Organization:	**SuperPower**
Project Title:	**Progress in scale up of 2G conductor at SuperPower**
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FY 2004 Funding:	FY 2005 funding : $ 2,000 k

Project Purpose and FY 2006 Objectives: The main purpose of this program is to scale up 2G conductor technology to pilot-scale manufacturing. In particular for FY'06, our goal was to demonstrate high-throughput processing of high quality 2G conductor in long lengths and then use this process to manufacture 10,000 meters of 2G conductor to deliver to Albany Cable project to construct a 30 m cable. As outlined in our FY'05 Peer Review presentation, the objectives for FY'06 were :

<u>Long Lengths</u>

- All pilot deposition facilities to employ helix tape handling for high throughput
- Multi-pass process by helix tape handling demonstrated with reactive sputtering of MgO & LMO buffers and MOCVD of YBCO
- Retrofit high-speed XRD tool for in-process texture measurements on long lengths of IBAD MgO buffers & MOCVD
- Demonstrate 100 m lengths with 100 A/cm performance with linear tape speeds of at least 30 m/h of 12 mm wide conductor in every step (equivalent to 90 m/h of 4 mm wide conductor)
- Demonstrate 250 m single-piece lengths of complete conductor with Ic of 100 A/cm and uniformity better than 5% over entire length
- Demonstrate 100 m piece lengths with critical current performance of 300 A/cm
- Deliver 8000 m of 2G conductor for Albany Cable Project

<u>Improved Conductor & Testing</u>

- Work with LANL, ORNL, and ANL to improve Jc of thick films of MOCVD on IBAD MgO. Ic of 500 A/cm in 2 micron thick films
- Work with LANL, ORNL, and ANL to evaluate modified buffers & substrate for IBAD MgO-based conductor to reduce # layers and problems with diffusion
- Work with ORNL & LANL to improve in-field properties by chemical substitution
- Achieve Je of 100,000 A/cm^2 at 77 K and Je of 25,000 A/cm^2 at 65 K and 3 T
- Demonstrate patterned + twisted conductor for ac loss reduction in long lengths
- Complete mechanical testing of conductor with 50 micron substrates (axial strain, fatigue) as well as with thick YBCO films with NIST, U. Houston, Florida State Univ.
- Fabricate coils with high Je conductor to achieve field of 3 T at 65 K
- Modify 2G conductor to meet specific customer requirements such as fault current, high voltage, high centripetal forces in rotating machinery etc.
- Quench testing of 2G coils in collaboration with Rockwell Automation
- Dielectric testing of 2G conductor with ORNL

FY 2006 Performance & Results and FY 2007 Plans:

In the 2005 Peer review, we demonstrated our first 200 m tape by MOCVD where a critical current of 200 A/cm was achieved over the first 70 m but then the Ic degraded steadily to a level of 100 A/cm over the rest of the tape. There were numerous comments from the reviewers urging us set a high priority to solve this problem. In FY'06, we took on this challenge as well as worked on meeting the above goals which the reviewers categorized as "aggressive…as they should be". A major limitation in FY'05 was slow tape speeds : 1 m/h with IBAD YSZ and 5 m/h with MOCVD. In order to achieve high throughput processing in all steps to produce long lengths of high quality conductor, we made numerous hardware modifications to all our Pilot equipment. First, we stopped production of IBAD YSZ and completely transitioned to a much faster, but more complex IBAD MgO in our Pilot IBAD system. Next, we brought into operation a brand new Pilot Buffer system with the capability of simultaneously depositing two buffer layers (homo-epi MgO & LMO) atop the IBAD MgO. Both process chambers for depositing these two buffer layers were fitted with helix tape handling allowing up to 12 tape wraps. Finally, we retrofitted our Pilot MOCVD system with a helix tape handling system for 6 tape wraps as well as increased the length of the deposition zone by 2x using a new longer and wider heater and showerhead. We systematically solved the several problems that confronted us with these concurrent modifications to our key Pilot processes & equipment.

After a successful implementation of the above modifications, we now routinely produce several hundred meters of IBAD MgO in our Pilot IBAD system at a speed of 65 m/h of 12 mm wide tape. Homo-epi MgO and LMO are each processed at a speed of 40 m/h in our Pilot Buffer system in lengths of several hundred meters. In order to quantify the texture value and uniformity of our long tapes, we modified our reel-to-reel in-plane XRD system for testing any material. In-plane texture values of 6 to 7 degrees have been measured over 300 m lengths of IBAD MgO buffers with a uniformity of 1 – 2 %.

Achieving high quality HTS films with good uniformity by MOCVD on long lengths of IBAD MgO buffers turned out to be the most difficult challenge. By means of process refinement and hardware modifications, we were able to meet or exceed every key metric : critical current of 219 A/cm over 322 m lengths with a uniformity of 4.3%, at a MOCVD speed of 30 m/h of 12 mm wide tape. This performance corresponds to a critical current * length value of 70,520 A-m, which is 35% higher than the previous world record. Our successful integration of IBAD MgO with MOCVD in long lengths is the first ever demonstration of a 2G manufacturing technology based on high throughput processes in *every* step.

Next, we focused our attention to producing high quality conductor in long lengths for the Albany Cable project. The requirement was to deliver nearly 10,000 m of 2G conductor in at least 43 m piece lengths with a critical current of at least 100 A/cm. This would be the single-largest delivery of 2G wire by any entity in the world. We have demonstrated routine, high-yield manufacturing in all process steps and exceeded specs for piece lengths and critical current. Detailed performance results from this monumental 2G wire manufacturing campaign will be provided in our presentation.

We enhanced our Quality Control operation significantly in FY'06 to support our 2G conductor manufacturing. 100% tape inspection was done in our automated inspection system after every process step (substrate polishing, IBAD, Buffer, and MOCVD). Film thickness of every buffer layer of every long tape was quantified by spectroscopic ellipsometry. Composition, texture, and microstructure of every MOCVD tape were quantified using ICP, XRD, and SEM analyses. Yield of every process step was monitored and tape inventory of every process was maintained.

While the bulk of our effort in FY'06 was focused on scale up of 2G conductor, we achieved success in improving the performance characteristics of MOCVD films in short lengths too. By optimizing the MOCVD process parameters, we improved the microstructure to substantially enhance the critical current density of our 0.7 micron films. Using these improved films as a foundation, we built thicker films assisted by process refinement to achieve a critical current value of 557 A/cm over the entire tape width of 12 mm. The HTS film thickness was 2.1 microns corresponding to a Jc of 2.65 MA/cm^2.

We had previously demonstrated a photolithographic process for patterning of 2G conductor to significantly reduce ac losses. Last year, we also demonstrated twisting of 2G conductor to a twist pitch less than 5 cm using 2 mm wide conductor. In FY'06, we constructed and tested the world's first patterned *and* twisted conductor. We used our reel-to-reel ac loss measurement system to directly measure the ac loss of the patterned and twisted conductor.

In the last two years, working with Sumitomo Electric Industries, we demonstrated the world's first and second 2G cables made with 4 mm wide conductor. Also, in the last two years, working with Rockwell Automation, we demonstrated the world's first and only 2G rotating machine, namely a 7.5 h.p. motor built in a 5 h.p. conventional motor frame. In FY'06, we directed our efforts towards employing 2G for FCL applications. Excellent fault current limiting performances were reproducibly achieved in our 2G conductor including first peak limitation. Quench current was in the range of 1.8 to 3 times I_c, and the response time was within 1 ms. Recovery tests under no load conditions showed that conductors completely cooled down in 4-6 sec after each fault with energy up to 35 J/cm/tape, and survived energy level higher than 100 J/cm/tape under repetitive faults at 3-second intervals. Results from recent high-power tests done on a 2G prototype FCL assembly will be discussed.

While FY'06 was our transition year to Pilot-scale manufacturing of 2G conductor, FY'07 would be the year for further enhancing its commercial viability : higher throughput, higher critical current and longer lengths. We will increase the tape speed to at least 100 m/h of 12 mm wide tape in both the Pilot IBAD and Pilot Buffer systems while maintaining a uniform texture of 6 – 8 degrees over 500 m. We will demonstrate a 3-fold increase in the tape speed in Pilot MOCVD i.e. 90 m/h of 12 mm wide tape while maintaining a critical current level of at least 200 A/cm. We will extend single-piece lengths of conductor made by substrate electropolishing and IBAD MgO to 1000 m and single-piece lengths of final conductor to 500 m with a critical current performance of at least 200 A/cm. New Quality Control and Test equipment will be brought into operation to support the high-throughput, long-length manufacturing. On-line tape inspection systems will be added to our Process equipment. Transport and non-contact critical current test equipment will be introduced to reduce test duration of long tapes by a factor of 4. We will extend our thick MOCVD film work to reach levels of 750 A/cm in short tapes and 300 A/cm in lengths greater than 250 m. We will complete delivery of nearly 10,000 m of fully-tested 2G conductor to Sumitomo Electric to fabricate a 30 m 2G cable for the Albany Cable project. The pathway to reaching these milestones will be guided by our strong collaboration with national labs and Universities to solve issues with thick film performance, robustness of thin buffers etc. We will continue our development work on improving the conductor structure with support from the labs and Universities to reduce ac losses, improve quench stability, improve in-field performance and achieve higher Je. In collaboration with our industrial and lab partners, we will also continue to demonstrate prototype devices for cable, FCL, and coil applications.

Research Integration: SuperPower benefited from collaboration with several national labs and Universities this year. In our sixth year of our CRADA partnership with LANL, we worked closely with the lab to successfully solve the process issues in integrating IBAD MgO and high-rate buffers with MOCVD as well as developing a high-current thick film conductor. Through our CRADA with ORNL which is in its fourth year, we improved the in-field performance of our conductors through compositional refinements to our MOCVD precursors. To further enhance this collaboration, we transferred our Research MOCVD system to ORNL for on-site process development. Staff from ORNL were trained at SuperPower on the hardware and process aspects of this system. Dielectric testing, quench stability and ac loss measurements were performed on unique conductor geometries in our collaboration with ORNL. ANL assisted us in solving the uniformity issues in long MOCVD tapes. NIST, NRL, AFRL, NAVSEA, FSU, U.Houston, OSU, U. Wisconsin, U. Albany, and U. Kansas supported our effort by testing of mechanical properties, quench stability, ac losses, and by characterization to understand in-field properties and thick film performance. Mechanical tests on our modified 2G conductor by both NIST and U. Houston shows a yield stress value of 1200 MPa with 95% critical current retention, which is two times that demonstrated with even other IBAD-based conductors ! Several visits have been made by SuperPower employees to various national labs and Universities and vice versa. SuperPower employees closely interacted with the lab scientists by frequent e-mail and phone communication. Our 2G program has been reviewed multiple times this FY on site at SuperPower as well as at Wright Patterson Air Force Base by DOE and DOD lab representatives, for the Title III program.