Warren J. Baker Endowment
for Excellence in Project-Based Learning
Robert D. Koob Endowment *for Student Success*

CAL POLY

Proposal Cover Page

Title of Project: Development of a Sub-$200 Quantum Tunneling Current Measurement Device

Proposal Author: Justin Jee Cal Poly Email: jtjee@calpoly.edu

Student ID: 007058658 Dept.: Electrical Engineering / Physics

Signature (Optional): [signature]

Signature provides permission to check financial aid eligibility.

Previous Baker/Koob Endowment funding? (circle one): Yes **(No)**

Is this request to support a Senior Project or thesis? (circle one): Yes **(No)**

Team Member(s)	Signature	Cal Poly Email	Department
Justin Jee	[signature]	jtjee@calpoly.edu	Electrical Eng & Physics
Lexa Hall	[signature]	Lhall07@calpoly.edu	Computer Engineering
Cameron Simpson	[signature]	csimps04@calpoly.edu	Computer Engineering
Sergio Aguayo	[signature]	seaguayo@calpoly.edu	Physics & Math

Faculty Advisor: Greg Scott Department: Chemistry & Biochemistry

Faculty Advisor email: gscott02 Telephone: 6-2617

Anticipated Start Date: January 1st, 2018 Anticipated End Date: January 1st, 2019

Total Funds Requested ($): 1849.00

Signature of Faculty Advisor: [signature] Date: Nov 6, 2017

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PROPOSAL NARRATIVE

(Max. of 3 pages including figures/tables but excluding budget page, 1" margins, 12-point font. See Sec.XII of RFP for more details.)

Proposals not complying with format guidelines will not be considered.

I. Project Title

Development of a Sub-$200 Quantum Tunneling Current Measurement Device

II. Abstract

Scanning tunneling microscopy is a modern technique which creates images of atoms in a material surface, the invention of which won a 1986 Nobel Prize in Physics [1]. The importance of a scanning tunneling microscope (STM) branches across many industries and fields of study, but a cost on the order of $100,000 makes it impractical for undergraduate lab courses. Development of an inexpensive STM gives chemistry, physics, materials engineering, and electrical engineering students at "Learn by Doing" schools hands-on experience with modern imaging techniques, inspiring them and further preparing them for a successful career. This grant provides the crucial first step in developing an open-source STM for use in classrooms and research activities. In this step, the team creates a working apparatus that measures the quantum tunneling current and plots it as a function of distance and bias voltage on a computer. The device also prevents tip crashing with automatic tip height sensing using an electronic control system [2], enabling easy student use and low maintenance costs. Cal Poly and many other colleges, could implement this open source device into lab sections of many courses across various majors, including solid state physics, quantum mechanics, physical chemistry, and electronics manufacturing.

III. Introduction

In "A Student-Built Scanning Tunneling Microscope", Tom Ekkens writes "Several students were so excited by the [STM] project that they wrote an article about their lab experience in the student paper and arranged a short presentation to the entire student body [3]." Ekkens' project at Walla Walla University was one of few undergraduate labs where students built their own STM. This lab however, used National Instruments PCIe-6323 data acquisition cards at a cost of $961.00 [4]. The proposed project uses a microcontroller unit to interface with a computer, reducing the projected cost from approximately $1100 to under $200. The scan head also adds a considerable cost to an STM. Typically, the piezo system in the scan head requires high voltages, imposing the need for costly electronics and reducing student safety [5]. The scan head in this design uses a $1.00 unimorph piezo transducer, often used as beepers in smoke detectors.

A unimorph transducer exhibits its full range of motion in a range of ±15V, making control circuitry affordable while vastly improving student safety. Removing the need for a vacuum chamber further reduces cost. The chamber keeps materials from interacting with the atmosphere, limiting the usable materials, though substrates such as highly ordered pyrolytic graphite (HOPG) can be used in ambient conditions. The project objectives incorporate knowledge of chemistry, physics, electrical engineering, and computer engineering thereby encouraging interdisciplinary teamwork and communication among students and faculty from varied departments.

IV. Objective(s)

1. Model the device subsystems.
2. Simulate, build, and verify each subsystem.
3. Build and characterize a manually controlled tunneling current measurement device.
4. Build and characterize a motor controlled tunneling current measurement device.
5. Create project website and present the project at internal and external conferences.

Overall, this project creates an open source and open hardware solution for characterizing material surfaces. The design stays mindful of educational constraints through simple design, readily available parts, and low cost.

V. Methodology

This project consists of five major subsystems; the scan head, current amplifier, approach system, power system, and user interface. Appendix C contains a 3D model of the measurement unit and more detail about the subsystems. For the current amplifier and power system, Spice simulates circuitry which then gets a PCB design in DipTrace. Toner transfer PCB fabrication creates inexpensive, handmade PCBs that allow for rapid prototyping, then professional manufacturing creates a final product. An MSO-X2012A Oscilloscope, HP E3640A Power Supply, and Keithley 2400-LV source meter adequately characterize the power supply noise, piezo amp performance, and tunnel preamp characteristics. Electrical Engineering labs have these instruments readily available for student use. For the scan head and approach systems, modeling in SOLIDWORKS aids the planning of the manual and automatic approach devices. Once models verify designs of each phase and simulations indicate success of the system, system fabrication and testing begin. Built first, the manual approach device measures the tunneling current, but uses thumb screws instead of the stepper motor for coarse approach. This removes the control electronics and vibrations from the motor, allowing more stable testing of the preamp and scan head. After the successful creation of the manual device, the motor design phase begins. Stepper motor integration starts with a premade motor control board. The board is interfaced with the MCU which sends position data and calculates descent distances. After completing the control system, the final assembly phase begins, and the team writes the automatic approach MCU code. In parallel with hardware systems, a team member creates the user interface in LabVIEW. Throughout the duration of the project, team members keep detailed lab notebooks and post progress on a dedicated website.

VI. Timeline

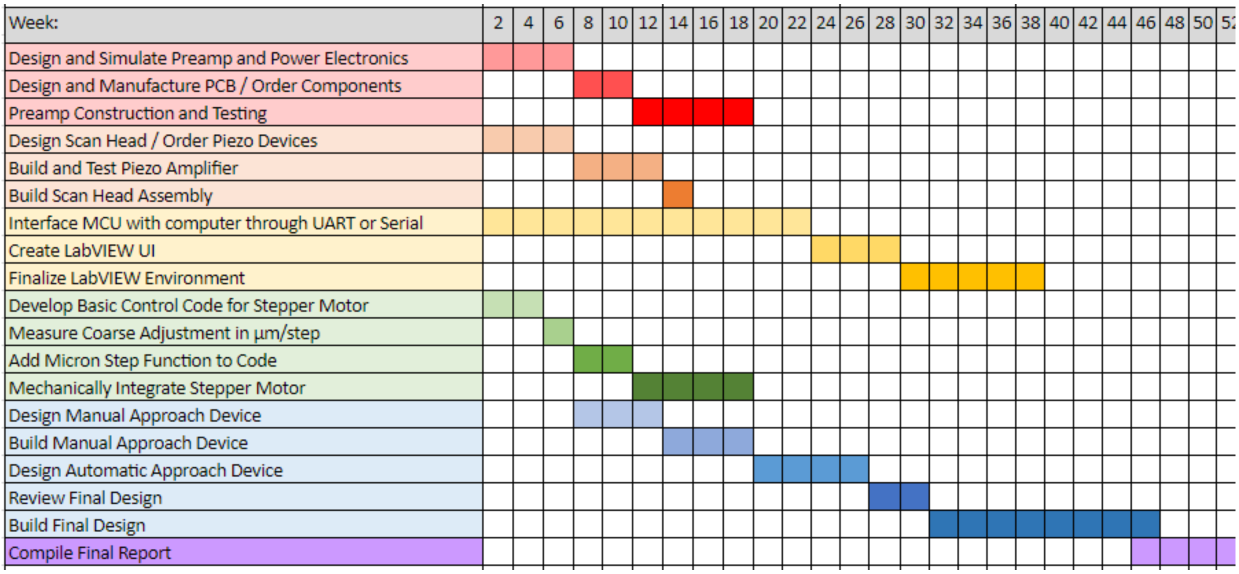

Figure 1. Timeline of objectives for the tunneling current measurement device. The independent nature of each subsystem makes parallel development possible and speeds up the prototyping processes. Each event includes a two-week buffer for shipping times.

VII. Final Products and Dissemination

Project completion results in an inexpensive device which measures quantum tunneling currents. Documentation of design procedures, source code, 3D models, and schematics become publicly available for amateur, professional, and educational use. Beyond publishing the results of the project on a website, members of the team intend to submit an article to the Journal of Engineering Education and present results at an internal and external conferences such as the CSM Research Conference and Senior Project Expo.

VIII. Budget Justification

This proposal requires $1,474 for materials, electronics, and mechanical hardware; $75 for a 3X5 poster from Cal Poly Print Shop; and $300 for manufacturing and machining services. Parallel development requires two of each microcontroller development board, Arduino Uno and MPS432 Launchpad. Each board has an advantage, the team is familiar with the MSP432, while the Arduino interfaces with LabVIEW easily. A prebuilt motor controller removes the cost and time of developing another complex electronic system. The sensitive nature of the tunnel current amplifier requires a soldered connection of the OpAmp to the board. This means each major revision of the preamp board may require a new chip. All other electronics boards utilize sockets for expensive components and support breadboard prototyping. Cal Poly's machine shop charges $16.00/hr for internal projects, contracting their services significantly reduces prototyping time. Shipping costs from major distributors were also considered when writing the budget.

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PROPOSAL BUDGET

Student Applicant(s): Justin Jee, Lexa Hall, Cameron Simpson, Sergio Aguayo	
Faculty Advisor: Gregory Scott	
Project Title: Development of a Sub-$200 Quantum Tunneling Current Measurement Device	**Requested Endowment Funding**
Travel *subtotal*	$ 0
Travel: In-state	$ 0
Travel: Out-of-state	$ 0
Travel: International	$ 0
Operating Expenses *subtotal*	$ 1549
Non-computer Supplies & Materials	$ 1,474
Computer Supplies & Materials	$ 0
Software/Software Licenses	$ 0
Printing/Duplication	$ 75
Postage/Shipping	$ 0
Registration	$ 0
Membership Dues & Subscriptions	$ 0
Multimedia Services	$ 0
Advertising	$ 0
Journal Publication Costs	$ 0
Contractual Services *subtotal*	$ 300
Contracted Services	$ 300
Equipment Rental/Lease Agreements	$ 0
Service/Maintenance Agreements	$ 0
TOTAL	$ 1849

Appendix A: References

[1] The Royal Swedish Academy of Sciences, *Press Release*. Available: www.nobelprize.org/nobel_prizes/physics/laureates/1986/press.html [Accessed October 10, 2017]

[2] Dawn Bonnell, *Scanning Tunneling Microscopy and Spectroscopy.* New York USA, VCH Publishers, 1993

[3] Tom Ekkens, *A Student-Built Scanning Tunneling Microscope.* The Physics Teacher Vol. 53, 2015

[4] National Instruments, *PCIe-6323.* Available: http://www.ni.com/en-us/support/model.pcie-6323.html [Accessed October 10, 2017]

[5] Julian Chen, *Introduction to Scanning Tunneling Microscopy.* Oxford UK, Oxford University Press, 1993

[6] *Scanning Tunneling Microscopy.* Available: www.ieap.uni-kiel.de/surface/ag-kipp/stm/stm.htm [Accessed November 2, 2017]

[7] *Scanning Tunneling Microscopy / Spectroscopy.* Available: http://www2.cpfs.mpg.de/~wirth/rec/stm3.html [Accessed November 2, 2017]

[8] Michael Munowitz, *Principles of Chemistry.* New York, W.W. Norton and Company, 2000

[9] IBM, *Scanning Tunneling Microscope.* Available: www-03.ibm.com/ibm/history/ibm100/images/icp/O615894E37594U80/us__en_us__ibm100__scanning_tunnel__microscope__400x269.jpg [Accessed November 2, 2017]

[10] IBM, *A Boy and His Atom: The World's Smallest Movie*. Available: https://www.youtube.com/watch?v=oSCX78-8-q0 [Accessed November 2, 2017]

Appendix B: Scanning Tunneling Microscopy

Consider a tennis ball thrown at a brick wall, but instead of hitting the wall and bouncing off, the ball teleports to the other side of the wall. In a similar way, electrons have the ability to quantum tunnel, where they travel through potential barriers. For example, an electron tunneling from a conductor, through an insulator, to another conductor. The probability of tunneling depends on the distance from where the electrons are initially. STMs measure the number of electrons, current, that tunnel from the sample to the tip at different locations, then convert the data into an image.

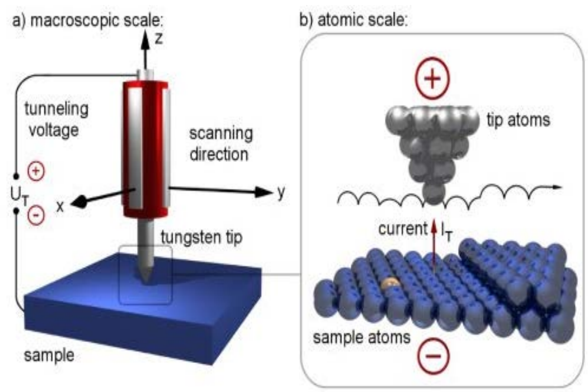

Figure 2: Illustration of a scanning tunneling microscope with a piezo tube scanner. [6]

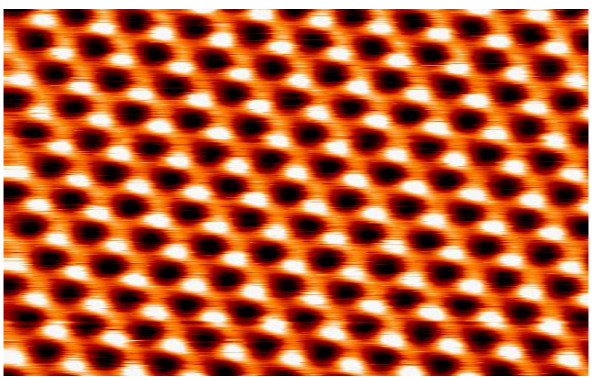

Figure 3: The structure of HOPG imaged with an STM. The proposed project uses this material as a substrate for measurements in atmospheric conditions. [7]

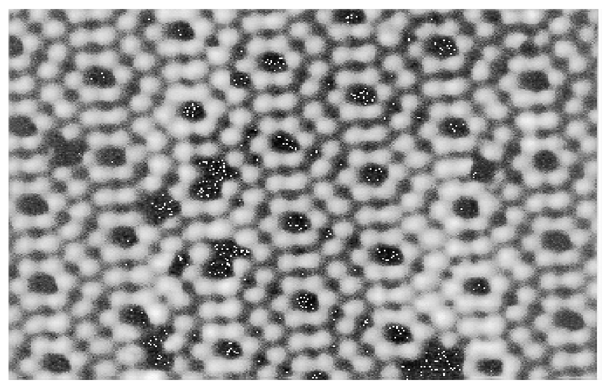

Figure 4: The structure of a silicon crystal imaged with an STM. The empty spaces in the structure are impurities. [8]

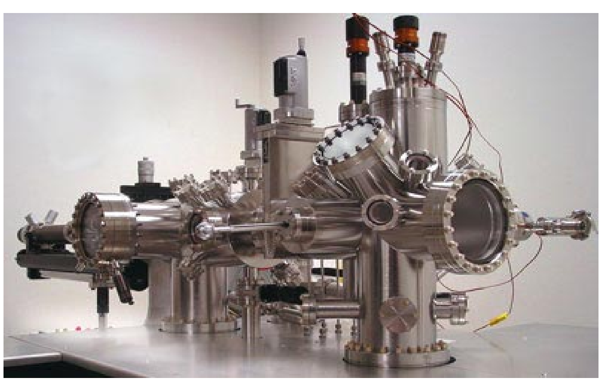

Figure 5: IBM's scanning tunneling microscope. The actual device is inside the large vacuum chamber shown in this image. [9]

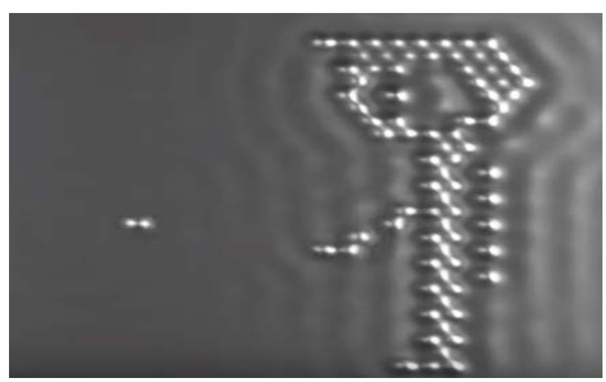

Figure 6: An image from the world's smallest movie, "A Boy and His Atom". IBM created this image using their STM. [10]

Appendix C: Subsystems

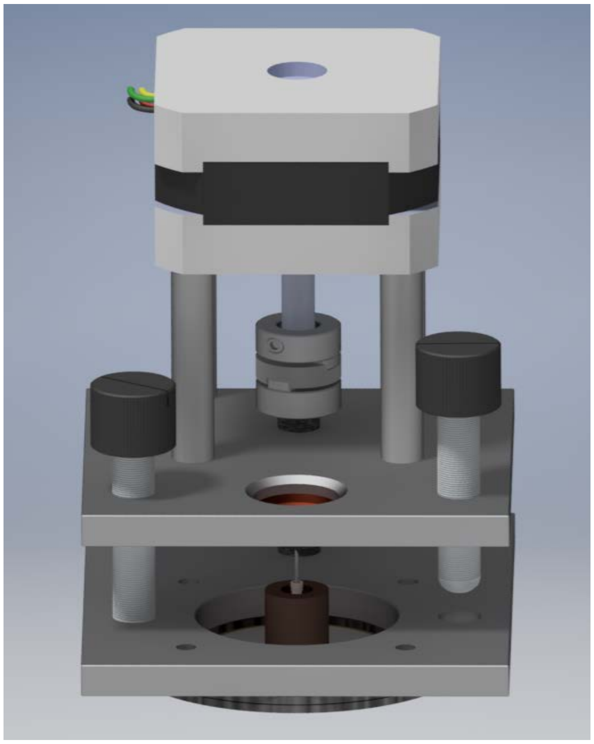

Figure 7: 3D model of the finished tunnel current device. This model describes the direction of the project, not necessarily the exact finished product. Designed by Justin Jee using SOLIDWORKS Student Edition.

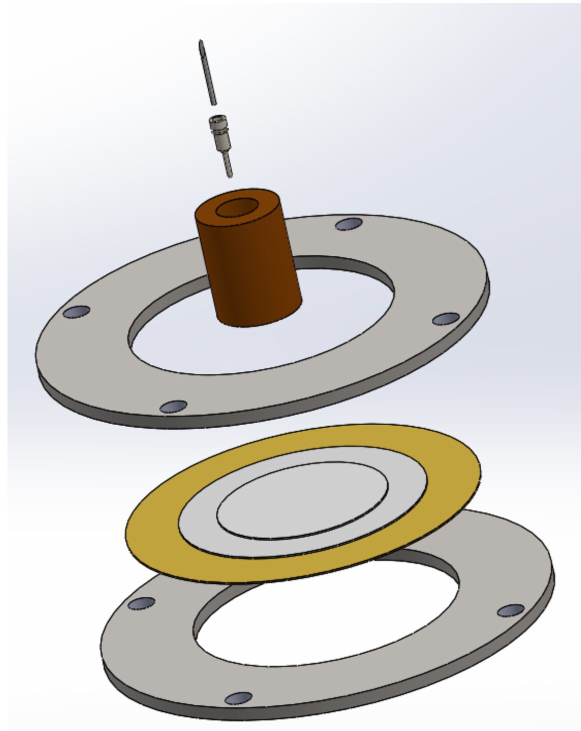

Figure 8: 3D model of the scan head subsystem. Parts shown from bottom to top: steel washer, piezo transducer, steel washer, phenolic standoff, DIP socket, tip. Designed by Justin Jee using SOLIDWORKS Student Edition.

Figure 9: Screws used for adjustment system. The top screw has a coupler for connection to the stepper motor. These screws lower the sample to the tip. Designed by Justin Jee using SOLIDWORKS Student Edition.

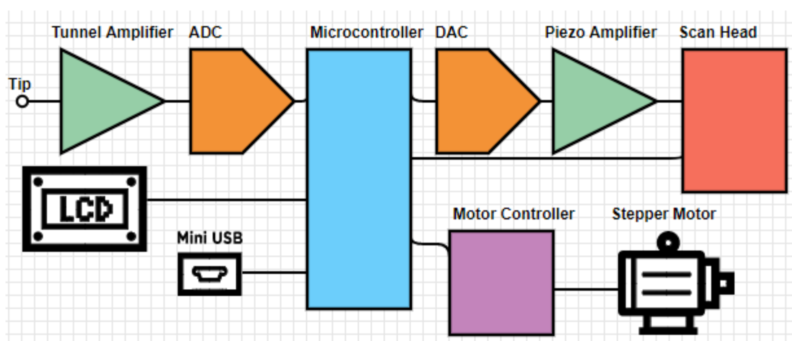

Figure 10: High level block diagram of tunnel current measurement device. Along with the power supply unit and keypad (not shown), these components complete the general architecture of the device. The 4x20 LCD displays basic information while built into the chassis.
DAC-Digital to analog converter   ADC-Analog to digital converter
Modeled by Justin Jee using Digikey Scheme-It

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November 2, 2017

Dear Baker and Koob Endowments Selection Committee,

I am writing to support the proposal "Development of a Sub-$200 Quantum Tunneling Current Measurement Device" prepared by Justin Jee, *et al*. I have talked at length with Justin about his proposal and have reviewed the written proposal. The project has scientific and educational merit, is ambitious yet realizable, and will contribute to a body of knowledge on low-cost instrumentation.

The type of instrument proposed, a simplified version of a scanning tunneling microscope (STM), is a powerful tool for characterizing the morphological and electrical properties of surfaces and nanomaterials deposited thereupon. Commercial STM instrumentation is expensive—on the order of $100k—though the basic principle of operation of an STM is relatively simple. The high cost of commercial instruments is commanded by the specific requirements of the controlling electronics. Modern, inexpensive microcontrollers now have the computational capability to operate these instruments. The idea to build a low-cost, open-source platform, as proposed here, will provide educational opportunities stretching from instrument design and manufacture to material characterization. Additionally, it could be potentially disruptive progress in the instrumentation field as there are companies selling "education-grade" STMs at large markups. With this platform, students could potentially build their own instrumentation and use it at a fraction of the cost of commercial devices.

My expertise is in the use of STM for nanomaterial characterization. My graduate work was done in laboratory that built all of its own instrumentation and I am currently building my own STM for use in research with Cal Poly undergraduates. The instrument we are building in my own lab is significantly more costly than the one proposed here for several design and functional reasons, but much of the equipment and expertise required in the building and testing phases is the same as required for the proposed project. The students involved in the project will have the opportunity to utilize much of the equipment we are using (*e.g.* space, oscilloscope, computers).

Comments on the specific review criteria.

- **Interdisciplinary in focus and participation**: This project lies at the intersection of electrical engineering, mechanical engineering, materials science, and physical chemistry.

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- **External validation**: The applicants have proposed to make their materials freely available online. I believe there is also an opportunity to serve the education community through a peer-reviewed journal article in a publication such as the *Journal of Engineering Education* or the *Journal of Chemical Education.*
- **Budget is appropriate to attain project objectives**: Because the authors are proposing a low-voltage device using standard microcontrollers, the cost of the project is appropriate.
- **Timeline is appropriate to attain project objectives**: The timeline thoughtfully described by the applicants is ambitious, but achievable.
- **Project objectives are measurable and attainable given time and financial constraints**: The applicants have wisely chosen to take the "scanning" out of the scanning tunneling microscope during the scope of this particular project in order to simplify the design and ensure that they can create a working approach, measurement, and feedback system.
- **Clear plan to disseminate results**: The applicants plan to make their design freely available online. I also believe their work would be suitable for internal or external conferences and potentially in a peer-reviewed science or engineering education journal.

I have been impressed by the careful planning undertaken by the applicants. In meeting with the project lead, Justin, it was clear that he had done his research and he had even developed a detailed line-item budget to estimate costs for equipment and supplies. Our conversations suggest that he has sufficient electrical engineering expertise to facilitate a successful project. I am happy to lend my support to this student-led project.

Sincerely,

Gregory E. Scott, Ph.D.