

**ITP, IMF
Washington, DC**

Refractories for Industrial Processing: Opportunities for Improved Energy Efficiency

May 16, 2005

**H. Wayne Hayden#
James G. Hemrick*
Peter Angelini*
Robert E. Moore§
William L. Headrick§**

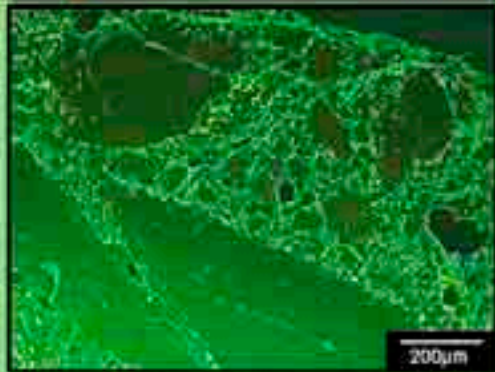
#Metals Manufacture, Process, and Controls Technology, Inc.

**Oak Ridge National Laboratory*

§R. E. Moore and Associates



Prepared for the DOE-EERE Industrial Technologies Program



Introduction:

Efforts on Refractories can lead to major benefits

- **Refractories are a critical part of industrial processes**
 - used over wide temperature ranges and in varying environments
 - several refractory challenges limit the energy efficiency of furnaces
 - impact various industrial sectors
- **Estimates of opportunities for improving energy efficiency of processes show large energy benefits:**
 - evaluation of four common furnaces used in U.S industrial processes – **400 Trillion Btu/year**
 - conservative extrapolation of results for all industrial process furnaces **over 800 Trillion Btu/year.**
- **Four major crosscutting research focus areas and seven specific R&D areas with barriers and pathways can lead to improved energy efficiency of processes**

Refractory materials are critical components for many industrial processes

- **Refractory materials are used throughout U.S. industry –**
 - **insulation and containment vessel linings**
- **Materials must perform at elevated temperatures –**
 - **bear mechanical loads, and transfer heat**
- **Refractories are strategic materials in support of American industrial processes through:**
 - **ability to contain heat, chemicals, and melts**
 - **crosscutting nature of their applications**

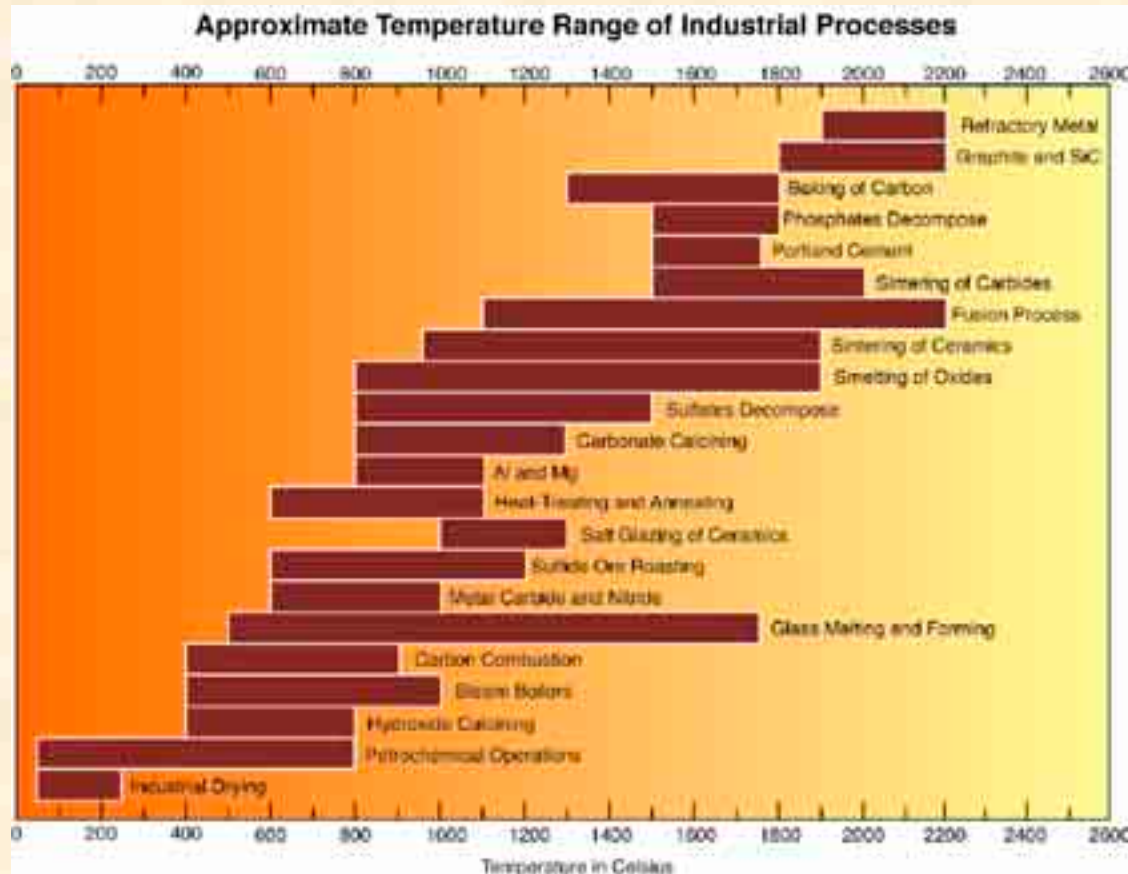
How can improved refractories lead to energy savings?

- **Facilitating the use of energy saving technologies**
 - oxygen enrichment
 - heat recovery
 - improved convective heat transfer
- **Reducing heat losses through the walls and roofs of furnaces**
 - lower thermal conductivity
 - reduced rates of corrosion, erosion, and wear
- **Increasing product yield**

A multi-step approach was used to evaluate energy efficiency opportunities and needs for industrial processes

- **Evaluated current status and needs across various industries**
- **Categorized opportunities based on furnace types**
 - analyzed energy benefits for four of the most common process furnace types
 - extrapolated for entire industry
 - conservative estimate taken for US industry
- **Identified overall technical goals, barriers, and pathways**

Refractories operate over wide temperature ranges and in varying environments



- Refractories are used in industrial processes from ambient to 2200°C.
- Industrial process environments can be:
 - oxidizing
 - reducing
 - humidified
 - corrosive
 - abrasive

Refractories are used in many types of industrial process furnaces

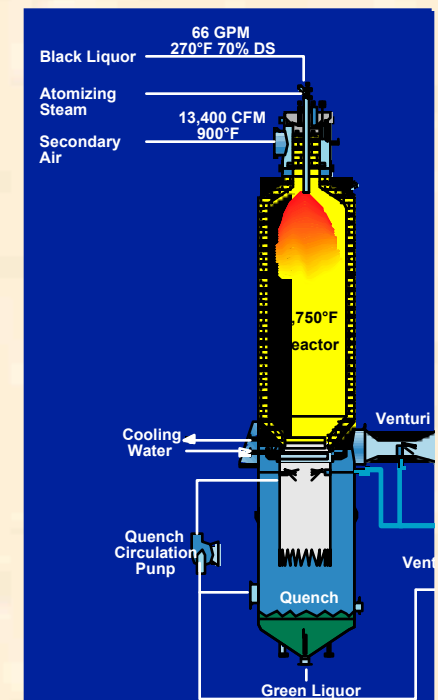
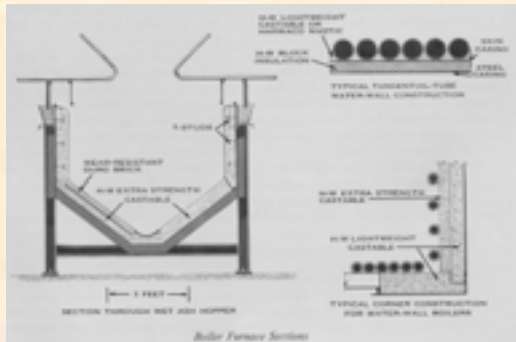
| Furnace type | Industrial furnace applications | | | | | | | |
|-----------------------------|---------------------------------|---------------|-------------|--------------|-------|------------|-------------|-------------|
| | Al | Cement & Lime | Chem/ Petro | Forest Prod. | Glass | Heat Treat | Iron/ Steel | Metal Cast. |
| Blast furnace | | | | | | | | |
| BOF | | | | | | | | |
| Reverbs | | | | | | | | |
| Ladle/tundishe | | | | | | | | |
| Electro smelting | | | | | | | | |
| Kilns | | | | | | | | |
| Electric arc furnaces (EAF) | | | | | | | | |
| Cupola | | | | | | | | |
| Heat treat | | | | | | | | |
| Distillation | | | | | | | | |
| Reactor/reformer | | | | | | | | |
| Boiler | | | | | | | | |
| Gasifier | | | | | | | | |
| Heat exchanger | | | | | | | | |

Refractory challenges limit the energy efficiency of industrial process furnaces

| Furnace type | Refractory challenges | | | | | | | | |
|------------------|-----------------------|--------------------------|---------------------------|---------------------|---------|---------------------------|-----------------------|--------------------------------------|-----------------------------|
| | Abrasion | Caking/ agglomeration | Contamination/ fouling | Corrosion & Wear | Erosion | Mechanical degradation | Thermal insulation | Thermo- mechanical degradation | Refractory life/ repairs |
| Blast furnace | | | | | | | | | |
| BOF | | | | | | | | | |
| Reverbs | | | | | | | | | |
| Multiple hearth | | | | | | | | | |
| Ladle/tundish | | | | | | | | | |
| Electro-smelt | | | | | | | | | |
| Kilns | | | | | | | | | |
| EAF | | | | | | | | | |
| Cupola | | | | | | | | | |
| Heat treat | | | | | | | | | |
| Distillation | | | | | | | | | |
| Reactor/reformer | | | | | | | | | |
| Boiler | | | | | | | | | |
| Gasifier | | | | | | | | | |
| Heat exchanger | | | | | | | | | |

Evaluations made of four common furnace types

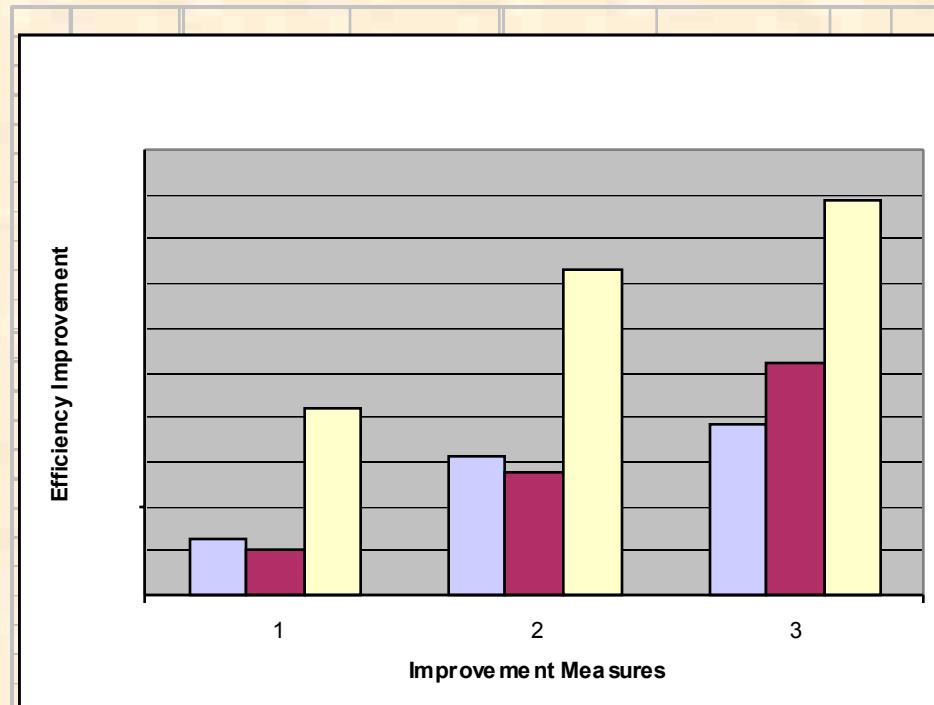
- Boilers and Chemical Reactors
- Kilns and Calciners
- Reverberatory furnaces
- Gasifiers



Energy efficiency gains can be significant from refractories research and development efforts

| Energy Improvement Actions and Effects | | | | |
|----------------------------------------|-------------|-------------|-------------------------|-------------------------------------------------|
| Operation | Base Case | Flame Up | Flame Up + Exhaust Down | Flame Up + Exhaust Down + Wall & Roof Loss Down |
| Btu/ton | | | | |
| Lime Kiln | 10,920,000 | 10,244,000 | 9,220,000 | 8,840,000 |
| Al Melting | 35,191,000 | 33,431,000 | 8,840,000 | 26,073,000 |
| Glass Melting | 127,630,000 | 101,040,000 | 80,832,000 | 71,332,000 |
| Energy Efficiency Improvements | | | | |
| Lime Kiln | 0% | 6% | 16% | 19% |
| Al Melting | 0% | 5% | 14% | 26% |
| Glass Melting | 0% | 21% | 37% | 44% |

Energy efficiency improvement can result for kilns and reverberatory furnaces



| Legend | | |
|------------------|------------------------------------------------------|--|
| Operations | Improvement Measures | |
| Lime Kiln | 1. Flame T Up | |
| Aluminum Melting | 2. Flame T Up + Exhaust T Down | |
| Glass Melting | 3. Flame T Up + Exhaust T Down + Wall/Roof Loss Down | |

Insulation and process complexity affect energy efficiency of boilers/chemical reactors and gasifiers

- **Boilers/chemical reactors**
 - Improved boiler insulation
 - Improved pipework insulation in transfer systems
- **Gasifiers**
 - For coal combustion - compared conventional combustion process at 33-35% efficiency to combined cycle process with efficiency of 45-50%
 - For pulp and paper – compared present Tomlinson boiler technology to high efficiency Tomlinson boilers and combined cycle gasification

Refractories - Boiler Energy Efficiency Opportunities

| All Units TBtu/Year | Chemical | Pulp & Paper | Petro-chemical | 3 Industry Total |
|--------------------------------------|-------------|--------------|----------------|------------------|
| Present Usage | 1,540 | 2,596 | 1,675 | 5,811 |
| Increase Boiler Efficiency 85 to 87% | 35 | 60 | 39 | 134 |
| Cut Line Losses 10 % | 30 | 49 | 31 | 110 |
| Total Savings | 65 | 109 | 70 | 244 |
| New Usage | 1,475 | 2,487 | 1,605 | 5,567 |
| Improvement | 4.2% | | | |

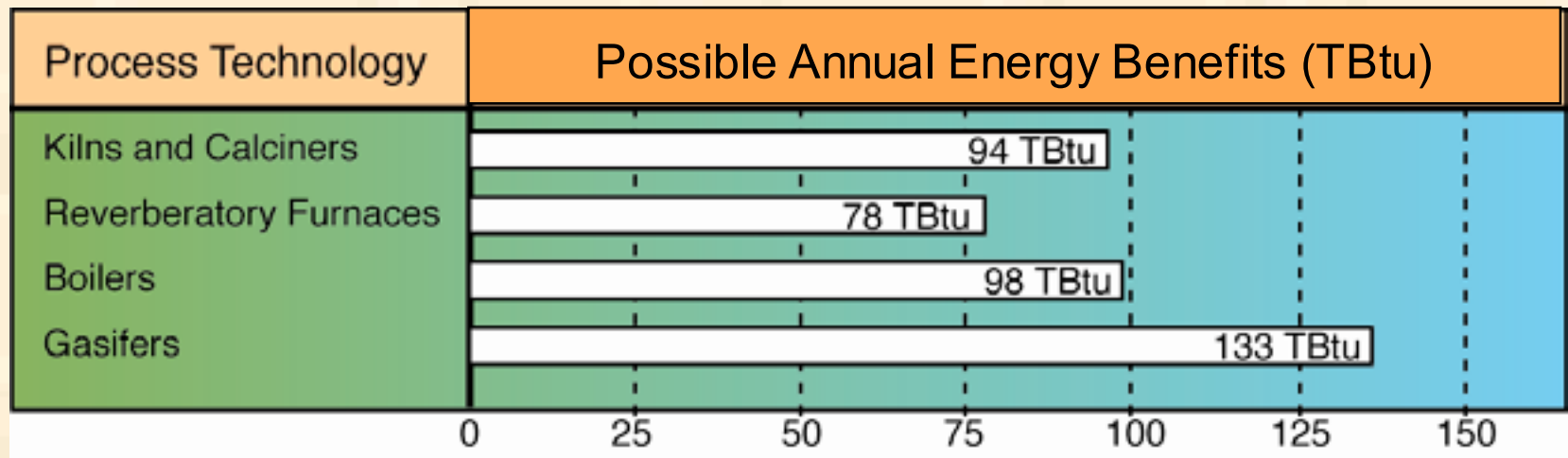
Conservative Estimates of energy benefits for improved refractories in boilers and chemical reactors total nearly 100 TBtu per year

| Industry segment | TBtu | % | Capture basis (%) | Projected fuel savings (TBtu) |
|------------------------------------------------------------|------------|-----|-------------------|-------------------------------|
| Chemical industry steam opportunities | | | | |
| Present usage of fuel for generating steam | 1,540 | | | |
| Opportunity for improving boiler efficiency from 85 to 87% | | 2.3 | | |
| Fuel saved | 35 | | | |
| Opportunity for reduced line heat losses by 10% | | 1.9 | | |
| Fuel saved | 30 | | | |
| Chemical industry fuel reduction | 65 | | 40 | 26 |
| Pulp and paper steam opportunities | | | | |
| Present usage of fuel for generating steam | 2,596 | | | |
| Opportunity for improving boiler efficiency from 85 to 87% | | 2.3 | | |
| Fuel saved | 60 | | | |
| Opportunity for reduced line heat losses by 10% | | 1.9 | | |
| Fuel saved | 49 | | | |
| Pulp and paper industry fuel reduction | 109 | | 40 | 44 |
| Petrochemical steam opportunities | | | | |
| Present usage of fuel for generating steam | 1,675 | | | |
| Opportunity for improving boiler efficiency from 85 to 87% | | 2.3 | | |
| Fuel saved | 39 | | | |
| Opportunity for reduced line heat losses by 10% | | 1.9 | | |
| Fuel saved | 31 | | | |
| Petrochemical industry fuel reduction | 70 | | 40 | 28 |
| Total steam opportunity | 244 | | 40 | 98 |

Estimated energy benefits for new refractories in gasifiers total over 130 TBtu per year

| Technology | Potential by 2020 (billion kWh/year) | Equivalent energy (TBtu/year) |
|----------------------------------------------------|-----------------------------------------|----------------------------------|
| Chemical | | 440 |
| Conventional coal combustion (33–35% efficient) | | 726 (energy needed) |
| Combined cycle gasification (45–50% efficient) | | 660 (energy needed) |
| <i>Total improvement</i> | | 66 or 9% |
| Forest products | | |
| Tomlinson recovery boiler | 4.4 | 15 |
| High-efficiency Tomlinson recovery boiler | 16.7 | 57 |
| Combined cycle gasification | 36.2 | 124 |
| <i>Total improvement</i> | | 67 or 54% |
| | | Total 133 TBtu/year |

Energy efficiency benefits projected for improved refractories in four evaluated furnace types total over 400 TBtu per year



Extrapolation of above results to all industrial process furnaces leads to an estimated **1,400 TBtu/year** opportunity

Refractories can have significant energy benefits on U.S. industrial processes (conservative estimate)

| Process Industry * | NAICS codes * | Total TBtu/year* | Usage affected by refractories | | Conservative Energy Benefits from New Refractories (TBtu/yr) | |
|---------------------------|-------------------|------------------|--------------------------------|--------------|--------------------------------------------------------------|---------------|
| | | | Percent | TBtu/Yr | Near-term 2% | Long-term 10% |
| Aluminum | 3313XX1 | 441 | 90% | 397 | 7.9 | 39.7 |
| Chemical | 325XXX | 3,704 | 50% | 1,852 | 37.0 | 185.2 |
| Fabricated metals | 33281 | 445 | 90% | 401 | 8.0 | 40.1 |
| Forest products | 321XXX, 322XXX | 3,248 | 40% | 1,299 | 26.2 | 129.9 |
| Foundries | 3315XX | 233 | 90% | 210 | 4.2 | 21.0 |
| Glass | 3272XX | 203 | 70% | 142 | 2.8 | 14.2 |
| Iron & steel | 33111 | 1,672 | 85% | 1,422 | 28.4 | 142.1 |
| Petroleum & coal products | 324XXX | 3,622 | 50% | 1,811 | 36.2 | 181.1 |
| Stone, clay products | 327XXX | 766 | 100% | 766 | 15.3 | 76.6 |
| Total | | 14,334 | — | 8,300 | 165 | 830 |

* US DOE, Energy Information Administration; DOE Manufacturing Consumption Survey (MECS); NAICS – North American Industrial Classification System

Four research and development goals focused on new and improved refractory materials can have positive energy benefits



Seven specific R&D areas identified

- **Improved castable and monolithic refractories**
- **Modified fiber materials**
- **Surface modification (coatings, physical or thermal alteration)**
- **Synthetic aggregates and powders**
- **In situ and graded refractories**
- **High-temperature properties of refractories**
- **Sensors for materials performance**

Specific identified R&D areas are crosscutting in nature

| Technical R&D potential pathways | Industry segment | | | | | | | |
|-----------------------------------------------|------------------|---------------|------------------------|-----------------|-------|----------------|--------------|---------------|
| | Aluminum | Cement & lime | Chem. / petro-chemical | Forest products | Glass | Heat treatment | Iron & steel | Metal casting |
| Improved castable and monolithic refractories | | | | | | | | |
| Modified fiber materials | | | | | | | | |
| Surface modifications (coatings, alterations) | | | | | | | | |
| Synthetic aggregates and powders | | | | | | | | |
| Elevated temperature refractory properties | | | | | | | | |
| In situ and gradient refractories | | | | | | | | |
| Sensors for materials performance | | | | | | | | |

Several refractory issues exist which must be addressed

Current

- Castables and monolithic refractories more resistant to corrosive and mechanical wear
- Fiber insulation materials with lower thermal conductivity, greater chemical resistance, and higher temperature stability
- Information on the high-temperature and corrosion properties of current and new refractory materials

Near Term

- Techniques and materials for applying surface coatings or inducing physical alteration of refractory surfaces
- Higher-performance aggregates and matrix materials that would increase the life and durability of refractory
- Sensors to monitor refractory-related issues

Long Term

- R&D to improve existing in-situ refractory systems and develop new in-situ systems for new industrial applications
- Refractory materials possessing a gradient structure to permit varying properties in the surface, bulk, and back side to optimize resistance to corrosion and permit reduced thermal losses

Breakthrough technology development is required to address refractory needs

Current

- Fusion-cast refractories that do not include silica or other glass formers
- Oxide/nitride grain boundary additives leading to closure of open porosity
- Frothed latex/fiber mixes for gunning to reduce airborne fibers during installation and with enhanced adhesion to steel and other metals
- New inorganic binder systems
- Fibrous materials with greater strength and lower friability
- Realistic test methods and environmental test systems

Near Term

- Corrosion/erosion resistant coatings for use in several process industries
- Radiation-heating attenuation/mitigation to optimize radiant heat transfer
- Aggregate coatings for “additives” that control or bind grain boundary effects for improved refractory processing
- Sensors and methods for measurement of spectral emissivity
- Sensors and methods for monitoring wall regression due to corrosion, erosion, and wear

Long Term

- Models of crack initiation and growth as a function of material, depth, and service properties
- High-intensity infrared heating techniques for fabrication of optimized graded refractories
- Microstructures that promote creep and erosion resistance
- Refractory layers with microstructures that minimize thermal stresses
- Optimized substrate geometries that will minimize shear stresses in thermo-environmental barrier refractory coatings

Major conclusions and results from this study

- **Refractories are a critical part of industrial processes**
 - used over wide temperature ranges and in varying environments
 - several refractory challenges limit the energy efficiency of furnaces
 - impact various industrial sectors
- **Estimates of opportunities for improving energy efficiency of processes show large energy benefits:**
 - evaluation of four common furnaces used in U.S industrial processes – **400 Trillion Btu/year**
 - conservative extrapolation of results for all industrial process furnaces **over 800 Trillion Btu/year.**
- **Four major crosscutting research focus areas and seven specific R&D areas with barriers and pathways can lead to improved energy efficiency of processes**

The authors wish to acknowledge the expertise and support that helped make this document possible

- **The report has been sent out for review**
 - To several industrial, national laboratory, and academic experts
 - For general review through the DOE website (<http://www.oit.doe.gov/imf/>)
- **We appreciate the help and support of colleagues and the document reviewers**
- **The authors thank the DOE-EERE Industrial Technologies Program for continued support and guidance**

Steel Industry Refractory Barriers

- **Corrosion of refractories in furnaces, ladles, and tundishes.**
- **Refractories for better protection of runners, water cooling pipes and stirrers.**
- **New, advanced monolithic materials.**
- **Improved impact pads for ladle bottoms.**
- **Improved alumina ladle shrouds.**
- **Data/Experience bases for new refractories.**