AC 2007-887: BIODIESEL ALGAL BIOREACTORS AS EDUCATIONAL PROJECTS: ENGINEERING FACTORS AND A CASE STUDY OF ESTIMATION

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Biodiesel Algal Bioreactors as Educational Projects: Engineering Factors and a Case Study of Estimation.

Abstract:

Two experimental closed-system bioreactors that produce algae for biodiesel are described, along with a discussion of the basic requirements for algae growth. The reactors were built by students and faculty, and are producing algae in support of research grants. For one of the reactors, detailed cost and scheduling data was collected, allowing careful comparison with initial estimates. The case provides a useful example that illustrates the inaccuracies of textbook estimating techniques, in some circumstances.

Introduction:

Algae is an alternative and advantageous source of biomass for biodiesel production, with a realistic potential per-acre yield of perhaps 200 barrels per acre per year, well beyond that of competing crops. The same algae crop can produce carotenoids as a by-product, enhancing its financial attractiveness. Because inputs include carbon dioxide and farm waste, algae production can mitigate pollution. Algae can be produced in open ponds or in continuous flow closed systems. Closed systems will prove more productive, but they are also more costly and they present different technical challenges.

Figure 1: Algae seeded into a full bioreactor tank.

These systems are not particularly complex, but they do pose challenging and educationally useful engineering problems. Efficient algal production requires environmental control of temperature, CO2 and pH levels, nutrients, aeration and mixing, and light. Design and construction of a reactor that maintains optimal environmental conditions and resists corrosion poses standard engineering problems that engineering students can successfully work through, with a sense of real accomplishment. However, the real challenge for development of algal biodiesel is to bring the cost of plant and operation down so that large-scale farms are economically competitive. Temperature control and aeration require piping systems and consume water and power. The tanks the algae grow in are costly as well – they must admit as much light as possible, and while tanks with considerable vertical depth are preferred, the resulting water pressure imposes limits on their design. The need to periodically clean the tanks and deal with corrosion also drives costs up. These are key problems to commercialization, but they can be understood and productively addressed by creative engineering students. In addition, bioreactor design and construction offers students an opportunity to practice project management skills, and the cost of building a small demonstration bioreactor module is very reasonable.

Two different closed bioreactor systems are described, a ‘stepped’ reactor that was student designed and built, and a 700 liter in-line unit developed by the authors with student assistance during construction. Detailed cost and schedule estimates for the 700 liter reactor are presented, along with actual funding and time expended on the project, as an example of these aspects of project management. The results provide an illuminating example useful when teaching costing and scheduling as part of a project management module.

Typical Algal Bioreactor Requirements

Algae must be well aerated, with an air flow rate of about 10% of the tank volume per minute. Carbon dioxide is added to the air as a nutrient. Aeration also serves the purpose of mixing the algae; water with robust algae growth will be as opaque as pea soup, with almost all light absorbed within a matter of millimeters. Algae trapped in dark areas will die, and well-distributed aeration prevents that. Aeration bubbles should be as small as possible to maximize gas transfer to the water.

Cooling is also important. The algae in use at ASU grows best between 25 and 30 C, and it dies between 36 and 37 C, well below the local ambient air temperature, which reached 47 C last summer. In addition, solar energy is fairly effective in heating up the tanks. Evaporative cooling was selected for these reactors, simply achieved by spraying water on the faces of the tanks. There should be enough spray to completely coat the glass face of the tank and run off, because if the water fully evaporates it will quickly leave opaque hard water deposits. It is hard to uniformly wet the glass until it is weathered. Cooling water must be recycled, to keep the ground dry as well as for conservation. It is worth noting that the ambient air temperature often exceeds the 40C specification for most regenerative aeration blowers as well. No appropriate units with higher limits were found, but with some shading the blowers have survived.

Farm waste water is added to the tanks as food, along with various chemicals intended to maintain pH or otherwise help the algae grow. In particular, calcium is added to the already hard water, complicating efforts to limit calcium accretions. These items are thus far added and monitored manually, but automatic control systems will be needed on larger installations.

In addition, there are ancillary concerns. It must be easy to clean hard water deposits and dead algae on the glass and in the plumbing. Leaks are an issue, not only for water loss, but because of environmental issues like mosquito control, weeds, and mud. As noted previously, the overall cost of the installation must be reasonably low to justify construction of larger farms, and the physical appearance of the units should be pleasing because the prototypes are used for marketing the technology.

The Stair-step Bioreactor

A bioreactor consisting of 6 tanks arranged in stair-step fashion (Figure 2) was designed by graduate biology students. The tanks can be switched to either batch or flow through production by means of valves between each tank. The students had the steel support frame made in a University shop, and painted it for corrosion protection. The glass tanks, with plastic frames, are 0.45 m high, 2.1 m long, and 0.15 m thick, and were purchased from an aquarium shop. Standard glass 6 mm thick was used, and this limited the height of the tanks; thicker glass is more costly, and also reduces light transmission. The biology students also correctly sized and purchased a regenerative blower for aeration. Funding for this reactor was provided through a local Edson Student Entrepreneur Grant.

Figure 2: Students Stewart Clark and Linda Graham with the stairstep reactor they built.

Unfortunately, the biology students graduated and left before the reactor was complete. No provision for cooling was made, and the units were not assembled. To keep the project moving, two senior mechanical and manufacturing technology students, Linda Graham and Stewart Clark, were assigned the task of completing the reactor for their Capstone project. These students designed a cooling system and plumbing, checked the suitability of existing components, and completed construction. They used common, low-cost materials as much as possible.

Specifically, they elected to pour small concrete pads to support the welded frame and the aeration pump on the site. Cooling was provided through copper tubing fitted with misting heads, run across the top front (south facing) edge of each tank. Excess water was collected in household rain gutters run across the bottom of the tanks, and piped to an underground sump – a plastic 35 gallon trash can – which houses the cooling pump.

The students completed this reactor in a one-semester portion of their Capstone class, and it was seeded with algae at the end of the semester. It worked well as a prototype, and provided useful lessons for the next reactor design. For instance, biology students used acid to periodically clean calcium deposits, leading to rapid corrosion of metal parts like the rain gutters. Changes to the plumbing during use led to leaks, mud, and weeds. The steel support framework and piping also made it hard to access for service. These and other issues were addressed in the 700-liter unit built next.

The AzTE Reactor

Arizona Technology Enterprises funded a follow-on bioreactor, a 700-liter batch unit, which is commonly referred to as the AzTE bioreactor (Figures 3,4). There are eight independent tanks of different thicknesses, from 2.5 cm to 30 cm, to allow study of this parameter's effect on algal growth. However, tanks of different thicknesses can easily can be installed, allowing expansion to a maximum overall capacity of 2000 liters.

This unit features a concrete block base and underground piping for easy access to the tanks. There are no footings under the blocks. Thunderstorm winds have been clocked at 42 m/sec (95 mph) in the area within the past year. To reduce the risk of overturning the tanks, which present a large surface area, the concrete block pedestals are tied together underground with an 18 mm rebar grid. Concrete poured in the blocks locks the rebar in place, and prevents the units from overturning. Due to cost and technical issues, the installation will probably only resist a wind of 25 m/sec (55 mph) if it comes from an inopportune direction, but this was deemed sufficient in consultation with the customer.

Other features include better sealing to limit leakage, landscaping to control weeds, a bench to shade the aeration pump, and a long metal tube to cool the compressed air before it is fed to the tanks. Corrosion problems were addressed by using plastic rain gutters instead of metal, hot-dip-galvanized steel support beams for the tanks, and operator education to prevent acid use anywhere outside of the tanks. Denatured alcohol is used instead, to clean hard water deposits from the exterior glass when necessary.

This unit was built by the authors, graduate students, and hired undergraduates over one summer. As an exercise, careful records were kept of the initial cost and time estimates, as well as time and money actually spent on the project. This information, which follows, was used as a detailed example or case study for lectures in project management.

Figure 3: The AzTE reactor seen from the southeast.

Figure 4: The AzTE reactor from the northwest, and after landscaping. The wet ground resulted from a spill, not from leakage.

Cost Estimating and Scheduling for the AzTE Bioreactor

This reactor was estimated in the spring of 2006 and built over the summer by one of the authors with some occasional hired student labor. Initial cost and time estimates were prepared with the intent of comparing them to actual figures. The estimates were made by breaking down the proposed installation into a detailed bill of material, along with a detailed work breakdown structure, and estimates were tabulated for each item.

Actual cost and time data was collected daily. Time was broken down into various categories of activity (design, construction, meetings, travel, 'shopping', and office overhead). Design time includes technical documentation. Shopping includes both on-line activity and time spent in local stores to select, purchase, or pick up supplies. Office overhead includes record keeping and billing time. Times were estimated to the minute at the end of each day. Miles driven were also recorded, including the 10-mile round trip to the work site when that travel was solely to work on the reactor.

AzTE Bioreactor Cost Estimates, Without Contingencies, and Actual Costs		
Item	Original Estimate	Actual
Parts and Supplies	$ 9217	$ 8582
Construction Hours	90	275
Construction Labor (Hired)	$ 1354	$ 630
Engineering Hours (no contingency added)	196	Approx. 235*

* Engineering time includes all design time, 75% of the meeting hours, and 40% of the shopping and office overhead hours.

Table 1: Original bioreactor estimates and actual values.

Parts costs are below the estimate because attention to cost during the design phase resulted in several advantageous modifications. The most significant improvement came from eliminating the concrete footings originally envisioned to support the concrete block pedestals. The original budget included $2000 to have these poured. Instead, the blocks were tied together with rebar just beneath the soil, to ensure they do not tip over, reducing the cost by over $1500. One impetus for this specific design change was the need to define inexpensive construction so that larger farms would be financially feasible. A more immediate impetus was a University requirement that any contractor hired to pour the concrete had to be on the University's approved list. An estimate from an approved vendor was almost exactly double the cost estimate from a skilled but non-approved vendor ($2500 vs. 1200), which made it advantageous to limit concrete work. On the negative side, the initial budget did not include landscaping. Overall, however, the cost estimate and actual costs are not far apart. Note that $1000 earmarked for electrical service is not included in the cost estimates above.

Ninety hours of construction labor essentially represents a summation of expected times for specific anticipated tasks. A rule of thumb often cited – and sometimes used – is to make your best estimate and double it, or better. The breakdown showing where the time actually went is interesting, and serves to illustrate why this rule can be so appropriate.

Time Expenditures for the AzTE Reactor		
Item	Hours	Percent
Construction	223	39
Design & Technical Documentation	134	23
Shopping	80	14
Travel	59	10
Meetings	42	7
Office Work & Overhead	39	7
TOTAL	577	

Table 2: Time breakdown

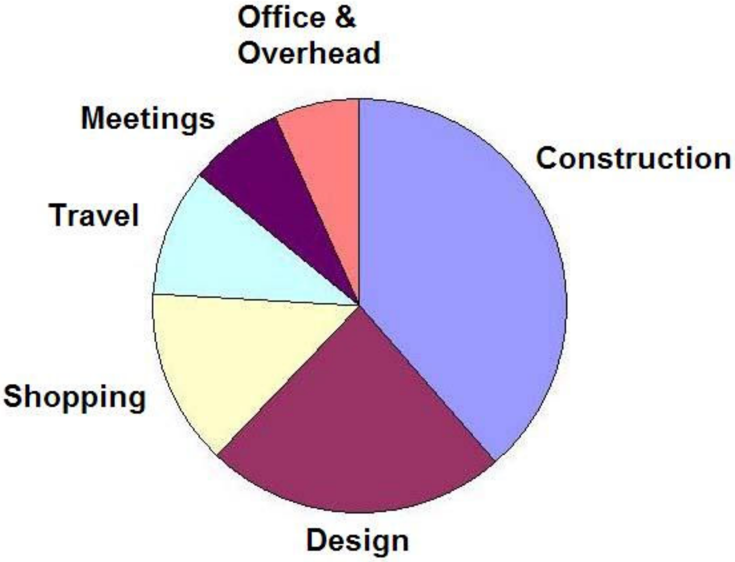

Figure 5: Time breakdown

Design time is longer than might otherwise be expected because the project was of a research nature, and the initial specification was more fluid than might be the case in industry. This factor also drives up meeting time. Shopping time includes both internet searching and making local purchases – specifically, time in local stores. While most purchases were anticipated and combined to limit trips to the store, oversights and design changes inevitably require more trips than necessary. Travel totaled 2947 km (1831 miles), far more than might be anticipated. Of that, 330 km involved making two round trips to the galvanizing plant, and the remainder was for short trips to local stores, to meet with the customer, or visit the site.

Firms with prior experience with a particular type of product can often estimate time and labor requirements quite well, but for unusual products that is not the case, hence the rule of thumb. Few estimators might expect that 10% of project hours would go into driving a vehicle, 7% into meetings, and 14% into shopping, for example. The actual time spent on this project, 577 hours for engineering and construction, is almost exactly double the original time estimate of 286 hours. Formal estimating techniques should be taught and used, and if the rule of thumb is applied, this formal estimate will be the necessary starting point. However, this case illustrates nicely why the commonly quoted rule of thumb – to double an estimate - often leads to a more realistic estimate.

It should be noted that although the original labor time estimate is low, this did not inflate the cost excessively because some of the labor was provided by student volunteers, hired labor was less expensive per hour than expected, and because the authors did much of the construction, with compensation coming from other sources.

The Future of the Algal Bioreactor Project

The AzTE reactor is currently being used to define optimal growth conditions for the algae, and it is being expanded to accept two additional tanks. The University recently received a significant research grant to provide algae to a refiner for the purpose of making fuel, experimentally, for the military. To meet demand, additional ‘flow-through’ reactors patterned after the AzTE unit will be built on the current site. As oil prices rise, interest in constructing a pilot farm is increasing as well. The faculty is working to involve students from biological sciences and from electrical and mechanical engineering technology in the design and construction of the units, and they are expected to become a major feature at the ASU Polytechnic campus.