AFRL-PR-WP-TM-2003-2005

# CRYOGENIC POWER RESEARCH
## High-Temperature Superconducting (HTS) Conductors

Dr. Paul N. Barnes

Power Generation Branch (AFRL/PRPG)
Power Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

SEPTEMBER 2001

Final Report for 01 October 1993 – 30 September 2001

Approved for public release; distribution is unlimited.



PROPULSION DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

# NOTICE



PAUL BARNES
Project Engineer
Power Generation Branch

SCOTT RUBERTUS
Chief
Power Generation Branch

FOR THE COMMANDER

JERRY E. BEAM
Deputy for Technology
Power Division

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** ***(DD-MM-YY)***
September 2001

**2. REPORT TYPE**
Final

**3. DATES COVERED** ***(From - To)***
10/01/1993 – 09/30/2001

**4. TITLE AND SUBTITLE**
CRYOGENIC POWER RESEARCH
High-Temperature Superconducting (HTS) Conductors

**5a. CONTRACT NUMBER**
IN-HOUSE

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**
62203F

**5d. PROJECT NUMBER**
3145

**5e. TASK NUMBER**
32

**5f. WORK UNIT NUMBER**
Y2

**6. AUTHOR(S)**
Dr. Paul N. Barnes

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Power Generation Branch (AFRL/PRPG)
Power Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

**10. SPONSORING/MONITORING AGENCY ACRONYM(S)**
AFRL/PRPG

**11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)**
AFRL-PR-WP-TM-2003-2005

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The program addresses the scientific and engineering issues related to the development of an HTS conductor and incorporation of that conductor into magnet and generator coil windings.

**15. SUBJECT TERMS**
HTS coated conductor, YBCO, HTS generators

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT: | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON (Monitor) |
|---|---|---|---|---|---|
| Unclassified | Unclassified | Unclassified | SAR | 26 | Dr. Paul N. Barnes<br>**19b. TELEPHONE NUMBER** *(Include Area Code)*<br>(937) 255-4410 |

HES&S 31-15093-1

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std. Z39-18

TABLE OF CONTENTS

## IN-HOUSE RESEARCH PROGRAM SUMMARY

**Title:** Cryogenic Power Research

**Job Order Number and Associated LRIR Number if Basic Research:** 314532Y2

**Principal Investigator and Office Symbol:** Dr Paul N. Barnes, AFRL/PRPG

**Start and Completion Date:** 1 OCT 93 - 30 SEP 01 (JON 314532Z9 replaces this one)

This is the latest update to this in-house effort.

**Narrative Description of Program:**

*Give a description of the research project including program goals, technical objectives, challenges and approaches and relevance to the Air Force or technical community.*

Program Goal

This program addresses the scientific and engineering issues related to the development of the second generation high temperature superconducting (HTS) conductor and incorporation of that conductor into magnet and generator coil windings.

Technical Objectives

Previously, YBCO has been determined to best meet the needs of the AF in the current circumstances. This determination was based on the overall capabilities of the conductor as well as its ability to be manufactured in a usable form. Some of the criteria included $J_c > 10^5$ A/cm$^2$, $J_e > 10^4$ A/cm$^2$, magnetic fields of 1-4 T, operating temperatures of 65-80 K, potential long length production, commercially viable product, etc

The current objectives of the in-house program are:

- Determine and minimize ac losses experienced by the conductor as experienced in a high power generator—*high priority*--category AC LOSS ISSUES
  - Conductor configurations
  - Material properties
- Develop properties of the YBCO superconductor for optimal performance as a coated conductor in HTS generators and magnets to include—*high priority*--category YBCO COATED CONDUCTORS:
  - Substrate
  - Buffer layers
  - YBCO
  - Processing issues
- Explore alternate superconducting materials that may offer improvements or prove beneficial for future AF needs—*low priority*--category ALTERNATE CONDUCTORS
- Determine HTS generator requirements for the incorporation of superconductors—*medium priority*--category POWER GENERATION

Challenges & Approach

Current work on the YBCO coated conductor focuses on the development of dc and ac conductor equally. The dc coated conductor development is done as part of an overall AF program including industry and universities and coordinated with the Department of Energy's Coated Conductor Program to ensure integration with no redundancy. Flux pinning of the dc conductor will be a significant focus in the upcoming year. Ultimately ac considerations must be considered for study and work has commenced in this area with the in-house program now that the dc conductor is preparing to go reel to reel (an important challenge). Currently, little if any research is performed for ac loss considerations and aspects of the conductor outside the AF. In order for the conductor to be ready for projected power generation and directed energy weapon (most pressing is active denial) demonstrations, the AF has taken the lead to initiate and address these ac loss issues in the next few years. Upon determining the effectiveness of striated YBCO, a challenge will remain to devise a viable manufacturing process for producing it in long lengths. As the conductor issues are resolved and dc conductor becomes available, the ac conductor issues will take priority in the in-house research and the YBCO Coated Conductor will be relegated to a medium priority. This in turn will lead to research and development under the Power Generation category also becoming high priority.

Relevance

The Air Force is interested in the development of directed energy weapons as well as hypersonics. High temperature superconducting generators and magnets are needed for these types of airborne applications since they are lightweight and compact compared to conventional high power generators and high field magnets. Not only do they enable high power airborne applications but enhance ground mobile applications. Long lengths of YBCO coated conductor are required to make coil windings in HTS generators as well as the HTS magnet windings. As such, the YBCO coated conductor is a military requirement as the critical component for Air Force applications as well as several defense applications across all military services. The systems requirements include Air Force directed energy applications (power generators and radio frequency source magnets), Navy superconducting motors and magnets (aircraft launch and mine sweeping operations), and Joint Non-Lethal Weapons involving the Marine Corps and the Air Force (for non-lethal weapons applications). The Army Dismounted Battlespace Battlelab, together with the Marine Warfighting Lab and the Air Force Force Protection Battlelab are sponsoring and participating in the demonstration of active denial technologies, which also require the coated conductor for use in power generation.

**Detailed Technical Approach for Next Fiscal Year:**

*Give a detailed narrative description of work to be performed during the fiscal year. Tell where you are now, where you expect to be by the end of the fiscal year and how you intend to get there. The work description and must contain milestones which give a quantitative indication of progress. In particular, show milestones for Technical Report completion, presentation and publications. For continuing work units, identify and explain any technical or non-technical changes.*

NOTE THAT 2305PGW0 AND 314532Y2 ARE WELL INTEGRATED PROGRAMS. TASKS LISTED BELOW ARE LABELED AS EITHER 6.1 (2305PGW0) OR 6.2 (314532Y2). ALTHOUGH A MAIN TASK HEADING MAY BE LISTED AS 6.1/2, ITS SUBTASKS ARE SPECIFIED AS ONE OR THE OTHER. PROVIDING THE TASKS THIS WAY PROVIDES A BETTER PICTURE THAN THEY WOULD SEPARATELY.

AC LOSS ISSUES

*Task 6.1/2-AC-1, Striated YBCO.* The design of lightweight superconducting generators requires a high speed rotor (6000 to 24,000 rpm), a high magnetic flux density (1 to 2T) and high frequency (200 to 1000 Hz). These conditions make it very difficult to minimize ac losses in a wide superconducting tape. Advances in YBCO coated thin film tape allows narrow filaments with very high current density on a thin metal alloy substrate that is separated from the superconductor by a dielectric buffer. These tapes can exhibit minimized ac loss by subdividing the YBCO layer with barriers which exhibit high electrical resistance. This configuration acts to decouple the filaments, unlike the metallic matrix of low temperature superconductors which permits significant coupled currents induced by perpendicular applied fields. The underlying alloy metal substrate can be non-magnetic with a very high resistivity to minimize eddy currents in the substrate. Twisting the conductor is necessary to minimize coupling loss even though the YBCO filaments are separated by high electrical resistance barriers. Research on this concept is initiated to explore the possibility. The following are the relevant sub-tasks:

*Task 6.1-AC-1a, Striated YBCO-VSM.* This particular work was initiated with Dr. Ted Collings of OSU through the PR Summer faculty program. Brent Cobb is preparing and operating the vibrating sample magnetometer (VSM) under Dr. Collings direction. In the upcoming fiscal year, striated samples are being prepared to measure the resistive losses. These samples will be fabricated by overlaying a mask on prepared YBCO samples and laser ablating the material to form the striations. The masks are designed and presently on order. Variations in widths and the resulting ac losses will be examined to determine the relationships and properties of the material.

*Task 6.1-AC-1b, Striated YBCO-Resistive Barriers.* The Slovak Academy of Sciences (Polak) is using ion milling to make various width trenches in YBCO coatings which will be wide enough to prevent proximity coupling. Some samples will be subsequently coated with metal or $CeO_2$ to provide variable barrier resistance which will be measured by Polak with the intent of separating the barrier bulk resistance from the interface resistance at the two sides. When barrier resistances are known parametrically, suitable configurations will be selected and multiple, parallel barriers will be created in several samples with varying resistance for subsequent ac loss measurements. AC loss measurements will be conducted with a Hall probe technique. The University of Cambridge (Campbell) will alter the barrier resistance between adjacent filaments by using a magnetic material coating and will share samples with Polak for barrier resistance measurements. We will conduct high field (up to 9T) AC loss measurements at various temperatures in a vibrating sample magnetometer (VSM) on samples provided by both Campbell and Polak. We will provide the sample design configurations for Campbell and Polak based on models of prospective generator and transformer requirements. The team will then assess the best YBCO tape and barrier configurations for AC loss minimization. We will then transition this effort to conductor process design and design of electrical power components compatible with mechanical cryogenic refrigerators.

*Task 6.2-AC-1c, Striated YBCO-Techniques.* A variety of methods will be used to create the striated YBCO samples. The techniques will allow us to examine various striations and the subsequent material response. After an understanding of the ac loss issues is assessed then methods more suitable to manufacturing to obtain the optimum conductor will be explored. Conductor design tradeoffs will be considered to allow ac loss minimization techniques compatible with realistic YBCO coated conductor processing.

*Task 6.2-AC-1d, Striated YBCO-Nanopatterning.* This in-house effort supports a low ac loss by nanopatterning effort (BMDO SBIR Phase I) by Applied Thin Films, Inc. (ATFI). ATFI has a scaleable process for stamping YBCO filaments on nickel or nickel alloy substrates. This process could enable long lengths of striated YBCO for low ac loss applications. This effort was initiated with our group providing preliminary dimensions for the low-loss nanopatterning (based on Task 6.2-AC-4). ATFI will provide patterned substrates for us to deposit the YBCO and we will provide coated conductor samples for patterning of the YBCO. Verification of best method will be conducted and ac loss characterization performed. VSM testing will measure hysteretic and eddy current losses as a function of YBCO filament width.

*Task 6.2-AC-3, Low Loss Substrates.* There are presently three sub-tasks in this area which covers metallic, non-metallic as well as round versus flat conductor.

*Task 6.2-AC-3a, Low Loss Substrates-Non-magnetic.* The recrystallization texture experiments are being conducted on a number of binary alloys, based on nickel. The alloys of various compositions were melted from virgin metals in a vacuum induction furnace, and vacuum cast in square billets. The billets were hot isostatic pressed and then hot rolled to achieve a total reduction of 60% in thickness. After surface conditioning, the hot rolled plates were cold rolled to 90% reduction in thickness, in increments of 10% reduction per pass to achieve a final thickness of 0.07 to 0.10 mm. Presently we are focused on the alloy with a nominal composition of Ni-12 wt% Cr. Studies were performed on pure nickel (supplied by EURUS) and the Ni-Cr alloy to study and compare the quality of the substrates. The grain structure, with rotation angle boundaries and pole figure data, was determined for each case. The misorientation observed in the pure nickel specimen is minimal, as shown by a major fraction of rotation angle boundaries less than 10 degrees. The grain structure in case of the Ni-Cr specimen shows a number of twins which results in multiple poles with twin orientation, and a decrease in intensity of the cube orientation. Also, the scanning electron micrograph studies on the surface show the formation of a thin oxide layer on the Ni-Cr specimen. OIM studies in both cases were performed without any surface preparation. As such an alternate metallic substrate with better physical and mechanical properties compared to nickel has been identified for coated conductor applications. Although reproducible, sharp and single cube texture with FWHM of $\sim 10^0$ can easily develop in nickel-chromium alloy after 95% cold reduction by rolling and heat treatment in the temperature range 900 $^0$C to 1000 $^0$C, further improvement in the substrate is necessary and compatibility with buffers needs to be check. Additional processing parameters will be performed and buffers will be deposited on the Ni-Cr substrate.

*Task 6.2-AC-3b, Low Loss Substrates-Sapphire Wire.* Rey Research Corp. prepared sapphire fibers for deposition to be performed in our PLD system. The advantage of the substrate is its non-magnetic nature and being round wire the engineering current density can be increased significantly as well as a means to be smaller strands for low ac loss configurations. When the PLD system is fully relocated and operational, a buffer and YBCO film will be deposited to determine the ability to maintain proper texture. Even though the deposition will not be completely around the strand, if proper texture can be maintained on the top surface, proof of concept is made. Solution based methods can be used for full coverage.

*Task 6.2-AC-3c, Low Loss Substrates-Ni Wire.* In support of Hyper Tech Research, Inc.'s investigation of low ac loss YBCO coated conductors (BMDO SBIR Phase I), we will be using our facilities to deposit the YBCO with the appropriate buffer layers onto the metal substrate (i.e. Ni wire) provided by Hyper Tech. The samples will be evaluated for appropriate texture by x-ray and $J_c$ and then returned to Hyper Tech for further material analysis. Initial samples of the bare substrate are being analyzed by Hyper Tech for improvements to substrate grain features.

*Task 6.2-AC-4, AC Loss Calculations.* See **Modeling and Simulation** section below for a full description of this task.

<u>YBCO COATED CONDUCTORS</u>

*Task 6.1-CC-1, Flux Pinning.*

*Task 6.1-CC-1a, Flux Pinning-Thin Film.* Effort was used this past year to enhance flux pinning of YBCO films. The method chosen was to deposit multiple alternating layers of {YBCO/insulator/YBCO}. The system chosen to initially be tested used multiple layers of {~8 nm $YBa_2Cu_3O_{7-\delta}$ / ~1.2 nm $Y_2BaCuO_5$}. The reason for choosing the $Y_2BaCuO_5$ (211) phase as an insulating layer is the chemically compatibility with YBCO at the processing temperatures and $O_2$ pressures used for film deposition. The thickness of the insulating layer was used to match the coherence length of YBCO (~1 – 1.5 nm), which in general is the size of Abrikosov flux vortices in YBCO, and the size of defects expected to be necessary to pin the vortices. Initial results achieved with the {YBCO/211} multilayer system showed significant improvement for $J_c$ in applied magnetic fields, e.g. total $J_c$s were 100% higher at 1-2 T applied magnetic fields in the entire temperature range tested from 4.2 to ~ 75 K. This multilayer film also showed unusual surface smoothness and no surface cracking, which probably resulted as a consequence of the multilayer growth process. The smoothness of the film surface is important since it suggests this process can be used to produce much thicker films (~1 to 5 μm) without degradation of $J_c$, Typically the $J_c$ of single layer YBCO degrades as the film thickness is increased greater than 1 um thick. Without using the multilayer structures, we found that 1 to 2 μm thick YBCO films on $LaAlO_3$ had significantly degraded surface structure, and $J_c$ was reduced to 0.3 to 0.4 $MA/cm^2$ from 6 to 8 $MA/cm^2$. The thicker films showed cracking, as expected from the mismatch of thermal expansion coefficients of the substrate and YBCO film. In the next year, the multilayer approach will be continued, both as a method to increase flux pinning, and as a way to increase the total critical current without degrading $J_c$. Future work will include testing different insulating compounds, varying the layer thickness, and optimizing process conditions to improve properties. Also, the results from Task 6.1-CC-1b will be implemented into this task for further development and understanding.

*Task 6.1-CC-1b, Flux Pinning-Bulk.* This effort was started in June 2001 to determine how substitution doping of Nd for Y in the $YBa_2Cu_3O_{7-\delta}$ phase can enhance flux pinning. Thus far, 20 compounds have been made in the $(Y,Nd)_{1-x}Ba_{2+x}Cu_3O_{7-y}$ system. Efforts are underway to measure the flux pinning properties in this system using the Vibrating Sample Magnetometer (VSM). In the future, compounds that have optimal pinning in the bulk will be used to deposit thin films using PLD. Also, samples will be sent to NIST-Gaithersburg for X-ray and neutron diffraction, to determine how the changes in the crystal structure are affecting flux pinning. This collaborative effort will continue with other rare earth substitutions.

*Task 6.1-CC-1c, Flux Pinning-Nanoparticles.* An initial report of nanoparticle formation from by laser ablation of $Y_1B_2C_3O_{7-X}$ (YBCO) was made for the past fiscal year. The nanoparticles are created by irradiating a target of bulk YBCO with a KrF excimer laser in a pulsed laser deposition setup used for making thin film YBCO. Background pressures of 5 Torr $O_2$ are used. The nanoparticles range in size from ~3 to 5 nm for the conditions used with a laser energy of 50 mJ per pulse. Characterization of the laser plume is performed using optical emission spectroscopy. Although the visible plume emission is very weak under the conditions used to create the nanoparticles, the plume remains collisionally dynamic at the high pressure and low laser energy used. Use of the nanoparticle formation for flux pinning will be discussed. The next step is to determine how well the nanoparticles will pin the flux in the YBCO. Working with UD, the PLD system will be alternated to deposit the nanoparticles in the YBCO. VSM measurements will be made to determine the improvement in current transport characteristics.

*Task 6.1/2-CC-2, Substrates.*

*Task 6.1-CC-2a, Substrates-Alloys.* This is a new task initiated this year. The new alloys are being prepared by the metals processing group in the Materials Directorate (MLLM). Final deformations and heat treatment will be performed in our facilities. The preparation of the materials will be as follows: Forging Schedule-- preheat to 1150°C for ½ to 1 hour, forge at 1150°C and a ram speed to 0.6"/min, final desired dimension: 0.3-0.38" thick; Hot Rolling Schedule--can the forged and descaled stock in 1/8" thick Ni picture-frame, preheat to 1100°C for ½ hour, roll at 1100°C, 10% reduction per pass at 25-50 rpm, final thickness (with can) 0.2-0.25"; Cold Rolling Schedule--descale the hot rolled sheet, cold roll using 'low' speeds mineral oil lubricant, turn head-to-tail and top-to-bottom between passes. After this rolling schedule the metal will be deformed and treated in or facilities to obtain proper texture. These alloys will be tested for improvement in epitaxy based on substrate alterations. The alloys are not specified here to protect the information.

*Task 6.2-CC-2b, Substrates-Ni.* Heat treatment processes similar to other tasks will be performed on Ni. Improvement in texture based on x-ray diffraction has been demonstrated in the past year. This year further refinement of the process will be accomplished to eliminate all undesired orientation. The primary purpose of this task is to provide textured Ni substrate for all other taskings and as a benchmark for the other substrate development work. It is expected that this task will end this coming year with the desired high texture.

*Task 6.1-CC-2c, Substrates-Etching.* The effects of surface roughness and substrate etch are being determined in this research. Various samples are being etched under different conditions that provide a variety of surface roughness from 2nm (rms) up to 70 nm (rms) in an argon inductive discharge. Halogenated discharges were previously used, but resulted in surface contamination with halides. Samples were prepared on untextured hastelloy substrates for IBAD deposition at Los Alamos and Argonne National Laboratories—we do not have IBAD capability here. The depositions from Argonne proved of poor quality for all samples including the control sample. Los Alamos, who has better IBAD processing, were unable to do the samples sent due to time constraints. Substrate etching will be performed on textured Ni substrates for epitaxial growth by WPAFB facilities (deformation texturing approach). After this study and importance of surface roughness determined, if no improvements in YBCO performance is noted the experiment will be terminated.

*Task 6.1-CC-3, Buffer Layers.*

*Task 6.1-CC-3a, Buffer Layers-ATFI YSZ.* Under a BMDO SBIR, Applied Thin Films, Inc (ATFI) is developing an innovative process for applying Yttria-Stabilized Zirconia (YSZ) buffers for subsequent YBCO deposition working with our group to develop this proprietary process. Although YSZ is a commonly used buffer layer, the process created by ATFI and currently being developed with us applies the YSZ buffer much more rapidly than typical processes which allows a reduction in processing time and cost. ATFI will deposit the YSZ layer and we will apply the cap buffer layer and YBCO on the YSZ for development of the process.

*Task 6.1-CC-3b, Buffer Layers-TiN.* In this task, the epitaxial growth of YBCO layers on TiN(001) surfaces was explored, both with and without $CeO_2$ intermediate layers. Advantages of nitride buffer layers compared to conventional oxide buffers, include high electrical and thermal conductivity, better mechanical toughness, good diffusion barrier characteristics, and relative ease of deposition. The epitaxial TiN layers were grown on MgO (001) and textured Ni substrates by Applied Thin Films (ATFI) using high-rate, reactive magnetron sputtering. The out-of-plane texture of the TiN layer was improved over the starting Ni substrate. Additionally, the TiN films are smooth with no evidence of any microcracking, indicating the potential of the TiN as a primary buffer layer for YBCO. Thin $CeO_2$ (~200 nm thick) and YBCO (~300 nm thick) layers were grown on TiN coated MgO substrates, using pulsed laser deposition at WPAFB. While YBCO grown directly on TiN was of poor quality, good epitaxial quality of the YBCO layer was obtained with a $CeO_2$ layer. A superconducting critical transition temperature (Tc) of 89 K was measured by AC susceptibility. A critical current density ($J_c$) of $6x10^5$ A/cm$^2$

was obtained at 77 K by whole body transport current measurement in self-field using a 1μV/cm criteria. These results suggest that transition-metal nitrides such as TiN are potentially useful as buffer layers for YBCO thin films. It is not clear what is minimum thickness of $CeO_2$ intermediate layer required for subsequent growth of high quality YBCO. While the $J_c$ and $T_c$ values obtained were lower than those of YBCO grown on epitaxial YSZ and $CeO_2$ buffer layers, further improvements in the Jc values are expected upon optimization of intermediate oxide layer. However, work on this task has halted in favor of Task 6.1-CC-3a.

*Task 6.1-CC-3c, Buffer Layers-ISD.* In this task, UES, Inc. provides MgO buffered substrates using the inclined substrate deposition (ISD) approach. This process is being developed via an AF STTR joint with Argonne National Laboratory. We will be depositing buffer cap layers and the YBCO. This task was recently initiated. We are helping to determine the viability of the ISD approach.

*Task 6.2-CC-4, Diagnostics.*

*Task 6.2-CC-4a, Diagnostics-Resistive $T_c$.* The diagnostic was fabricated in-house and completed late in FY 01. Current is passed through thin films while the temperature is constantly lowered until a measurable voltage (1 μV/cm criteria) exists across the conductor. Initial testing of the device resulted in sample breakage and modifications will be made. These resistive $T_c$ measurements allow for the first time in-house characterization of critical temperature and provides an comparison to $T_c$ data taken from magnetic susceptibility tests. Both tests are preferred in the HTS community: resistive $T_c$ for overall conductor performance and magnetic susceptibility for intrinsic material property. Continual measurements of resistive $T_c$ will be performed throughout FY 02 upon finalization of the diagnostic.

*Task 6.2-CC-4b, Diagnostics-In-field $J_c$.* An objective for FY 02 is to develop an in-field measurement diagnostic for critical current measurements of YBCO films. In-house staff has made initial designs during the past year. These designs will be modified and further developed in the initial part of the upcoming year based on the past attempt. Fabrication of the rotating platform for thin films located inside the sample space of an 11 T magnet will then commence with the initial diagnostic completed for testing in the latter part of the fiscal year. Subsequent in-field measurements will provide data of critical current dependence on the angle of the applied magnetic field. This measurement is essential for flux-pinning characterization of the coated conductor which will experience variable applied magnetic fields such as in a power generator. Only a couple of labs worldwide have in-field measurement capabilities and testing is done on basic YBCO samples. Flux-pinned samples are generally characterized by perpendicular magnetic field variance only, necessitating the diagnostic in-house.

*Task 6.2-CC-4c, Diagnostics-Stress & Strain.* Another objective for increasing our YBCO diagnostics is to develop stress & strain measurement capabilities essential for the coated conductor application in power generation and magnet windings. In-house staff will design and fabricate stress-strain measurement apparatus to be co-located with the in-field critical current measurement apparatus. Experiments will compare the effect of transverse stress on the critical-current density of various high-temperature tape superconductors such as textured nickel tapes and nickel-chrome alloy tapes. Very little data presently exists on the electromechanical properties of YBCO tapes. Electromechanical data will directly support our efforts in developing YBCO conductors for coil windings in superconducting generators. Estimated completion date of this project is early FY03. When completed, PRPG will be only one of two labs with this diagnostic capability.

*Task 6.1/2-CC-5, Processing Issues.*

*Task 6.1-CC-5a, Processing Issues-XPS.* This is a collaborative relationship with WSU that was initiated with the PR Summer Faculty Program. X-ray Photoelectron Spectroscopy (XPS) is used to investigate the compositional and chemical profile of a typical YBCO coated conductor architecture. The initial sample consisted of YBCO-$CeO_2$-YSZ-$CeO_2$-Ni layered substrate and current samples consists of YBCO on $LaAlO_3$ YBCO-$CeO_2$-YSZ(sc). Additional samples are being made as well as obtaining samples from AMSC and IGC SuperPower prepared in alternate ways for comparison. The chemical depth profiling involved bombarding a small area of the specimen surface with 3 KeV Ar+ ions and analyzing the freshly exposed surface after each bombardment. Results of the process show that the Y(3d) photo-electronic peak shape in these films is very different from YBCO superconductors made by other techniques (sintered, melt texturing, sputtering etc.) which may indicate a possible difference in the atomic co-ordination between PLD films and those grown differently. The correlation between chemical binding states of the ions and superconducting properties needs to be investigated in details. The lower portion of the YBCO film showed distinct signs of contamination including Ce, Zr, and traces of Ni. We will explore the coated conductor for other issues, but the two current findings are: the peak shapes of the Y(3d) photoelectron peak are different in these films compared to bulk YBCO specimens and the presence of Zr in the YBCO (probable diffusion from the YSZ layer). The mechanisms behind these two observations and their implications (in terms of coated conductor quality) will be investigated in the upcoming year.

*Task 6.1-CC-5b, Processing Issues-Plume Dynamics.* This is a new joint task being conducted by AFIT and us that is important to industry (CRADA). While the PLD technique has enjoyed great success, the fundamental mechanisms involved in the deposition process remain poorly understood. To make the continued advances necessary in the YBCO coated conductor, a better understanding of the growth mechanisms is certainly required. Furthermore, process control for economic manufacturing of HTS wires requires advanced, in-situ deposition diagnostics. The major research issues being worked on for this task areas follows: development of advanced optical diagnostics for process monitoring of YBCO deposition and an investigation of plume dynamics and collisional kinetics to develop a better understanding of the gas phase mechanisms and film growth. The products of this research task will include advanced temporally-resolved, spectrally-resolved emission and absorption diagnostics in the visible and infrared spectrum for the AFRL PLD facilities; new optical signatures strongly correlated with the quality of deposited YBCO films to develop complimentary control signals; and enhanced understanding of deposition mechanisms from analysis of PLD plume spectra.

*Task 6.2-CC-5c, Processing Issues-ML.* This task supports ML initiated research. Since ML's system was down for a year and a half and only recently became available, future tasks are not yet determined.

*Task 6.2-CC-5d, Processing Issues-PLD.* A new pulsed laser deposition (PLD) system was assembled this past year. The purpose of this system was to deposit YBCO films and study flux pinning processes. The system is essential and important for a variety of reasons: (1) ML's system was down for a year and a half (way too long), sample production is a bottleneck, and response time was very slow at ML; (2) nationally, there is a shortage of good quality PLD systems—PLD is used to not only produce quality samples, but test other processes (substrates, buffers, etc.); we have multiple requests from other agencies requesting support for worthwhile research; (3) our system produces (for 1/3 micron thick YBCO films on single crystal) some of the best samples in the world—nationally, only LANL and us currently can repeatably do 5-9 $MA/cm^2$, we intend to extend this capability to thicker films.

Pulsed laser deposition (PLD) is the most well known method for depositing YBCO thin films with generally superior properties, compared to other deposition methods. However, even though PLD of YBCO has been studied extensively, there are many factors that are unknown yet. The parameter space for PLD includes many variables, such as substrate temperature, oxygen pressure during deposition, laser fluence, target-to-substrate distance, laser wavelength and beam uniformity, target properties including density and optical absorption, laser spot size (which affects the plume shape), as well as substrate parameters such as chemical composition and lattice constant matches. These parameters are frequently inter-related, and optimization for one parameter can involve a range of optimization for others. The effect of $O_2$ deposition pressure on $T_c$ and $J_c$ was examined and compared to results from the literature. The $T_c$ and $J_c$ of the films obtained thus far are significantly better than previous work. The process parameters used in this work will be useful for PLD optimization, and can be transferred to industry for possible fabrication of long length conductors. In addition to depositing YBCO films, effort has been made to optimize the $CeO_2$ buffer layer in the system YBCO/$CeO_2$/ Zr(9%Y)$O_2$ single crystal. Results so far are inconclusive, as $J_c$'s with a wide range have been achieved thus far (0.3 to 5 MA/cm$^2$ at 77 K). The reason for this inconsistency is unknown yet and will be studied in the next year.

*Task 6.2-CC-5e, Processing Issues-IGC CRADA.* A new CRADA with IGC SuperPower, LLC and AFIT was signed this last month with the purpose to transition technology to IGC SuperPower to help them produce long lengths of YBCO coated conductor. The processes IGC Super Power intends to use is not publicly disclosed and will not be discussed here. Inference should not be made from other tasks listed since the skills developed there may well be useful in other applications and processes.

*Task 6.2-CC-5f, Processing Issues-Reel to Reel.* A reel-to-reel deposition system is being considered and the priority and benefits to the AF objectives is presently being determined to see if it will replace existing work planned. This will provide the AF an internal ability to create long length YBCO prior to industrial supply allowing YBCO coil testing to proceed—note an initial simple YBCO coil test is planned as part of the AMSC DUST Program but is limited in nature. It will also allow advanced ac loss testing and offfer other advantages that will not be listed here. The only reel to reel PLD system currently available is at LANL and is dedicated to IBAD buffered substrates. The leading institution in buffered RABiTS substrates, ORNL, is also requesting AF support in providing reel to reel PLD. If extra funding is provided for the reel to reel system, it will be built. As such this task is currently in limbo until a final determination is made.

## ALTERNATE CONDUCTORS

*Task 6.1-AM-1, $MgB_2$.* We will assist Hyper Tech Research in an EMTEC proposal by creating PLD $MgB_2$ films for comparison to the bulk melt textured films. This newly discovered superconductor offers several possible advantages over BSCCO, but YBCO is expected to be better. This task will allow us to remain intimately aware of the $MgB_2$ progress with minimal effort.

*Task 6.1-AM-2, Tl/Hg-based conductors.* In this task substrate material (presently Ni-Cr) is provided to the National Renewable Energy Laboratory (NREL), the lead agency in development of the Tl-based superconductors. These HTS conductors have a higher $T_c$ then YBCO, but currently its performance in magnetic fields is not as good unless better flux pinning methods are found. This task requires minimal effort and allows us to further test our substrate material development and keep in intimate touch with Tl-based superconductor progress.

POWER GENERATION

*Task 6.2-PG-1, Modeling.* See **Modeling and Simulation** section below for a full description of this task.

*Task 6.2-PG-2, Coil Testing.* This task is on hold awaiting the development of longer lengths of YBCO to be placed in a coil configuration. It is possible that initial testing may commence at the end of FY02 or the beginning of FY03. As the possibility approaches for YBCO coils the testing system will be readied for operation.

**Modeling and Simulation:**

*Reference any modeling and simulation work supporting this research effort.*

AC LOSS ISSUES

*Task 6.2-AC-4, AC Loss Calculations.* Modeling of the striated YBCO coated conductor for ac loss is performed in this task. A fully penetrated magnetic field is assumed and low loss conductor concept was developed for incorporating into a 1 megawatt armature design. Various configurations of striated YBCO conductors over the frequency range of 50 to 1000 Hz were considered. Low ac loss armature conductor designs are developed for megawatt class generators loss for both a 50 to 60 Hz utility application and a higher frequency aircraft application. Calculations indicate the ac loss in YBCO armature windings of a synchronous alternator may for the first time permit practical, lightweight all-cryogenic generators which can deliver ≥ megawatt at frequencies much greater than 50 to 60 Hz. Initial calculations of the significant ac loss in superconductors with fully penetrated ac fields included loss terms for hysteresis, coupling currents between filaments and eddy currents in the metallic substrate. These ac losses were calculated individually to determine their relative impact on the generator design. Numeric methods for simultaneous ac transport currents in externally applied ac fields are not planned to be attempted. The total loss for a Gramme ring armature winding is calculated for a variety of magnetic flux densities (B), frequencies and conductor configurations found in realistic generators. At aircraft power generator frequency (400 Hz) ac losses become large and a refrigerator becomes a serious problem because of size, weight and electric power requirement. At 200 Hz and 1 T, megawatt class armature losses can be accommodated by commercially available refrigerators. The generator design limitations at 200 to 400 Hz due to ac loss ease at 50 to 60 Hz and conductor design restrictions on substrate width thickness, filament width, barrier resistivity and twist pitch could be significantly relaxed. These ac loss results may be extended to synchronous generators and motors in the 1 to 5 megawatt range. As the rotor becomes extended in length for higher power, lower rpm machines, a twist pitch limit for coupling loss could be exceeded. A twist along the active length of the armature would be required which could be difficult and would reduce the electromagnetic performance of the machine for wide tapes. As such, we have calculated the major ac loss terms in a superconducting armature winding and have found a broad range of applications possible for appropriately configured YBCO coated conductors. Eventually, it will be necessary to trade off machine and conductor design parameters to arrive at a tractable solution both for commercial utility and high frequency aircraft applications. As ac losses are determined in Task 6.1/2-AC-1, the calculations conducted here will be refined. Cambridge will assist us in assessing the ac loss model for multifilamentary YBCO coated tapes and will help evaluate future processing methods to evolve long length YBCO conductors with low AC loss. We will continue to evolve the AC loss model for wide thin tapes using techniques developed by W. J. Carr Jr. under AFOSR contract.

POWER GENERATION

*Task 6.2-PG-1, Modeling.* A conventional diamond or reentry armature winding requires many tight radius bends, some of which would be edgewise to the tape. YBCO tape can operate at a bending strain of 0.2% but cannot follow the tortuous winding path required in these windings. Consequently, a Gramme ring armature design is currently selected for modeling which can be wound with flat racetrack or double pancake coils with a bend radius of several centimeters. In the active length of the Gramme ring winding the wide surface of the multifilamentary YBCO tape will be perpendicular to the radial component of B. In the end turns and the outer return path, B is greatly reduced so losses in these regions are ignored. The armature winding for a low power (1 to 5 megawatts) superconducting generator has a very short active length where the bulk of the ac loss occurs. The end turns and outer return path are quite long in comparison and conductor twist can be accomplished there for armatures that have short active lengths. Megawatt superconducting generator armatures delivering 10's kV will require very low currents so the armatures will not require centimeter wide tapes. The applied radial component of B is assumed to be a pure sinusoid with no harmonics. One problem with the Gramme ring armature of a lightweight generator is that the return path conductors on the outer part of the racetrack contribute little to power generation but constitute an extra size and weight penalty in comparison with the diamond winding. Other armature winding configurations can be devised that overcome the excessively tight turn radius of the diamond winding and allow more efficient flux coupling similar to the diamond winding while still permitting the necessary transposition of the superconducting tape in the armature end turns. Generator designs developed by Larry Long of Long Electromagnetics can be placed in the Ansoft software for modeling verification; however, Dr. Oberly, the lead on the modeling effort, is currently focusing the study on modeling transformer designs for the integrated power system package. This modeling using the Ansoft software will commence in the upcoming fiscal year.

**Payoff and Technology Transition:**

*Outline the payoff(s) of this research project for the Air Forces and for the DoD. Also, an important part of R&D work is the successful transition of new technology. Describe how you intend to accomplish this in your work. Through which organization or procedure will this be done?*

The coated conductor work directly supports the high power generator and MHD magnet programs. The high power HTS generator program directly supports electrically driven directed energy weapons and in particular the high power microwaves. The nearest term driver for the HTS generator in directed energy weapons is the non-lethal active denial program. In this program the HTS generator is incorporated into planning and development activities being an integral part. With respect to HTS activities, the Air Force is the lead agency in DoD with other services working with the AF for development of the HTS generator and depending on the AF for development of the coated conductor. A MHD power generation program is underway for hypersonic flight and the HTS conductor development is an integral part of these activities also. HTS conductor will be used in the magnet windings and YBCO coated conductors are part of the plasma dynamics theme (MHD activities) at AFOSR. Nationally, for all applications, DOE and the AF are the lead agencies in development activities for the HTS coated conductor.

**Review of Other Organizations Doing Similar Work:**

*List other government, industry and academic organizations known to be working in this technical area.*

Below is a listing of other agencies working in related areas. A short description of their work is given to indicate the differences in work being performed toward the common goal of the HTS coated conductor. We do have collaborative relationships with several of the institutions.

Industry:

Details of the industrial effort will not be provided since company proprietary information may not be appropriate to this report. General Information will be provided that is publicly available.

*American Superconductor Corporation.* (COLLABORATIVE RELATION on XPS studies) Pursues development of long length YBCO coated conductor especially using the textured substrate approach. Has an AF DUST Program and BMDO SBIR and AF SBIR. Supplies BSCCO conductor commercially.

*Intermagnetics General Corporation.* (CRADA with AF) Pursues development of long length YBCO coated conductor. Has an AF DUST Program.

*3M Corporate Research.* Pursues development of long length YBCO coated conductor considering both the IBAD and textured substrate approach.

*EURUS Technologies (now under Hyper Tech Research).* (COLLABORATIVE RELATION on low ac loss) EURUS dropped its coated conductor development (stiff competition) this past year but *Hyper Tech Research, Inc.* has picked up the HTS conductor development technologies. Has several BMDO SBIRs.

*Oxford Superconducting Technology.* Produces long length substrate for HTS coated conductor.

*Microcoatings Technologies.* Develops the combustion chemical vapor deposition (CCVD) process for buffer layers and YBCO in long length processing. Has BMDO SBIR.

*Applied Thin Films.* (COLLABORATIVE RELATION on buffer layer development) Develops buffer layer processing for the HTS coated conductor. Has several BMDO SBIRs.

Government:

*NIST (MD).* (COLLABORATIVE RELATION on flux pinning) Develops phase diagrams that are critical for the processing of the second generation RABiTS and IBAD coated conductor tapes. Provides basic equilibrium data for the ex-situ processing of Y-123. Investigates the occurrence of melt, the defluorination process, and follows the phase formation of the Y-123 phase using high temperature x-ray diffraction (HTXRD).

*Argonne National Laboratory.* (COLLABORATIVE RELATION on substrate etching for IBAD until redirected by DOE to do ISD in place of IBAD) Develops the inclined substrate deposition (ISD) method to fabricate high-$J_c$ coated conductors for high-temperature and high-field applications: develops the ISD technique and use it to fabricate high-$J_c$ coated conductors; measures residual stresses and correlate them with processing and geometrical parameters in order to optimize processing conditions and predict mechanical reliability of conductor specimens; explores how interface physics and chemistry influence, the nucleation and propagation of biaxial texture, the development of strain from layer to layer, and ultimately, the current carrying capacity of the conductor.

*Los Alamos National Laboratory.* (Previous COLLABORATIVE RELATION) Relates transport current to selected microstructural features in sections of tapes exhibiting non-uniform (i.e. high and low) current densities. Understands the reaction chemistry of thin buffer layers and transfer results into continuous processing, and determine the primary structure-property relationships of (110)[001] low angle boundaries (critical current density versus grain boundary angle measurements) using a series of bicrystal substrates. Improves both the performance of and commercial prospects for coated conductors based on Ion Beam Assisted Deposition (IBAD) and Pulsed Laser Deposition (PLD). Improves the reproducibility and texture for ion beam assisted deposition of MgO on moving tape.

*Oak Ridge National Laboratory.* (COLLABORATIVE RELATION being discussed for reel to reel) Improves the structure, processing, and throughput of RABiTS using reel-to-reel equipment. Fabricates meter-length RABiTS using textured alloys. Further develops the ex-situ process to convert lengths of YBCO on RABiTS. Continues fundamental studies of epitaxial oxide growth on metals, including alloys. Increases $I_c$/width to consistent values > 150 A/cm for ex-situ processed YBCO coatings. Develops solution-based buffer layer deposition on alloy tapes. Collaborates with LANL to develop ex-situ YBCO on IBAD-MgO substrates. Continues studies of thermomechanical processing for improved texture in metals. Performs research on fundamental issues of continuous processing with CRDA partners.

*National Renewable Energy Laboratory.* (COLLABORATIVE RELATION on NiCr substrates) Demonstrates biaxial texturing of Tl-1223 on buffered textured Ni, Ni alloy, or IBAD substrate with transport properties $J_c > 10^5$ A/cm$^2$ @ 77K, in-field. Demonstrates current density for electrodeposited Bi-2212 film on polycrystalline Ag comparable with dip-coated films and initiate experiments to explore biaxial texturing for Bi-2212. Explores cation exchange processing of "thick" ED deposited Tl-1212 or Tl-2212 to produce Hg-1212 films with high transport current and $T_c >$ 120 J on LAO single-crystals, followed by experiments on buffered textured nickel.

*Sandia National Laboratories.* (COLLABORATIVE RELATION discussed for PLD YBCO on sol-gel buffers) Develops high-rate solution deposition, especially sol-gel, methods that produce high quality, biaxially-oriented buffer layers on technologically important substrates (RABiTS, IBAD, ISD) for future commercial production. Produces YBCO coated conductors, via high-rate fluorinated solution deposition methods, with current carrying capabilities competitive with vacuum processed films (> 1 MA/cm$^2$ at 77K).

*Brookhaven National Laboratory.* Performs detailed characterization of the microstructures in $YBa_2Cu_3O_7$ thick films to assist in understanding the formation mechanisms, as well as the factors controlling critical current densities, of the superconductor. Develops synthesis methods which, in particular, emphasize studies of the YBCO formation in the $BaF_2$ processes that is suitable for the fabrication of YBCO conductors.

*Lawrence Berkeley National Laboratory.* Develops a new method for ion-beam nano-texturing (ITEX) of buffer layers, so that single crystal or pre-biaxially textured substrates are not necessary for epitaxial film growth of YBCO superconductors. Demonstrates the efficacy of the ITEX process and begin parametric studies. Plans a new deposition system for ITEX and IBAD development.

Academic:

*University of Wisconsin at Madison.* (Previous COLLABORATIVE RELATION on substrate grain boundaries) Understands the role microstructure plays in determining $J_c$ of YBCO coated conductors--a new emphasis in 2001 was to relate local transport superconducting property measurements to local microstructure using coupled magneto optics and crystallographic orientation imaging. Understands the current limiting mechanisms in BSCCO-2223 conductor. Analyzes, measures and improves the conductor properties and processing to raise $J_c$. Understands the loss mechanism associated with shuttle heat transfer in pulse tube refrigerators--this knowledge enables scalable designs for active-valve pulse tube refrigerators. Studies coated conductor quench and stability and characterize dissipation around conductor defects.

*Stanford University.* Explores the in-situ YBCO process to find the highest rate consistent with high $J_c$ and a large total current. Develops a basic materials science understanding of the observed finding of the stability of YBCO in low pressure oxygen and of the finding that under certain conditions the growth appeared to be in a liquid flux, and thus rate and thickness independent.

*Massachusetts Institute of Technology.* Measures stability margin and normal zone propagation in the temperature range 4.2-80K and field range 0-20T. Measures transient behaviors of a small test coil in the presence and absence of solid nitrogen.

*University of Kansas.* Develops Hg-based high temperature superconductors and application to coated conductors, especially Hg cation exchange conversion of Tl-based superconductors.

**Reports:**

*List all reports (TR, TM), papers and Journal articles published under this work during the past fiscal year.*


R. Nekkanti, V. Seetharaman, L. Brunke, I Maartense, D. Dempsey, G. Kozlowski, D. Tomich, R. Biggers, T. Peterson, P. Barnes, *Development of Nickel Alloy Substrates for YBCO Coated Conductor Applications*, Applied Superconductivity Conference 2000 (2000).

J.L. Reeves, D.M. Feldmann, S.E. Babcock, D.C. Larbalestier, G. Kozlowski, R.R. Biggers, R.M. Nekkanti, I. Maartense, P. Barnes, C.E. Oberly, T.L. Peterson, M. Tomsic, *Influence of the Substrate Grain Structure on the Structure and Properties of YBCO Coated Conductors*, Applied Superconductivity Conference 2000 (2000).

C.E. Oberly, G.L. Rhoads, L. Long, and W. J. Carr Jr., *Loss Minimazation in YBCO coated conductors with Fully Penetrated AC Magnetic Fields*, Applied Superconductivity Conference 2000 (2000).

G. Kozlowski, K. Hix, R. Biggers, D. Dorsey, N. Boss, J. Jones, I. Maartense, J. McDaniel, M. Tomsic, R. Nekkanti, *Effects of Metallic Substrate Imperfections on Superconducting Properties of YBCO Films*, Applied Superconductivity Conference 2000 (2000).

R. Biggers, N. Boss, D. Dempsey, I. Maartense, R. Kleismit, J. Jones, J. Busbee, D. Dorsey, G. Kozlowski, R. Nekkanti, *Plume Emission Spectra, Plume Imaging, and YBCO Raman Backscattering for Improved Real-Time Process Control of PLD of YBCO on Nickel Tapes*, Applied Superconductivity Conference 2000 (2000).

G. Kozlowski, R. Biggers, I. Maartense, K.E. Hix, M. Tomsic, R. Nekkanti, J. McDaniel, N. Boss, J. Jones, R. Kleismit, D. Dempsey, M. White, T. L. Peterson, P. Barnes, J. Maguire, A, Sarkar, and C.E. Oberly, *Effects of Surface Preparation of Nickel Substrates on the Superconducting Properties of YBCO Coated Conductors*, International Cryogenic Materials Conference 2000 (2000).

P. Barnes, *New Grain Boundary Effect in High-Temperature Superconducting Material Discovered*, Technology Horizons, **1**, p. 20-22 (2000).

C.E. Oberly, G.L. Rhoads, P. N. Barnes, and L. Long, *Lightweight Superconducting Power Systems for Multimegawatt Continuous HPM Power Requirements*, High Power Microwave Conference (2001).

P.N. Barnes, *High Temperature Superconductors for Power Generation and Magnets*, Electric Ships Conference (2001).

R. Nekkanti, V. Seetharaman, L. Brunke, I Maartense, D. Dempsey, G. Kozlowski, D. Tomich, R. Biggers, T. Peterson, P. Barnes, *Development of Nickel Alloy Substrates for YBCO Coated Conductor Applications*, IEEE Trans. on Appl. Superconductivity, **11**, pp. 3321-3324 (2001).

C.E. Oberly, L. Long, G.L. Rhoads, and W. J. Carr Jr., *ac Loss analysis for superconducting generator armatures wound with subdivided Y-Ba-Cu-O coated tape*, Cryogenics, **41**, p. 117-124 (2001).

C. Oberly, L. Long, G. Rhoads, S. Prestemon, J. Carr, P. Barnes, and F. Rodriguez, *The Importance of Interfilamentary Barrier Resistance in YBCO Coated Conductor to Minimize AC Losses*, Cryogenic Engineering Conference/International Cryogenic Materials Conference (2001).

T. Haugan, P. Barnes, R. Nekkanti, I. Maartense, L. Brunke, and J. Murphy, *Pulsed Laser Deposition of $YBa_2Cu_3O_{7-x}$ Thin Film Coated Conductors in High Oxygen Partial Pressures*, ISTEC and MRS International Workshop on Superconductivity (2001).

P. Barnes, S. Mukhopadhyay, R. Nekkanti, R. Biggers, and T. Haugan, *Chemical Depth Profiling by XPS of YBCO Coated Conductor*, Cryogenic Engineering Conference/International Cryogenic Materials Conference (2001).

P.N. Barnes, S. Mukhopadhyay, R. Nekkanti, T. Haugan, R. Biggers, and I. Maartense, *XPS depth profiling studies of YBCO layer on buffered substrates*, submitted to Cryogenics.

P.N. Barnes, T.P. Murray, T. Haugan, R. Rogow, G. Perram, *In-situ creation of nanoparticles from YBCO by pulsed laser deposition*, draft.

I.W. Kim, S. Sambasivan, S, Barnett, P.N. Barnes, R. Biggers. G. Kozlowski, C. Varanasi, I. Maartens, R. Nekkanti, T. Peterson, T. Haugan, and A. Goyal, *Growth of YBCO Thin FIlms on TiN(001) and CeO2-Coated TiN Surfaces*, submitted to Physica C.

C.E. Oberly, G.L. Rhoads, P.N. Barnes, L. Long, D.J. Scott, and W.J. Carr Jr., *The Importance of Interfilamentary Barrier Resistance in YBCO Coated Conductor to Minimize AC Losses*, submitted to Cryogenics

I.W. Kim, S. Sambasivan, S, Barnett, A. Goyal, M. Paranthaman, C. Park, P.N. Barnes and C.E. Oberly, *YBCO Growth on TiN buffered biaxially textured Ni*, draft.

T. Haugan, W. Wong-Ng, L.P. Cook, M.D. Vaudin, L. Swartzendruber, and P. N. Barnes, *Partial Melt Processing of Solid-Solution Bi2Sr2CaCu2O8+d Thick Film Conductors with Nanophase Al2O3 Additions*, draft.

T. Haugan, P. Barnes, R. Nekkanti, J. Murphy, L. Brunke, and I. Maartense, *Pulsed Laser Deposition of $YBa_2Cu_3O_{7-\delta}$ Thin Films in High Oxygen Partial Pressures*, draft.

**REFERENCES:**

P. Barnes, *New Grain Boundary Effect in High-Temperature Superconducting Material Discovered,* Technology Horizons, **1**, p.20-22 (2000)

C. E. Oberly, L. Long, G. L. Rhoads, W. J. Carr Jr.,*AC Loss Analysis for Superconducting Generator Armatures Wound with Subdivided Y-Ba-Cu-O Coated Tape*, Cryogenics, **41**, p. 117-124 (2001)

C. E. Oberly, G. L. Rhoads, P. N. Barnes, L. Long, D. J. Scott, and W. J. Carr, Jr., *The Importance of Interfilamentary Barrier Resistance in YBCO Coated Conductor to Minimize AC Losses*, Cryogenic Engineering, **48B**, p. 621-630 (2001)

R. M. Nekkanti, V. Seetharaman, L. Brunke, I. Maartense, D. Dempsey, G. Kozlowski, D. Tomich, R. Biggers, T. Peterson, P. Barnes, and C. E. Oberly, *Development of Nickel Alloy Substrates for Y-Ba-Cu-C Coated Conductor Applications*, IEEE Transactions on Applied Superconductivity, **11**, No. 1, p. 3321-3324 (2001)

D. M. Feldmann, J. L. Reeves, A. A. Polyanskii, G. Kozlowski, R. R. Biggers, R. M. Nekkanti, I. Maartense, M. Tomsic, P. Barnes, C. E., Oberly, T. L. Peterson, S. E. Babcock, and D. C. Larbalestier, *Influence of Nickel Substrate Grain Structure on $YBa_2$ $Cu_30_{7-x}$ Supercurrent Connectivity in Deformation-Textured Coated Conductors*, Applied Physics Letters, **77**, No. 18, p. 2906-2908 (2000)

W. J. Carr, Jr. and C. E. Oberly, *Filamentary YBCO Conductors for AC Applications*, Transactions on Applied Superconductivity, **9**, No. 2, p. 1475-1478 (1999)

R. Biggers, C. Varanasi, I. Maartense, D. Dempsey, D. Mast, D. Liptak, J. Jones, T. L. Peterson, T. Murray, and J. Busbee, *Spectral-Component Monitoring of the Plumes Generated During the Deposition of RE(Y.Nd) $Ba_2$ $Cu_30_{7-x}$ Films by Pulsed Laser Ablation*, Mat. Res. Soc. Symp. Proc., **502**, p. 215-219 (1998)

R. R. Biggers, J. G. Jones, I. Maartense, J. D. Busbee, D. Dempsey, D. Liptak, D. Lubbers, C. Varanasi, and D. Mast, *Emission Spectral-Component Monitoring and Fuzzy-Logic Control of Pulsed Laser-Deposition Process*, Engineering Applications of Artificial Intelligence, **11**, p. 627-635 (1998)

C. Varanasi, R. Biggers, I. Maartense, T. L. Peterson, J. Solomon, E. K. Moser, D. Dempsey, J. Busbee, D. Liptak, G. Kozlowski, R. Nekkanti, and C. E. Oberly, *$YBa_2$ $Cu_30_{7-x}$-Ag Thick Films Deposited by Pulsed Laser Ablation*, Physica C, **297**, p. 262-268 (1998)

C. Varanasi, R. R. Biggers, I. Maartense, D. Dempsey, T. L. Peterson, J. Solomon, J. McDaniel, G. Kozlowski, R. Nekkanti, and C. E. Oberly, *Pulsed Laser Deposition of Nd-Doped $YBa_2$ $Cu_30_{7-x}$ Films for coated Conductor Applications,* Mat. Res. Soc. Symp. Proc., **526**, p. 263-267 (1998)

D. E. Moxey, R. Kalyanaraman, A. Sharma, J. Narayan, C. B. Lee, and J. Muth, *Pulsed Laser Deposition of Undoped and Af-Doped Staced Structures of YBaCuO for Bolometer Device Applications*, Mat. Res. Soc. Symp. Proc., **526**, p. 269 (1998)

R. R. Biggers, P. T. Murray, D. Mast, I. Maartense, T. L. Peterson, D. Dempsey, C. Varanasi, S. Murray, D. P. Lubbers, S. Laube, B. Lovett, E. K. Moser, J. L. Brown, D. C. Liptak, and J. D. Busbee, *Spectral-Component Monitoring and Control of Pulsed Laser Deposition of YBCO Films*, SPIE, **2999**, p. 371-382

G. Kozlowski, C. Varanasi, I. Maartense, and C. E. Oberly, *Use of High Density $Y_2Ba$ $CuO_5$ Substrates in the Melt Processing of $YBa_2$ $Cu_30_{7-x}$ Bars with High Transport Critical Current*, Physica C, **276**, p. 197-201 (1997)

V. Selvamanickam, D. Kirchoff, C. E. Oberly, K. Salama, Y. Zhang, and S. Salib, *Growth Kinetics and Process Time Reduction in Melt Texturing of Y-Ba-Cu-O Superconductor*, High-Temperature Superconductors: Synthesis, Processing and Applications II, p. 117-125 (1997)

V. Pavate, L. B. Williams, and E. P. Kvam, *Identification and Correlation of Microstructural Defects with Flux Pinning in Ni-Doped Melt Textured* $YBa_2 Cu_3O_{7-\delta}$, Appl. Phys. Letter., **65**, (2), p, 246-248 (1994)

I. Chen, J. Liu, Y. Ren, R. Weinstein, G. Kozlowski, and C. E. Oberly, *Quasipermanent Magnets of High Temperature Superconductor: Temperature Dependence*, Appl. Phys. Lett., **62**, (25), p. 3366-3368 (1993)

M. K. Chyu and E. E. Oberly, *Influence of Operation Temperature and Contract Thermal Resistance on Normal Zone Propagation in a Metal-Sheath High-*$T_c$ *Superconductor Tape*, Second Joint Seminar on Basic Mechanisms of Helium Heat Transfer and Related Influence of Superconducting Magnets, Cryogenics, **32**, No. 5, p. 519-526 (1992)

N. Kenny, T. R. Shrout, F. Rodriguez, C. E. Oberly, G. Kozlowski, I. Maartense, R. Spyker, and J. C. Ho, *Evaluation of Y-Ba-CU-O Tubes Prepared by Tape Casting and Subsequent Rate-Controlled Sintering*, Advances in Cryogenic Engineering (Materials), **38**, p. 867-873 (1992)

G. Kozlowski, D. Hansley, C. E. Oberly, J. C. Ho, X. W. Cao, R. L. Spyker, and R. E. Leese, *Systematic Study of Ni-Doping Effect on Melt-Processed YBCO Superconductor*, Advances in Cryogenic Engineering (Materials), **38**, p. 977-982 (1992)

M. K. Chyu and C. E. Oberly, *Influence of Operating Temperature on Stability and Quench of Oxide High-*$T_C$ *Superconductors*, Advances in Cryogenic Engineering, **37**, Part A, p. 307-313 (1992)

G. Kozlowski, A. K. Sarkar, C. E. Oberly, R. Spyker, I. Maartense, T. L. Peterson, and J. C. Ho, *Study of Relaxation Effect in the Lead-Doped Bi-Sr-Ca-Cu-O System*, Advances in Cryogenic Engineering (Materials), **38**, p. 1147-1153 (1992)

C. E. Oberly, G. Kozlowski, and R. T. Fingers, *Implications of High Temperature Superconductors for Power Generation*, Advances in Cryogenic Engineering (Materials), **38**, p. 479-489 (1992)

G. Kozlowski, I. Maartense, R. Spyker, R. Leese, and C. E. Oberly, *Critical Current Density Enhancement in* $YBa_2 Cu_3O_{7-x}$ *–Silver Composite Superconductor*, Physica C, **173**, p. 195-200 (1991)

G. Kozlowski, C. E. Oberly, I. Maartense, R. Leese, J. Ho, D. Barker, T. Jones, and T. Brown, *Bi-Based High Temperature Superconducting Tapes by Cold Rolling Method*, IEEE Transactions on Magnetics, **27**, No. 2, p. 890-893 (1991)

C. E. Oberly, G. Kozlowski, C. E. Gooden, R. X. Lenard, A. K. Sarkar, I. Maartense, and J. C. Ho, *Principles of Application of High Temperature Superconductors to Electromagnetic Launch Technology*, IEEE Transactions on Magnetics, **27**, No. 1, p. 509-514 (1991)

C. E. Oberly and J. C. Ho, *The Origin and Future of Composite Aluminum Conductors*, IEEE Transactions on Magnetics, **27**, No. 1, p. 458-463 (1991)

M. K. Chyu and C. E. Oberly, *Effects of Transverse Heat Transfer on Normal Zone Propagation in Metal-Clad High Temperature Superconductor Coil Tape*, Cryogenics, **31**, p. 680-686 (1991)

A. K. Sarkar, G. Kozlowski, and I. Maartense, *Superconductive Properties of the* $YBa_2 Cu_4O_8$ *Superconductor*, Journal of the American Ceramic Society, **73**, p. 3110-3112 (1990)