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SUITE 713
ARLINGTON VA 22203
Dr Gernot Pomrenke

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This report summarizes the use of the AFOSR ADURIP grant for obtaining an ICP etching tool to add state-of-the-art fabrication tool to prof. Adibi's research group at the Georgia Institute of Teclmology to improve the fabrication quality of nano and micro photonic structures for chip-scale integrated photoriic circuits. Since this grant is primarily focused on obtaining a major piece of equipment, this report summarizes the properties of the obtained system. It is expected that the addition of this etching tool will considerably enhance our capabilities for making photonic crystal structures as well as other photonic structures such as microdisk and microring-based integrated photonic structures.



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**Final Report to the**
**Air Force Office of Scientific Research (AFOSR)**

# An ICP Etching Tool for Accurate Fabrication of Photonic Crystal Structures

Georgia Institute of Technology

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May 30, 2006

## I. Introduction

This report summarizes the use of the AFOSR DURIP grant for obtaining an ICP etching tool to add state-of-the-art fabrication tool to prof. Adibi's research group at the Georgia Institute of Technology to improve the fabrication quality of nano and micro photonic structures for chip-scale integrated photonic circuits. Since this grant is primarily focused on obtaining a major piece of equipment, this report summarizes the properties of the obtained system. It is expected that the addition of this etching tool will considerably enhance our capabilities for making photonic crystal structures as well as other photonic structures such as microdisk and microring-based integrated photonic structures.

I have a funded research entitled "Chip-scale WDM devices using photonic crystals" through Optoelectronics program (Dr. Gernot Pomrenke) of AFOSR. The main goal of the proposed research is to utilize the major advantage (yet not highly explored) of photonic crystals (possibility of completely designing the electromagnetic modes) for optimizing the discrete photonic crystal (PC) devices as well as for optimally coupling these discrete devices in a unified integrated platform. A key requirement for the success of this research is the development of an accurate and reliable fabrication procedure for making robust PC structures. The addition of an $8M direct electron beam lithography tool to the fabrication facilities at Microelectronics Research Center at Georgia Tech has been an immense step towards the fabrication goals of my AFOSR-funded program. The addition of an ICP deep Si etching tool capable of etching PC structures with accurate shapes of the holes and good uniformity over the size of the integrated chip-scale structures is currently an essential need for my research. Combined with extensive computation and characterization facilities currently available at my lab (more than $1M equipment) and with the unique direct electron beam lithography tool currently available at Georgia Tech, the addition of the requested etching tool will go a long way in the development of low-loss large bandwidth PC integrated structures that are robust to minor fabrication imperfection.

## II. The Acquired ICP Etching Tool

After reviewing the existing vendors and obtaining detailed information about the research-grade ICP etching tools manufactured by each vendor, we selected the ICP etching tool manufactured by STS as the best match to our needs. In this process, We talked with several colleagues who worked with ICP etching tools from one or more vendor. Also, the staff members at the Microelectronics Research Center (MiRC) at Georgia Tech were of great help in making this important decision. After choosing the right machine, we added all necessary features (for example the mechanism for heating substrates like InP for successful etching) so that we can fabricate all structures of our interest using this etching tool. We considered Si, a variety of oxides, and III-V semiconductors as possible materials for fabricating nano- and micro-photonic devices. We also added enough number of mass flow controllers so that we can have at least 11 different gases for etching different samples. After applying the discounts from STS, the ICP etching tool was purchased for a final price of $412,500. In addition to the ICP tool, we also acquired state-of-the-art gas cabinets for the toxic gases as requested by Georgia Tech's safety office. The ICP tool has been delivered and is currently being installed at the MIRC of Georgia Tech under a mutual agreement so that the full control of the processes implemented with the machine is with the PI (A. Adibi). The total cost of installation and gas cabinets is $57,500. This results in a final cost of $470,000. AFOSR

provided, $355,200, and the rest was provided by Georgia Tech. The final quote from STS that also includes different features of the acquired etching tool is summarized in Appendix A.

## III. Major Research Enabled by the Acquired ICP Etching Tool

### III.A. Motivation

Simulations are a basic part of photonic crystal research where at some points there is little or no initial insight on the behavior of devices. By performing a good modeling and simulation step, The concept of an all-optical integrated information-processing module is of great interest for information processing, optical communications and sensors. Typically, an optical beam carries several wavelength information channels. An example is a wave-length division multiplexed (WDM) signal. Processing of such a signal includes separation of the different channels, filtering of the individual channels, and possibly incorporation of the filtered channels into one signal for retransmission or detection. Currently, these processes can be performed using individual non-integrated optical devices (prisms, thin film filters, waveguides, etc.). Most fiber optic systems deployed today are constructed from rather large discrete components, requiring many fiber-coupling connections that are inherently expensive, large and introduce losses. So far, it has been difficult to miniaturize devices for coupling, sorting, and multiplexing of light. Historically, it can be seen that integration of individual devices on a single platform (or substrate) increases reliability and reduces cost tremendously. Some examples are microprocessors, ATM modules, and VLSI and GSI systems. Integration of discrete devices at the scale of a chip also offers the promise of lower weight, more reliability, smaller size and less sensitivity to electromagnetic interference. It further eliminates the need for labor-intensive alignment of discrete optical devices. As a result, integrated chip-scale WDM modules have been of high interest recently. Along with several other funding agencies, Air Force Office of Scientific Research (Physics and Electronics Division, Optoelectronics: components and information processing program, Dr. Gernot Pomrenke) is especially interested in the "integration of nanocavity lasers, filters, waveguides, and diffractive optics, which can form nanofabricated photonics integrated circuits" (AFOSR BAA2004-1 announcement, page 12).

The main challenge in the development of chip-scale modules is to develop a unified platform that allows the integration of the ultra-small discrete devices. Photonic crystals are currently considered as the best candidates for such a platform. Photonic crystals (or photonic bandgap materials) are microstructured materials in which the dielectric constant is periodically modulated on a length scale comparable to the desired wave-length of light. Multiple interference between wave structures scattered from each unit cell of the structure may open a "photonic bandgap", i.e., a range of frequencies within which no propagating electromagnetic field exists. Therefore, two- and three-dimensional photonic crystals act as two- and three-dimensional mirrors for optical frequencies within the photonic bandgap. By adding point defects with sizes on the order of a wavelength, ultra-small cavities have been designed and demonstrated. These cavities can be combined to form ultra-small optical filters with sophisticated frequency response (or cavity lineshape). Photonic crystal waveguides have been made by adding line defects to a photonic crystal. These narrow channel waveguides make the routing and interconnection of optical signals (even around sharp corners) possible.

Due to their unique properties for the development of novel optical devices, photonic crystals have been the subject of more than 1000 journal papers in the last few years. Almost all government funding agencies with programs in the area of optics (i.e., NSF, DARPA, ONR, AFOSR, ARO, etc.) are currently supporting research in photonic crystals. A main research direction in the Optoelectronics: components and information processing program (Dr. Gernot Pomrenke) of the Physics and Electronics Division of AFOSR is the application of two-dimensional and three-dimensional photonic crystals for chip-scale WDM. This research direction combines the two current primary program thrusts of (1) the development of optoelectronics devices and materials, and (2) the insertion of these components into optoelectronic computational and information processing systems (AFOSR BAA2004-1 announcement, page 12).

**III.B. Current AFOSR-funded research related to the DURIP proposal**

Simulations are a basic part of photonic crystal research where at some points there is little or no initial insight on the behavior of devices. By performing a good modeling and simulation step, The concept of an all-optical I have a single-PI funded research entitled "Chip-scale WDM devices using photonic crystals" through the Optoelectronics: components and information processing program (Dr. Gernot Pomrenke) of the Physics and Electronics Division of AFOSR. The proposed research is focused on the design and optimization of discrete photonic crystal devices and on the development of optimum coupling schemes for integration these de-vices to form optical information processing modules.

One unique nature of this research is the development of systematic methods for the design of electromagnetic modes in photonic crystals (PCs). Most of the previous work in photonic crystals has been focused on designing structures that can be made using other techniques. Two major examples are microcavities and waveguide bends. In these structures, photonic crystals are used as mirrors, and the result is a smaller micro-cavity or a tighter waveguide bend than previously available. However, the major advantage of photonic crystals is the possibility to completely design an electromagnetic mode (field pattern, effective index, dispersion, etc.) by tailoring appropriate defects. There has been little research on this subject, both at the fundamental level and for the applications. This is a main thrust in my research. Dispersion properties of photonic crystal devices can be modified by changing the geometry of the defects. The range of control over the dispersion in photonic crystals is several orders of magnitude larger than that in the bulk materials, and it can serve as a major advantage in designing WDM devices. There has been little research on this subject, both at the fundamental level and for the applications like WDM. This is a main thrust of my research.

Another trust in my AFOSR-funded research is to optimally combine individual discrete devices in a unified platform to design integrated chip-scale optical modules for WDM applications. Three major functionalities required for WDM are wavelength multiplexing/demultiplexing, accurate filtering, and routing (or guiding) optical beams. These functionalities are directly available in PCs. Three major discrete devices that will be optimized and coupled in this research are PC superprisms, PC waveguides, and PC cavities. PC superprisms are necessary for wavelength multiplexing and demultiplexing. PC waveguides play the important role of routing different channels as well as connecting discrete devices in an efficient way. PC cavities are used for filtering different channels. The study and optimization of dispersion engineering and optimum coupling of these three devices constitute the heart of my research. My group is currently

developing systematic methods for controlling the mode properties in these three PC devices. In addition, being able to design the electromagnetic modes of discrete PC devices is a very important step in optimizing the coupling of different devices.

Several functionalities that can result from the proposed research in the form of an integrated planar photonic crystal device are shown in Figure 1. The multi-channel input light is coupled into the photonic crystal device from the left side. The dispersion of the input region of the photonic crystal structure is designed to have a strong superprism effect to angularly separate the different wavelength channels. Each wavelength channel is optimally coupled into a photonic crystal waveguide on the same substrate. Appropriate filtering is performed on each channel by designing cavities coupled to the waveguides. Both on-chip filtering and out-of-chip filtering can be performed by appropriately de-signed cavities. After the filtering operations, the signals from different waveguides will be combined using another superprism region to form one output signal for detection or retransmission. We can also route separate channels after filtering to different detectors if needed. Note that Figure 1 is prepared to show that all functionalities required for any WDM device can be implemented in an integrated form in PCs. Specific WDM devices (for example add/drop filters) might use only a subset of these functionalities or may only affect a few channels of the WDM signal.

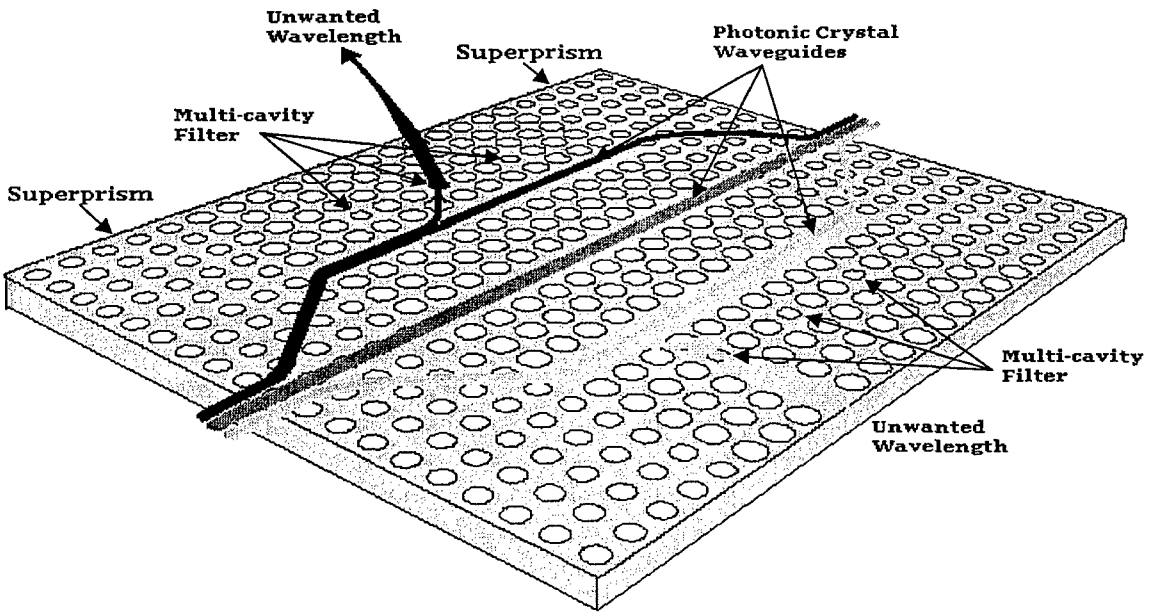


**Figure 1:** Proposed photonic crystal structure for optical information processing. The input signal enters the structure from the left side. Different wavelength channels are separated and guided into separate waveguides in the superprism region. Each channel is filtered using matched filters made by photonic crystal defects. The filtered channels will be recombined (if necessary) using superprism effect. The output signal (right side) will enter an optical detector for the final measurement steps, or will be retransmitted through a fiber. Only three channels are shown here for simplicity. Different ideas for filtering are represented in the figure.

The major elements of the proposed device shown in Figure 1 are superprism regions, waveguides, and multi-cavity filters. All these elements are designed using dispersion engineering. Therefore, the study and optimization of dispersion engineering for photonic crystal superprisms, waveguides,

and multi-cavity filters constitutes the heart of my research. Superprisms, waveguides, and cavities in photonic crystals have already been demonstrated. However, the control of these effects has not been investigated yet. To add this degree of control to the key elements of an integrated all-optical information processing module, my approach is to investigate the following issues:

**1. Controllable photonic crystal superprism:** The superprism effect is due to the sharp variation of the dispersion of the photonic crystal modes, i.e., strong dependence of the effective index of refraction of the mode with wavelength. Due to this sharp variation, different channels of a multi-wavelength input light are refracted in different directions. All the wavelengths separated by the superprism effect are out of the photonic bandgap (PBG) of the photonic crystal. Therefore, they can propagate inside the structure. The dispersion of the electromagnetic modes in the superprism region can be varied by changing the geometry of the air holes. Therefore, the angular separation of the different channels can be controlled by designing the geometry of the air holes in the photonic crystal superprism. Different configurations of these air holes will be studied in this research. The main goal in this investigation is to separate the channels of a multi-wavelength signal (like a WDM signal) into a series of desired angles in order to efficiently couple them into single-channel (or single-wavelength) waveguides.

**2. Waveguides with controllable dispersion**: The guided modes of a photonic crystal waveguide are mainly confined in the guiding region. Therefore, their dispersion properties can be controlled by changing the geometry of the air holes next to the guiding region. I have been investigating the properties of PC waveguides in detail in the last four years. I have developed a complete description of the guiding mechanisms in these waveguides. I have also shown, for the first time, a systematic method for designing single-mode PC waveguides. My group is actively involved in the development of a systematic method for completely designing the dispersion diagram (and therefore, important properties like group velocity) of the guided modes in these waveguides. As an example, we recently demonstrated (under AFOSR funding) a new type of PC waveguides, namely biperiodic PC waveguides, with lowest loss and largest guiding bandwidth among all reported structures that have been fabricated using simple electron beam lithography and dry etching. Having better fabrication tools, we expect to reduce the propagation loss in these novel waveguides by at least one order of magnitude bringing it to below 2 dB/cm, which is acceptable for practical applications of nano-optical integrated circuits. We are currently investigating the use of dispersion engineering in PC waveguides for control-ling group velocity and time delay. Controlling the time delay of a waveguide is very useful in designing separate delay lines for different wavelength channels for distortion compensation purposes as well as for delay lines required for planar integrated circuits for next generation optical packet switching. Again, a key requirement for making practical devices is a reliable and accurate fabrication tool.

**3. Cavities with controllable modes:** Photonic crystal cavities are the key elements for designing filters. The frequency response of a filter depends on the mode structure of each cavity used in the filter. The control and design of the cavity modes are extensively investigated in this research. Our approach is to use the geometry of the cavity and the coupling between multiple cavities to control, design, and optimize the overall mode structure of the multi-cavity system as well as the overall frequency response of the filter. The design of the matched filters for the analysis of weak signals is a crucial need for several applications such as sensing and information processing.

**4. Optimum coupling between discrete PC devices:** My group is also involved in the development of an optimal coupling scheme between different PC devices de-scribed above. PC Superprism to PC waveguide and PC waveguide to PC cavities must be optimally coupled in an integrated WDM module. Waveguide bends with high bending efficiency are also under investigation.

## Appendix A: The Final Quotation from STS for the Acquired ICP Etching Tool

The attached quotation summarizes the detailed information of the acquired ICP etching tool and its accessories. The accessories were selected to enable the use of at least 11 different gases as well as the use of multiple substrates (including S, III-V semiconductors, and a variety of oxides). The attached quotation only includes the ICP tool itself and does not list the installation costs that are about $57,500.

# QUOTATION

**(Provided on behalf of Surface Technology Systems plc)**

SURFACE TECHNOLOGY SYSTEMS

## Prepared by:

**ST Systems USA**
611 Veterans Boulevard, S107
Redwood City
CA 94068

**Quotation Number:100886B**
**Date:** August 5th, 2005

## Prepared for:

**Georgia Institute of Technology**
**Atlanta**
**Georgia**

**Attention: Prof. Adibi**

## STS Multiplex$^{RD}$ ICP System

## Inductively Coupled Plasma Process Chamber With Single Wafer Loadlock

## Multipurpose System Configured for III-V (incl HT InP) and Shallow Silicon (There is NO Bosch process with this system)

## SECTION A: System Configuration and Pricing

| Item | Qty | Code | Description | Price US $ |
|---|---|---|---|---|
| 1 | 1 | | **Multiplex[RD] ICP System with Single Wafer Vacuum Load Lock** | **$526,850** |
| | 1 | | **Control System and User Interface** | |
| | 1 | A90 | Windows 2000 software control PC with CD-RW | |
| | 1 | A85 | Standard Control System | |
| | 1 | M21 | Standalone VDU, keyboard and mouse | |
| | 1 | | **Vacuum Load Lock with single wafer loader** | |
| | 1 | D55 | Vacuum Load-Lock with single wafer loader | |
| | 1 | L04 | Load lock parts for 1 x 100mm wafer | |
| | 1 | YSP | Scroll pump – TS100 | |
| | 1 | | **ICP Process Module** | |
| | 1 | R85 | ICP SC160M Process Chamber (MESC) | |
| | 1 | H15 | ICP 240BF Source (exc. PSU and Matching) | |
| | 1 | S27 | 1 KWatt (13.56 MHz) RF Supply and Matching Unit (for ICP source) | |
| | 1 | R49 | Mechanical Wafer Clamping Electrode (pin lift) with He Backside cooling | |
| | 1 | W44 | Chamber parts for 1 * 100mm substrate (Mechanical Clamping) | |
| | 1 | S26 | 300/30 Watt (13.56 MHz) RF Supply and Matching Unit (for lower electrode) | |
| | 1 | K67 | Electrode Temperature Control (+5 to +40 deg C) [AFF-RWA012] | |
| | 2 | G01 | On-board mini gas box (max 8 lines) | |
| | 7 | G12 | Gas Line(s) – Non Hazardous<br>-N2, O2, Ar, He, CHF3, CF4, 1 Spare (N2) | |
| | 3 | G15 | Gas Line(s) (with Purge and Bypass) (add 1xG23 for each heated line)<br>-CL2, BCL3, HBr | |
| | 2 | G18 | Gas Line(s) (interlocked to Oxygen gas line)<br>-CH4, H2 | |
| | 1 | G23 | Heater for gas line (for BCL3) | |
| | 2 | G20 | Gas Line Control Module for >4 gas lines | |
| | 1 | Y41 | Turbo Pump: Leybold MAG 900 CT | |
| | 1 | Y50 | Dry Pump: Edwards iQDP80(H) for chlorinated processes | |
| | 1 | QCK | Quick Change Kit - Spare set of ceramics for the process chamber including main ceramic vessel, ceramics for platen, clamp assembly, | |
| | 1 | HT | High temperature electrode upgrade;<br>- HT electrode capable of operation up to 180 degrees<br>- High temperature heat exchanger/chiller | |
| | | | ***There is no BOSCH Licence included in this system*** | |

**Price Offered including a 22% University Discount $412,500**

## Section B: no options quoted

**Note: A range of additional options is available for End Point Detection, Pump Insulation and Stacking Frames depending upon the desired configuration of the system.**

## Section C: Validity of Quotation

**Validity of Quotation** **To August 31st, 2005**

## Section D: Typical Delivery

**Typical Delivery:** **Shipment By December 31st, 2005**

This assumes that STS is in receipt of an agreed technical specification, and that no factory acceptance of the system is required prior to shipment.

An exact shipment date can only be quoted at the time of order.

**Delivery terms are:**
**Packed F.O.B STS, UK**

## Section E: Order Details and Payment Terms

| | | |
|---|---|---|
| Payment 1: | With Order | **30%** |
| Payment 2: | On Shipment to Customer | **60%** |
| Payment 3: | On satisfactory commissioning or 60 days after delivery (if the delay in commissioning is not the fault of STS). | **10%** |

**Payment Terms are:** **Nett 30 days**

**All Prices are in:** **US Dollars**

Orders and payment for systems should be placed on the main STS office listed below and a copy sent via fax or mail to your local STS sales and support office shown on the front page of the quotation. Orders for spares should be placed on your local STS office.

### Order and Payment Address

Surface Technology Systems Plc
Imperial Park
Newport
NP10 8UJ
UK
Tel: 011 44 1633 652400
Fax: 011 44 1633 652405

Should you wish to make payments via electronic/wire transfer please contact your local STS office for details.

## Section F: Taxes

The price quoted does not include any (if applicable) importation duties, state or local taxes

## Section G: Warranty

**Warranty Period** **12 Months**

STS warranty the system against faulty design, materials and workmanship for the warranty period and will make good any faults arising from these by repair or replacement within that period.

The warranty period begins after the system is commissioned, or 60 days after shipment, whichever is earliest, if failure to install and qualify the system is in no way the fault of STS.

If, during manufacture, the customer delays the shipment beyond STS advised delivery dates the warranty will commence 60 days after the advised shipment date.

The system warranty does not include the cost of consumable items.

It is the responsibility of the customer to complete the system preventative maintenance schedules as specified in our technical manual. The system warranty is only valid if these procedures are correctly followed.

## Section H: Packaging

For shipment the system is completely enclosed in vacuum sealed foil/plastic packaging and then packed in a closed export quality packing crate.

## Section I: System Documentation

The following comprehensive technical manual package is supplied with the system:

1 x Operator Manual on clean room paper.
1 x Interactive Operator Manual on CD-ROM
1 x OEM Manuals in a separate folder on plain paper
1 x Interactive Service Manual on CD-ROM
1 x Modular (Spare) parts manual on plain paper
1 x Set of electrical schematics on plain paper

Additional Technical Manual package as specified above **$750**

## Section J: System Installation

The quoted price includes electrical / mechanical commissioning of the system by STS engineers as well as system functionality testing both at STS and the customer's facility.

It is the responsibility of the customer to supply and connect all facilities required for system operation (such as, but not limited to, electrical power, compressed air, cooling water, nitrogen, helium, exhaust facilities and process gases).

Customer is responsible for reviewing and following local regulatory code to determine if a scrubber or other abatement system is required for the process pump exhaust. Customer is responsible for supplying any necessary scrubber or abatement system.

Your STS representative will supply you with a Pre-Install Facilities Guidelines brochure for you to review system layout and facilities requirements before you purchase your equipment.

A comprehensive Pre-Installation Package fully detailing the facilities required will be supplied by STS after order. It will also be the responsibility of the customer to supply any gas cylinder storage cabinets, process gas-lines and cylinder pressure regulation equipment required.

## Section K: Process Commissioning and Applications Support

Prior to the shipment of your system it will undergo a series of STS standard process tests to confirm that the equipment meets STS basic quality standards.

Where customer specific application specifications have been agreed in writing (at the time of sale), the system will be subjected to further process testing before shipment to show that it meets these application specifications.

Following installation, STS will provide on-site support to demonstrate that the system meets the agreed application specifications. System performance is only guaranteed for the specified qualification applications agreed between STS and the customer at the time of sale.

The customer is responsible for supplying all wafers for these additional process tests at STS and on-site. Wafers must be at STS 6 weeks prior to the system shipment date in order for STS to demonstrate compliance. Wafers must be available on-site at the time of installation. If wafers are not supplied to perform this testing we will be unable to demonstrate the compliance and the specification will not be guaranteed.

## Section L: Training

The quoted price includes 1 day of basic system operation and maintenance training on the system for up to two (2) people, to be provided by STS' engineers at the time of system commissioning. STS also offers a wide range of structured maintenance training courses. Please contact you local representative for further details.

## Section M: Service Contracts

STS offers a range of preventative maintenance and post warranty service contracts. Please contact your local STS representative for further details.

## Section N: Spares Packages

The quoted price does not include system spares or consumables. Preventative maintenance kits, consumables kits and spares packages are available. Please contact your local STS representative for further details.

**Andrew .J. Tucker**
**Vice President – Sales (North America)**

Georgia Tech Research Institute

Document No: A784500000R27
5 June 2006

To: 542 EWSG/LSELS
380 Richard Ray Blvd., Suite 104
RAFB, GA 31098-1638

Attention: Ms. Martina Leschinsky, Ms. Suzanne Mason
(martina.leschinsky@robins.af.mil; suzanne.mason@robins.af.mil)

Subject: Contract Funds Status Report – Month Ending May 31, 2006
Contract Number: FA8523-05-D-0003, D.O.#0001
CDRL Item: A00H

Attached please find the Contract Funds Status Report for the MH-53M HEWP BCC1 Software Development and Test Program.

Please address any questions or comments to the undersigned.

Prepared By,

*Signature on File*
Joe Brooks, Project Director

Attachment: "A7845 May 2006 CFSR.xls"