Report 41164R07

ADAPTIVE FULL-SPECTRUM SOLAR ENERGY SYSTEMS
Cross-Cutting R&D on adaptive full-spectrum solar energy systems for more efficient and affordable use of solar energy in buildings and hybrid photobioreactors

Semi-Annual Technical Progress Report
August 1, 2004 – January 31, 2005

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ABTRACT

This RD&D project is a three year team effort to develop a hybrid solar lighting (HSL) system that transports daylight from a paraboloidal dish concentrator to a luminaire via a bundle of small core or a large core polymer fiber optics. The luminaire can be a device to distribute sunlight into a space for the production of algae or it can be a device that is a combination of daylighting and electric lighting for space/task lighting. In this project, the sunlight is collected using a one-meter paraboloidal concentrator dish with two-axis tracking. For the second generation (alpha) system, the secondary mirror is an ellipsoidal mirror that directs the visible light into a bundle of small-core fibers. The IR spectrum is filtered out to minimize unnecessary heating at the fiber entrance region.

This report describes the following investigations of various aspects of the system. Much of the planned work has been slowed due to significant procurement delays of the primary mirror. However, taken as a whole, they do confirm progress towards the technical feasibility and commercial viability of this technology.

- Performance specifications were developed for the tracking subsystem and collector optics,
- Thermal management experiments for the fiber optic bundle entrance region,
- Bioreactor testing, cost-modeling, and redesign.

Due to this procurement delay, a no-cost extension of the project completion date has been requested and approved.

DISCLAIMER

PREFACE

This report is a joint effort between Oak Ridge National Laboratory and the University of Nevada, Reno, and as such it satisfies the reporting requirements for the University and ORNL as the M&O for this project. The reporting period is from August 1, 2004 through January 31, 2005.

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The contributions of each of these individuals in the preparation of this report are gratefully acknowledged.

EXECUTIVE SUMMARY

This RD&D project is a three year team effort to develop a hybrid solar lighting (HSL) system that transports daylight from a paraboloidal dish concentrator to a luminaire via a bundle of small core or large core polymer fiber optics. The luminaire can be a device to distribute sunlight into a space for the production of algae or it can be a device that is a combination of daylighting and electric lighting for space/task lighting. In this project, the sunlight is collected using a one-meter paraboloidal concentrator dish with two-axis tracking.

During the first budget period (August 2001 – April 2003) a bench mark prototype system was developed and evaluated to determine technical feasibility of using full-spectrum solar energy systems to enhance the overall sunlight utilization in buildings and biomass production rates of photobioreactors.

During the second budget period (May 2003 – April 2004), emphasis was placed on determining those aspects of the solar lighting system that characterize performance efficiency, reliability, durability and ultimately minimum cost potential. The major accomplishment was the second generation (alpha) system for which the secondary mirror is an ellipsoidal mirror that directs the visible light into a bundle of small-core fibers.

During this reporting period, the design requirements and specifications for dish-tracker subsystem of the hybrid solar lighting system have been divided into four categories: 1) Environmental, 2) Optical, 3) Operational, and 4) Mechanical.

Recent research by Oak Ridge National Laboratory and University of Wisconsin has revealed the major cause of over heating of the entrance region of the fiber optic bundle (FOB). Subsequently, the FOB has successfully been able to remain on-sun for extended periods of time (on the order of weeks). To facilitate design and manufacturability a working model of the bundle heating process has been developed.

During this reporting period the bioreactor at Ohio University experienced a long stretch of good weather to conduct an extended test for algal productivity. The new header design proved to be more than satisfactory for populating and harvesting of the membranes. These results are significant because they show that the cyanobacteria have a remarkable ability to grow once acclimated to the membrane substrate. Further, it strongly indicates that the harvesting method of higher water flow does not physically stress the algal mass that remains on the substrate. That is critical for long term sustainability.

Although the project has experienced a six month procurement delay, the Research Team has high confidence in the low cost primary mirror being manufactured by Bennett Mirror Technologies Limited, New Zealand. The first mold made of fiber board material produced low quality mirrors. A scale model mold was made from aluminum. It produced mirrors that met the Team's requirements. Thus, a new full sized mold is being made from aluminum and should be completed during February 2005. Due to this procurement delay, a no-cost extension of the project completion date has been requested and approved.

PROJECT DESCRIPTION

This project is part of the FY 2000 Energy Efficiency Science Initiative that emphasized Cross-Cutting R&D in Solicitation No.: DE-PS36-00GO10500. It is a three year research project that addresses key scientific hurdles associated with adaptive, full-spectrum solar energy systems and associated applications in commercial buildings and new hybrid solar photobioreactors. The goal of this project is to demonstrate that full-spectrum solar energy systems can more than double the affordability of solar energy in commercial buildings and hybrid solar photobioreactors used in CO_2 mitigation and compete favorably with existing alternatives.

This project is a multi-team effort to develop a solar lighting system that transports solar light from a paraboloidal dish concentrator to a luminaire via a bundle of small core or large core polymer fiber optics. The luminaire can be a device to distribute sunlight into a space for the production of algae or it can be a device that is a combination of daylighting and electric lighting for space/task lighting. In this project, the sunlight is collected using a one-meter paraboloidal concentrator dish with two-axis tracking. For the second generation (alpha) system, the secondary mirror is an ellipsoidal mirror that directs the visible light into a bundle of small-core fibers. The IR spectrum is filtered out to minimize unnecessary heating at the fiber entrance region.

SCOPE OF WORK

Phase I. Assess Technical Feasibility

Determine technical feasibility of using full-spectrum solar energy systems to enhance the overall sunlight utilization in buildings and biomass production rates of photobioreactors. This was accomplished during Budget Period 1 by developing a benchmark prototype system that could evaluate the collection, distribution and utilization of concentrated solar light.

Phase II. Assess Commercial Viability

Determine the commercial viability of using full-spectrum solar energy systems to enhance the overall sunlight utilization in buildings and biomass production rates of photobioreactors. This was the emphasis for Budget Period 2. R&D was directed at characterizing performance efficiency, reliability, durability and ultimately minimum cost potential. The goal was the design and construction of a second generation or an alpha system that shows significant improvement in the performance cost ratio.

Phase III. Assess System Affordability

Demonstrate the HSL technology in a building application and a photobioreactor application. The emphasis for Budget Period 3 is the development of a third generation beta system or pre-commercial prototype system that potentially can meet the performance and cost targets.

PROGRESS TOWARDS PROJECT OBJECTIVES

The emphasis during this reporting period has been on the following items:

1) Performance specifications were developed for the tracking subsystem and collector optics
2) Thermal management experiments for the fiber optic bundle entrance region
3) Bioreactor testing, cost-modeling, and redesign

A summary of each investigation is given below.

1. Requirements for a Hybrid Solar Lighting Dish-Tracker System

1.1 Introduction

This section contains requirements for the dish-tracker subsystem of the hybrid solar lighting system. The requirements may be divided into several categories:

1) Environmental (related to the outdoor exposure of the system, and taking into account such things as temperature extremes, resistance to weathering, and protection of the system against environmental hazards such as snow and wind loads)
2) Optical (related to the basic requirements of delivering a certain amount of solar light to the aperture of the optical fibers)
3) Operational (related to tracking the sun, power requirements, and interfaces)
4) Mechanical (including the interfaces to the building roof, to the fiber bundle, and other mechanical connections)

These requirements are detailed in the following sections.

1.2 Environmental Requirements

The dish-tracker system shall operate normally within the following ranges of environmental conditions.

Temperature Limits
-40C to 50C Ambient temperature during operation

Altitude
0 to 5000m Altitude above sea level

Location
Capable of being installed anywhere in the world. Module replacement for time synchronization may be required for other than North American installations.

Relative Humidity
0 to 100% Relative humidity, including condensing conditions

Wind
30 mph Maximum operating wind speed (avg)
50 mph Maximum wind speed for normal operation (peak)
90 mph Maximum survival wind speed (at stow)

120 mph Maximum survival wind speed (tied down)

Rain/Snow

All components shall be protected from rain and snow, including blowing rain and snow. NEMA 4 or IP65 protection of all exposed electrical components is required.

Dust

All electronics and mechanical components shall be protected from blowing dust and sand.

Insolation

1200 W/m^2 Maximum direct-normal solar insolation

All components shall be designed for, or protected from, exposure to concentrated solar radiation and solar UV radiation.

Service Life

The system shall be designed for a normal service life of 10 years. Within that service life, degradation of performance of 10% shall be deemed acceptable.

1.3 Optical Requirements

The basic purpose of the dish-tracker system is to deliver light energy to the optical fiber bundle. The following requirements are based on a nominal system. Requirements for optical alignment of the primary and secondary reflectors with the fiber bundle are given at the end of the section.

Solar Concentration

80 Peak lumens/sq.mm. on fiber bundle aperture (based on visible light portion of the solar spectrum, net after reflection and other losses)

60 Average Lumens/sq.mm of light over fiber bundle aperture at 1000 W/ m^2 direct normal insolation

Incidence Angle

15 degree Maximum incidence angle of solar radiation, from normal, onto fiber bundle aperture

Tracking Accuracy

Tracking accuracy shall be sufficient to maintain the solar concentration on the aperture of the optical fiber at nominal values at all times when conditions are within operational limits.

0.1 degree Maximum allowable tracking error/minimum tracking system resolution

Primary Dish Optics

1 m^2 Minimum net reflective area

90% Minimum solar-weighted (AM1.5) reflectance (350-700nm)

0.419m (16.5 in.) Focal length

Secondary Dish Optics

10% Maximum reflectance in IR (700nm – 2500nm)

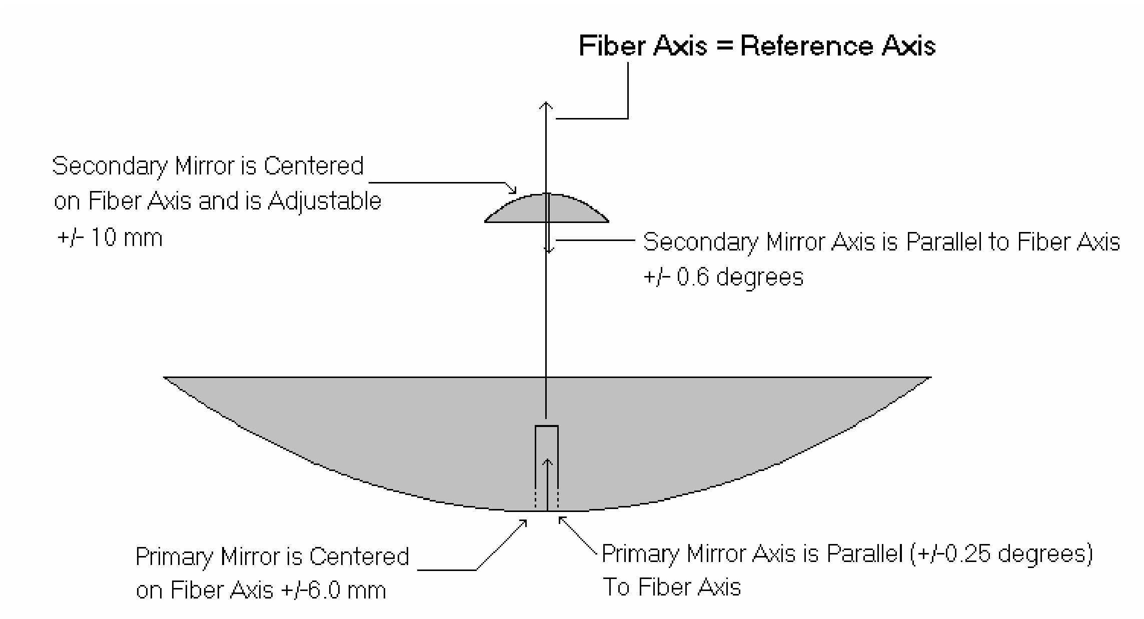


Figure 1.1 Schematic of Beta system primary and secondary mirrors.

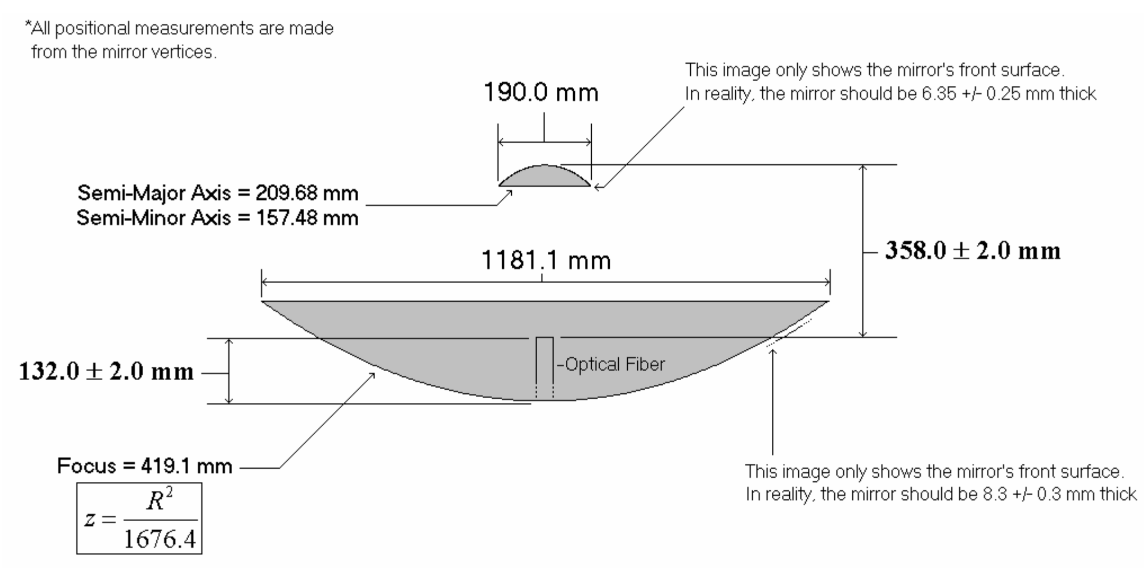


Figure 1.2 Dimensions for Beta system primary and secondary mirrors

1.4 Operational Requirements

Autonomy

The system shall operate autonomously once initially installed and aligned. The only operator control necessary shall be an enable switch closure. The system shall synchronize itself via GPS signals (an alternative is to use radio signals from the WWV transmitter in North America), and be capable of synchronization to other transmitters via modular replacements in the control system. Synchronization to within 10 seconds of the correct time shall be maintained at all times.

Power

The dish-tracker system shall be self-powered from a small PV array on the hybrid solar lighting system. A rechargeable battery shall provide energy storage. Alternatively, the system may be powered from utility power. The system power level shall be nominally 12VDC.

Alignment

Once aligned, the system shall self-calibrate its tracking to maximize the solar energy delivered to the optical fibers and PV array.

Maintenance

The system shall be designed to provide easy access for maintenance. Connectors shall be used to simplify installation and component replacement. The initialization/maintenance serial interface shall provide access to stored parameters and data and allow manual movement and control of the system for maintenance purposes.

User Control

The operational control shall be dry contact closures to remotely enable operation of the system and select offset-tracking or stow.

Automated Operation

When enabled, the system shall automatically acquire and track the sun from sunup to sundown. When disabled, the system will offset track. At night, the system shall move to a face-up stow orientation and place itself in a low-power configuration.

Initialization

A serial interface (RS-232 or USB) shall allow connection to an installer's interface system. This system shall be used to provide initial latitude and longitude data if a WWV time base is used, set system parameter values, and to allow manual initialization of the system orientation.

Data Acquisition

The control system shall monitor and accumulate operational data and allow that data to be downloaded to the maintenance interface. Data to be recorded shall include the following:

1) Cumulative hours of on-sun operation
2) Daily summary data: hours of tracking operation, battery voltage, PV energy delivered, lumen-hours delivered to fiber bundle.
3) Tracking offset table data
4) Detailed tracking and system operational data from latest day(s) of operation (azimuth/elevation vs. time, PV power and battery voltage vs. time)
5) Event log with faults and other events (enable on, enable off, start/stop tracking, faults with timestamp, etc.)

1.5 Mechanical Requirements

Mounting
The system shall be mounted using a standard 3 in. pipe mount as for a satellite dish. A skid-mounted pipe support may be used on a flat roof structure to avoid structural roof penetrations.

Control Enclosure
The control system components shall be housed in a NEMA 4 enclosure mounted on the dish structure to protect them from the environment. The control enclosure and backup battery shall be located in a shaded area to minimize overheating.

Weight
The total system shall not exceed 200lb, excepting ballast used for roof mounting. No component shall be more than 50lb. The system shall not exceed 20lb/ft^2 of roof loading.

Connectors
All replaceable components of the control system shall be connected with quick-disconnect polarized electrical connectors and simple, easily-accessed mounts to minimize installation and maintenance costs.

Motion Limits

0 degrees (horizon)	Minimum tracking elevation
90 degrees (zenith)	Maximum tracking elevation
350+ degrees	Range of azimuth tracking

Motion shall be self-limited using electrical limit switches or mechanical limits (e.g., runoff at end of gears).

Tracking Speed

0.5 degrees/sec	Maximum slew speed
0.1 degrees/sec	Nominal tracking speed in elevation or azimuth

Fiber Bundle
The weight of the fiber bundle shall be supported at the roof level with sufficient free length above the roof to accommodate all motion of the tracker. The fiber bundle may enter the building through a single non-structural roof penetration or through the mounting pipe.

PV Panel Mount
The PV panel providing power to the system will be mounted separately from the tracker.

User Interface
System control shall be via a multiple-conductor cable to a dry contact closure. The cable shall be sized to be suitable for 1A, 12VDC operation with less than 1VDC voltage drop.

Initialization/Maintenance Interface
A serial port shall be provided within the control enclosure to allow attachment of an initialization/maintenance interface device. A system on-off switch or disconnect shall be provided in the control enclosure to control power to the control system.

Visual Interface

LED's to indicate system operational status shall be provided, visible at the unit. The LED's shall include:

1) Red LED to indicate a fault condition. LED will flash if a fault is present. Fault type can be indicated by the number of flashes.
2) Green LED to indicate battery/PV status. LED will flash to indicate the status of the battery. The battery voltage level will be indicated by the number of flashes.
3) Yellow LED to indicate enabled status. LED will flash to indicate system operation has been enabled by the remote enable switch.

2. Fiber Optic Bundle Heating Experiments

2.1 Experimental Setup for Fiber Optic Bundle Heating Measurements

Recent research at Oak Ridge National Laboratory done by Duncan Earl has revealed some of the major contributors to the heating of the fiber optic bundle (FOB). In turn, the FOB has successfully been able to remain on-sun for extended periods of time (on the order of weeks). However, there is still no working model of the bundle heating process. August, then, was spent at ORNL expanding upon this initial research in hopes of furthering the progress of a FOB heating model.

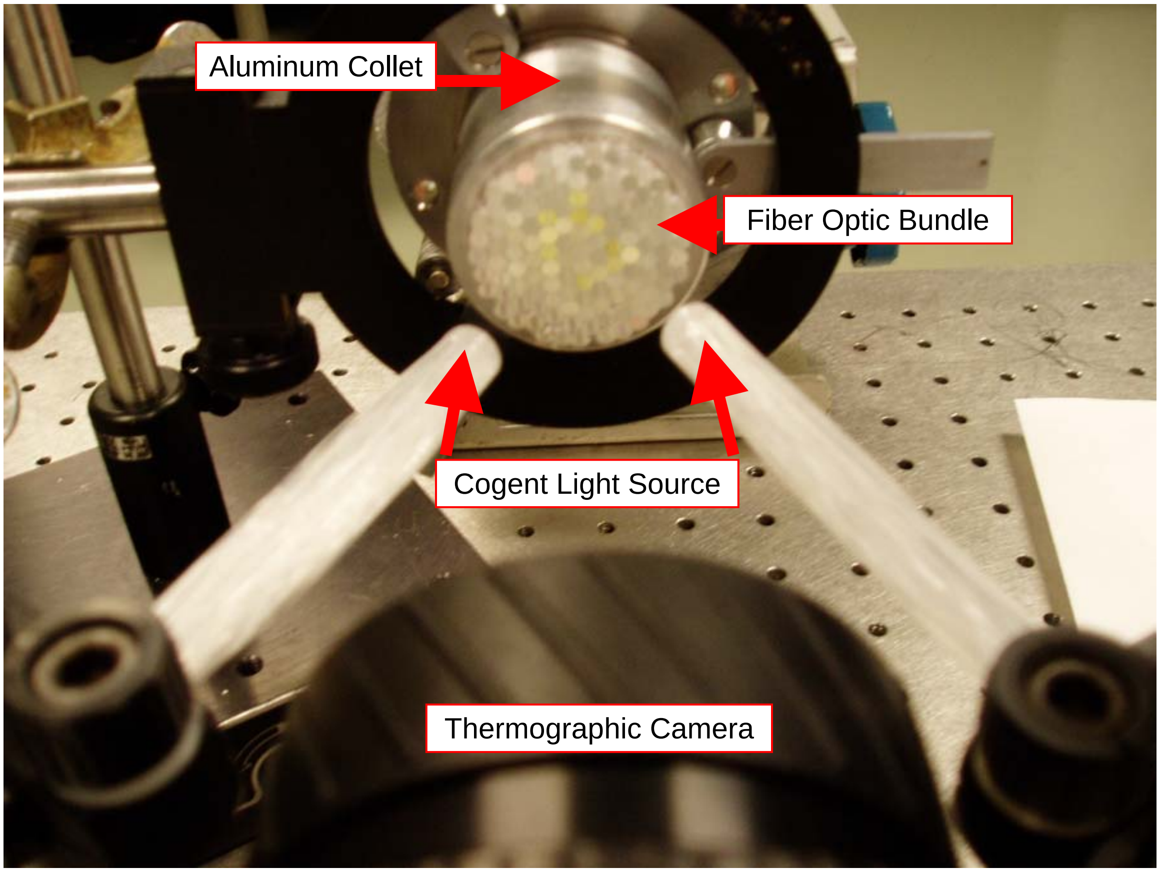


Figure 2.1. Experimental setup.

Figures 2.1, 2.2 and 2.3 show the laboratory setup used to simulate on-sun conditions. The setup consisted of a Cogent light source, the spectrum and data of which are shown in Figure 2.1, a thermographic camera made by FLIR Systems, and an FOB held in a collet.

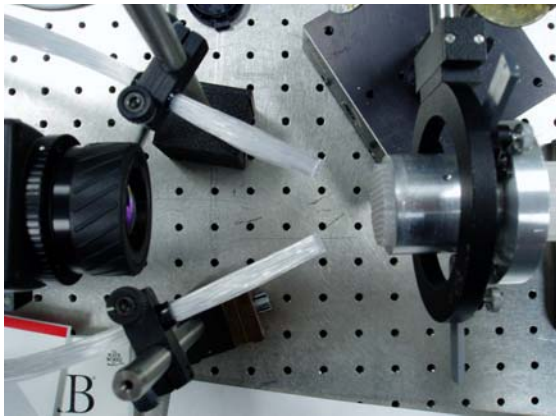


Figure 2.2. Bird's-eye view of experimental setup

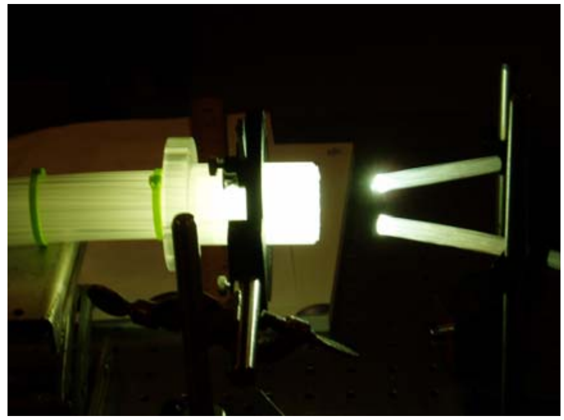


Figure 2.3. Side-view of experimental setup with a FOB in an acrylic collet and Cogent light source on.

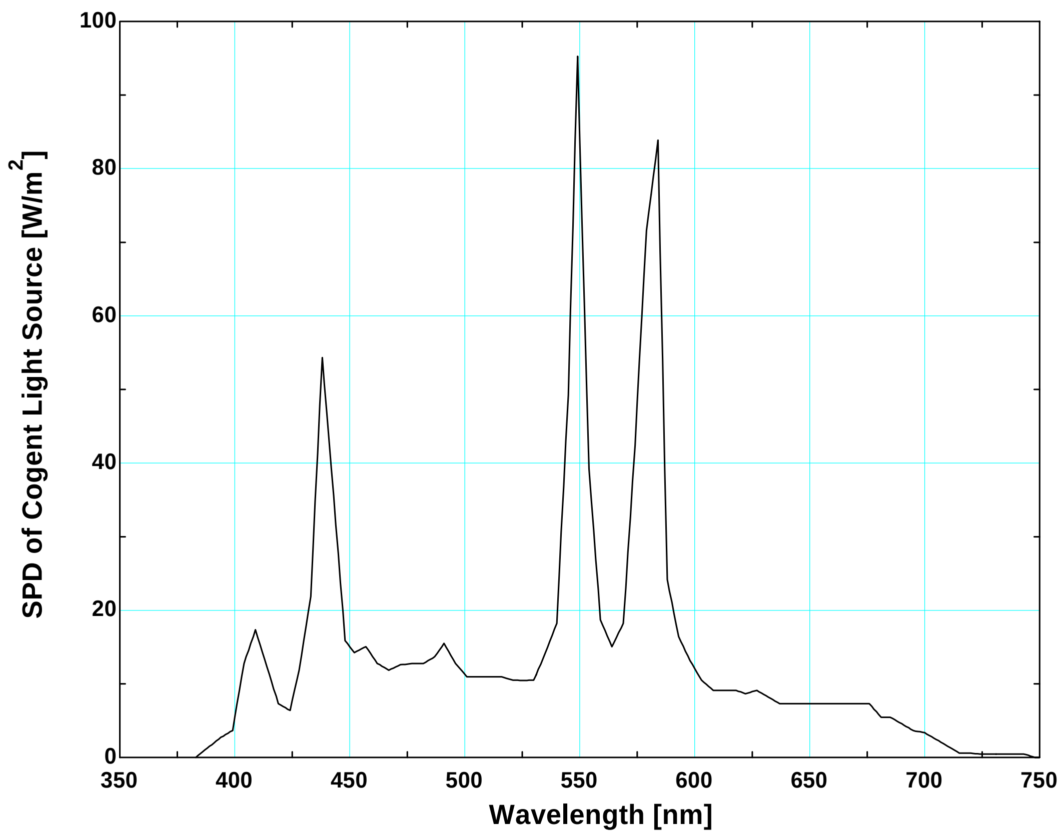


Figure 2.4. Spectral Power distribution of the Cogent light source. Integrated over all wavelengths gives a total power of 5548 W/m^2**.**

2.2 Fiber Optic Bundle Construction

Fiber optic bundles for the experiment were constructed by recycling unused fibers from previous bundles. Two methods of bundle construction were used. The first method consisted of gathering a number of fibers together, fitting them snugly in a collet and then polishing them as an FOB. The second method consisted of polishing each fiber individually and then putting the fibers together and fitting them snugly into a collet. The number of fibers varied from N=120 to N=127 depending on inner collet diameter. During polishing of the FOB, some of the excised material from the polishing process becomes trapped in the air gaps between the fibers. These contaminant particles, along with other forms of contamination, are believed to contribute to the heating of the FOB by absorbing radiation incident on them. In an effort to reduce the amount of contaminants in the air gaps at the FOB face the second method of polishing was implemented. Pictures of FOB's polished using both methods are shown in Figures 2.5 and 2.6.

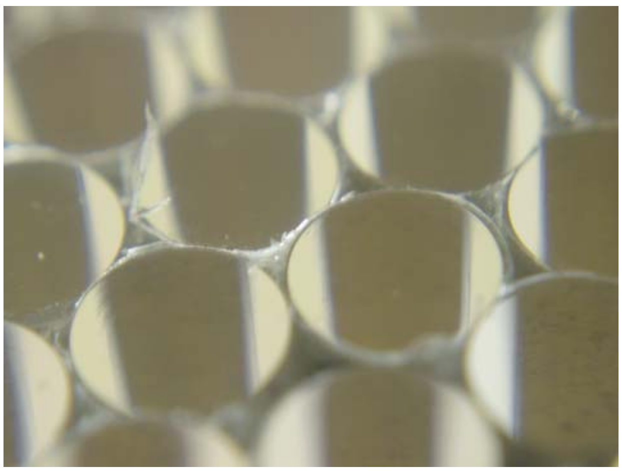


Figure 2.5. FOB polished using method one. Note the hanging debris around the edge of the individual fibers.

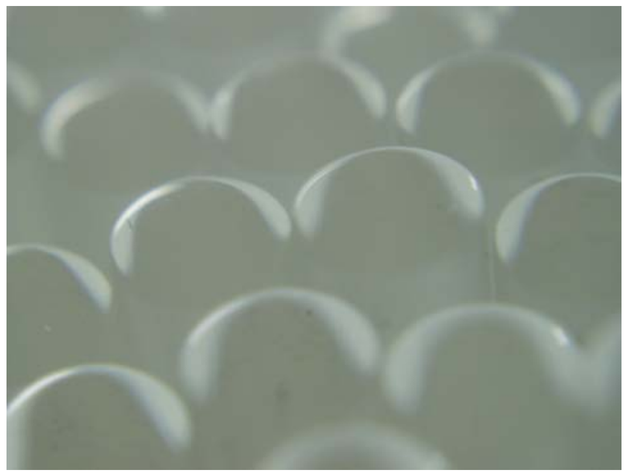


Figure 2.6. FOB polished using method two. Note the lack of debris around the edge of individual fibers.

Of particular interest was the effect of collet material, aluminum or acrylic, on the heating of the FOB. The experiment used to determine this effect is described below.

2.3 Experimental Results of Heating Using Different Collet Materials

Three FOB configurations were tested to determine the effects of collet heating. FOB 1 had an aluminum collet, FOB 2 had an acrylic collet and FOB 3 had no collet. The same fibers were used in each experiment, only the collet was changed. The FOB's were constructed using method two described above. Each FOB was allowed to equilibrate to room temperature before being exposed to the Cogent light source for a period of 1800s. The temperature rise of the FOB's was calculated over this time period by subtracting the temperature at time = 0s from the temperature at time=1800s. The software provided for the thermographic camera has the ability to measure the temperature of an individual spot or an average temperature of a number of spots defined by an area. Both types of measurements were used. Initial results of FOB heating are shown in Figure 2.7.

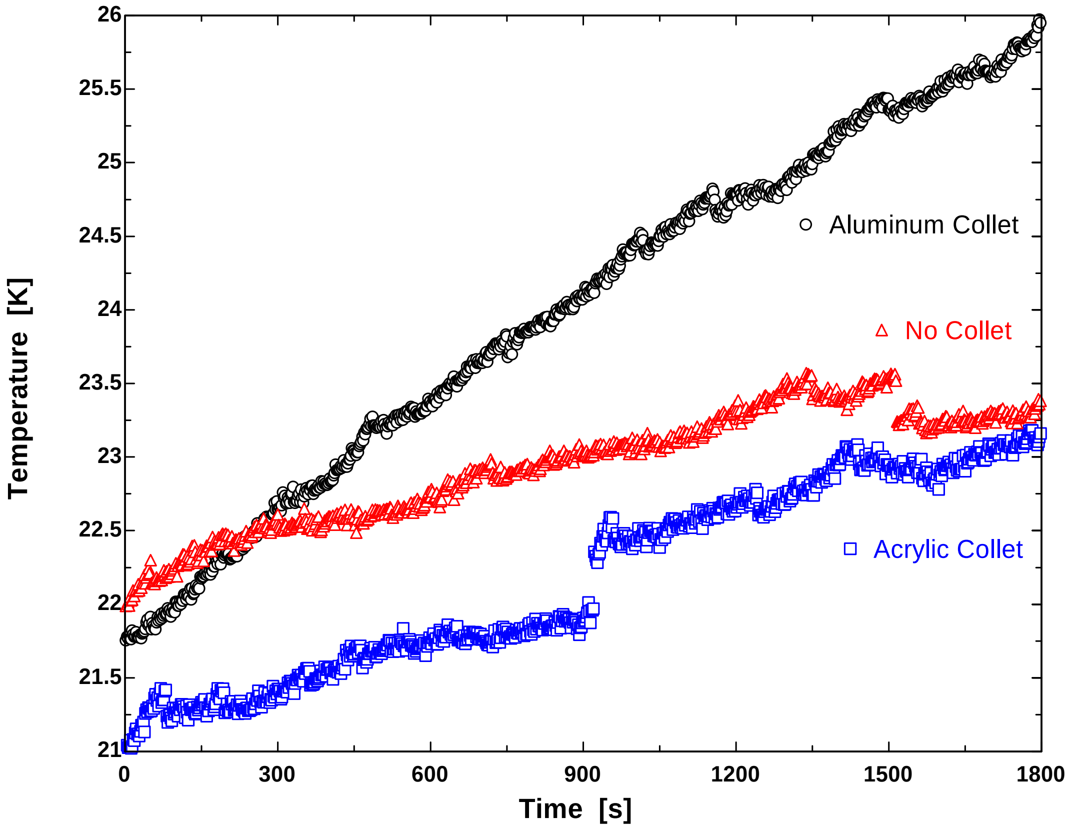


Figure 2.7. Average temperatures of different bundle configurations.

Data for Figure 2.7 were taken using an average temperature calculation over the surface area of the FOB face, not including the collet. The temperature differences over 1800s for the average data shown in Figure 2.7 are as follows: $\Delta T_{Alu\min um} = 4.12°C$, $\Delta T_{Acrylic} = 2.17°C$, and $\Delta T_{NoCollet} = 1.38°C$. It is suspected the discontinuities in temperature data, around t=900 s for the acrylic collet and t=1500s for no collet, are due to the automatic shutter on the thermographic camera. Figure 2.8 shows the data of Figure 2.7 corrected by subtracting (or adding) the discontinuity in temperature to the data that follows the discontinuity. The result of the correction shows a change in the temperature differences of the acrylic collet FOB and the no-collet FOB as follows: $\Delta T_{Acrylic} = \Delta T_{NoCollet} = 1.65°C$.

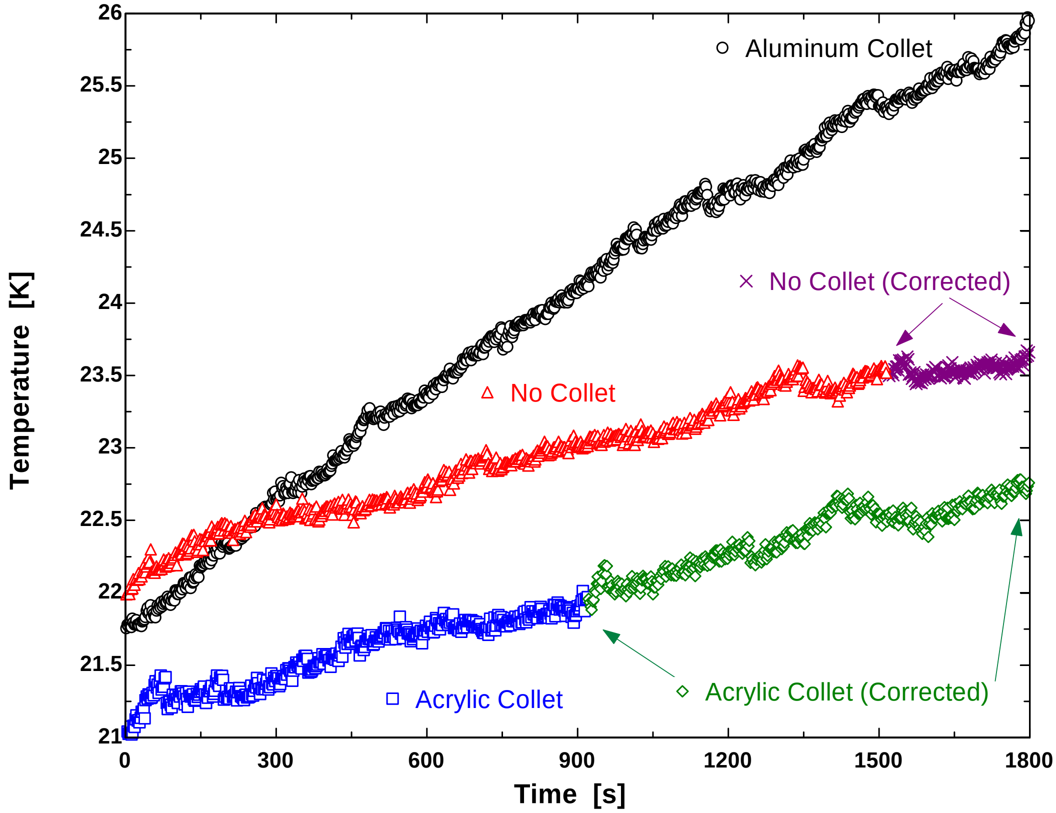


Figure 2.8. Corrected average temperature data for all FOB's over 1800s.

Consideration of the spot size and distribution of the Cogent light source is important in determining whether the FOB collet is contributing to the heating of the FOB. Figure 2.9 shows the spot size of the Cogent light source as exposed on sheet of black paper. Each bundle's center was placed in the center of the spot to ensure consistent results for each bundle. Under the conditions of this set up, one would expect the highest temperatures of the bundle to be in the center because of the more intense radiation at this location. Consequently, the sides of the bundle should be at lower temperature. Indeed this is the case for the no-collet bundle.

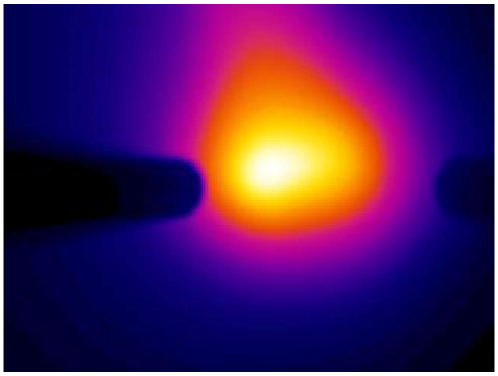
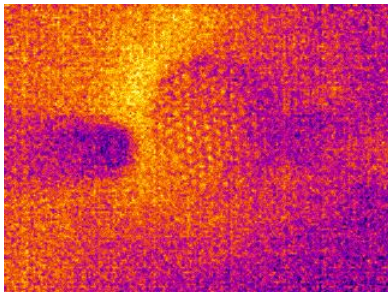
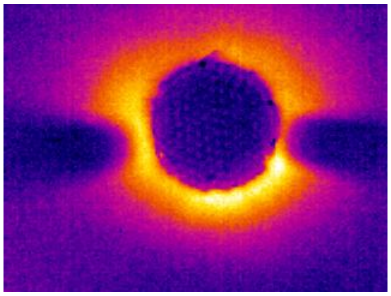


Figure 2.9. Image of the spot size of the Cogent light source as taken by the FLIR Systems thermographic camera.

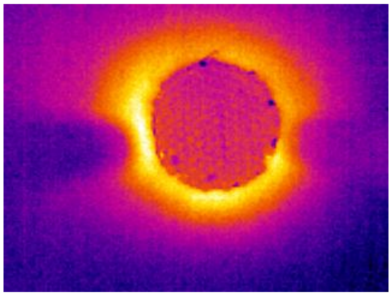
Figure 2.10 shows a sequence of pictures of the no-collet bundle during on-light exposure. Note the higher temperatures in the center of the FOB versus lower temperatures on the outside. This effect is perhaps not noticed due to the small temperature difference, $\Delta T_{NoCollet} = 1.38°C$, and the resolution of the thermographic camera, ~0.5-1 $°C$. Single spot temperature data for this FOB were taken at the FOB outer edge and center. The results are shown in Figure 2.11. Corrected data are shown in Figure 2.12.



a) Before light source on



b)Just after light source on



c)After ~30 min on light

Figure 2.10. No-collet FOB sequence.

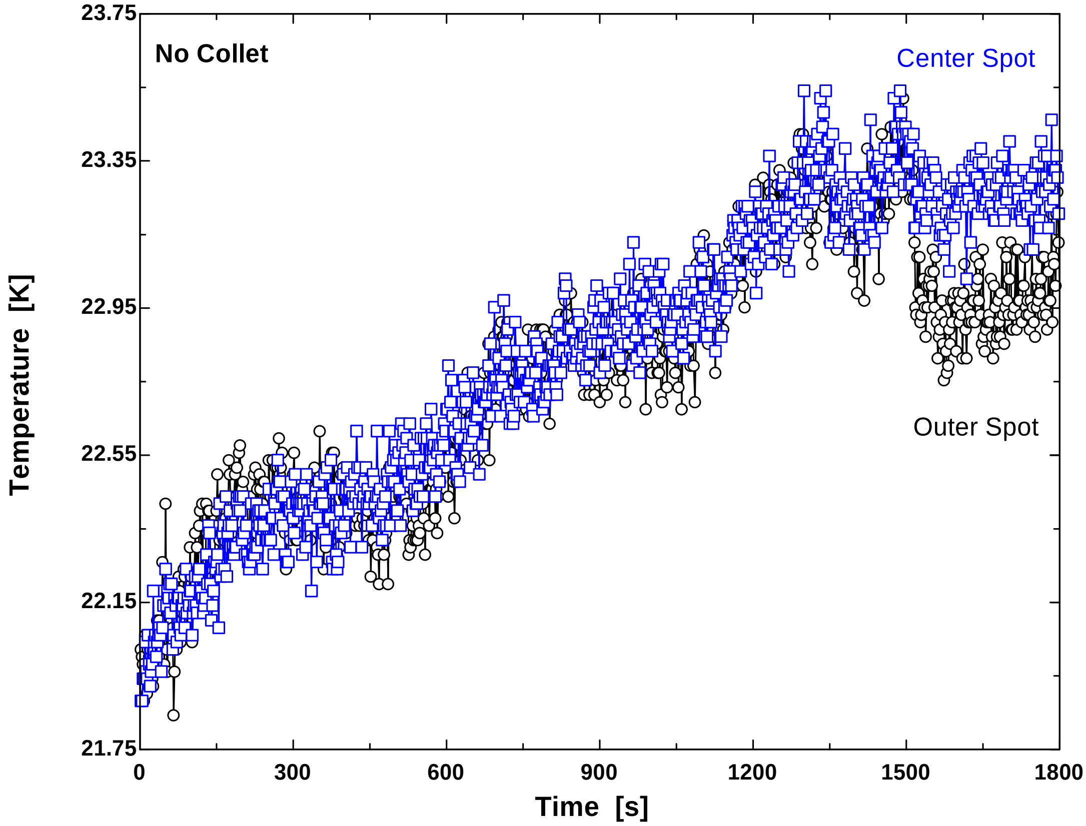


Figure 2.11. Temperature measurements of FOB center and outer edge for the no-collet bundle. Note the lack of temperature difference for this bundle.

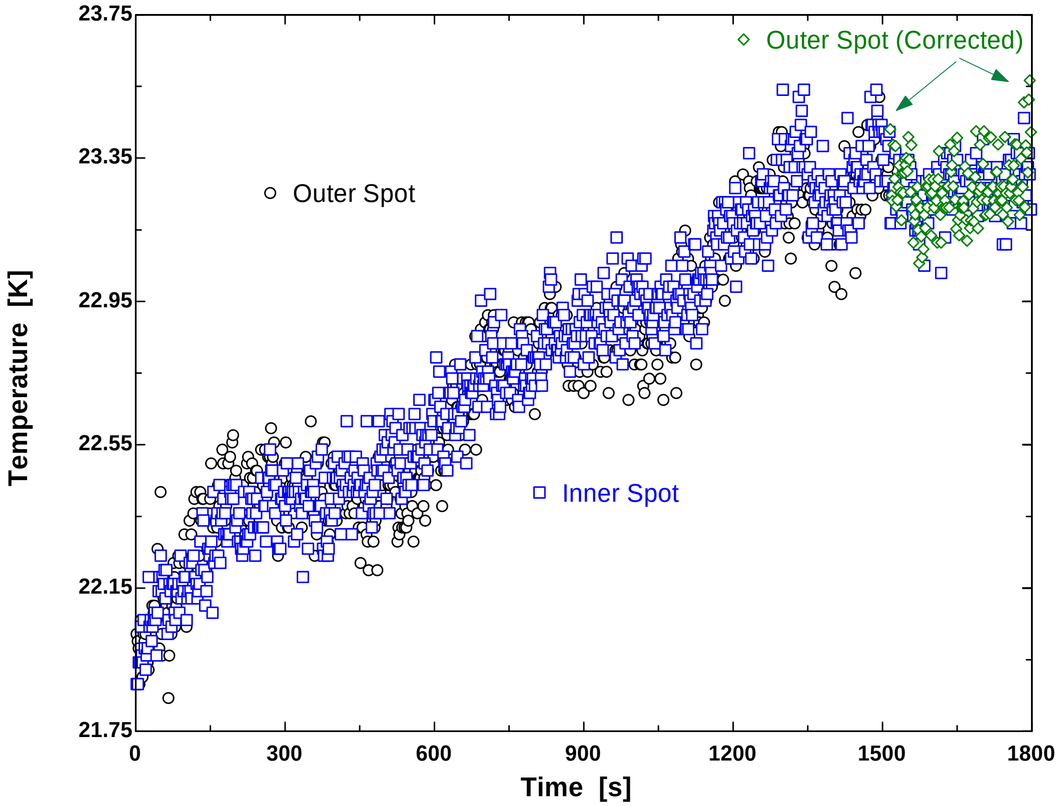


Figure 2.12. Corrected temperature data for the no-collet FOB.

The aluminum-collet FOB, however, shows a greater temperature rise at its edge as compared with its center. Figure 2.13 shows the temperature of the center of the FOB and the temperature of the outer edge.

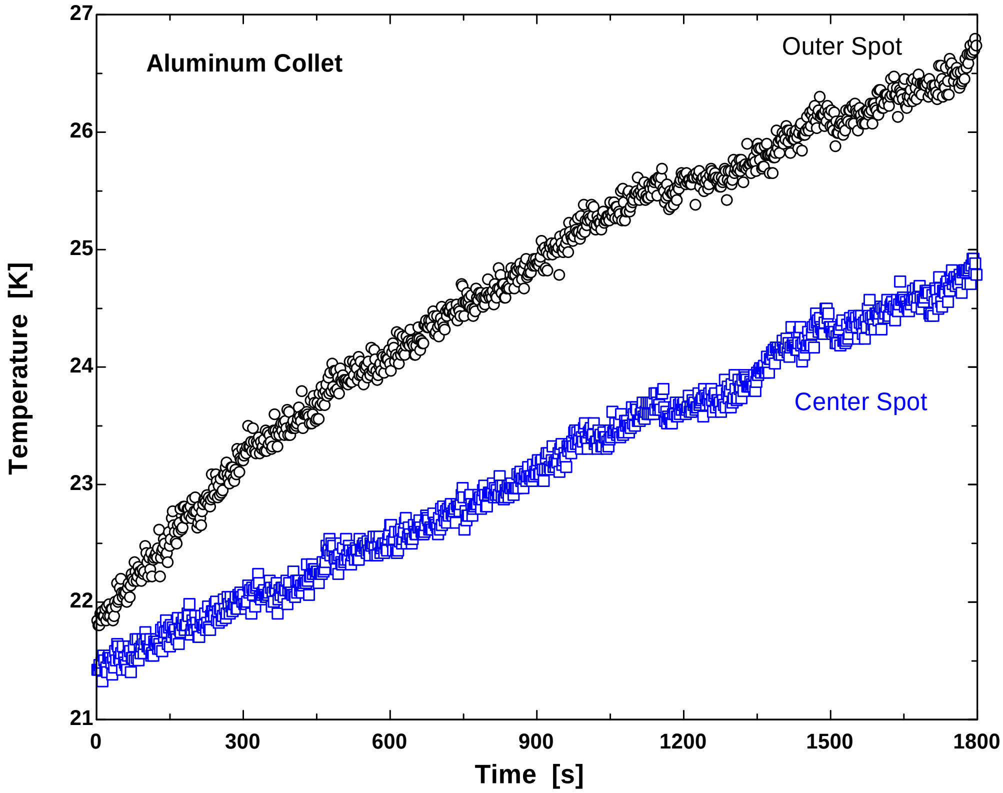
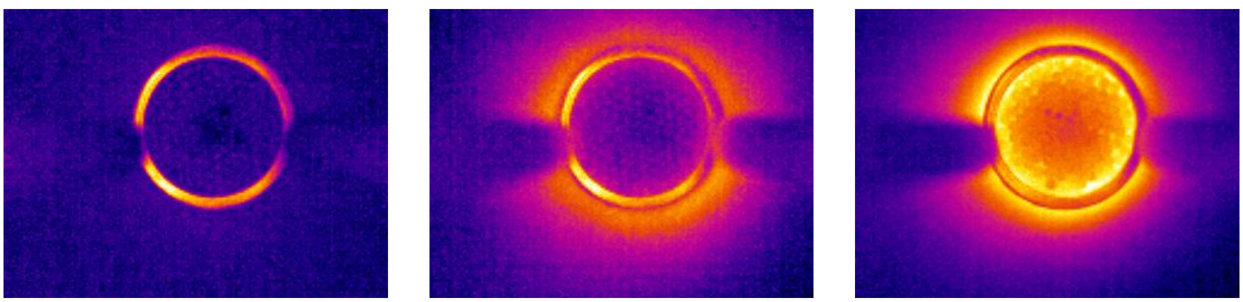


Figure 2.13. Temperature measurements of FOB center and edge for the aluminum-collet bundle. Note the increasing temperature difference between the spots.

This temperature difference corresponds to a heat transfer from the edge of the FOB to the center. This contradicts what one might expect of the heating process as seen with the no-collet FOB. Possible reasons for this will be discussed later. Figure 2.14 shows the heating sequence for the aluminum-collet bundle.



a) Before light source on b)Just after light source on c)After ~15min. on light

Figure 2.14 Heating of bundle with aluminum collet. Note the heat transfer from the FOB edge to the center.

Edge and center temperature data for the acrylic-collet FOB are shown in Figure 2.15 with the corrected data shown in Figure 2.16.

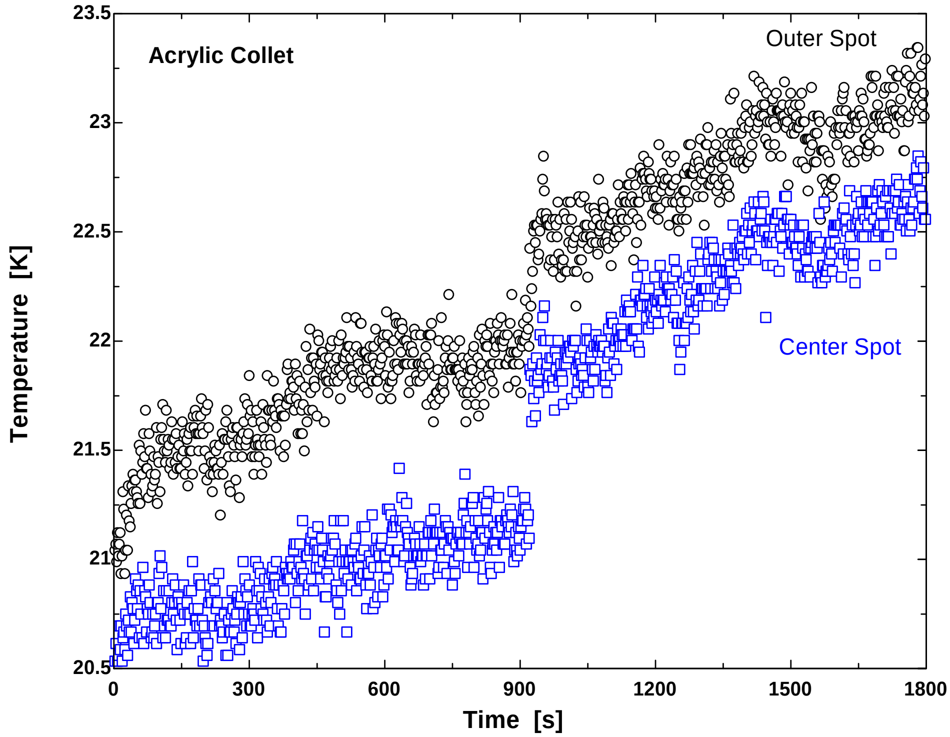


Figure 2.15. Temperature measurements of FOB center and edge for the acrylic-collet FOB.

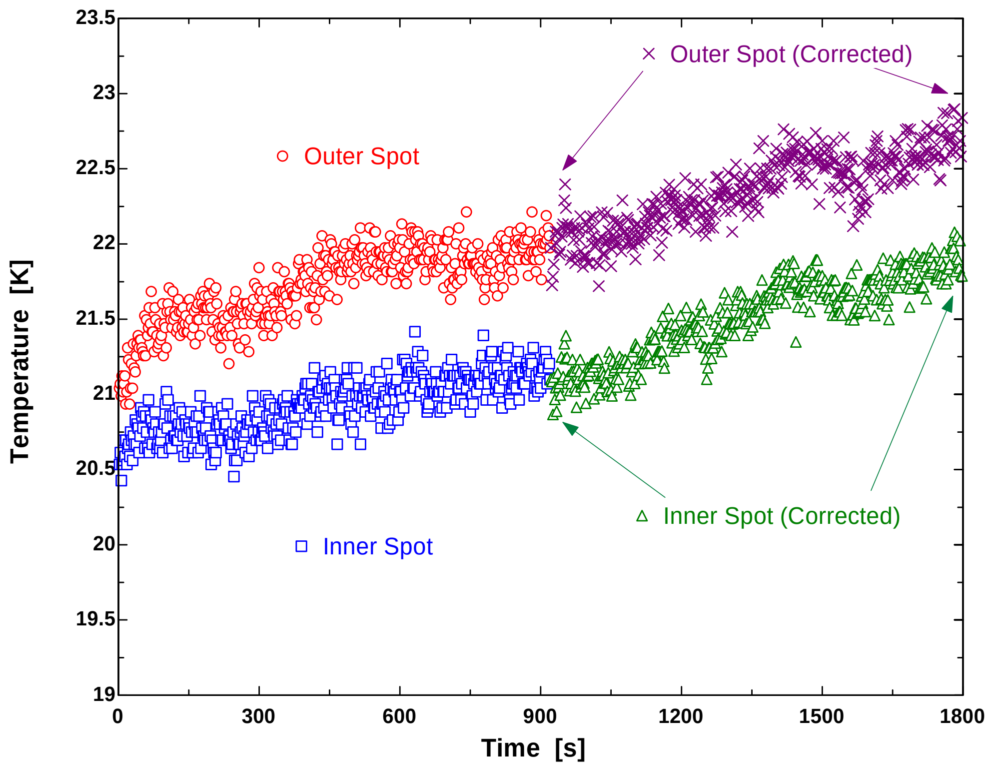


Figure 2.16. Corrected data for acrylic-collet FOB. Though difficult to discern from this graph, a rise in temperature difference between the bundle edge and center exists. This is shown clearer in Figure 2.17.

Data for the Acrylic collet shows that it behaves like the aluminum collet, though to a lesser degree. Figure 2.17 shows the temperature difference from bundle edge to bundle center for the three collet configurations. According to this graph, a no-collet bundle is optimal for reduced heating, however it is obviously not practical. The acrylic collet provides a useful compromise.

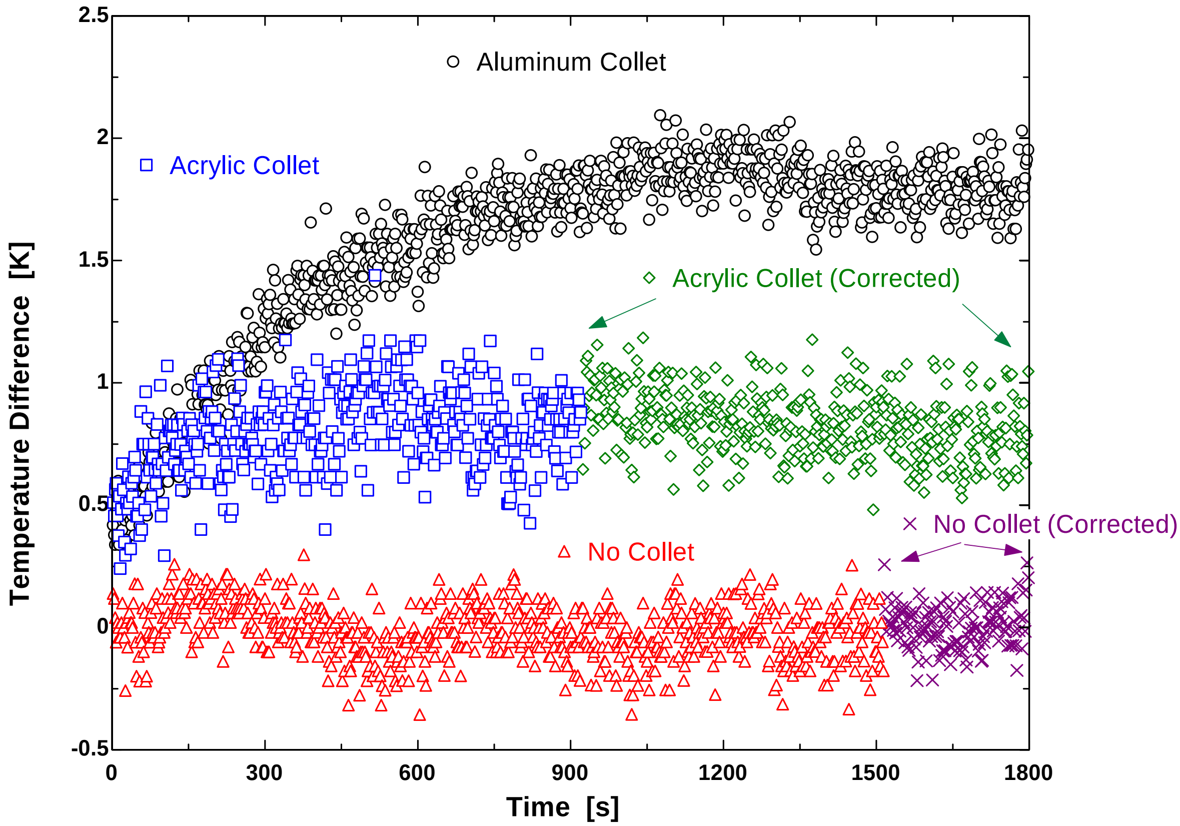


Figure 2.17. Temperature difference between edge and center of FOB for all three collets.

Measuring the absolute temperature of the collet using the thermographic camera is difficult. As can be seen from Figure 2.18, the temperature of the collet reported by the camera varies considerably. This is attributable to variations in emissivity of different spots on the collet or perhaps a misalignment of camera and collet. However, the temperature change of a particular point should be nearly equal to the temperature change of any other point on the collet because emissivity is not factored into the difference. Figure 2.18 also shows the collet with several spots chosen at a variety of reported absolute collet temperatures. Data were taken for these spots over 1800s of on-light exposure. Graphs of temperature versus time for these spots are shown in Figure 2.19. Table 2.1 shows the temperature difference for each spot and the average temperature difference for all spots. Though the absolute temperatures vary considerably, the change in temperature is consistent within the resolution of the camera.

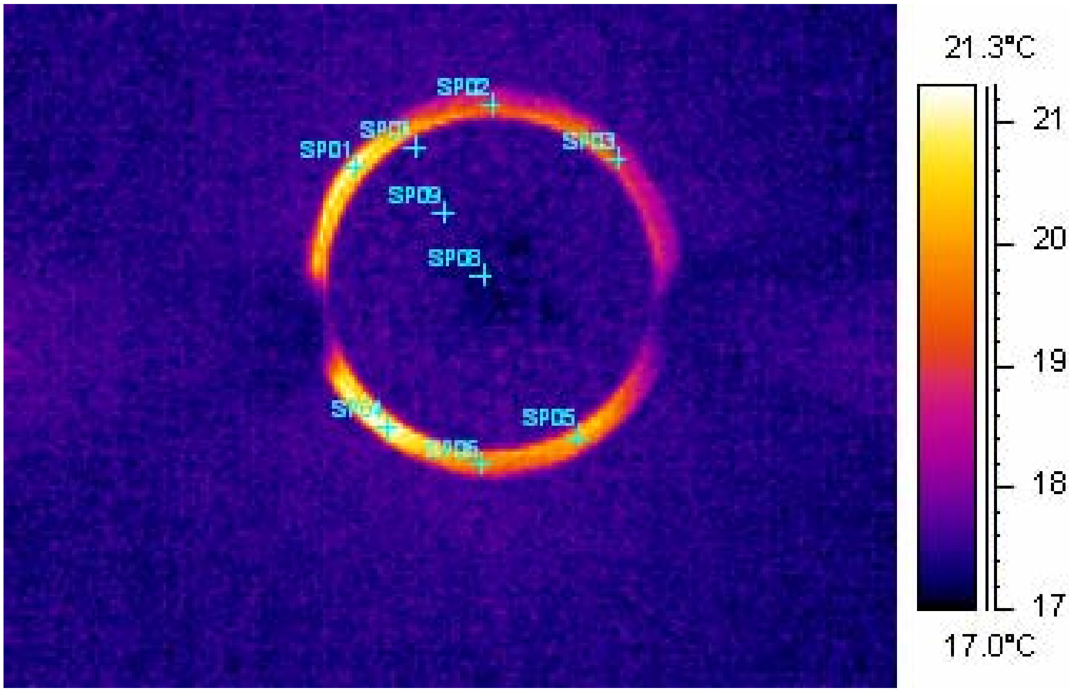


Figure 2.18. Thermographic image of collet and bundle with analysis. Note spots 1-6 are on the collet.

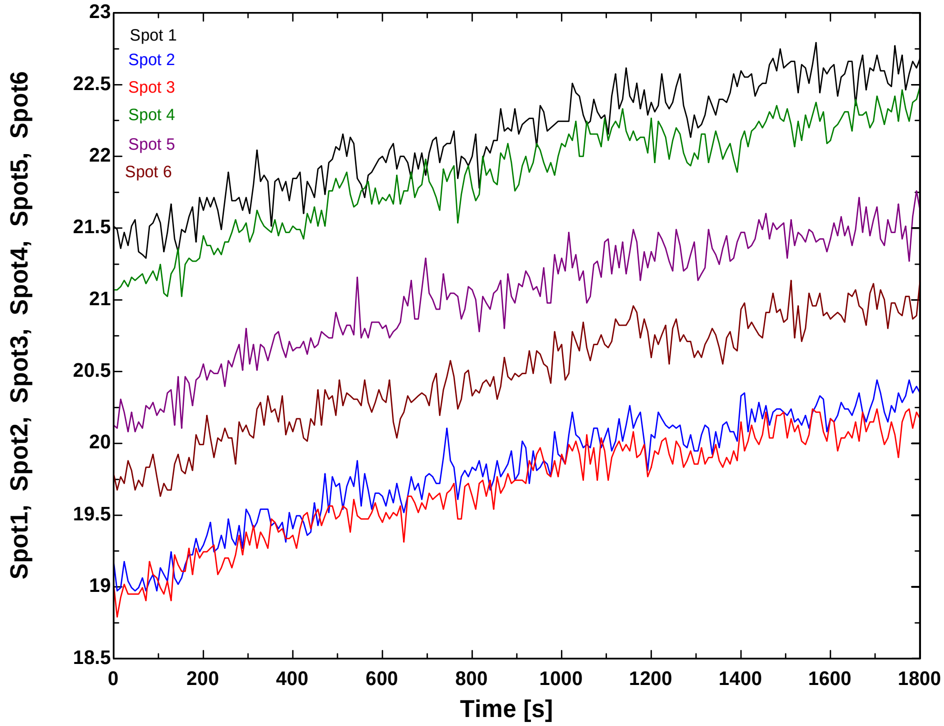


Figure 2.19. Temperature rise for spots 1-6 of Figure 2.18.

<u>Table 2.1. Temperature difference for spots 1-6 of Figure 2.18.</u>

Spot	Delta T [C]	Average Temperature [C]
1	1.087273	1.134178
2	1.096932	
3	0.997477	
4	1.244182	
5	1.14775	
6	1.231455	

What is interesting to note about the collet heating is a point just inside of the collet wall. Figure 2.20 shows a plot of the temperature of a point just inside the collet wall (spot 7 of Figure 2.18), presumably at a void, and a point on the collet (spot 1 of Figure 2.18). One will note the significant increase in temperature of the point just inside the collet vs. the smaller increase in temperature of the collet itself.

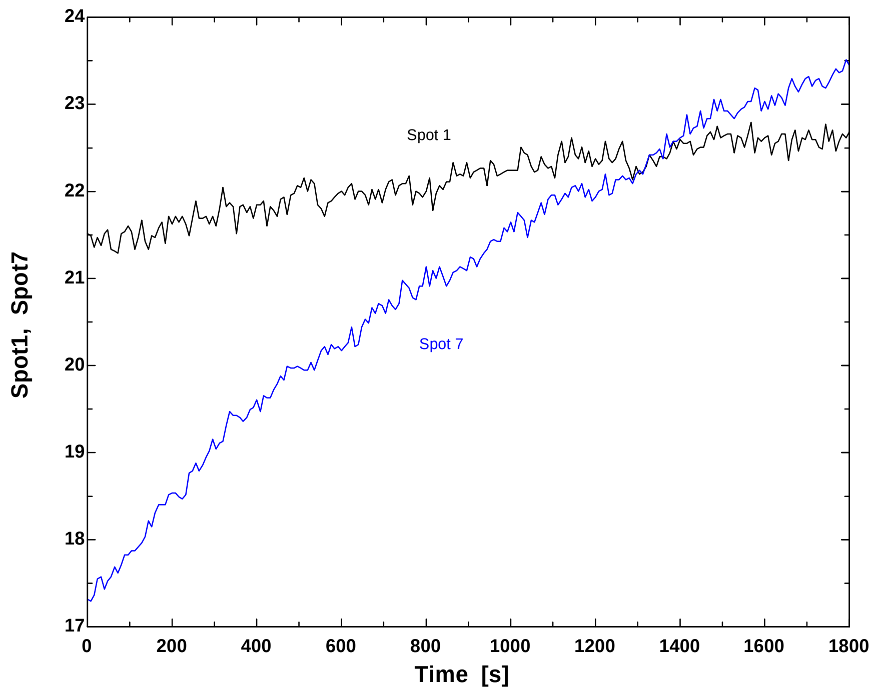


Figure 2.20. Temperature versus time for a spot on the collet (spot 1) and a spot just inside the inner wall of the collet (spot7). These spots are shown in Figure 2.18.

3 Photobioreactor Testing, Cost Modeling, and Redesign

3.1 Bioreactor Testing

During July 2004, there was a long stretch of good weather to conduct an extended test for algal productivity. Also the header design, which had had problems before, proved to be more than satisfactory for populating and harvesting of the membranes.

The following data shows the algal growth in the bioreactor per day over a period of ten days following an acclimation period of seven days. The results were slightly lower than the results presented in the June 2004 monthly progress report, especially when normalized to the average solar flux from the day before. This is likely because the solar collector experienced significant loss of reflective coating between May and July, 2004.

However, these results are significant because they show that the cyanobacteria have a remarkable ability to grow once acclimated to the membrane substrate. Further, it strongly indicates that the harvesting method of higher water flow does not physically stress the algal mass that remains on the substrate. That is critical for long term sustainability.

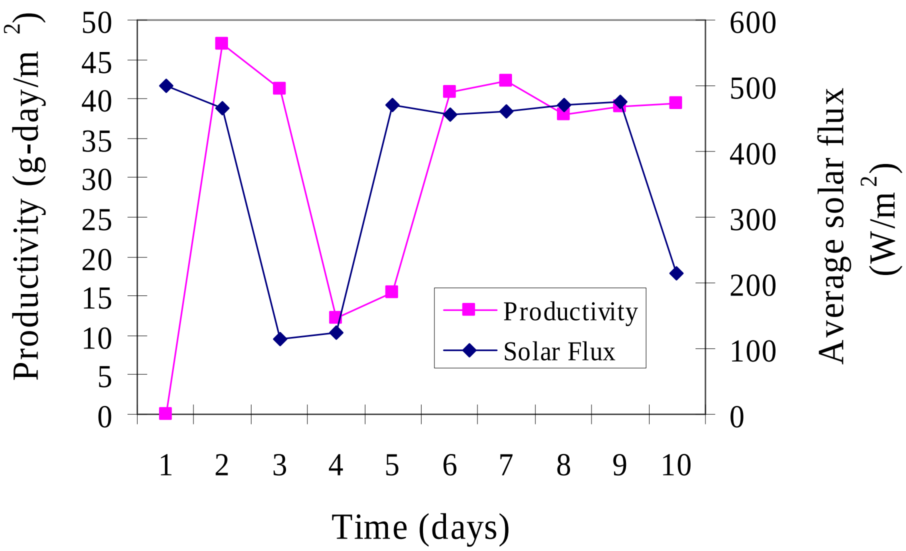


Figure 3.1. Productivity Results

3.2 Cost modeling

The possibility of hydrogen recovery has been incorporated into the cost model for CO_2 control using the photobioreactor system. This was done by adding hardware for anaerobic digestion of the biomass and crediting the system \$2.00 per kilogram of H_2 produced. Note that the model shows that the costs do not scale with the same slope. This is due to the increased cost of handling additionally produced hydrogen.

The results of the model – cost of CO_2 "sequestered" as a function of photosynthetic conversion efficiency of the cyan bacteria – is shown in Figure 3.2. Of course, this assumes a significant decrease in collector cost (\$800/m^2) in both models.

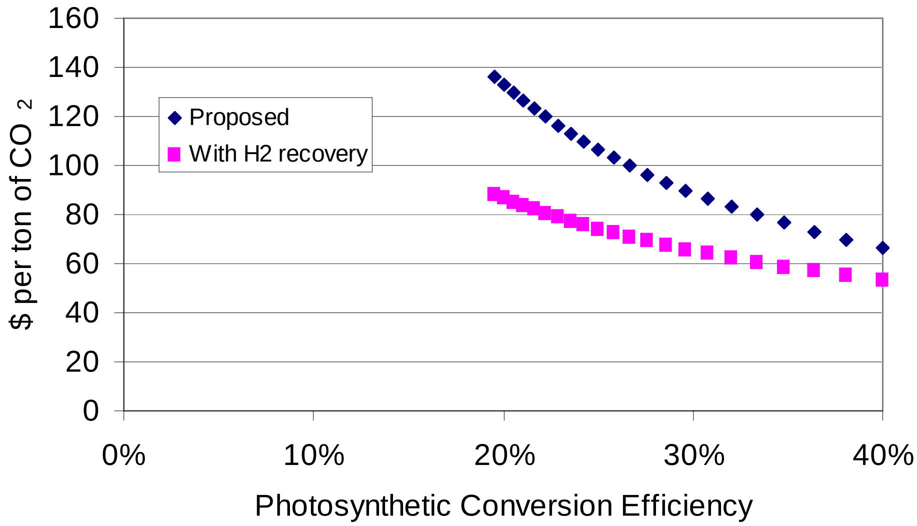


Figure 3.2. Cost of CO_2 sequestered for proposed system with and without hydrogen production

3.3 Bioreactor Redesign

As of October 2004, the pilot bioreactor at Ohio University was shut down and disassembled and moved from its off campus location. Since that date, it has been a continual effort to find a suitable on-campus location. Two problems derailed every prospective location:

1. Placement of the solar collector on a building roof and
2. Proper ventilation to be able to evacuate the circulating simulated flue gas in the bioreactor should a problem develop.

Finally, a suitable, but not ideal location was procured in Stocker Center. Due to the size constraints of the available space, the bioreactor itself had to be redesigned. This section includes the schematics of the new design. The primary feature of the design is the smaller footprint and the air vanes which direct the flow upwards across the membranes, instead of horizontally.

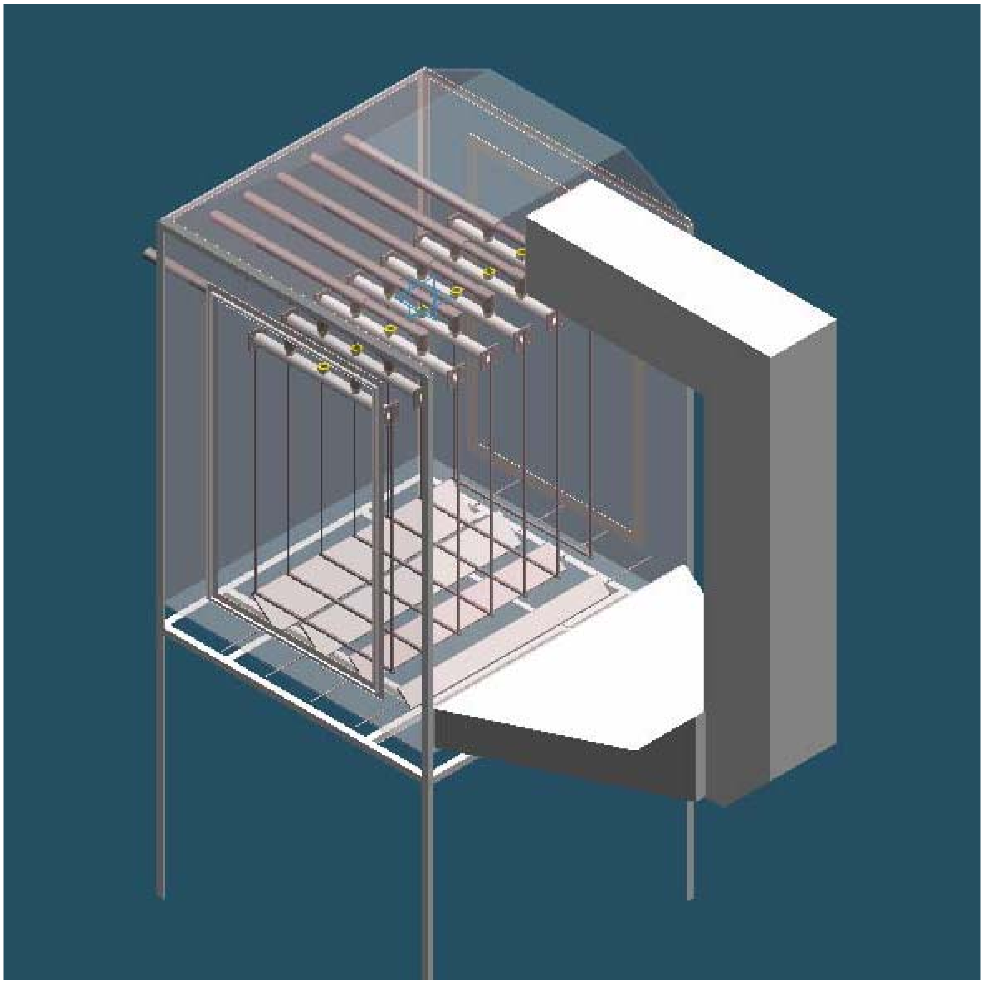


Figure 3.3. Pilot Bioreactor Assembly

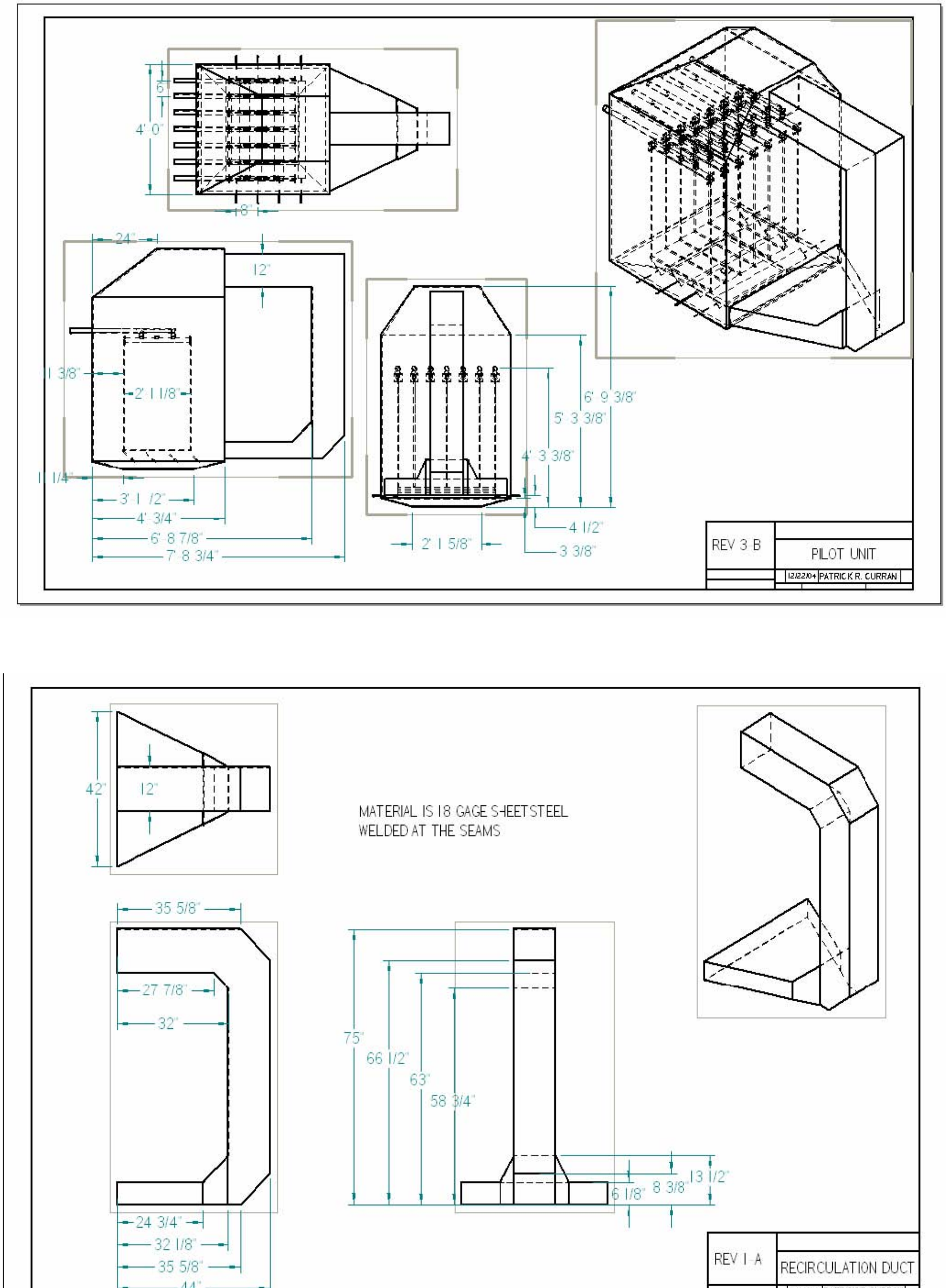


Figure 3.4. Pilot Reactor Schematics

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