power plant efficiency through hybrid vehicles and fuel cells are the two major strategies. Most major OEMs are currently developing hybrid vehicles, those that use both a gasoline/diesel engine and electric motors. Fuel cells and advanced battery and electric motor technology will require joining development efforts. Lighter-weight vehicles will require the welding community to develop better methods of joining non-ferrous alloys and higher strength steels.



Environmentally Friendly Welding Processes will include low weld fume and spatter generation and the formulation of filler materials that do not pose health concerns



6 The Integrated Technology Roadmap

In 2020, welding will continue to be the preferred method by which metals and other engineered materials are joined into world-class products. U.S. industry will be the world's leading source of these cost-effective, superior-performing products by virtue of its leadership in joining technology, product design, and fabrication capabilities, and a globally competitive workforce. --- *Welding Industry Vision*

The industry's vision clearly states that the United States expects to maintain its superiority in joining technologies in the future. Technologically advanced welding and joining processes will be integrated into the design and manufacture of high-quality products and structures, helping U.S. manufacturers meet the changing demands of customers, compete with foreign manufacturers, and comply with government regulations. The research priorities contained in this technology roadmap should help guide the welding industry in accomplishing its vision.

Key Themes

A number of key themes are common to all of the welding markets. These market-wide themes include:

- the integration of welding into materials development, product design and manufacturing
- the overriding importance of quality
- the need to attract and maintain a skilled and educated workforce
- the transition of welding to a more rigorous science-based technology, and the corresponding change in industry mindset

Integration of Welding into the Product Life Cycle

The *Vision* states that welding will not be seen as an impediment to smooth manufacturing, but will be integrated into product design, development, and manufacturing and will be a primary contributor to product quality. In a multi-disciplinary approach, the welding engineer will be teamed with the design engineer, the manufacturing engineer, and the customer, to optimize the results obtained by welding in the manufacturing process.

Many of the high-priority R&D needs in this welding roadmap indeed focus on better integration of welding with other components of the development/production cycle, including design, manufacturing, materials development, and filler metal development. Integration will provide more tools and knowledge to appropriate personnel during product design and materials selection, encouraging them to use welding and helping them select the most appropriate process.

Welding should also be integrated with process technologies in the manufacturing and construction industries.

Weldability must be considered during the development of new materials. Historically, some materials have been developed without determining if and how they can be welded. Welding engineers must work in partnership with metal producers and materials engineers to develop new materials and adapt existing materials that are specifically designed to be welded into high-quality fabricated products. Weldability must also be routinely included in materials specifications, requiring materials to be qualified as weldable.

Integration of welding into the product life cycle, and accurate models of life-cycle costs will help customers better understand the relative cost and value of welding. Companies could share information on welding applications as part of a "virtual scientific community," using state-of-the-art information technologies.

Key Role of Quality as a Strategic Goal

The concept of quality is intertwined with virtually every other strategic goal relating to the use of welding by industry. Competitive pressure will drive fabricated products toward having zero defects and lifetime repairability. Because connections are always seen as the weak link in manufactured structures, they receive special attention from designers trying to gain a competitive edge. While most welded products are produced to meet a high standards of quality, some industries are moving toward "six-sigma quality" in their welded fabrication. The term "six-sigma" refers to a level of quality requiring that more than 99.999 percent of all welds will exceed the standards.

Improving weld quality lowers production costs and consumption of natural resource reduces by reducing the amount of product that must be reworked. Welding will be associated with products that offer performance and endurance, leading to new applications and markets.

The ultimate goal is process-based quality, of which enough is known about the process and materials to accurately predict weld lifetime and performance under any conditions. Integrity assessment and standards play a role in determining weld quality. Regular revision and updating of standards combined with effective integrity assessment techniques should help eliminate unnecessary repairs, thereby improving life-cycle costs.

Attracting and Maintaining a Skilled, Educated Workforce

Like many other aspects of industry, there is difficulty attracting and keeping good workers with knowledge of and skills in welding. A skilled, and educated workforce is critical to the survival and growth of welding. Without an appropriately educated workforce, the industry will be unable to support the technological revolution that will ensure its competitive position as the joining technology of choice in manufacturing.

Exhibit 6-1 lists some of the human resource issues facing the welding industry. The industry must improve the attractiveness of welding as a vocation and engineering profession.

Exhibit 6-1. Key Human Resource Issues in Welding

Issues	Possible Solutions
WORKFORCE	
Lack of design, manufacturing, and welding engineers, as well as faculty	High-level industry/government focus on the problem and potential solutions
Lack of pride in craftsmanship	Increased exposure to advanced technologies through interaction with companies abroad
Waning interest in heavy industry and primary metals at U.S. universities	Benchmarking of the heavy industries in the U.S. to create a common level of awareness
Expectation that next generation manufacturing work force will be highly mobile, lack loyalty	
EMPLOYERS	
Loss of corporate knowledge	Welding/joining as a corporate core competency
Lack of flexibility at the shop floor level	More flexibility for welders to advance within a company
Lack of company loyalty to its workers and vice versa	
EDUCATION	
Disconnection between what trade schools teach (basic skills) and where welding is headed (robots, computers)	More thorough integration of the education system with corporate needs
Low support for welding curricula and research in universities	Revitalization of welding education and research at universities
Lack of corporate investment in universities because of long payoff	Continuous in-house training
Lag time between industry requirements and change of focus at universities	Updating of curricula at vocational and trade schools
Absence of adequate apprenticeship programs	Computer-aided welding as junior high/high school science projects
Departure of welding students leaving school prior to completion of training	Promotion of flexibility in the educational system
	More summer internships/co-op programs at colleges and universities to expose students to real work environment
PUBLIC PERCEPTION	
Industry image discourages talented people	Public information effort to improve the image of welding
Perception of welding as a problem in manufacturing, not a science	Recognition in the education system of manufacturing engineering as a desirable career
Lack of public awareness of the strategic need for welding	

The perception of welding will continue to change as education and training increase the awareness of newly developed welding technologies. Students need to know that welding can be a viable starting point for an exciting, high-tech career in industry.

A public information effort may be one avenue for improving the image of welding. Apprentice programs for welders and technicians could improve the prestige of welding as a vocation as certification programs become more rigorous. Mentoring programs that begin as far back as elementary school could help influence people to choose welding as a career.

Education and training will be needed for all levels of the workforce involved in welding from welders on the shop floor, product designers and even corporate management. For example, training modules for design engineers could promote welding as a viable design concept. Assurance of university-level education, including graduate-level for students interested in welding science and engineering and related fields, must be pursued.

With the current trend toward downsizing and takeovers, the welding industry should be able to provide more technology transfer both nationally and globally. The industry should take the lead in setting up and maintaining knowledge-based systems so that its progress can be shared by all stakeholders. Through the use of information technology, new findings can be disseminated quickly and accurately to all interested parties.

Transition of Welding from an Empirical-Based to a Physical-Based Process

Welding processes based on engineering analysis, numerical modeling, and computer-based automated manufacturing will be widely used in 2020. The industries using welding hope to create a "virtual factory" in which welding technologists go outside the traditional scope of welding to better understand, control, and automate welding processes.

Exhibit 6-2 illustrates the transition of manufacturing processes based on welding into a more rigorous science. Information technology will play a key role; the core of the transformation is a comprehensive knowledge-based model incorporating data on weld properties, processes, materials, and applications. The welding industry is optimistic that it can match the success of the gas turbine industry, where scientific advances led to the gradual replacement of empirical data with hard physical data. This requires parallel knowledge building in the physical, chemical, mechanical, and materials sciences that support welding science.

The comprehensive physical-based model envisioned by the industry would cover the entire life-cycle of the welded product. Robust knowledge on historical applications feeds into the initial experience-based model; as more scientific and engineering data are obtained, the underlying nature of the model shifts. The model itself is not the end point; it captures knowledge which is then disseminated as needed.

Data would be continually added to the model, creating an archive of weld properties, processes, and applications. Technologies that support welding – materials and sensors, for example – would be incorporated, as would new welding technologies, as they are developed.

Parallel with the development of the model would be educational activities aimed at helping engineers and other members of the welding workforce understand the model inputs and outputs. Designers are accustomed to using models and simulation tools in designing manufactured products and processes. Access to a comprehensive information system that integrates welding operations with product design and other manufacturing steps will help them predict the materials response to a given welding process and reduce product lead time.

The model will also facilitate the move to process-based quality for welding. Integrity assessment and lifetime prediction would be integral functions of the model, capable of simulating the design, construction, and service of integrated welded structure. Fabrication instructions issued to the user would provide a firm basis for process-based quality.

A major stumbling block is a lack of understanding of the fundamental physics of the materials used in welding. The variety of materials is vast, and little is known about the relationships between material behavior (in terms of melting and solidification) and material properties, especially high-temperature properties. Other physical, chemical, electrical, thermal, and mechanical characteristics of welded materials and structures are needed.

If successful, welding's transition to a manufacturing science should help the welding industry meet its strategic goals in cost, productivity, markets, quality, and education and training. Without this type of progress, future expansion of the market for welding is unlikely.

(Page for Exhibit 6-2)

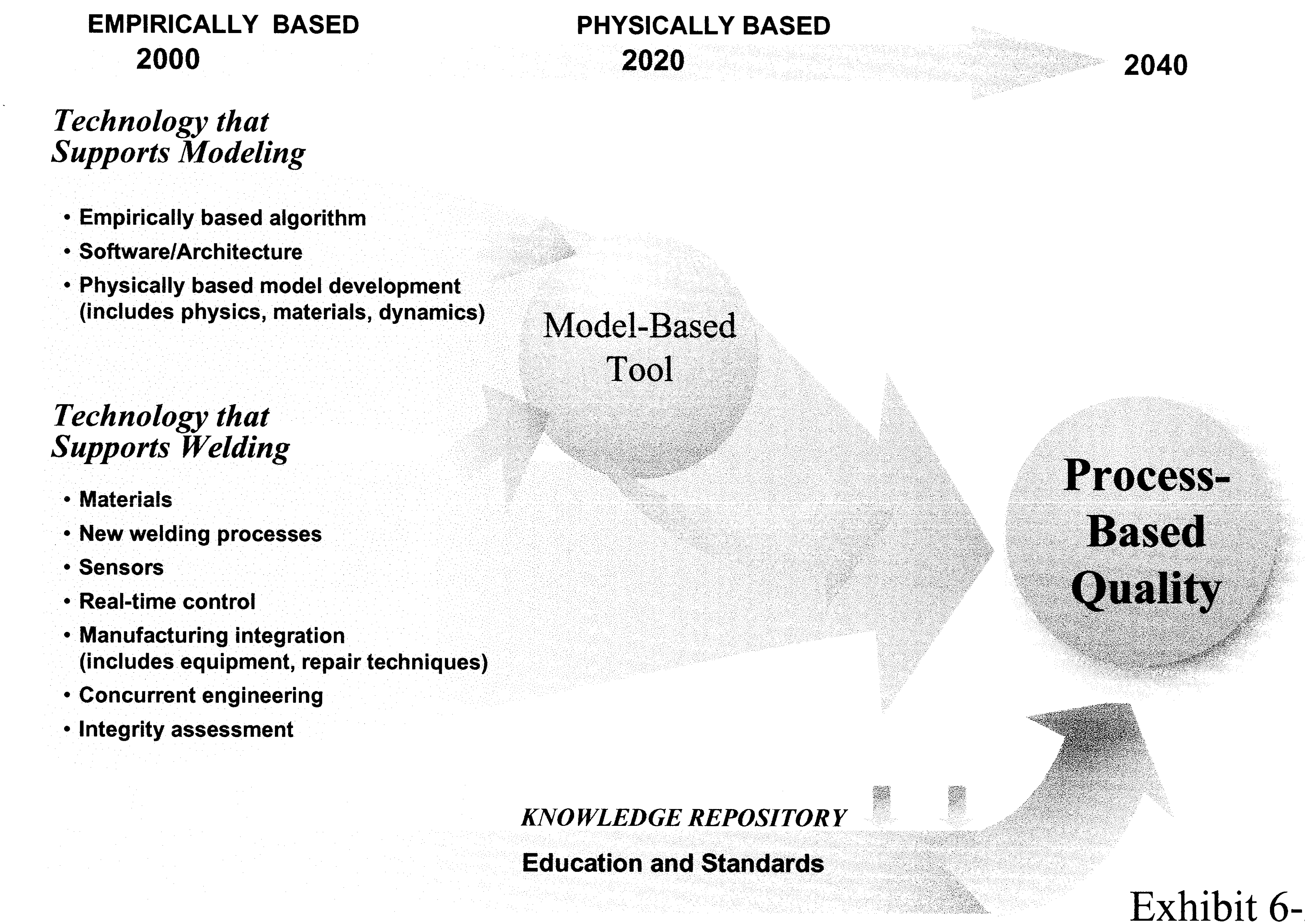

EMPIRICALLY BASED
2000
PHYSICALLY BASED
2020
2040
Technology that Supports Modeling
• Empirically based algorithm
• Software/Architecture
• Physically based model development (includes physics, materials, dynamics)
Technology that Supports Welding
• Materials
• New welding processes
• Sensors
• Real-time control
• Manufacturing integration (includes equipment, repair techniques)
• Concurrent engineering
• Integrity assessment
Model-Based Tool
Process-Based Quality
KNOWLEDGE REPOSITORY
Education and Standards

Exhibit 6-2

Appendix

Workshop Attendees

Frank Armao
Alcoa

Rick Arn
RAMtech Industries, Inc.

Dean Dearing
Caterpillar, Inc.

Tom Doyle
McDermott Technology, Inc.

Glen Edwards
Colorado School of Mines

Richard French
American Welding Society

Karl Graff
Edison Welding Institute

Earl Helder
GE Aircraft Engines

Jim Jellison
Sandia National Laboratories

Tarsem Jutla
Caterpillar, Inc.

Don Kim
Shell Development Co.

William King
Pratt & Whitney

Lee Kvidahl
Ingalls Shipbuilding

Ernest Levert
Lockheed Martin Missiles and Fire Control

Paul Murray
Idaho National Engineering and Environmental Laboratory

Tom Mustaleski
Lockheed Martin Energy Systems

Bill Myers
Dresser-Rand TPD

William Owczarski
McDermott Technologies, Inc.

Larry Perkins
United States Air Force

Tom Powers
McDermott International

Charles Robino
Sandia National Laboratories

Fritz Saenger
Edison Welding Institute

Mike Santella
Oak Ridge National Laboratory

Lee Sherman
Case

James Snyder II
Bethlehem Steel Corporation

Krishna Verma
Federal Highway Administration