Steel Industry Technology Roadmap

Barriers and Pathways for Yield Improvements

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Executive Summary

In 1995, the U.S. steel industry reached consensus on broad goals for the future and published its vision in *Steel: A National Resource for the Future*. In 1998 the industry mapped out the technology path to achieving that vision in the *Steel Industry Technology Roadmap*. Technology roadmaps are dynamic documents, and regular updating is essential to reflect important changes in the industry and the world in which it operates. The steel technology roadmap was updated in December 2001 in response to technological advances, changes in the global market, and new technical insights.

The *Steel Industry Technology Roadmap – Barriers and Pathways for Yield Improvements* represents a subset of the overall industry roadmap. In addition, North American steelmakers were consulted to identify additional R&D needs for improving yield to be included in this roadmap. Improving yield directly impacts production costs, energy efficiency, and environmental performance. The ability to obtain higher yields using the same amount of energy reduces the energy intensity of a process and any associated emissions.

Yield Loss in the Steel Industry

In a typical year, the U.S. steel industry consumes approximately 120 million tons of metallics and ships approximately 100 million tons of products. Roughly 53% of these shipments are produced by integrated steelmakers, i.e. blast furnace and BOF operators, and 47% via the electric furnace route. This represents a total yield loss of about 20 million tons each year. The losses are realized throughout many different operations in a steel mill. They appear in the form of “home” scrap and waste oxides; integrated producers also lose a small percentage of coal and coke.

Yield losses also reduce the overall energy efficiency of steelmaking. The steel industry consumes about 18.1 million Btu per ton of product, 22% more than the practical minimum energy consumption of about 14 million Btu/ton. These energy losses – about 4 million Btu/ton – are a result of the energy “embedded” in yield losses and process inefficiencies.

Additional losses are generated in the use of steel as it is manufactured into steel products. Examples of these “intrinsic” losses are excess scrap generated because of quality rejects, poor or inconsistent steel properties, or corrosion; excess material consumption due to excessive corrosion and safety factors; the misapplication of materials; and manufacturing rejects and excesses from manufacturing operations.

Table ES-1 lists four major steel industry unit operations (plus a fifth category covering applications and materials properties) and their estimated yield losses. The table presents the steel industry’s targets for reducing these losses through an R&D program focusing on several broad topics discussed below. The reduction in energy intensity resulting from achieving the targets is also shown for each unit operation.

Table ES-1. Steel Industry Yield Losses and Targets			
Unit Operation	**Estimated Yield Loss (%)**	**Yield Loss Target (% Reduction)**	**Energy Savings Target[a] (million Btu/ton)**
Ironmaking[b]	2 - 6	25%	0.1 – 0.2
BOF Steelmaking[c]	7 - 9	33%	0.2 - 0.3
EAF Steelmaking[c]	6 - 8	33%	0.2 – 0.3
Finishing Operations[d]	1	33%	0.1
Applications and Material Properties[e]	19	50%	1.7

a Reduction in energy intensity that will result from achieving the corresponding yield loss target

b Includes tapping, metal handling, skimming, and desulfurization

c Includes ladle refining and casting

d Includes hot and cold rolling, coating, scarfing, etc.

e. Based on 14 million tons of prompt scrap plus 5 million tons reduced production resulting from improved properties

R&D Opportunities to Improve Yield

The sections that follow discuss five broad topics presenting significant opportunities for R&D that could improve process yield in ironmaking and steelmaking:

- Modeling, measurement, and control
- Operating techniques and practices
- Process equipment
- Fuels, feedstocks, and recycling
- Material properties and manufacturing technologies

Each section identifies the barriers to improved yield (including obstacles to increased throughput as well as quality and consistency issues) and lists potential R&D solutions or opportunities that have been identified by industry to overcome these barriers. The R&D opportunities have been derived from information contained in the *Steel Industry Technology Roadmap* and a recent survey of mills performed for this study.

As shown in Table ES-1, the largest potential impact on the industry's overall energy intensity could come from Applications and Materials Properties research since yield may be improved by improving upstream operations as well as yield losses occurring during the use of steel to manufacture products. Key needs include steel plant manufacturing & processing improvements, microstructure control and reliable property data for advanced steels.

Table ES-2 summarizes those opportunities in each of the five topic areas considered to have the largest potential impact on reducing yield loss. The lists of opportunities are not meant to be exclusive; rather, they are representative of the kinds of activities that could be included in the overall pathway for yield improvements.

Table ES-2. Key R&D Opportunities for Yield Improvements

Modeling, Measurement, and Control

- Robust, low-cost sensors to measure key ironmaking and steelmaking parameters (chemistry, temperature, etc.)
- Real-time off-gas analysis method and chemistry adjustment methods
- Detection systems to detect and classify inclusions
- Process control practices that reduce shape defects
- Improved control of heat treatment processes for precise control of properties
- Advanced combustion control systems for furnaces

Operating Techniques and Practices

- Optimization of energy use in EAF steelmaking
- Techniques to minimize or eliminate scaling
- Technology to eliminate casting or oscillation marks
- Improved furnace heat transfer

Process Equipment

- Longer-lasting refractories that do not interact with steel or slag
- Other materials and technologies that reduce maintenance requirements
- Technologies that allow higher rolling speeds and faster processing in other processes
- Higher productivity RHF operations

Fuels, Feedstocks, and Recycling

- Improved understanding of coal injection to the blast furnace
- Economical processes for recycling ironmaking and steelmaking by-products
- Recycling spent pickle liquor to produce a higher value by-product

Material Properties and Manufacturing Technologies

- Improved microstructure control
- Reliable property data for advanced steels

Yield loss in steelmaking is a function of waste oxide production, slag formation, and in-plant scrap returns. In addition, off-spec steel that is returned from the customer represents a substantial yield loss since this product must be scrapped. Finally, the yield loss associated with the use of finished goods cannot be ignored; improvements in steel processing techniques that improve steel quality and the development of new materials and their implementation by customers have the potential to save up to six times the amount of energy required to manufacture the steel used in the product.

The energy loss associated with these yield losses (excluding in-house scrap, customer rejects, and excesses from manufacturing operations) is approximately 1.7 million Btu/ton for ore-based steelmaking and 1.0 million Btu/ton for EAF steelmaking.

Factoring in the effect of scrapped steel results in an additional 4 million Btu of energy lost per ton of steel produced.

The steel industry needs more precise knowledge of steelmaking processes, feedstocks, and products in order to address the complex combination of inefficiencies that lead to yield losses. Better understanding and control of ironmaking and steelmaking manufacturing processes will help reduce these inefficiencies. More precise knowledge of material properties could lead to higher quality products and fewer customer rejects, thereby reducing yield losses.

Advanced technologies, operating practices, and materials that increase steelmaking productivity and yield will also generate sizeable energy savings. A research program focused on improving steel industry yield will reduce the industry's energy intensity while helping steelmakers meet the increasing demands of end-users for higher quality products.

AISI's Research and Development Program

"The mission of the Institute is to promote steel as the material of choice and to enhance the competitiveness of its members and the North American Steel industry." To accomplish its mission, AISI has established two key goals:

- Enhance the comparative value of North American steel
- Achieve leadership in environmental health, health, and safety performance

As part of its strategy for achieving the goals, AISI has created an extensive high-risk R&D program to develop new technologies and reduce the lead time between discovery and commercialization. The program is highly leveraged by steel-producing companies, steel users, and equipment suppliers. Because much of AISI's R&D accomplishes a public purpose as well as the industry's objectives, the U.S. Department of Energy has cost shared many of the R&D projects. The two organizations share several common goals, including maintaining a globally competitive manufacturing sector, increasing energy efficiency, reducing environmental impact, and creating and saving jobs. The numerous benefits of this collaborative partnership are summarized below.

Increasing Energy Efficiency and Improving the Environment: Energy consumption per ton of steel is down 10% since 1990 as are CO_2 emissions. Much of this achievement is a direct or indirect result of the collaborative Steel Program.

Leveraging High Risk Research: Industry/government cost sharing mitigates the high risk often associated with developing breakthrough technology. This allows industry to undertake R&D projects it might not otherwise pursue.

Maintaining Globally Competitive Manufacturing: Maintaining a globally competitive manufacturing sector means high-paying manufacturing jobs are available. The program's many research projects involving universities (e.g., University of Pittsburgh, Carnegie Mellon, University of Alabama and Colorado School of Mines) have the additional benefit of preparing highly qualified professionals to fill those jobs.

Delivering Safe, Low-Cost Consumer Goods: The results of many of the R&D efforts benefit industry and consumers alike. For example, crash modeling of automobiles using advanced computing power and software can help design a new generation of lighter and safer vehicles.

Utilizing Government Resources and Expertise: Federal labs often have expensive test and simulation equipment and advanced computing facilities that individual companies (or even entire industries) cannot afford.

Accelerating Technology Development: International competition is so fierce in the steel sector that even a small technological difference can create a competitive advantage. By partnering with the government in R&D, the steel industry is able to undertake a broader range of projects, thus accelerating development and increasing the opportunity for competitive advantage. Under the Steel Program, the government partners in the testing and validation of research ideas. However, it is industry's responsibility to take technologies through commercial realization, and industry alone is responsible for these costs.

1 Modeling, Measurement, and Control

Precise measurement and control provide a variety of yield saving opportunities. Making the steel and internal products correctly the first time minimizes waste oxide generation, in-plant returns and, most importantly, customer rejects. Proper measurement and control will also maximize process throughput.

There are two major sources of yield losses that can be addressed by R&D in modeling, measurement, and control:

- The production of home scrap, customer returns, and wastes from the manufacturing process where steel is turned into finished goods
- The production of waste oxides in the blast furnaces, BOF, EAF, reheat, and other heat treating furnaces

For example, reheat furnaces are only 50% efficient; this inefficiency arises from a lack of proper heat treating data as well as the inability to control furnaces precisely or the ability to integrate heating schedules with mill upsets. An estimated 1% of all production is returned from the customer because it does not meet specifications. In-house scrap represents another 8 million tons per year that must be reprocessed. Both kinds of scrap represent significant yield loss since the energy consumed in the production of these is lost. Examples of R&D opportunities to improve microstructure control and reduce defects include better sensors for chemistry, cleanliness, and other key parameters, and improved NDE technologies and defect detection systems (see Table 1).

Waste oxide generation in steelmaking furnaces is estimated to be about 14 million tons per year with about 7 million tons of contained iron. A major barrier to reducing this loss is maintaining reliable process control and furnace stability. Potential R&D opportunities to overcome this barrier include sensors for critical chemical and physical parameters in the BF, BOF, and other furnaces; real-time chemistry adjustment technologies; and advanced combustion control systems.

TABLE 1. MEASUREMENT AND CONTROL: BARRIERS AND R&D OPPORTUNITIES
Barrier: Optimization of Process Sequencing
• Pacing program to optimize and coordinate the blast furnace, BOF, ladle refining, and caster • Artificial intelligence techniques to optimize EAF operation • Advanced computer diagnostic controls for identification of potential operation problems and scheduling of maintenance

Barrier: Difficulty Maintaining Reliable Process Control and Furnace Stability
• Sensors and measurement systems ➢ Low-cost sensors to measure gas composition, temperature, bed permeability, and hearth level ➢ Robust process sensors for the BOF (chemistry, temperature, waste gas composition, etc.) ➢ Real-time off-gas analysis method ➢ Reliable sensors for lance-to-steel bath distance ➢ Improved flux raw materials analysis and computer-controlled batching • Control systems ➢ Improved process control and on-line data collection for cokemaking and ironmaking ➢ Real-time chemistry adjustment methods ➢ Advanced combustion control systems for furnaces ➢ Integrated melter guidance system • Models ➢ Comprehensive model of the blast furnace and BOF ➢ Charge control model for better end-point control
Barrier: Control of Inclusions and Other Product Quality and Consistency Issues
• Sensors and measurement systems ➢ Better sensors and control systems for chemistry, cleanliness, and temperature ➢ On-line chemical and temperature sensors ➢ Detection systems to identify the location of inclusions ➢ Improved on-line non-destructive evaluation technologies ➢ Cold surface defect detection and classification ➢ On-line dynamic roll surface inspection during hot rolling ➢ Automated in-line system to quantify steel surface cleanliness ➢ Rapid contact inspection techniques for coating • Control systems ➢ Process control practices that reduce physical surface and shape defects ➢ Techniques to control width and shape ➢ Active control of fluid flow, temperature, and chemistry ➢ Fluid mixing control • Models ➢ Ability to predict cast shape, inclusion, or bubble distribution and structure ➢ Slab reduction models for minimizing centerline segregation ➢ Models to predict the location and rate of accretion • Processing technologies ➢ Ability to produce liquid steels with strictly controlled inclusion contents ➢ Methods to limit exposure of steel to air during tapping and refining • Roll maintenance ➢ Hot mill roll crowning, bending models, and roll cooling technology ➢ Deformation modeling

2 Operating Techniques and Practices

Improvements in operating techniques and practices can reduce the yield losses associated with in-house scrap returns, waste oxide production, excess slag formation, lower throughput, and reworking. The operation of electric arc furnaces, for example, presents an opportunity for improving yield by optimizing charging practices, reducing furnace heat time, and optimizing operating cycles. The productivity of many finishing processes can also be increased by minimizing process times and adopting practices that reduce defects that will reduce plant returns of prompt scrap. Other examples are scaling due to improper atmosphere control and excess soaking time in the reheat and annealing furnace. Lack of chemical control produces excess slag volume and iron losses in the blast furnace, BOF, and EAF.

Table 2 lists some representative R&D opportunities in operating techniques and practices that can help reduce steelmaking and processing times downstream of the steelmaking furnace, and increase productivity in refining and casting.

TABLE 2. OPERATING TECHNIQUES AND PRACTICES: BARRIERS AND R&D OPPORTUNITIES
Barrier: Electric Arc Furnace Heat Times
• Feed materials ➢ Understanding of how feed material size and shape affect melting time and yield ➢ Understanding of how preheating feed materials affects the EAF process ➢ Scrap preheating techniques • Time utilization ➢ Optimized EAF operating cycles ➢ Time utilization improvement techniques • Power issues ➢ Improved flicker control ➢ Finding limitations of secondary voltages
Barrier: Productivity of Unit Operations Downstream of Steelmaking
• Time utilization ➢ Improved heat transfer in annealing, heat treating, and other furnaces ➢ Optimization of batch annealing cycles ➢ Minimized component process times of parallel/concurrent processing methods for refining • Techniques to minimize or eliminate scale
Barrier: Product Quality, Cleanliness, and Consistency Issues
• Refining ➢ On-line chemical and temperature sensors ➢ Improved formulation and quality of alloy additions ➢ Alternative forms of carbon or better addition methods to improve carbon dissolution rate during refining ➢ Methods to limit exposure of steel to air

- Surface marks
    - Technology to eliminate casting or oscillation marks
    - Hot surface defect detection and classification techniques

- Novel liquid flow control techniques for strip casting

3 Process Equipment

As with improved operating practices, improvements to furnaces such as higher productivity rhf operation, rolling systems, and other process equipment can reduce generation of in-house scrap and minimize the creation of prompt scrap, improve waste oxide recycling and slags while increasing productivity and yield. Advanced refractories and other improved materials can reduce the frequency of both scheduled and unscheduled downtime for furnaces and ladles. The development of rolling and finishing technologies with reduced maintenance requirements or faster operating speeds can eliminate bottlenecks that inhibit productivity in these stages. Examples of the types of R&D that can result in higher yields through improved process equipment are presented in Table 3.

TABLE 3. PROCESS EQUIPMENT: BARRIERS AND R&D OPPORTUNITIES
Barrier: Furnace Maintenance Requirements
• Refractories ➢ Longer-lasting refractories (for ladles, degassers, and other equipment) that do not interact with steel or slag • Equipment and components ➢ Radiant tubes immune to thermal fatigue and creep ➢ Improved, easy-to-maintain hoods ➢ Higher productivity rhf operation • Maintenance techniques ➢ Techniques for mechanical and ancillary systems to take advantage of increased BOF lining life from slag splashing ➢ Technology to characterize the condition of the furnace and ladles
Barrier: Processing Times and Maintenance Requirements of Other Unit Operations
• Equipment and components that increase processing speed ➢ Dross management systems for coating operations ➢ Technologies to allow higher rolling speeds • Equipment and components that reduce scheduled and unscheduled downtime ➢ Improved nozzles ➢ Mill rolls that reduce the frequency of roll changes ➢ Improved automated roll scraper ➢ Longer-life, corrosion-resistant molten bath hardware for hot-dip metallic coating processes ➢ More reliable system to clean air knife lips gap in-line ➢ Dross management systems for coating operations ➢ Rolls that will peel and heal without microspalling and banding

4 Fuels, Feedstock and Recycling

The steel industry can improve its fuel efficiency and productivity by capturing the heat value of by-product gases and optimizing its mix of fuels and feedstocks. In a similar fashion, efficient use of iron and steelmaking by-products can improve yield by maximizing the industry's use of its iron-bearing feedstocks. Already, the U.S. steel industry relies on recycled iron units for more than half of its production. Recycling scrap consumes less than half the energy required for iron ore reduction. R&D needs to increase recycling include improved measurement technologies to classify scrap and processes that enhance scrap (e.g., dezincing).

The reliance of ironmaking on coke is a productivity barrier that can be overcome by increased use of coke alternatives such as coal and natural gas. According to projections in the *Steel Industry Technology Roadmap*, injection of coal into the blast furnace is expected to rise to 500 lbs/ton of hot metal by 2015, up from current levels of about 300 lbs/ton of hot metal. However, increasing the amount of coal injected into the blast furnace is currently limited by the knowledge of and ability to control bed permeability and burden descent issues. As shown in Table 4, research is needed to develop a better understanding of coal and oxygen injection and to determine feasible levels of scrap and DRI as feedstocks to the blast furnace.

Iron-bearing by-products generated within the steel mill can also be used as feedstock to the blast furnace. Approximately 30 million tons of ironmaking and steelmaking by-products -- oxide dusts, sludges, scale, and slags -- are generated each year. Currently, about 50% of this volume is recovered and recycled. Steelmaking slags are treated to recover metallic iron where feasible. Waste oxides contain about 7 million tons of iron units plus lime, coal and coke fines. Research leading to increased internal recycling of these residues will increase the steel industry's primary yield while reducing disposal costs and saving energy.

TABLE 4. FUELS, FEEDSTOCK AND RECYCLING: BARRIERS AND R&D OPPORTUNITIES
Barrier: Reliance of Ironmaking on Coke
• Improved understanding of coal injection ➢ Improved injection systems ➢ Injection of combustion enhancers ➢ Study of maximum injectant levels ➢ Use of hot oxygen to increase coal injection rate ➢ Slag formers • Ability to use non-coking coals and low-value carbonaceous material • Better use of blast furnace off-gas and alternative fuels • Develop techniques to increase scrap and DRI usage

Barrier: Difficulty Recycling Ironmaking and Steelmaking Byproducts
• Economical processes for: ➢ De-oiling ➢ Recycling of zinc-bearing oxides ➢ Dewatering sludge ➢ Recovering zinc from coated scrap ➢ Recycling spent pickle liquor to produce a higher value by-product ➢ Segregating and recycling advanced high strength steel scrap ➢ Mixing and injecting various waste stream materials • Better and cheaper binders for cold briquetting by-product oxides • Economical raw material analysis, classification, and beneficiation • Alternative higher-value-added products for coke oven by-products
Barrier: Waste Heat Recovery
• Recovery of waste heat and retention of heat in slabs coming from the caster

5 Material Properties and Manufacturing Technologies

Material properties R&D can optimize steels in ways that minimize the yield loss in manufacturing and decrease the total amount of steel manufactured. In a typical year, 14 million tons of the 100 million tons of steel produced are returned from manufacturers in the form of parts rejects, stamping wastes, and other prompt industrial scrap. This high reprocessing rate results from sub-optimal manufacturing techniques and lack of precise knowledge of the materials and their behavior in the various forming operations by the OEMs and fabricators of steel products. Through material properties and fabricating R&D it may be possible to reduce "prompt scrap" generation by 50%. Improved steels that are more precisely engineered for their purpose could reduce the total demand for steel by 5% or 5 million tons per year. R&D in material properties and manufacturing technologies could possibly increase yield production by a total of 19 million tons per year.

There are three major opportunity areas under the topic of material properties:

- Microstructure control and defect minimization,
- The development of accurate property data for new grades and advanced steels, and
- The development of new forming and joining processes and adaptation of existing processes to new grades.

Microstructure Control and Defect Minimization

As stated in Section 1, the combination of customer rejects and in-house scrap generated at the plant itself represent a significant tonnage of steel that must be reprocessed, losing the heat value from the fuels used to produce the steel in the first place. R&D to help steelmakers predict and control microstructure is critical to reducing these losses (see Table 5).

Development of Accurate Property Data for Advanced Steels

The application of advanced high strength steels with superior properties has great potential for improving the energy efficiency of both the steel manufacturer and the end user. Increased strength directly impacts the amount of material that must be used for a particular application. For example, increasing steel strength by a factor of "x" allows the weight of a piece to be reduced by a factor of $1/x^{0.5}$. Although the price of the new, improved steels typically rises slightly due to increased alloy content and/or processing, the overall price of the finished good falls because of its lower weight. The replacement of ASTM A36 steel, a universally applied structural steel (yield strength 36,000 psi), with ASTM A526 (yield strength 50,000psi) occurs because A526 is less costly overall. A smaller amount of the high-strength grade can substitute for the conventional grade, meaning lower steel production and a corresponding reduction in yield loss. Additional benefits are realized because less energy is used in the manufacture, fabrication, and transport of products.

Development of New Forming and Joining Processes

New forming and joining processes can significantly reduce the excesses from manufacturing operations, a significant contributor to yield loss. Processes that can be used with new grades of steel, particularly advanced steels, will facilitate the use of these steels and help the industry realize their benefits (described above).

In many cases, the energy savings related to the use of enhanced finished goods are even greater than the energy savings in manufacturing. For example, the use of advanced high strength steels in automobiles saves four times their own weight in CO_2 emissions annually due to reduced gasoline consumption. However, extensive properties research will be required for this and similar substitutions to be realized. For example, appropriate alloying, rolling, and heat treating practices must be determined as well as weldability, forming, and annealing schedules. The results of this research, if successful, will include lower energy consumption by the end user, fewer CO_2 emissions, and stronger, safer, and less costly goods.

TABLE 5. MATERIAL PROPERTIES AND MANUFACTURING TECHNOLOGIES: BARRIERS AND R&D OPPORTUNITIES
Barrier: Microstructure Control
• Models and measurements ➢ Investigation of reduction ratio versus microstructure and final properties for very thin and near-net-shape cast products ➢ Prediction of cooling behavior in laminar flow systems ➢ Dynamic measurement of phases in galvanneal coating ➢ Quantification of the effects of residual steel elements on continuously annealing and coating processes ➢ Methods to effectively communicate the interrelationship between end properties, production route, microstructure, and cost ➢ Comprehensive data and modeling of plate finishing to predict product properties ➢ Material property characterization and the development of new coatings for shape changing and surface modification technologies ➢ Development of stability properties of steel inclusions and precipitates • Control systems ➢ Closed-loop control of heat treating incorporating feedback from microstructure sensors ➢ Improved control of microstructures of as-rolled, high-strength grades ➢ Grain size control or steel texture using laser ultrasonics
Barrier: Product Quality and Consistency Issues
• Process control practices that reduce variability of coating appearance and coating weights • Techniques for better coating uniformity • Improved process seam welding techniques

Barrier: Lack of Property Data for Advanced Steels
• Alloying, rolling, and heat treating practices for advanced high strength steels • Weldability, forming, and annealing schedules for advanced high strength steels