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Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988

Fiscal Year 1993 Annual Report

U.S. Department of Energy
Office of Industrial Processes
Office of Energy Efficiency and Renewable Energy
Washington, DC 20585

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EXECUTIVE SUMMARY

The Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988 (Act), commonly referred to as the Metals Initiative, was signed into law on November 17, 1988 (Public Law 100-680). The Act, 15 U.S.C. 5101 *et seq.*, has the following purposes: (1) to "increase the energy efficiency and enhance the competitiveness of American steel, aluminum, and copper industries"; and (2) to continue the research and development efforts begun under the Department of Energy (DOE) program known as the Steel Initiative. Section 8 of the Act requires the Secretary of Energy to prepare an annual report to Congress describing the activities carried out under the Act during each fiscal year. 15 U.S.C. 5107 In addition, with respect to reports on fiscal years 1993, 1995, and 1997, Section 8 requires a complete summary of activities under the management plan and research plan from inception with an analysis of the extent of their success in accomplishing the purposes of the Act. *Id.*

The Metals Initiative is currently supporting six steel industry research and development projects: (1) Superplastic Steel Processing with Lawrence Livermore National Laboratory; (2) Direct Steelmaking with the American Iron and Steel Institute; (3) Electrochemical Dezincing of Steel Scrap with Argonne National Laboratory and Metal Recovery Industries (U.S.), Inc.; (4) Rapid Analysis of Molten Metals Using Laser Produced Plasmas with Lehigh University; (5) Direct Strip Casting using a single wheel caster with Armco, Inc.; and (6) Advanced Process Control, also with the American Iron and Steel Institute. At the close of the fiscal year, a seventh project, Waste Oxide Recycling with the American Iron and Steel Institute, was selected for inclusion in the Direct Steelmaking project.

There are three projects with the aluminum industry. The first, Wettable Cathodes for Alumina Reduction Cells with the Reynolds Metals Company, continues from the prior periods. Financial Assistance Agreements for two new projects are being negotiated with the Aluminum Company of America (Alcoa) for: (1) High Pressure Calcining of Aluminum Ores; and (2) Spray Forming of Aluminum Sheet.

This report describes the program activities performed during fiscal year 1993. Also included are the appropriations history, the actual obligation of funds through fiscal year 1993, and the anticipated obligation of funds necessary to continue these projects. The participants provided the requisite nonfederal cost sharing for each project.

The successful development of **Superplastic Steel Processing** for the fabrication of steel components will enable complex parts to be forged from a single large piece of metal, thereby improving yield and saving energy. It is estimated that the market for superplastic steel is 2-5 million tons per year. The use of superplastic steel has an annual energy savings potential of at least 0.01 quadrillion BTUs per year, and manufacturing costs could be reduced 17 percent. During fiscal year 1993, Lawrence Livermore National Laboratory verified its computer simulations of superplastic forming of simple shapes. North Star Steel made two attempts to cast 40 ton heats of low aluminum superplastic steel. These both failed because conventional mold and machine designs are not suitable for casting steels with as wide a freezing range. An examination into possible solutions to this problem is ongoing. In fiscal year 1994, one of Caterpillar's suppliers will forge a series of complex automotive parts to test this material. A private firm has been contracted to prepare a technoeconomic assessment of Ultra High Carbon Steel (UHCS) and superplastic forming. An excellent description of this research and the benefits of superplastic steel processing was included in National Public Television's special "The Stuff of Dreams".

The objective of the **Direct Steelmaking** project is to develop a coal based, energy efficient, economically competitive, continuous process that will replace the conventional steelmaking operations composed of coke ovens, blast furnaces, and basic oxygen furnaces (BOF). The advantages of a direct steelmaking process are the elimination of coke and the high capital requirements and adverse environmental impacts of coke ovens. When implemented on a commercial scale, the direct operating costs of direct steelmaking are expected to be about 10 percent less than the conventional steelmaking process. The estimated energy savings potential is about 0.2 quadrillion BTUs per year. The environmental benefits of direct steelmaking would

be an improvement in the ambient air quality through the minimization of volatile organic hydrocarbons and particulates. This process would also reduce greenhouse gas emissions. During fiscal year 1993, a pressurized pilot smelting vessel with offgas treatment and dust recycling facilities was installed in place of the horizontal vessel. Initial operation showed promise by achieving the increased efficiency expected. A feasibility study for a 350,000 ton-per-year Direct Ironmaking demonstration plant was completed. Based on the success of the research to date and the attractive return projected in the feasibility study, a steel company has submitted a proposal to construct such a plant. A study of batch and continuous refining processes to convert the continuously produced hot metal from the smelter to steel has been made. In fiscal year 1994, operation of the pressurized smelter will be continued to optimize the process (using funds from fiscal year 1993).

The Department of Energy has agreed to support a second American Iron and Steel Institute project at the pilot plant smelter. It is entitled, "**Steel Plant Waste Oxide Recycling and Resource Recovery by Smelting.**" The **Waste Oxide Recycling** project is aimed at developing a process to recover the over three million tons of blast furnace and basic oxygen furnace dusts and one half million tons of rolling mill sludge which the steel industry generates each year. Smelting is an ideal way to accomplish this because the process is completely enclosed, therefore the waste oxides will be recovered in an environmentally friendly manner. A Financial Assistance Agreement is being negotiated. This project is scheduled to be completed in fiscal year 1995.

The objective of the **Electrochemical Dezincing of Steel Scrap** project is to build and operate a pilot plant to demonstrate a two-step process for the continuous dezincing of steel scrap. The products from this process are clean, dezincing steel scrap and metallic zinc. A scrap dezincing process could save the nation approximately 50 trillion BTUs per year; the operating costs benefits are estimated to be \$140 million per year compared to using nonscrap sources of iron units; and the United States could realize a \$128 million savings in foreign exchange through the reduction of zinc imports. The process also has major environmental benefits. The removal of

zinc from steel scrap increases the recyclability of steelmaking fume and eliminates zinc from waste water streams. The main element of work during fiscal year 1992 was installation of the pilot plant at East Chicago, Indiana. In fiscal year 1993 the plant was used to dezinc over 600 tons of automotive stamping plant scrap with over 90 percent effectiveness in removing zinc. About 80 tons of this dezincing material was tested and judged satisfactory by the largest captive automotive foundry and resulted in a request for a commercial proposal for dezincing on a toll basis. About 1,500 tons of scrap are being dezincing, baled, and accumulated to execute a BOF furnace test program. A memorandum of invention has been filed based on pilot plant experiments that could significantly increase production rates. Pilot plant operation has also resulted in refined mass and energy balances, refined process economic projections, and an improved visibility to, and understanding of the world market for the dezincing process. Serious inquiries about licensing the dezincing process have been received from Europe and Japan. The zinc recovery circuit has not been installed at the pilot facility; this is scheduled to be completed during fiscal year 1994.

The objective of the **Rapid Analysis of Molten Metals Using Laser Produced Plasmas** project is to develop a sensor probe to rapidly determine the chemical composition of molten iron and steel using spectroscopic analysis of laser produced plasmas. Widespread implementation of this probe by the carbon steel industry could save approximately 10 trillion BTUs per year and reduce operating costs by \$488 million annually. During fiscal year 1993, Phase A was nearly completed. This work includes developing protocols for calibration of molten metal compositions and selecting refractory sheath materials which will be immersed into the molten steel. Steel plants in which to test the two probes have been selected.

The objective of the **Direct Strip Casting** project is to develop a near-net-shape casting process for the production of low carbon steel sheet. Direct strip casting would eliminate the energy and capital intensive steps of continuous slab casting, slab reheating, and hot rolling that are now required for the production of steel sheet. The operating cost of these facilities is estimated to be \$75 per ton; their replacement with a direct strip casting process will save an estimated \$50

per ton and 0.2 quadrillion BTUs annually. This project aims to establish the technical and economic feasibility of casting low carbon steels on a single wheel caster utilizing the open channel casting process. During fiscal year 1993, major modifications were made to the caster which resulted in greater strip thickness and improved quality. A heat transfer and solidification model was completed. This model has permitted modifications to the nozzle design at the caster and routine planning and analysis of casting trials. Several casts of stainless steel were performed resulting in strip with very high quality surfaces. In spite of the excellent progress made by this research, Armco Inc. advised DOE in August that it would withdraw from the project. Armco's reason for canceling is that the corporation has restructured since the project was funded. Armco is now a stainless and alloy steel producer. Because this project is designed to develop a process to produce carbon steel strip, it no longer fits into Armco's long term corporate strategy. The Department of Energy is now working with Armco to develop a plan to bring this research to a conclusion and preserve the knowledge gained thus far.

At the close of fiscal year 1992, DOE elected to support a third project with the American Iron and Steel Institute (AISI) entitled, **"Advanced Process Control for the Steel Industry."** The objective of this project is to develop sensor and control system technology which will increase the competitiveness of the domestic steel industry by making improvements in steel quality and the industry's energy utilization efficiency, and by decreasing the cost of production of steel products. The program consists of six projects to be conducted collaboratively by national laboratories, universities, and private industry. The six projects address various steelmaking phases from primary steelmaking through finish processing. When implemented on a commercial scale, advanced process control could save the industry approximately \$300 million annually, or an estimated two to four percent of the operating cost of the steelmaking operation to which the control system is applied. The estimated energy savings potential is 0.014 quadrillion BTUs per year. In fiscal year 1993, a Co-operative Agreement was negotiated with AISI and work began on all six projects.

The objective of the **Wettable Cathode for Hall-Heroult Alumina Reduction Cells** project is to demonstrate the technical and economic benefits of electrolyzing alumina in commercial cells equipped with titanium diboride-graphite (TiB₂-G) cathodes. Retrofitting existing alumina reduction cells with these wettable cathodes has the potential to save 0.1 quadrillion BTUs per year. The first test cell was originally scheduled for startup in November 1991, at Reynolds Metals' plant in Troutdale, Oregon. Due to a temporary shutdown at Reynolds, it became necessary to relocate the test cell to Kaiser Aluminum's Mead, Washington plant. Work during fiscal year 1993 consisted of the production of the TiB₂-G cathode elements by Great Lakes Research, cell construction, installation of the process control system, and start-up and operation of the first cell. The cell operated for 145 days and much was learned about the causes of cathode breakage, cathode to anode shorting, and fabrication techniques. A second cell will be started in fiscal year 1994.

At the end of the year, DOE elected to support two projects with Alcoa. Separate Financial Assistance Awards are being negotiated for each of these projects. The first project is entitled: **"Energy Efficient Pressure Calciner."** Improvements in the alumina calcination process could save the industry \$160 million annually and 0.01 quadrillion BTUs per year. The second project is entitled **"Spray Forming of Aluminum."** This is a near-net-shape casting process to produce aluminum sheet. This process will save approximately 27 percent of the energy used by the conventional ingot casting process, and reduce the cost to produce finished sheet approximately two cents per pound.

Because of the vast tonnage of products which the steel and aluminum industries produce, they generate large quantities of solid, liquid, and gaseous byproducts. Metals Initiative technologies have the potential to reduce pollution and increase recycling. Pollution is reduced because they have potential to save an estimated 0.31 quadrillion BTUs/year, eliminating 63 million tons of CO₂ emissions every year. These technologies improve product yield, thus maximizing the total quantity of steel and aluminum produced from a given raw material input. Increased recycling is the objective of both the Waste Oxide Recycling and Electrochemical Dezincing projects.

INTRODUCTION

The Department of Energy's Metals Initiative Program is a result of the Steel and Aluminum Energy Conservation and Technology Competitiveness Act of 1988 (Act). 15 U.S.C. 5101 *et seq.* The Act has the following stated purposes:

- (1) to "increase the energy efficiency and enhance the competitiveness of American steel, aluminum, and copper industries"; and
- (2) to continue steel research and development efforts begun under the DOE program known as the Steel Initiative.

The Act directs the Secretary of Energy (Secretary) to "reestablish an industrial energy conservation and competitive technology program to conduct scientific research and development of steel and aluminum technologies to carry out the purposes of this Act," to "publish an update of the management plan," and to "publish an update of the research plan."

As originally enacted, the term "management plan" referred to the Steel Initiative Management Plan issued in April 1987 by DOE, and the term "Research Plan" referred to the Steel Initiative Research Plan issued in April 1988 by DOE. Consistent with statutory amendments, these plans were updated to include the aluminum and copper industries, and were reissued and transmitted to Congress on August 18, 1989 as the Metals Initiative Management and Research Plans. No revisions were made to either the Management or the Research Plan during fiscal year 1993.

The Management Plan describes DOE policies and practices followed in implementing the program. It also defines the roles and responsibilities of those organizations involved in the Metals Initiative Program, including industry, the national laboratories, and universities. The Research Plan identifies and establishes priorities for research and development activities to

increase the energy efficiency and enhance the competitiveness of the domestic steel, aluminum, and copper industries.

Finally, Section 8 of the Act also requires that the Secretary "prepare and submit annually to the President and the Congress at the close of each fiscal year a complete report of the research and development activities carried out under this Act during the fiscal year involved, including the actual and anticipated obligation of funds, for such activities, together with such recommendations as the Secretary may consider appropriate for further legislative, administrative, and other actions, including actions by the American steel, aluminum, copper and other metals industries, which should be taken in order to achieve the purposes of this Act". 15 U.S.C. 5107 Section 8 also requires a special analysis in the reports for fiscal years 1993, 1995, and 1997 summarizing activities under the Management and Research plans from their inception and an analysis of the extent of their success in accomplishing the purposes of the Act.

This is the fifth Annual Report on the Metals Initiative Program; it provides a description of activities conducted during fiscal year 1993. As in previous years, the report focuses on the:

- Status of research and development activities,
- Actual obligation of funds,
- Anticipated obligation of future funds, and
- Program management.

The Metals Initiative Program is managed by the Office of Industrial Processes.

STATUS OF RESEARCH AND DEVELOPMENT ACTIVITIES

During fiscal year 1993, the Metals Initiative included the following research and development projects:

STEEL INDUSTRY

- (1) Superplastic Steel Processing with Lawrence Livermore National Laboratory;
- (2) Direct Steelmaking with the American Iron and Steel Institute;
- (3) Electrochemical Dezincing of Steel Scrap with Argonne National Laboratory and Metal Recovery Industries (U.S.), Inc.;
- (4) Rapid Analysis of Molten Metals Using Laser Produced Plasmas with Lehigh University;
- (5) Direct Strip Casting Using a Single Wheel Caster with Armco, Inc.; and
- ** (6) Waste Oxide Recycling with the American Iron and Steel Institute.

ALUMINUM INDUSTRY

- (1) Wettable Cathodes for Alumina Reduction Cells with the Reynolds Metals Company;
- ** (2) High Pressure Calcining of Aluminum Ores with Alcoa; and
- ** (3) Spray Forming of Aluminum Sheet with Alcoa.

NOTE: Projects denoted ** have not begun. They have been accepted by The Department of Energy and Financial Assistance Agreements are being negotiated by the industrial participants and the Department's Idaho Operations Office.

The Superplastic Steel Processing and Direct Steelmaking projects began prior to enactment of the Act, and therefore have continued under the earlier Steel Initiative Management Plan (issued April 1987). The current phases of these projects will be completed during the coming year using funds from fiscal year 1993 or earlier. All other projects are administered under the new Management Plan and are Metals Initiative projects.

SUPERPLASTIC STEEL PROCESSING

This project was first funded in March 1988. The overall objective of the project is to develop an ultrahigh carbon steel (UHCS) and a steel processing sequence to produce superplastic steel on a production scale. This project is managed by Lawrence Livermore National Laboratory (LLNL). To date, cost-sharing has been provided by three industrial participants: North Star Steel Co.; Ladish Co., Inc.; and Caterpillar, Inc. Ladish, for reasons unrelated to the merits of this technology, has withdrawn its financial support from the project. However, it has continued to provide its technical expertise in die manufacturing and forging. Caterpillar and North Star Steel remain in the program and are providing the industrial cost-sharing.

Superplasticity is a phenomenon exhibited by some metals and alloys that permits them to be deformed in large amounts without fracturing. The advantage of superplastic materials is their ability to be formed into complex parts thus eliminating the need to join numerous, less complex parts. In the approach taken by this project, superplastic behavior is produced from UHCS which maintains a fine grain, duplex microstructure as the steel is deformed in the warm working range (750-850 °C). Depending on its properties and its ultimate cost, the market for superplastic steel is estimated to be 2-5 million tons per year. At 2 million tons, the energy savings potential of this material is 0.01 quadrillion BTUs per year. This savings will be realized primarily through the elimination of waste materials during manufacturing. Superplastic steel is predicted to reduce manufacturing costs by 17 percent, through reductions in material and machining costs.

The four main objectives of the superplastic steel processing project are to: (1) establish the composition and processing steps necessary for the commercial-scale production of UHCS having the prerequisite microstructures; (2) produce and process the UHCS under industrial production conditions; (3) demonstrate the die-filling capability of the UHCS by superplastically forming a complex net-shape part; and (4) conduct a technoeconomic evaluation comparing the production of parts manufactured from superplastic steels to making the same parts by conventional technology.

Work performed prior to fiscal year 1992 accomplished the first objective resulting in the discovery of a family of low and high aluminum steel alloys with relatively low flow stress at high strain rates. The flow stress for this material has been decreased from 25,000 psi to as low as 3,000 psi (122,000 to 15,000 kg/m²). Simultaneously, the permissible strain rate (which is inversely related to flow stress) has been increased from 10⁻⁴/sec to 10⁻²/sec. Further, the industrial partners have developed the ability to cast these superplastic UHCS alloys on pilot-scale continuous casting machines. A technoeconomic analysis of the process identified a large number of potential applications for superplastic steels. However, further development of the alloys' properties was required.

As a consequence, the current phase of this project was initiated at the beginning of fiscal year 1992. The major objectives of this phase are to continue to improve the mechanical properties of the steel alloys (e.g., fracture toughness); to continuously cast this material on an industrial scale; and to demonstrate the process by superplastically forming a commercial part.

To accomplish these objectives, LLNL was assigned the tasks of: (1) continuing bench-scale research into forming and casting properties; (2) developing computer models to predict alloy behavior during forming; and, (3) investigating the application of superplastic UHCS to other forming operations, such as blow forming and pressure forming. Caterpillar, a potential user of this material, would study applications and select an alloy to be produced on a commercial continuous casting machine. North Star Steel would develop industrial-scale casting practices for the alloy and then cast commercial-size heats. In order to demonstrate the process, Caterpillar would take blanks from the steel produced at North Star and superplastically forge them into a complex diesel engine part.

During fiscal year 1992, LLNL developed computer codes to predict superplastic behavior while forging simple shapes. During fiscal year 1993, verification of these codes was performed in a special, new facility, which permitted close monitoring of the steel as it was forged, measuring the coefficient of friction between the steel and the die, and establishing the relative benefits of

various die lubricants. This new facility is now available to evaluate and compare the behavior of most metals in open or closed die forging operations. Standard operating procedures for such evaluations and comparisons have been prepared and reported for consideration of ASTM applications.

In earlier phases of this research, North Star Steel demonstrated the feasibility of continuous casting rounds of the low aluminum (<1.6% Al) UHCS in 1000 pound batches but had difficulty casting high aluminum (>7.5% Al) UHCS. Since the engine part selected by Caterpillar to demonstrate superplastic forming requires the low Al alloy, North Star Steel directed their efforts towards casting 40 ton low Al heats. During fiscal year 1993, North Star made two attempts to continuously cast 40 ton heats of the low Al UHCS. The first casting attempt failed due to excess superheating of the melt. The second attempt failed due to insufficient cooling of the strand casting walls which caused a breakout of the molten steel. North Star is reviewing these results before attempting a third casting. The 40 tons of low Al UHCS were cast into large ingots for possible use by another company as sheet product. LLNL is assisting North Star in developing a process for this conversion into sheet product.

Caterpillar and LLNL are working with a forging company selected by Caterpillar to forge commercial engine components. Computer code simulations of this forging are being evaluated to determine the blank size and die shape(s) needed to form the part. Preliminary forging tests have been performed with low Al UHCS steel provided by LLNL from ingot cast material used in previous development efforts. Since continuously cast UHCS is not available for the early forging attempts, ingot cast steel has been prepared for Caterpillar's demonstration. Should North Star succeed in continuously casting the low Al UHCS during fiscal year 1994, a second series of engine component forgings could be made with this material as well.

Other forming operations with UHCS have been explored to facilitate broader areas of applications. The forming of sheet by warm and cold rolling of UHCS has been demonstrated and the limited property data is encouraging. While some improvements in fracture toughness

have been made in fiscal year 1993, it is still too low for some common applications. An LLNL patent disclosure has been filed on a promising process for improving this property.

A private firm, Crow Engineering Services, has been contracted to assist in the technoeconomic assessment of UHCS and superplastic forming. A first draft has been received by the industrial partners, however this assessment cannot be completed until the forging experiments and testing of the forged part is completed.

During fiscal year 1993, the investigators published the following paper: "The Case for Ultrahigh-Carbon Steels as Structural Materials", D.R. Lesuer, C.K. Syn, A. Goldberg, and O.D. Sherby, *Journal of Metals*, Volume 45, Number 8, August 1993, pp. 40-46.

National Public Television included an excellent description of this research and its benefits in their televised special "The Stuff of Dreams".

DIRECT STEELMAKING

Steelmakers have long sought a direct steelmaking process which would replace the blast furnace, coke plant, and basic oxygen furnace. After a worldwide review of technologies, a proposal to develop an in-bath, coal charged, smelting process, coupled to continuous refining, was submitted by the American Iron and Steel Institute (AISI) for Steel Initiative funding. This project was approved by DOE and funding began in May 1989. The project is being managed by the AISI and the U. S. member companies of AISI are the cost-sharing participants.

The primary objective of this project is to develop an energy efficient, economically competitive, direct steelmaking process. The advantages of such a process would be: (1) more effective use of domestic raw materials, (2) continuous, rather than batch, operation, (3) eliminating the need for coke and the adverse environmental impacts of the coke manufacturing process, (4) ease of start-up and shutdown, and (5) modular design, which will facilitate incremental adjustments in capacity, and thus easy adaptation to market conditions. Such a process would reduce the capital cost required for new steelmaking facilities by approximately 40 percent. The current operating costs for a modern integrated plant are estimated to be approximately \$175 per ton of molten steel. Direct steelmaking is expected to reduce these costs by \$20 per ton. The estimated energy savings is 20 percent, therefore nation-wide implementation of this process would save approximately 0.2 quadrillion BTUs per year. The replacement of these facilities would reduce greenhouse gas emissions and improve the ambient air quality through the reduction of volatile organic hydrocarbons and particulates emitted by the current processes.

The direct steelmaking process consists of a smelting vessel into which is charged coal, oxygen, and partially reduced iron ore. The offgas from the smelting vessel is used to preheat and prereduce the incoming iron ore. The key requirement for the success of this process is the efficient use of the energy of the gases generated by the combustion of the coal. The carbon in the coal is used as a reductant for the iron ore and as a source of thermal energy. Carbon monoxide is produced in the smelting process and must be combusted in the slag and above the

molten metal bath. The critical technical hurdles to overcome are the transfer of heat from the combustion of carbon monoxide back to the molten metal bath to support the endothermic reduction of wustite, and the attainment of a high metal-production rate.

Initially there were five main areas of experimental work on this project: (1) laboratory studies of the physical and chemical phenomena of smelting and refining steel, (2) laboratory-scale experimental work on post-combustion and heat and mass transfer, (3) laboratory and pilot-scale pre-reduction of hematite (Fe_2O_3) pellets to wustite (FeO), (4) smelting and refining in a pilot-scale smelter at Universal, PA, and (5) post-combustion trials in large-scale steelmaking furnaces.

Laboratory studies of the physical and chemical phenomena of smelting and refining steel were completed by MIT and Carnegie Mellon University in fiscal year 1991. The results from this university research were incorporated into the pilot plant program and are being used for modeling the overall smelting process. Laboratory studies on post-combustion and heat and mass transfer were completed by Union Carbide (now Praxair) and by McGill and McMaster Universities in fiscal year 1992. During fiscal year 1991-1992, laboratory and pilot-scale pre-reduction of hematite was studied at HYLSA. Here, large quantities of wustite were produced for the pilot-plant program, preliminary designs and specifications were prepared for a pilot-plant, and a demonstration moving-bed shaft preheater and prereducer. Simulated smelter offgas, at 40 percent post-combustion (the percentage of fully combusted gas to total gas), was used successfully as the fuel and reductant for the moving-bed shaft furnace to produce hot wustite from hematite. Dofasco successfully completed foaming-slag and post-combustion trials in their commercial OBM furnace in fiscal year 1991.

A pilot plant was constructed at Universal, Pennsylvania, in fiscal year 1990. It is an integrated production facility composed of a smelting reactor supported by: (1) a solid materials handling system, (2) a 15-ton induction furnace that furnishes molten metal to begin the smelting trials, (3) a pneumatic injection system to feed pulverized materials into the vessel, (4) a system to supply production gases, (5) a cooling water system, (6) sensors with a data acquisition and

process control system, (7) an off-gas pollution control system, (8) a water-treatment system, and (9) laboratory facilities.

The first phase of the pilot smelting program ended in August 1991 with the completion of the vertical vessel campaign. Successful trials were conducted with char, anthracite, and low, medium, and high volatile coals as fuel and reductant. Data are now available to predict how the smelter should perform with different coals. Fine coal was also successfully injected into the smelting vessel. Practices were developed to maintain a stable, foamy slag wherein most of the reduction takes place. Oxygen is supplied to achieve partial combustion in the foamy slag and to promote post-combustion in the freeboard region above the slag. Combustion in these regions must provide the heat necessary to support the endothermic reduction of FeO. The smelter operated well both with cold wustite pellets and with cold hematite pellets. Sufficient operating experience was gained to establish that the process can be readily controlled, can be operated continuously, can be restarted quickly after a shutdown, and will be responsive to computer process control.

Based on the success of the first phase of the pilot-scale smelting program conducted with the vertical vessel in fiscal year 1991, AISI commissioned a basic study to analyze and assess the ironmaking process. This study for a 350,000 ton-per-year plant, was completed in fiscal year 1991 by an independent organization, Mannesmann Demag Corporation. The study predicted significant benefits in reduced capital and operating costs and indicated that the process' productivity would be about five times greater than the conventional blast furnace process. In addition, the direct ironmaking process offers lower energy consumption and provides greater flexibility when making incremental changes in plant ironmaking capacity. Mannesmann Demag completed a pre-engineering study for a 350,000 ton-per-year plant in fiscal year 1992 that also confirmed the promise shown by the vertical vessel campaign and the earlier basic study.

In fiscal year 1991, mathematical and physical modeling work at Carnegie Mellon and U. S. Steel research laboratories indicated that a two-zone smelting vessel would increase the productivity

of the process and lower the carbon content of the molten metal from approximately 4 percent to 1 percent. Therefore, a horizontal vessel was installed in fiscal year 1992 that could be operated as a single-zone vessel or, with a barrier, as a two-zone vessel.

The operating campaign began in January 1992, and continued into September. Initial operation of the horizontal vessel as a single-zone vessel demonstrated that good productivity and process control could be achieved while operating with three oxygen lances. The water-cooled roof worked well and heat losses were controlled. The slag level was controlled without visual observation by use of on-line process models. However, more precise knowledge of the slag level would be an improvement, therefore a radar foam-height detector is under development.

The horizontal smelting vessel was also operated as a two-zone vessel. An internal barrier allowed flow of liquid metal from the ironmaking to the steelmaking side through a submerged aperture in the barrier, while slag flowed in the opposite direction on top of the metal over the barrier. The production of steel containing one percent carbon was demonstrated.

A 350,000 ton-per-year plant was designed based on the operation of a pressurized smelter at three atmospheres. Pressurized operation improves productivity and provides the force to drive the offgas through the prereducing shaft furnace. AISI decided to validate this design by installing and operating a vessel pressurized to two atmospheres, with an offgas cleaning and tempering system capable of providing an offgas suitable for a prereluction shaft furnace.

Based on the successful pilot-scale smelting work completed prior to fiscal year 1993, AISI installed a pilot scale pressurized smelter, integrated with a gas cleaning and tempering loop. The goal is to demonstrate sustained stable operation at a production rate of 10 tons per hour of molten iron using wustite pellets. Accomplishments in fiscal year 1993 included: (1) installation of the pressurized vessel and associated equipment; (2) initiating the pressurized smelting program; (3) thirteen hour smelting tests, with a continuous operation of 3.5 hours, have been conducted using the hematite pellets and mid-volatile coal; (4) production rates up to

5.8 tons per hour with 37 percent post combustion of smelter gasses have been demonstrated with the hematite pellets and mid-volatile coal (this is equivalent to 7.5 tons per hour with wustite pellets); and (5) problems with the bulk material handling system have been resolved. Based on the results to date, it appears that the project's goals for productivity, coal rates, and environmental benefits will be satisfied.

During fiscal year 1993, AISI assembled a task force to examine both batch and continuous refining alternatives for converting the hot metal into steel.

The following technology transfer activities were completed during fiscal year 1993:

Patents Applications:

"Fuel and Oxygen Addition for Metal Smelting or Refining Process", Mark Schlichting.

"Lance for Fuel and Oxygen Injection for Smelting or Refining furnace", Mark Schlichting.

In addition three Invention Disclosure Documents were filed.

Publications:

J. M. Farley, P.J. Koros, "The AISI-DOE Direct Steelmaking Process - Raw Materials Requirements", *MINExpo International '92 Session Papers*, November 1992, pp. 203-224.

L.B. McFeaters, R.J. Fruehan, "Desulfurization of Bath Smelter Metal", *Metallurgical Transactions B*, Volume 24B, June 1993, pp. 441-447, and *1993 Steelmaking Conference Proceedings*, Volume 76, pp. 671-677.

T. Nagasaka, R.J. Fruehan, "Kinetics of the Reaction of H₂O with Liquid Iron", *1993 Steelmaking Conference Proceedings*, Volume 76, pp. 713-721.

E. Aukrust, "Planning for the 400,000 tpy AISI Ironmaking Demonstration Plant", *Ironmaking Conference Proceedings*, pp. 341-346 and *Iron and Steelmaker*, June 1993, pp. 14-16.

H. Gou, G.A. Iron, W.K. Lu, "Mathematical Modeling of Postcombustion in a KOBM Converter", *Metallurgical Transactions B*, Volume 24B, 1993, pp. 179-190.

G.G. Krishna Murthy, Y Sawada, J.F. Elliot, "Reduction of FeO Dissolved in CaO-SiO₂-Al₂O₃ Slags by Fe-C Droplets", *Ironmaking and Steelmaking*, Volume 20, 1993, pp. 170-190.

G.G. Krishna Murthy, G.G. Hasham, U.B. Pal, "Reduction Rates of FeO in CaO-SiO₂-Al₂O₃ -X Slags by Fe-C Droplets", *Ironmaking and Steelmaking*, Volume 20, 1993, pp. 191-200.

M.B. Mourao, G.G. Krishna Murthy, J.F. Elliot, "Experimental Investigation of Dissolution Rates of Carbonaceous Materials in Liquid Iron-Carbon Melts", *Metallurgical Transaction B*, Volume 24B, 1993, pp 629-637.

In addition six presentations were made at various technical conferences.

ELECTROCHEMICAL DEZINCING OF STEEL SCRAP

Galvanizing is a process that applies a zinc coating to steel in order to prevent corrosion. Unfortunately, when galvanized steel scrap is recycled back into steelmaking and foundry melting operations, the zinc coating causes severe operating and environmental problems. The objective of the Electrochemical Dezincing of Steel Scrap project is to design, construct, and continuously operate a research pilot plant to remove and recover zinc from steel scrap. This work is being performed by Argonne National Laboratory and Metal Recovery Industries (U.S.), Inc. Metal Recovery Industries is the owner and operator of the pilot plant and the cost-sharing partner in this project. Technical assistance is being provided by an industrial advisory board composed of representatives from the steel and foundry industries (the major consumers of steel scrap), scrap dealers, and zinc producers.

Electrochemical dezincing is a two-step process. In the first step, the zinc bearing scrap is charged into an electrolytic cell containing a 70-90 °C aqueous sodium hydroxide electrolyte. An electrical potential is applied resulting in the anodic dissolution of the zinc into the hot caustic. The clean scrap is then removed from the cell, rinsed in water, and recycled. The electrolyte is pumped into a second cell where the zinc is electrolytically removed from the solution. The slightly oxidized zinc is then sold to zinc manufacturers for purification and resale.

The types of prompt scrap (e.g., automobile stamping plant returns) that are being dezincing in this project include hot-dipped, electrogalvanized, galvanized, galvalume, and nickel-zinc coated materials. The project will also dezinc specially prepared obsolete scrap (e.g., junked automobiles) that simulates the higher zinc contents predicted in future scrap streams.

There are four major tasks in this project: (1) design, build, and operate a pilot plant for the continuous dezincing of steel scrap; (2) produce 5,000 tons of dezincing scrap for melting in industrial furnaces and recover an estimated 100 tons of zinc; (3) provide a technoeconomic

assessment of the dezincing process; and (4) perform market development for dezincd scrap and recovered zinc.

The important technical hurdles in this research are: maintenance of anodic contact with the scrap; demonstration of continuous operations over a sustained period; determining the influence that the various coatings used on steel have on the dezincing process; and the conveyance of loose scrap through the electrolytic cell.

By the end of fiscal year 1992, Metal Recovery Industries had completed construction of their pilot plant with the exception of the zinc recovery system. The plant was used in fiscal year 1993 to dezinc over 600 tons of automotive stamping plant scrap; zinc removal was over 90 percent complete. About 80 tons of dezincd material were melted in induction furnaces and judged satisfactory by a captive-automotive foundry. This foundry requested and has received a commercial proposal for dezincing on a toll basis. About 1,500 tons of scrap are being dezincd, baled, and accumulated to execute a basic oxygen furnace test program. In addition to determining the effect of dezincd scrap on furnace operations, this test program will examine the integrity of large bales of shredded and loose stamping plant scrap composed of various types of galvanized scrap, and will test the process on about 400 tons of exclusively hot dipped shredded material. Since, hot dipped zinc coatings are the slowest to dissolve in the hot caustic this will establish the maximum retention time required for effective dezincing. A memorandum of invention has been filed for a discovery that could significantly increase production rates. Pilot plant operation has also resulted in refined mass and energy balances, refined process economic projections, and an improved understanding of the world market for the dezincing process. Serious inquiries about licensing the dezincing process have been received from Europe and Japan. A Japanese firm has sent scrap from Japan for dezincing tests in the pilot plant.

The zinc recovered from dezincing 600 tons of prompt scrap has been stored in the dezincing solution. In fiscal year 1994, the zinc recovery circuit will be completed and this zinc will be recovered. The zinc product will be distributed to interested parties for evaluation.

Improvements to the pilot plant to enhance throughput are planned for fiscal year 1994, and the effectiveness of the process on obsolete automotive scrap will be examined.

The application of this process to 4.5 million tons per year of galvanized scrap is estimated to: (1) conserve 0.05 quadrillion BTUs per year of energy; (2) reduce raw material costs to the U.S. iron and steel industry by at least \$140 million per year; and (3) reduce the need to import at least 135,000 tons per year of zinc at a cost of \$128 million per year.

Dezincing of steel scrap has environmental benefits in addition to the recycling benefits. Since iron-rich steelmaking fume captured in the gas cleaning system will not be contaminated with zinc, it can be used as a charge material for sinter plants and then recycled back into the blast furnace. Because zinc is toxic to some aquatic plant and animal life, elimination of zinc from scrap will eliminate the problem of zinc in the effluent water from wet pollution control systems used in the steel industry. Since cadmium and lead are removed with the zinc in the hot caustic, this process will minimize their incorporation in fumes generated during the steelmaking process.

The following technology transfer activities were completed in fiscal year 1993:

J.F. Dudek, E.J. Daniels, and W.A. Morgan filed a Memorandum of Invention entitled: "Improved Process for Degalvanizing Steel", Invention Report ANL-IN-93-063.

P.J. Koros, R.P. Muhlhan, "Zinc and Steel Scrap - Continued Recyclability and Zinc Recovery", *Proceedings of the 1993 International Zinc Conference*, American Zinc Association, Scottsdale, Arizona, February 21-24, 1993.

J.F. Dudek, E.J. Daniels, and W.A. Morgan, "A Process for Dezincing Galvanized Steel Scrap, Conference on Pollution Prevention for the Iron and Steel Industry", U.S. Environmental Protection Agency, American Iron and Steel Institute, and American Institute for Pollution Prevention, Chicago Illinois, October 14-15, 1992.

J.F. Dudek, E.J. Daniels, and W.A. Morgan, "Recycling Galvanized Steel: Operating Experience and Benefits", *Proceedings of the International Symposium - World Zinc '93*, Australian Institute of Mining and Metallurgy, and Canadian Institute of Mining, Metallurgy, and Petroleum, Hobart, Tasmania, Australia, October 10-13, 1993.

M. Pinkam, "Efforts Aimed at Cutting Dezinc Costs", *American Metal Market*, August 6, 1993, p. 8.

RAPID ANALYSIS OF MOLTEN METALS USING LASER PRODUCED PLASMA

The Rapid Analysis of Molten Metals Using Laser Produced Plasmas (LPP) project is in its second year; it began in September 1992 with the signing of a Financial Assistance Agreement with Lehigh University. The research is being cost shared by AISI, the State of Pennsylvania through the Ben Franklin Fund, a consortium of North American metals producers, the Electric Power Research Institute, and Lehigh University.

This project is a two-phase effort to design, install, and test two molten metal analyzing probes employing a high power pulsed laser. The LPP sensor-probe achieves real-time, in-situ determination of the elemental composition of a steel alloy while it is still in the molten state. The current practice requires procuring a molten sample, and sending it in solid form to a remote laboratory for analysis. Thus significantly lengthening the time required to produce a "heat" of steel. Deployment of the LPP sensor-probe is estimated to result in an 8.7 percent reduction in heat time. Other benefits include an estimated 0.4 percent improvement in yield and lower alloy and refractory costs, plus increases in productivity and product quality. The energy benefit is estimated to be 0.01 quadrillion BTUs per year under full application of the technology. LPP analysis of molten (and solid) metal should find applications in other materials industries.

The goal of Phase A is to develop a protocol for calibration of molten metal compositions and to identify refractory materials for manufacturing sheaths for that portion of the probe which penetrates the molten steel. Phase B is the industrial demonstration of the LPP sensor-probes. Phase B tasks includes designing, installing, and testing two probes at two different steel plants and locating a manufacturer to commercialize the probe.

The key to protocol development is the generation of a highly reproducible plasma plume (a fireball of alloy elements in exactly the same proportion as in the molten alloy) by pulsed laser illumination of the molten metal surface. This requires that the molten sample be produced rapidly and predictably in shape, temperature, and composition; that a plasma be produced using

a single laser pulse; and that the quantitative measures of the spectral emission intensities be fully determined at once. The technique invented to perform this research is to insert a rod-shaped specimen, 2 inches long and 0.25 inch in diameter, into a radio frequency (RF) induction heating coil where a small volume of steel on the top of the specimen is melted. The molten metal, rather than dripping down the rod like wax on a burning candle, is electromagnetically levitated to remain atop the rod. In this position it is exposed to the laser pulse to produce the plasma emission spectra to be detected. When the RF power is removed, the sample resolidifies into a hemispherical button on top of the rod. Following a check analysis by conventional analytical means, the button becomes a member of a complete set of molten metal calibration standards for single or multiple elements. In this manner, calibration curves have been developed for manganese, carbon, silicon, aluminum, and sulfur in a wide range of molten steel alloys.

The task of selecting the sheath materials for the penetration tube of the LPP sensor-probe has been successfully completed. The criteria for the sheath refractory are high resistance to thermal shock, high melting temperature, non-wetting to molten metal and slag, and long-term dimensional stability. Phase A is about to be completed. The remaining work consists of developing the calibration curves for the other elements normally found in steel, and establishing the long term performance statistics for the refractory sheath material. Phase B of this project, industrial trials, has been initiated. The two host sites for the two LPP sensor-probe systems have been selected. The first unit will be tested in a steel plant in fiscal year 1994. Following this work, it will be upgraded and demonstrated at the second host facility during fiscal year 1995.

DIRECT STRIP CASTING

The Direct Strip Casting project began in September 1991 as a 36-month effort designed to cast carbon steel strip directly on a rotating, water-cooled wheel. Armco, Inc. is the prime contractor and Westinghouse Electric Corporation is a cost-sharing partner. This Metals Initiative Project is a continuation of an earlier Armco/DOE project funded outside the Steel and Metals Initiatives. In the prior work, a 4-inch wide low carbon steel strip was cast in 500 pound heats. The objective of the current project is to increase the width and thickness of the cast strip, improve the top-surface quality, improve gauge control, and increase process productivity.

The major elements of work in this project are: (1) operate a single-wheel caster to produce 1000-3000 pound heats of steel strip, 12 inches wide in controlled thicknesses throughout the range of 0.03-0.125 inch; (2) develop process control sensors; (3) investigate magneto-hydrodynamic applications for molten steel flow control; (4) improve refractory materials; (5) perform process modeling; and (6) prepare a technoeconomic assessment of the process including conceptual engineering for a pilot plant.

During fiscal year 1993, much progress was made increasing both the thickness and quality of the strip. Quality was improved through improved mechanical stability in the critical solidification region and a change in substrate material that achieved a more uniform heat transfer. These have greatly reduced the incidence of cracking, which has been the most serious quality problem. Cast thicknesses have increased from .040 inches to around .065 inches for carbon steel. These improvements have come about through some major additions and modifications to the caster, which have consumed much of the fiscal year 1993 effort.

Support for the solidified strip as it exits the wheel was improved by the addition of a run-out table and upper pinch rolls on the caster that serve to isolate the sensitive solidification region from downstream handling. Also, the table was designed to make the cooling of the strip more uniform. This has resulted in decreased stresses and reduced hot tearing. Dimensional stability

in the solidification region was improved by modifications to the mounting system of the substrate wheel to reduce wheel-to-nozzle gap variations. Operating practices were changed to maintain a more uniform and stable thermal profile at the wheel and nozzle interface. The strip's thermal condition is constantly monitored using a thermal imaging camera. Other developments contributing to stable cast conditions and quality strip include: mold level sensing and control, on-line substrate conditioning using an array of grit blast nozzles, continuous nozzle and substrate temperature monitoring, and improved inert gas shrouding of the melt pool. While not all of these new systems are completely debugged, their effect on strip quality has been clearly demonstrated.

Larger cast thickness requires longer contact time between the melt pool and the substrate. New nozzle designs have increased the contact length from 3 inches to nearly 6 inches on the 24 inch diameter wheel. Additionally, flow control devices in the nozzle have reduced the tendency for corner freezing which allows for slower cast speeds and thus longer solidification times.

The laboratory scale experiments for electromagnetic metal flow control at the nozzle and wheel gap produced negative results. Further efforts in this area were canceled. The modeling program has been very successful. The solidification model is now routinely used for planning and analysis of the casting trials. All major modifications to nozzle design have been tested and refined using both the water and mathematical models.

A survey of nozzle refractories was performed using actual casting trials to evaluate performance. Of the seven materials tested, two prime candidates emerged.

Finally, in order to examine the nature of the cracking problem, several austenitic stainless trials were conducted to avoid the solid-state phase transformation in carbon steel. The surface quality of the stainless steel strip was markedly superior to carbon steel, thus confirming that cracking is a hot tearing problem resulting from solidification stresses at a critical region of strip formation. The increased strength of the austenitic steel permitted casting up to 0.075 inches thick.

In August 1993, Armco, Inc. advised DOE that it will withdraw from this project. Since this project was funded, the corporation has restructured and Armco is now a stainless and alloy steel producer. Since this project is intended to develop a process to produce carbon steel strip, it no longer fits into Armco corporate strategy. The Department of Energy is now working with Armco to bring this research to a conclusion and preserve the knowledge gained thus far.

Y. Sahai and R. Williams presented "*Modeling of Melt Flow in Strip Casting Tundish*" at the ISS Near-Net-Shape Casting Symposium, Scottsdale, AZ, Feb, 1993. In addition two patent disclosures were made.

ADVANCED PROCESS CONTROL FOR THE STEEL INDUSTRY

The Cooperative Agreement between DOE and the American Iron and Steel Institute for the Advanced Process Control project was signed April 29, 1993, initiating the five year, 23 million dollar program. The Advanced Process Control Program consists of six very diverse sensor and control system research tasks that focus on many aspects of steelmaking, ranging from basic oxygen furnace offgas composition sensors to an online instrument that measures phase distributions in galvanized sheet. This program has the strong support of the steel industry and indicates its commitment to collaborative research and development. It brings together the collective resources and capabilities not only of the Department of Energy and the steel industry, but also of distinguished universities, national laboratories, and advanced technology companies.

Each task in the program is an individual R&D project consisting of three key components:

1. One or more **Research Organizations** to perform the research through the appropriate investigative, developmental, prototyping, and verification phases.
2. A **Sponsoring Steel Company** acting as technical advisor on the project providing steelmaking know-how and specialized knowledge to be incorporated into the design of the sensor and control system. The sponsoring steel company will install prototype equipment on its production facilities for online testing.
3. A **Commercialization Organization** which will be an equipment manufacturer with the resources to commercialize the proven equipment or system.

The project participants are listed in Table 1.

When implemented in the American steel industry, the technology developed by this program is expected to result in a savings of approximately \$316,000,000 per year, which includes an annual energy savings of 0.014 quadrillion BTU.

	Task A Optical Sensors and Controls for Improved <u>BOF Operations</u> Sandia National Lab. Fossil Energy Research Corp.	Task B Improved Liquid Steel Feeding for Slab <u>Casters</u> Westinghouse North American Refractories Co.	Task C Microstructure Engineering for Hot <u>Strip Mills</u> NIST University of British Columbia
Research Organization			
Commercialization Organization	Insitec Measurement Systems	Westinghouse	Northwest Mettech Co.
Sponsoring Steel Company	Bethlehem Steel	U.S. Steel	U.S. Steel
	Task D Online Mechanical Properties <u>Measurements</u> Industrial Materials Inst. NIST	Task E Phase Measurement of <u>Galvanneal</u> Data Measurement Co. Jet Propulsion Lab.	Task F Temperature Measurement of <u>Galvanneal</u> Oak Ridge National Lab. University of Tennessee
Research Organization			
Commercialization Organization	Ultra Optec Data Measurement Co.	Data Measurement Co.	To Be Determined
Sponsoring Steel Company	LTV Steel	Inland Steel	National Steel

NIST: National Institute of Science and Technology

Table 1. Summary of Project Participants

Task A - Optical Sensors and Controls for Improved BOF Operation

The objective of Task A is the development of optical sensors for the basic oxygen furnace (BOF). The activity is organized in three parallel elements. The first element will provide the necessary research and development to produce optical sensors for real-time measurement of composition and temperature of the BOF off-gas components: CO, CO₂, and H₂O. The second will focus on the development of optical sensors for measurements of bath and hot spot temperatures from within existing oxygen lances. The third focuses on the use of this new online process information to develop a BOF control strategy.

Laboratory work at the Sandia Combustion Research Facility was initiated to develop optical sensors for the BOF off-gas. Theoretical modelling of infrared absorption spectra for CO/CO₂/H₂O mixtures was begun to determine optimum wavelength regions for the measurement of off-gas temperature and composition. Results of the model calculations were confirmed with high resolution Fourier transform infrared (FTIR) spectroscopy on high-temperature post-flame gas mixtures produced in a laboratory burner. Several pairs of adjacent CO lines were identified as promising candidates for gas-phase concentration and temperature determination.

Work was also initiated at the Combustion Research Facility to develop an optical sensor for measuring bath and hot spot temperatures in the BOF. Work is focused in two areas: (1) design, construction, and testing of a portable, remote-controlled thermography unit; and (2) detailed planning of field experiments scheduled for the BOF shop at the Bethlehem Plant.

Task A has three specific near term objectives: (1) to characterize the radiative environment inside the BOF, with particular emphasis on quantifying the emissions from the slag and refractory; (2) to characterize the optical properties of turbulent steel melts exposed by bottom injection; and (3) to evaluate promising sensor components and configurations for inclusion in the full scale lance based sensor.

Task B - Improved Liquid Steel Feeding for Slab Casters

Current caster feeding systems suffer significant problems due to alumina clogging of component parts when pouring low-carbon, aluminum deoxidized steels. This clogging occurs as a result of flow patterns caused by mechanical moving parts. Clogging causes quality problems and premature discarding of flow control components. To solve these problems, the objective of Task B is the development of an electromagnetic valve system with no moving parts. The important tasks of fiscal year 1993 were a literature survey of anti-clogging phenomena, preparation for pouring trials to test the performance of a prototype electromagnetic valve, and research into new refractory material.

The literature review on alumina clogging in aluminum deoxidized steels was completed on schedule. Four possible mechanisms for alumina clogging were identified. Flow deposition of alumina on the walls (by either flow separation/re-circulation or by boundary layer motion) is believed to be the primary mechanism of clogging.

The preliminary design of the test tundish for the casting trials was completed. The tundish design is a "batwing" or "V" shape channel with a dam in each leg. Preliminary design of the test platform was completed. It will use as much of the existing Westinghouse equipment as possible. This reduces the fabrication costs. Bids are under review for the detailed design of this equipment.

North American Refractories Company began the refractory development work. They have identified six potential material groups for the nozzle material. The critical parameters for the refractory selection have been identified as:

- Electromagnetic properties (electrical conductivity).
- Erosion resistance and compatibility with liquid steel.
- Thermal shock resistance, conductivity, and expansion.

- Thermo-mechanical properties and their influence on erosion resistance.
- Resistance to alumina clogging.

The nozzle design will consider both a unibody and a composite approach in the preliminary stages.

Task C - Microstructure Engineering for Hot Strip Mills

The Microstructure Engineering project will develop a predictive tool which can quantitatively link the properties of hot rolled products to the process parameters of a hot strip mill. The predictive tool will be a user-friendly computer model which incorporates heat flow, knowledge of microstructural phenomena (recrystallization, grain growth, precipitation, and austenite decomposition), and structure-property relationships to compute the thermal and microstructural evolution of steel during hot rolling and the final product properties as a function of mill design and operating practice. The project concentrates on difficult, property-critical microalloyed steel grades. Major activities in fiscal year 1993 were computer model analyses of the U. S. Steel-Gary Works' hot strip mill and experiments in the microstructural behavior of Columbium and Vanadium bearing steels.

Early in the project year, data was received from U. S. Steel on various mill parameters for 100 coils. Modeling was carried out for five stand rough rolling and seven stand finish rolling separately. Results from the modeling (at present) indicate that the existing University of British Columbia temperature-microstructure model is basically applicable to the continuous hot-rolling mills at Gary Works. The heat-transfer model for both rough rolling and finish rolling compared reasonably well with measured data, although the temperatures predicted by model are lower than those measured in practice at the roughing mills and higher than those measured at finishing mills. Currently, the investigators are analyzing new temperature data from U. S. Steel. When the analysis is complete, further modeling will compare the results with the measured data and

decisions will be made as to what revisions of the existing model are necessary, or if in-plant temperature measurements at Gary are required. Pilot plant trials on U. S. Steel's pilot plant hot strip mill were conducted to measure heat-transfer coefficients. The results are under evaluation.

A series of "round robin" tests were initiated in order to compare the test apparatus at University of British Columbia and National Institute of Standards and Technology. Compression testing on one grade is complete, tests on the second are on-going.

An image analysis computer program for quantitative microstructural evaluation has been completed. The program is designed to quantify inclusion content and distribution, pearlite volume fraction, grain size, grain orientation, and grain morphology of the steel. Data on these variables are collected at five locations in the cross sections of each sample: near top surface, quarter-thickness, mid-thickness, three-quarter-thickness, and near bottom surfaces. At each location in the cross section, a minimum of 36 different fields are measured. The data are analyzed to identify local variations and variations across the cross section of a sample.

This research on Microstructure Engineering for Hot Strip Mills resulted in the following professional society presentations:

"Modeling the Effect of Pinning Forces on Recrystallization Grain Growth", W. P. Sun, M. Militzer, J. Jonas, E. B. Hawbolt, Materials Week 1993 (Pittsburgh, October 1993).

Influence of Cooling Rate on Recrystallization and Precipitation During Hot Rolling", W. P. Sun, M. Militzer, J. Jonas, E. B. Hawbolt. ISS 35th. Mechanical Working Conference (Pittsburgh, PA).

Task D - Online Mechanical Properties Measurements

This objective of this task is the development of online sensors to determine mechanical properties such as grain size, yield strength, tensile strength, elongation, and n-value. Both magnetic and laser-ultrasonic sensors are being pursued. This project began in June with a kickoff meeting at the research offices of LTV Steel in Cleveland. Work on the magnetic sensor is underway. Contract negotiations for the laser sensor is not complete although talks were proceeding smoothly at the end of the fiscal year. The major fiscal year 1993 tasks included the identification and characterization of the magnetic properties of sheet steel.

The first phase of the program at NIST deals with the mechanical property characterization of three sheet steels. The steel grades selected for characterization were: a low carbon steel, an ultra low carbon steel, and a high strength, low alloy steel. Sample sizes and the number of samples per grade were agreed upon, based on obtaining statistically acceptable results for each grade. Sample selection by LTV Corporation and Weirton was initiated.

The following paper was presented discussing developments of the Online Mechanical Properties Measurements project: "Metallurgical Characterization of Selected Sheet Steels for Prospective Magnetic Properties Correlation", Y. Rosenthal, G.E. Hicho, L. Swartzendruber. Sixth International Symposium on Non-Destructive Characterization of Materials (Hilo, HI, June 1993).

Task E - Phase Measurement of Galvanneal

Galvannealing is the process which results in coating steel with a mixture of zinc and iron. Sheet products with this coating exhibit superior weldability and paintability characteristics and are replacing galvanized steel in many product applications including automobile body panels.

A critical parameter in making galvannealed sheet is the phase distributions in the zinc-iron coating. Presently this can only be measured offline in the laboratory. The objective of this task

is to develop an online instrument for measuring phase distribution. The major first year tasks are detailed x-ray and metallographic analyses of galvanized products by Data Measurement Corporation and Jet Propulsion Laboratory respectively.

The first set of galvanized samples from Inland Steel have been measured at Data Measurement Corporation and the data collected were within normal expectations. The samples were measured twice to avoid any random errors which would cause analysis problems. The samples were measured on different days and the laboratory gauge was monitored for drift during the night. In addition to Inland's samples, Data Measurement Corporation measured several "check" samples and five certified zinc foils. The foils act as a reference point to double check gauge performance. The samples have been forwarded to the Jet Propulsion Laboratory where destructive analysis to determine the actual alloy phase distribution is underway. Results comparing the two measurements will be available next fiscal year.

Task F - Temperature Measurement of Galvanneal

This project aims to develop the field of phosphor thermography, a non-contacting means of emissivity independent temperature measurement. The technique is based on measuring the decay rate of fluorescence emitted from a phosphor droplet on the object's surface. It is being applied to the problem of online temperature measurement of galvanneal sheet.

At the close of fiscal year 1993, this task had not started. Contract negotiations with Oak Ridge National Laboratory were ongoing and an agreement in principle had been reached.

WASTE OXIDE RECYCLING

In August 1993, DOE agreed to support a proposal from the American Iron and Steel Institute for a ten-month project entitled, "Steel Plant Waste Oxide Recycling and Resource Recovery by Smelting," to be conducted at the pilot smelter. This program is aimed at developing a process for recycling about 1.6 million tons of blast furnace sludge and dust, about 1.6 million tons of oxygen steelmaking sludge and dust, and about 0.4 million tons of rolling mill sludge that a steel industry task force on waste recovery has identified as potentially recoverable. Because much of this waste material is now being disposed of in landfills, successful recycling will conserve resources and benefit the environment.

The Waste Oxide Recovery Project will convert 1,000 to 2,000 tons of steel plant waste materials to pig iron. The project will also attempt the recovery of zinc and lead compounds contained in the dust for reprocessing by suppliers of these metals. Studies indicate that recycling of steelplant waste oxides through the smelter saves 25 - 50 percent of the energy that would be used in the blast furnace to produce a comparable amount of molten iron, that appreciable landfilling would be avoided, and that virtually all steel plant waste oxide materials could be economically recovered. The smelting process is completely enclosed so the wastes will be recovered in an environmentally friendly manner.

WETTABLE CATHODES FOR HALL-HEROULT ALUMINA REDUCTION CELLS

The objective of the wettable cathode project is to demonstrate the technical and economic benefits of electrolyzing alumina in commercial cells equipped with titanium diboride-graphite (TiB₂-G) cathodes. Retrofitting existing alumina reduction cells with these wettable cathodes has the potential to save 0.1 quadrillion BTUs per year. The first cell's test, originally scheduled for startup in November 1991 at Reynolds Metals' plant in Troutdale, Oregon, was relocated to Kaiser's Mead, Washington facility due to the temporary shutdown of the Reynolds facility. Work during fiscal year 1993 consisted of the production of the TiB₂-G cathode elements by Great Lakes Research, cell construction, installation of the process control system, and start-up and operation of the first cell.

The operation of the first cell was hampered by breakage of the TiB₂-G cathode elements, resulting in higher than desired cell operating voltages. This resulted in excessive sidewall erosion and failure of the cell after 145 days operation. Therefore the emphasis of the test program was shifted to determining the causes of the breakage. A combination of mechanical stresses caused by elements shorting to the anodes and fabrication flaws in the elements appear to be the dominant causes. Modifications to the operating procedures and control algorithms have been made to minimize the effects of anode shorting. Great Lakes continues to pursue improvements in element fabrication to eliminate internal flaws. Following resolution of the element fabrication problem and relocation of Great Lakes' fabrication facility to Niagara Falls, New York in fiscal year 1994, a second cell will be started at the Kaiser Mead plant to demonstrate the wettable cathode technology.

ENERGY EFFICIENT PRESSURE CALCINER

DOE has agreed to support a project with Alcoa entitled: "Energy Efficient Pressure Calciner." Pressure calcination of alumina will increase the competitiveness of the domestic aluminum industry because: (a) The alumina feed stock to the Hall-Héroult electrolytic cell will have improved physical properties, i.e. more uniform particle size and a lower attrition index that produces less dusting and therefore requires simpler environmental controls; and (b) the calciner will recover steam and use less energy per unit of production due to the lower operating temperature needed for calcination. The program consists of three phases that will be conducted consecutively. The phases address the development of the equipment needed, the design and economic analysis of a semi-commercial unit, and the construction and operation of the semi-commercial unit. When implemented on a commercial scale, the Energy Efficient Pressure Calciner could save the aluminum industry approximately \$160 million annually, or an estimated 3 to 5 percent of the operating cost of the aluminum operation to which the process is applied. The estimated energy saving potential is .01 quadrillion BTUs per year.

The Financial Assistance Agreement for this project is being negotiated by Alcoa and the Department's Idaho Operations Office.

SPRAY FORMING OF ALUMINUM

Alcoa is the prime contractor for the spray forming of aluminum project. The major subcontractors are Air Products & Chemicals, Olin Corporation, Massachusetts Institute of Technology, Idaho National Engineering Laboratory, and University of California-Irvine. The objective of this five year project is to translate current bench-scale spray forming technologies into a cost-effective process for the replacement of the energy intensive ingot casting method. Secondary objectives are an increase in aluminum recycling because of the ability to use off-specification aluminum with no loss of material properties, and to investigate the large scale production of alloys which will expand and create markets for aluminum.

The tasks required to accomplish these objectives are: (1) process development, (2) design and construction of a pilot plant, (3) product/alloy development, (4) investment analysis, and (5) program management.

The benefits of spray forming include:

- Energy savings over the ingot casting method of up to 27 percent;
- A cost savings of two cents per pound of finished sheet;
- Increased recyclability of aluminum products because microstructure can be controlled;
- Reduction in the waste produced in milling required for ingot cast alloys;
- Spray formed materials that are metallurgically superior to those from other cast methods;
- Facilitation of the use of aluminum parts and panels which leads to fuel savings; and
- Better combinations of corrosion resistance, strength, and toughness due to finer grain size.

The Financial Assistance Agreement for this project is being negotiated by Alcoa and the Department's Idaho Operations Office.

ACTUAL OBLIGATION OF DEPARTMENT OF ENERGY FUNDS

Steel Initiative funds were first released to DOE in July 1986. The appropriations history is as follows:

FY 1986	\$ 7,134,000
FY 1987	2,000,000
FY 1988	4,000,000
FY 1989	-0-
FY 1990	16,639,000
FY 1991	17,394,000
FY 1992	17,742,000
FY 1993	17,937,000
Total	\$ 82,846,000

Electromagnetic casting	\$ 2,184,000	(Discontinued)
Superplastic steel processing	4,026,000	
Spray-forming steel - Phase I	5,908,000	(Completed)
Direct steelmaking	45,298,000	
Steel Plant Waste Oxide Recycling	3,556,000	
Direct strip casting	3,901,000	
Electrochemical dezincing of scrap	1,400,000	
Molten metal analysis	3,019,000	
Advanced process control	4,508,000	
Aluminum cell cathodes	3,188,000	
Energy Efficient Calciner	496,000	
Spray Forming of Aluminum	2,121,000	
Program Support	3,241,000	
Subtotal	\$ 82,846,000	

INDUSTRY COST-SHARING

Industry has provided the legally required cost-sharing on each project. The original Steel Initiative program required industrial cost-sharing equal to 30 percent of the DOE share, or 23 percent of the total cost of a project. The new Metals Initiative Program, which replaces the Steel Initiative, increased the required industry cost-share to 30 percent of the total cost of a project.

The value of industry cost-sharing at the close of fiscal year 1993 was as follows:

Superplastic Steel Processing

Participant	Contributions through September 30, 1993	
North Star Steel	\$351,216	(estimated)
Caterpillar Inc.	\$739,194	
Ladish Company, Inc.	\$103,878	(estimated)
Total	\$1,194,288	

The Department of Energy expenditures for superplastic steel processing for all project work is \$3,600,000 through September 1993. Thus the value of industry's cost-sharing contribution is estimated to be over 33 percent of DOE expenditures. The Steel Initiative requires that industry's cost-share be 30 percent of the DOE contribution, thus industry's participation in superplastic steel processing is above the mandated minimum.

Direct Steelmaking

The value of the American Iron Steel Institute's cost-sharing at the close of fiscal year 1993 was \$12,860,022 which is equal to 30 percent of the DOE' expenditure of \$42,859,310 at the close of fiscal year 1993.

Electrochemical Dezincing of Steel Scrap

Through the end of fiscal year 1993 DOE has contributed \$1,400,000 to this project while Metal Recovery Industries (U.S.), Inc. has contributed \$1,453,000, which is well over the required 30 percent contribution.

Rapid Analysis of Molten Metals Using Laser Produced Plasmas

The total cost of Phase A of this project is \$574,084. The cost-sharing contributions are \$179,879 or 31 percent. For Phase B, DOE obligated an additional \$1,200,000 to this project for field testing the first probe. Industry will provide an additional \$360,000 or 30 percent of the DOE share to perform this work.

Direct Strip Casting

Through the end of fiscal year 1993, DOE had spent \$2,417,593 while Armco was estimated to have contributed \$1,036,111, which is equal to 30 percent of total expenditures. This project has been terminated at Armco's request; DOE will spend an additional \$73,092 while Armco will contribute \$31,325 in order to close down the work in an orderly manner. Armco's contribution is equal to 30 percent of the closeout costs.

Advanced Process Control

This project was initiated in fiscal year 1993. Total expenditures through the end of the fiscal year were \$665,846 with DOE contributing \$466,902 and AISI contributing \$199,754 or 30 percent of the total expenditures.

Wettable Cathodes for Alumina Reduction Cells

The value of Reynolds' cost-sharing at the close of fiscal year 1993, was \$851,463. This is 30 percent of the total value of the project, which is \$2,838,210.

ANTICIPATED OBLIGATION OF DEPARTMENT OF ENERGY FUNDS

The industrial partners may decide to attempt further 40 ton casting trials in the **Superplastic Steel Processing** project. No estimate of the added costs are available at this time.

Direct Steelmaking will require \$14,100,000 in fiscal year 1994; of this, \$1,091,000 is required to complete the pilot plant work and 13,009,000 will be used to initiate a **350,000 ton per year ironmaking demonstration** project. If funds are available, the demonstration plant would require an additional \$90,000,000 over a 5 to 7 year period.

Funding for **Electrochemical Dezincing of Steel Scrap** is complete. On the assumption that no unforeseen barriers are encountered, no further funding is required.

Rapid Analysis of Molten Metals Using Laser Produced Plasmas will require \$284,000 in fiscal year 1994. On the assumption that no unforeseen barriers are encountered, no additional funds will be required for this project.

The **Direct Strip Casting** project with Armco, Inc. is terminated. No further funds will be required. However, because of its great energy and cost savings potential, this technology remains an area of great interest both to DOE and to the steel industry.

The **Advanced Process Control** began with funds from fiscal year 1991 and fiscal year 1992. No funds were provided during fiscal year 1993, but \$3,109,000 will be required in fiscal year 1994. If funds are available, an estimated \$4,320,000 in fiscal year 1995 and \$4,017,000 in fiscal year 1996 would be required.

Waste Oxide Recycling requires no added funds for fiscal year 1994; if funds are available, \$1,094,000 would be required in fiscal year 1995.

Wettable Cathodes for Alumina Reduction Cells will require an additional \$400,000 in fiscal year 1994. On the assumption that no unforeseen barriers are encountered, no additional funds will be required for this project.

High Pressure Calcining of Aluminum Ores requires no funds in fiscal year 1994; if funds are available, \$428,000 would be required in fiscal year 1995 and an estimated \$3,000,000 in each of fiscal years 1996, 1997, and 1998.

Spray Forming of Aluminum Sheet requires no funds in fiscal year 1994; if funds are available \$6,700,000 would be required in fiscal year 1995, \$2,307,000 would be required in fiscal year 1996, and \$1,864,000 would be required in fiscal year 1997.

STATUS OF HOLDING COMPANY AGREEMENTS

As described on page 8 of the Management Plan, a holding company will be created or designated by the project's participants for the purpose of holding patents and licensing technology. The status of the holding company agreements with DOE is as follows:

The holding company for the **Superplastic Steel Processing** project is the University of California. The Holding Company Agreement was signed May 18, 1990.

The American Iron and Steel Institute has designated Steel Technology Corporation as the holding company for the **Direct Steelmaking** project. The Holding Company Agreement was signed June 1, 1989.

The holding company for the **Electrochemical Dezincing of Steel Scrap** project is Metal Recovery Industries (U.S.), Inc. The Holding Company Agreement was signed May 28, 1992.

The holding company for the **Rapid Analysis of Molten Metals Using Laser Produced Plasmas** project is Lehigh University. The Holding Company Agreement was signed September 28, 1992.

The holding company for the **Direct Strip Casting** project is Armco, Inc. The Holding Company Agreement was signed November 19, 1992.

The holding company for the **Wettable Cathodes for Alumina Reduction Cells** project is TIBCO Holdings. TIBCO holdings is a partnership formed by Reynolds Metals Company and Great Lakes Research Corporation for the purpose of commercializing this technology. The holding company agreement was signed June 3, 1993.

No holding companies have been established for the **Advanced Process Control, Waste Oxide Recycling, Energy Efficient Pressure Calciner, and Spray Forming of Aluminum** projects. It is the Department's goal to have the Holding Company Agreements fully executed during the first calendar year that the Co-operative Research Agreements are in place.

PROGRAM MANAGEMENT

The Department of Energy maintains frequent contact with the many institutions that have an interest in the Metals Initiative, including industry, universities, and government organizations, both state and Federal. The Department of Energy encourages discussion of emerging processes and of the Management Plan before any effort is made to prepare a written proposal.

Proposals continue to be submitted to DOE for funding consideration under the Metals Initiative Program. Proposals that fail to address the minimum requirements set forth in the Management Plan are rejected. Those that address the minimum requirements are subjected to a detailed peer review. In fiscal year 1993, a number of organizations expressed interest in the Metals Initiative and scheduled exploratory meetings with DOE. It is anticipated that DOE will continue to receive proposals aimed at increasing the energy efficiency and enhancing the competitiveness of the metals industry.

All proposals that address the requirements listed in the Management Plan undergo a detailed evaluation. This action is taken without regard to the availability of funds appropriated under the Act for new projects, in order to determine the relative merits of proposals if appropriations are made available.

Based on the results of the Metals Initiative Program to date, DOE has no recommendations for a change to the Metals Initiative legislation.

SUMMARY OF ACTIVITIES MANAGEMENT AND RESEARCH PLANS

Section 8 of the Act requires that the Annual Reports for fiscal year 1993, 1995, and 1997 contain "a complete summary of activities under the management plan and the research plan from the first year of their operation, along with an analysis of the extent to which they have succeeded in accomplishing the purposes of this Act", 15 U.S.C. 5107.

The updated Metals Initiative Management Plan outlines the roles and responsibilities of the various organizations involved in implementing the Act, including: the Federal Government, the national laboratories, industry, and universities. Other objectives of the plan are to provide information on non-Federal cost-sharing requirements, and to establish the organizational and administrative procedures which are to be followed in conducting the program. The Management Plan has been fully implemented.

Program management has been conducted in accordance with the plan. The Department of Energy's Office of Industrial Processes (formerly the Office of Industrial Programs), the Idaho Operations Office, and EG&G Idaho, Inc., have performed their assigned roles. Private industry, the potential users of the technology, have made the essential contributions to the Metals Initiative program. In addition to sharing at least 30 percent of the cost of each project, the companies submit research and development proposals, perform research and industrial trials, and serve in an advisory capacity for the benefit of the national laboratories and universities. The Department of Energy believes that technology transfer in the Metals Initiative Program is assured by the strong role played by private industry in the program.

The Department of Energy national laboratories were recognized as a source of technical expertise in the Management Plan, and therefore have been encouraged to submit field work proposals and to work with industry to develop new technologies. The national laboratories have responded enthusiastically. Currently four DOE laboratories (Argonne, Sandia, Oak Ridge, and

Lawrence Livermore National Laboratories), and two non-DOE Federal laboratories (National Institute of Standards and Technology and Jet Propulsion Laboratory) are performing Metals Initiative research. Through the Metals Initiative, the U.S. steel industry has come to recognize the national laboratories as a vital resource for their companies. The steel industry has provided a list of 17 problem areas and invited them to submit their proposed solutions.

Universities are playing a key role in the Metals Initiative. For example, on the Advanced Process Control project, the University of Tennessee is working with Oak Ridge and National Steel to develop an online temperature measuring system for galvanized steel. Carnegie Mellon University, and the Massachusetts Institute of Technology are major contributors to the Direct Steelmaking project. Lastly, Lehigh University is the prime contractor on the Rapid Analysis of Molten Metals project.

To ensure that the knowledge resulting from the research and development efforts will benefit the domestic industry, ownership of all intellectual property is waived to a holding company established by the participants in each project. The holding company licenses the technology and has the obligation of meeting the repayment provisions of the appropriations law. The status of the holding company agreements are detailed elsewhere in this report. In summary, except for projects which are less than one year old, all ongoing projects are now covered by a fully executed holding company agreement.

The Metals Initiative Research Plan continues to provide excellent guidelines for program priorities. For steel, the plan identifies ore-based steelmaking and near-net-shape casting as those technologies having the greatest potential to promote energy efficiency and improve competitiveness. The Department of Energy has made three financial assistance awards in these areas. Scrap beneficiation and thermomechanical processing were also identified as areas of opportunity; one financial assistance award has been made in each of these areas. Automated processing technology is also a high priority area; there are two ongoing projects in this area, and interest continues to be expressed by industry.

During fiscal year 1993, the American Iron and Steel Institute, Steel Manufacturers Association, and DOE sponsored a workshop entitled "Computer Automated Manufacturing in the Steel Industry." Over 100 representatives from the steel, computer, research, and academic communities participated. The workshop was a great success in aiding the Department's program planning efforts.

The Department's W. Obenchain presented papers entitled "The Metals Initiative Research Program and the Environment" at the Annual Meeting of the AIME's Iron and Steel Society, and "OIP Steel Industry Research" for the United States Trade Representative.

For the aluminum industry, the Research Plan identifies the highest opportunity to be the development of retrofit technologies to improve the efficiency of Hall-Heroult cells used in the production of aluminum from alumina. To this end, the Metals Initiative is supporting one project to develop wettable cathodes for Hall-Heroult cells. The new Spray Casting of Aluminum project results from the Research Plan which identified near-net-shape casting as an important area for research.

For copper, the Research Plan indicated that there is an opportunity to develop improved technologies for the extraction of copper from copper ores. No research proposals have been received for copper. The copper industry was informed of the Metals Initiative Program at the time that the management and research plans were published. During fiscal year 1991, DOE contacted all major copper smelting companies in the United States plus a number of universities and copper manufacturing associations to, once again, inform them of the Metals Initiative program. The Department of Energy maintains communication with the industry. All domestic copper producers will receive a copy of this Annual Report.

The Act has two purposes, to increase the energy efficiency and enhance the competitiveness of the American steel, aluminum, and copper industries, and to continue the research begun under the Steel Initiative. The latter purpose has been accomplished.

It is too early to judge the extent to which the activities under the Act have accomplished the twin goals of increased energy efficiency and enhanced competitiveness. However, several technologies are nearing commercialization. During the coming year, Superplastic Steel Processing will forge commercial parts for testing, and Rapid Analysis of Molten Metals will test a prototype unit in a steel plant. The results from the pilot plant research in Direct Steelmaking project are so promising that a proposal for a demonstration plant has been submitted to DOE. Electrochemical Dezincing of Steel Scrap is nearing commercialization. LTV Steel Company is planning a melting trial for 1500 tons in the Spring of 1994.

The proposal requirements detailed in the Management Plan have served well. Proposals which adhere to these instructions have enabled DOE to conduct its preliminary proposal review expeditiously. The procedures require that proposals meeting the Department's preliminary review be submitted for a detailed evaluation by a panel of experts in the subject technology. These panels, which are composed of private consultants and personnel from industry, universities, and the national laboratories, have provided DOE with excellent reviews.

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