CRADA NO. NFE-08-01464

OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE

FOR THE DEPARTMENT OF ENERGY

CRADA FINAL REPORT

A Study to Develop an Industrial-Scale, Computer-Controlled High Magnetic Field Processing (HMFP) System to Assist in Commercializing the Novel, Enabling HMFP Manufacturing Technology

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A Study to Develop an Industrial-Scale, Computer-Controlled High Magnetic Field Processing (HMFP) System to Assist in Commercializing the Novel, Enabling HMFP Manufacturing Technology

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The CRADA Final Report may describe the research done under the CRADA and/or incorporate technical data as needed to support conclusions.

ABSTRACT

As the original magnet designer and manufacturer of ORNL's 9T, 5-inch ID bore magnet, American Magnetics Inc. (AMI) has collaborated with ORNL's Materials Processing Group's and this partnership has been instrumental in the development of our ***unique*** thermo-magnetic facilities and expertise. Consequently, AMI and ORNL have realized that the commercial implementation of the High Magnetic Field Processing (HMFP) technology will require the evolution of robust, automated superconducting (SC) magnet systems that will be cost-effective and easy to operate in an industrial environment. The goal of this project and CRADA is to significantly expedite the timeline for implementing this revolutionary and pervasive cross-cutting technology for future US produced industrial components. The successful completion of this project is anticipated to significantly assist in the timely commercialization and licensing of our HMFP intellectual property for a broad spectrum of industries; and to open up a new market for AMI. One notable outcome of this project is that the ThermoMagnetic Processing Technology WON a prestigious 2009 R&D 100 Awards. This award acknowledges and recognizes our TMP Technology as one of the top 100 innovative US technologies in 2009. By successfully establishing the design requirements for a commercial scale magnetic processing system, this project effort has accomplished a key first step in facilitating the building and demonstration of a superconducting magnetic processing coil, enabling the transition of the ***High Magnetic Field Processing*** Technology beyond a laboratory novelty into a commercially viable and industrially scalable *Manufacturing* Technology.

STATEMENT OF OBJECTIVES

The primary objective for this project was to support and facilitate the transition of the *High Magnetic Field Processing* (HMFP) Technology beyond a laboratory novelty into a commercially viable and industrially scalable *Manufacturing* Technology. To achieve this goal, ORNL and AMI have collaborated to develop and evaluate the magnetic processing system hardware to: 1.) maximize the benefits and effects of magnetic processing; and 2.) be generically applicable to selected material systems of industrial interest and relevance, including selected ferrous and non-ferrous alloys.

Already a collaborator with ORNL in the development of this HMFP technology, AMI has collaborated with ORNL in this project to identify the design requirements required to investigate and develop a magnetic processing system design that would facilitate the commercialization of this technology.

To achieve this objective, AMI and ORNL have collaborated to: 1.) Develop different coil designs that could supply higher magnetic fields and larger bore diameters; 2.)

Evaluate/analyze these designs based on AMI's experience as well as perform the necessary calculations to achieve the most robust, yet, cost- and energy- effective designs needed for a magnetic processing magnet intended for use in industrial scale components; and 3) Provide a viable superconducting magnetic processing coil design of higher field (than 9T) that is a necessary step towards achieving the goal of a higher (11-Tesla six inch RT bore) superconducting magnet. This effort was anticipated to support and facilitate the building and demonstration of a superconducting magnetic processing coil that would be a key step in enabling the transition of the ***High Magnetic Field Processing*** (HMFP) Technology beyond a laboratory novelty into a commercially viable and industrially scalable *Manufacturing* Technology, by establishing these design requirements.

BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The key mission of the US DOE, Office of Energy Efficiency and Renewable Energy (EERE), Industrial Technologies Program, Energy Intensive Program (EIP) is to improve the energy efficiency and energy utilization in energy intensive US industries. The goal of this project is to improve the energy efficiency of processing ferrous and non-ferrous alloys in energy intensive US industries. The Superconducting (SC) magnets being developed in this CRADA High Field Magnetic Processing (HMFP) technology project provide a more energy efficient materials processing technology than other conventional and/or currently available materials processing alternatives. Actual energy benefits estimated from the development and industrial implementation will come from the following facets of magnetic processing:

- Superconducting magnets will be employed
    - Once at full field, no additional energy is consumed (persistent mode.)
- Phase Kinetics are Enhanced
    - Dramatically reduced thermal processing times (less processing time)
- Magnetic processing is a non-thermal process,
- Cryogenic and thermal treatments can sometimes be eliminated

TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

In order to accomplish the objectives of this project, ORNL and AMI have participated in many telecons and discussions together. ORNL has made numerous calculations to determine the extraction forces required for withdrawal of various sample sizes and weights from several magnet designs. In addition, AMI has considered several magnet system designs to achieve: 1.) viable higher magnetic field strength superconducting magnets with larger bore sizes; 2.) low maintenance cryostats; 3.) cryostats capable of withstanding and handling large (up to 2000 lb.) extraction forces; as well as simplifying the human user-to-magnet system interface.

AMI has provided two documents summarizing the results of their efforts- one details these design endeavors, and their other report details the most viable design criteria they determined considering the projected sample sizes anticipated. These reports are included as Appendices 1 and 2 in this final CRADA document. Only the results of these reports will be summarized here.

AMI's design efforts have yielded a 9T- 8-inch room temperature bore superconducting magnet system that is capable of handling up to a 2000 lb. extraction force generated by the Thermomagnetic Processing (TMP) of the various materials considered. AMI targeted a redesign for their current Power supply that would be better suited to be more user friendly. This redesign required the development of a new Power Supply Programmer and is an integral step in controlling the TMP system. This modification ensures smoother, and more consistent stable charging and discharging of the highly inductive superconducting magnet loads while eliminating magnet current oscillations. A menu driven format has also been developed that is more user friendly for use in commercial environments, allowing for more flexibility in power supply selection that can be accommodate a wider range of potential component applications. In addition, a rapid ramp-down feature has been added to minimize the otherwise much longer times that would be required. Push buttons have been incorporated where possible to simplify magnet operation for commercial settings. Additional features also have been added that minimize wiring confusion, enable the operator to more easily monitor and control the cryogen levels and protect against inappropriate operating conditions of the magnet, e.g., overvoltage, and overcurrent protections are built-in features of the controller. Remote interfaces now also include a RS-232 serial port, as well as an Ethernet port. All magnet controller settings can now be controlled via remote interfaces and trigger functions for data collection and/or logging are available during operation. These and additional features and specifications not summarized here for this new power supply and its controller are detailed in the first Appendix. The second Appendix summarizes AMI's evaluation of some additional modifications needed for systems or subsystems for operation of a superconducting magnet when it is transitioned from a laboratory to an industrial environment.

ORNL played a key role in making numerous calculations, including the axial and radial force gradients for a given magnet design, to determine the degree to which magnetic field uniformity and the length of the uniform magnetic field zone impacted the extraction forces that would be required to extract a given sample (weight and geometry). These results were compared with the extraction forces that are required for other available magnets, e.g., ORNL's current 9T magnet and the 20T -195mm bore magnet at the

National High Magnetic Field Laboratory (NHMFL). Based on these comparisons, These results suggest that up to ~ 5% uniformity over an 8" length (±4") represents a reasonable specification for most of the smaller sample size applications to date. This specification is estimated to be approximately equivalent to a specification of about 1.25% uniformity over a 4 inch length (for a solenoid of uniform current density).

SUBJECT INVENTIONS (AS DEFINED IN THE CRADA) - NONE

COMMERCIALIZATION POSSIBILITIES

The results developed as a result of this CRADA will provide the basis from which larger scale components will be able to be processed using HMFP.

PLANS FOR FUTURE COLLABORATION

The results from this work are being successfully used and implemented into updated magnet designs developed by AMI: 1.) to build a new 9T-8-inch bore superconducting magnet for ORNL; and 2.) to specify and build an 11T-5-inch bore SC magnet for Thermo-magnetic Processing of commercial scale components for another DOE-EIP project.

CONCLUSIONS

This CRADA has significantly accelerated the timeline for the development of a robust, automated, commercially-available, superconducting (SC) magnet system that can now be more easily implemented into a commercial system for larger scale industrial components. AMI and ORNL have collaborated to successfully accomplish this goal through an iterative process methodology of calculating and assessing the impacts of the various, desired, magnetic system options (e.g., maximizing the uniform field length, and inner magnet bore size), while still maintaining reasonable extraction forces on large ferromagnetic parts, that if too high would: a.) require either powering the magnet down or, b.) escalate the risk for quenching the magnet during processing. The limits of these various magnetic processing parameters were explored, and the relative (cost and energy efficiency impacts) resulting from them were determined for several viable, but different magnet design scenarios. As a result of this project, AMI has: 1.) Developed/evaluated different coil designs that can supply higher magnetic fields and larger bore diameters; 2.) Evaluated/analyzed these designs based on their experience as well as perform the necessary calculations to achieve the most robust, yet, cost- and energy- effective designs needed for a magnetic processing magnet intended for use in industrial scale components; and 3) Provided a viable superconducting magnetic processing coil design of higher (than 9T) field (a necessary step towards achieving the goal of an 11-Tesla five- inch RT bore superconducting magnet).

One notable outcome of this project is that the ThermoMagnetic Processing Technology WON a prestigious 2009 R&D 100 Award. This award together with our project results acknowledges and recognizes our High Magnetic Field Processing Technology as one of the top 100 innovative US technologies. This project effort provides a good and sound baseline for facilitating the building and demonstration of a SC magnetic processing system for the commercial implementation of the HMFP Technology. This project has defined a robust, automated SC magnet system that will be cost-effective and provide user-friendly operation in an industrial environment that: 1.) facilitates maximizing the benefits and effect of magnetic processing; and 2.) is generically applicable to selected materials systems of industrial relevance and interest, including selected ferrous and non-ferrous alloys.

By establishing these design requirements/criteria, this effort has accomplished a key, first step in facilitating the building and demonstration of a SC magnetic processing coil for enabling the transition of the High Magnetic Field Processing Technology beyond a laboratory novelty into a commercially viable and industrially scalable Manufacturing Technology.

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APPENDIX A

AMI Final Evaluation For Industrial Magnet System Applications

American Magnetics

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April 6, 2009

AMI Final Evaluation For Industrial Magnet System Applications

As part of subcontract 4000079653 American Magnetics, Inc. (AMI) has embarked on a path to redesign our superconducting magnet systems to be suitable for use in an industrial environment. Design efforts have focused on large bore high field superconducting magnets, efficient low maintenance cryostats, and an electronics suit that will be the corner stone to meet the requirement that High Magnetic Field Processing (HMFP) systems be automated, cost-effective, and easy to operate in an industrial environment.

Our design efforts have yielded a high field large bore superconducting magnet system designed for a 9 Tesla 8 inch Room Temperature Bore (RTB) system that is being purchased by ORNL as of the writing of this report. The associated cryostat for this system is capable of handling a 2,000 pound extraction force generated by Thermo Magnetic Processing (TMP) of various materials. The mammoth cryostat required for this system was designed to utilize liquid helium re-condensing technology in order to achieve near zero helium loss. Liquid helium has become an ever increasing concern as the global supply has diminished causing limited supply and escalating cost. Utilization of a re-condensing design results in extremely low maintenance requirements and lowered cost of operation.

Of key concern to the successful field deployment of TMP systems is simplification of the human to system interface. Traditionally superconducting magnet systems are designed for the research laboratory rather than industrial facilities. Following an evaluation of the systems and subsystems required for operation revealed that, with the exception of the magnet power supply controller, the majority of controls were somewhat benign. Operation of the superconducting magnet system is made through the power supply controller which allows the user to energize and discharge the magnetic field at a controlled rate, place and maintain the magnet in persistent mode as well as protect the magnet coil in the event of a quench. To this effect AMI has identified that a redesign of our existing Model 420 power supply controller would be beneficial to better offer industrial users intuitive control of the system.

To that end AMI has spent an extensive amount of time under this project developing a new Power Supply Programmer that will hence be known as the Model 430. Development of the Model 430 was an integral step in controlling the aforementioned TMP system. AMI's Model 430 is a reliable, compact, and economical superconducting magnet power supply programmer/controller that may be used in conjunction with many different power supplies. The Model 430 insures smooth, consistent and stable charging and discharging of the highly inductive superconducting magnet loads while eliminating all magnet oscillations.

A menu driven format guides the user to make inputs from the push button front panel interface by following simple menu driven language. This means the high precision capability of the Model 430 programmer can be applied to an extremely wide range of applications that will be required during TMP and offer customers much needed flexibility in power supply selection. Integration of AMI' s model 601, the magnetic field fast ramp down option permits the energy stored in large magnets as discussed above to be discharged rapidly. The discharge rate is determined by the voltage across the magnet terminal by the equation V = L di/dt. Since the inductance of a typical superconducting magnet may be several henries, it can take a very long time to discharge a magnet. The magnetic field fast ramp down option is capable of producing a constant 5-volt discharge. Current is routed from the power supply through the Model 601 and then to the magnet.

Front panel keypad and digital display allows direct and accurate entry of instrument settings. In addition to displaying the magnet voltage, either the magnet current or field in kilogauss or tesla is also displayed. The magnetic field readout is based on a user input coil constant. The Model 430 includes a regulated persistent switch heater current supply; the persistent switch is push-button activated. Power lead cable will connect conveniently to either vapor cooled or high temperature current leads of the magnet system.

Quench protection provides visual indication of a magnet quench and automatically sets the power supply output voltage to zero. The programmer prevents the power supply from initiating a recharge of the magnet current until the quench detection function is reset. A rear panel input is also provided for users who have a remote quench detection system. Another unique feature is a 25-pin rear panel connector on the Model 430 that allows the customer to connect signals such as cryogen level signals, temperature signals, experimental inputs, etc. directly from the cryostat. This means that all these signals can be easily combined into one standard shielded cable and eliminates the messy wiring, which often exists on experimental systems. Three separate output connectors are provided on the rear panel to route these signals to the appropriate devices. Overvoltage, overcurrent, and over temperature protection are built-in features of the controller.

The Model 430 provides remote interfaces via RS-232 serial port as well as an Ethernet port. All settings can be controlled via the remote interfaces and the front panel can be remotely locked to prevent accidental operation. The Model 430 also provides trigger functions for data collection and/or logging during operation.

Model 430 Specifications @ 25 °C

Magnet Current Control Parameters	Standard Model 430 Configurations: Programmable Limits						
	± 5 A	**± 10 A**	±125A	**±250A**	± 300 A	**±600A**	±2000 A
Measurement Resolution:	0.625 pit	1.25 pA	15.6 pA	31.3 pA	37.5μA	75 p.A	0.125 mA
Accuracy (% of I_{maz}):	0.04%	0.04%	0.04%	0.04%	0.04%	0.005%	0.005%
Minimum Ramp Rate.	10 pkrnin	!10 pA/min	0.1 mA/min	0.1 mA/min	0.1 mA/min	1 mA/min	1 mA/min
Maximum Ramp Rate:	1 A/sec	1 A/sec	10 A/sec	20 Nsec	SO Nsec	**80 A/sec**	100 A/sec

Additional Specifications for all Configurations

Magnet Current Control

Temperature Coefficient:	0.01% of $I_{m„}$ / °C
Stability:	Better than 0.02% of $I_{m„}$ after 20 minutes at desired current; better than 0.01% of I_{max} after 60 minutes at desired current
Programming Resolution:	15 digits[a]
Ramp Rate Resolution:	15 digits[a]
Nominal Load inductance Range:	0.5 to 100 H

Program Out Voltage

Programmable Limits:	–10 to +10 VDC
Accuracy:	3 mV (0,03% of Vmax)
Temperature Coefficient:	0.2 mV/ °C (0.002% of V,„/ °C)
Resolution:	0.3 mV
Stability:	Better than 10 mV p-p when paused or holding (with 0.5 to 100 H load)

Magnet Voltage Measurement

Maximum Limits:	–20 to +20 VDC
Accuracy:	20 mV (0.1% of V,„ I 'C)
Temperature Coefficient:	1.5 mV / ^{0}C (0.0075% of V_{max} /*C)
Resolution:	10 mV

Persistent Switch Heater Output

Programmable Limits:	0.1 to 125 mA DC
Accuracy:	0.2 mA
Temperature Coefficient:	0.01 mA / `C
Maximum Compliance:	14 V
Resolution:	**0.03** mA

Rampdown and Quench Inputs

Open Circuit Voltage:	5 VDC±5% 10
Input Resistance:	kilohm ± 1%

Quench Dry Contact Output

Maximum Switching Voltage:	60 VDC
Maximum Switching VA:	10 VA
Maximum Switching Current:	500 mA, unless limited by VA rating
Galvanic Isolation:	125 VDC

Power Requirements

Primary:	100-115 VAC or 200-230 VAC ±10% 50 / 60 Hz, 100 VA max., 30 W max.
Real-time Clock Backup Battery:	3 V CR2032 Lithium coin cell

Physical

Dimensions:	89 mrn H x 483 mm W x 191 mm D (3.5" H x 19' W x 10.75" D)
Weight:	8.5 Ibm (3.9 kG)
Torque Limits on Current Shunt Terminals:	5, 10, 125, and 250 A models: 48 in-lbs (5.4 N-m). 300 A model: 300 in-lbs (33.9 N-m) 600A and 2000A models: N/A (no shunt)

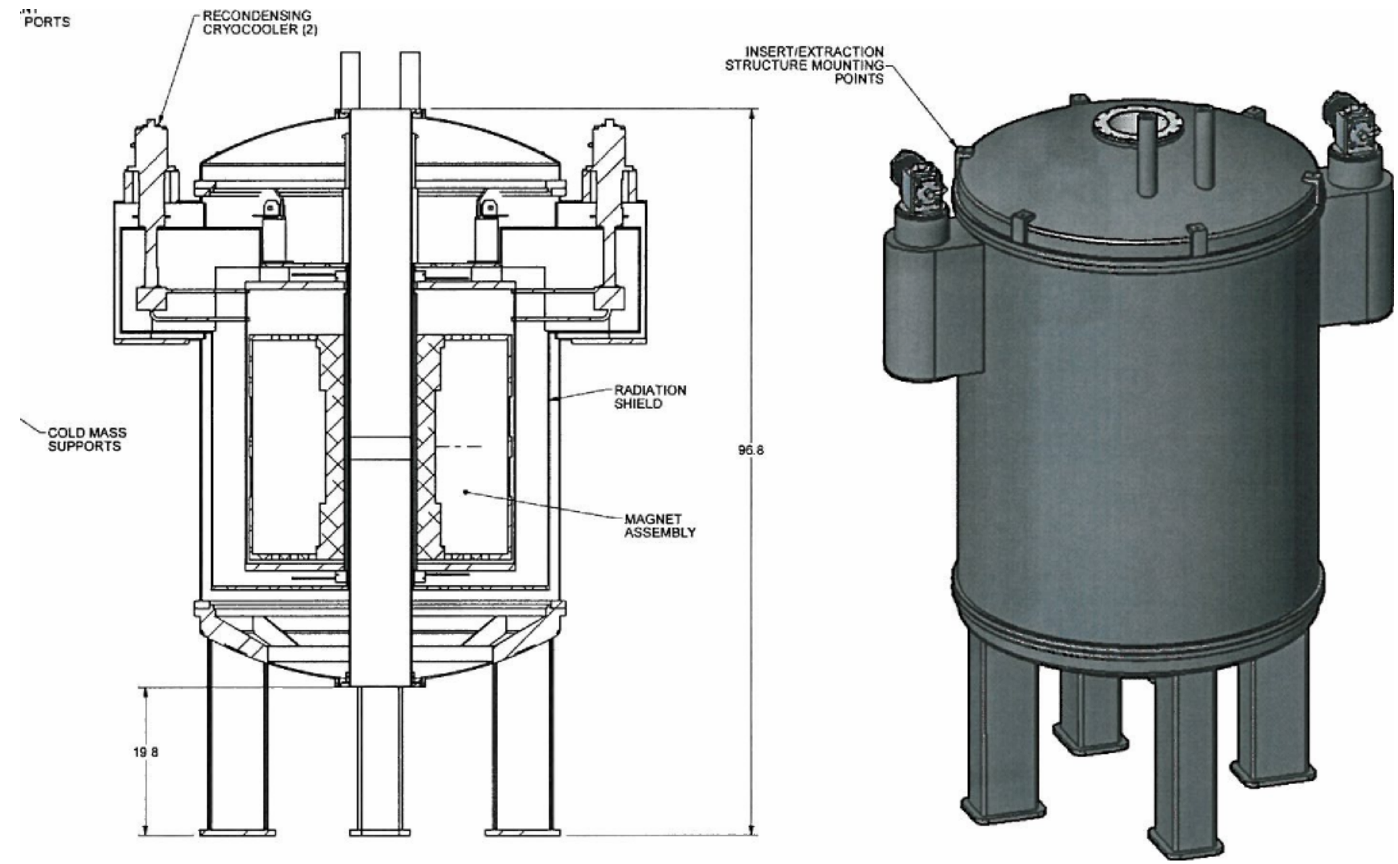
Environmental

Ambient Temperature:	Operating: 0 °C to 50 °C (32 °F to 122 °F) Nonoperating: —20 °C to 70 °C (-4 °F to 158 °F)
Relative Humidity:	0 to 95%; non-condensing

Standards

EMI/EMC Standards:	EN 61000-4-2	EN 61000-4-3
	EN 61000-4-4	EN 61000-4-5
	EN 61000-4-6	EN 61000-4-8
	EN 61000-4-11	EN 61000.3-2
	EN 61000-3-3	EN 55011
Safety Standard:	EN61010-1	
Installation Category:	Pollution Degree 2, Overvoltage Category II as defined by 1EC664	

a Resolution of the IEEE 754 double-precision floating point type consisting of a 52-bit fraction and 11-bit exponent.


PORTS
RECONDENSING CRYOCOOLER (2)
COLD MASS SUPPORTS
RADIATION SHIELD
MAGNET ASSEMBLY
96.8
19 8
INSERT/EXTRACTION STRUCTURE MOUNTING POINTS

APPENDIX B

Magnet System Summary

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System Summary:

As part of subcontract 4000079653 American Magnetics, Inc. (AMI) has embarked on a path to redesign our superconducting magnet systems to be suitable for use in an industrial environment. Design efforts have focused on large bore high field superconducting magnets, efficient low maintenance cryostats, and an electronics suit that will be the corner stone to meet the requirement that High Magnetic Field Processing (HMFP) systems be automated, cost-effective, and easy to operate in an industrial environment.

A summary evaluation was performed to identify which systems or subsystems required for operation of a superconducting magnet system would require modification to transition from a laboratory to an industrial environment.

Sub-Systems	**Function**	**Impact to Industrial Setting**
Magnet Solenoid	Produces magnetic field	Benign, responds to subsystem inputs
Liquid Helium Level	Level instrumentation, current hardware revision provides for analog and digital output for plc communication.	No user modification or input required once calibrated.
Liquid Nitrogen Level	Level instrumentation, current hardware revision provides for analog and digital output for plc communication.	No user modification or input required once calibrated.
Power Supply System	• Controls ramp rate of magnet • Provides charge/discharge current to magnet. • Quench detection circuit to prevent damage to magnet • Persistent mode control	Controls all functions of magnet system. Designed for the researcher, access to the many functions available through LCD display menus.

While the current Model 420 is designed to have a straightforward user interface, the sub-routines imbedded in the software do not lend themselves to the casual user which is expected to be encountered in an industrial setting. As this instrument is central to the successful operation of a superconducting magnet system, a modified user interface designed for intuitive magnet control is required.