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AN OUTDOOR TEST FACILITY FOR THE LARGE-SCALE PRODUCTION OF MICROALGAE

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ABSTRACT

The goal of the U.S. Department of Energy/Solar Energy Research Institute's Aquatic Species Program is to develop the technology base to produce liquid fuels from microalgae. This technology is being initially developed for the desert Southwest. As part of this program an outdoor test facility has been designed and constructed in Roswell, N. Mex. The site has a large existing infrastructure, a suitable climate, and abundant saline groundwater. This facility will be used to evaluate productivity of microalgae strains and conduct large-scale experiments to increase biomass productivity while decreasing production costs.

Six 3-m^2 fiberglass raceways were constructed. Several microalgae strains were screened for growth, one of which had a short-term productivity rate of greater than 50 g dry wt m^{-2} d^{-1}. Two large-scale, 0.1-ha raceways have also been built. These are being used to evaluate the performance trade-offs between low-cost earthen liners and higher cost plastic liners. A series of hydraulic measurements is also being carried out to evaluate future improved pond designs. Future plans include a 0.5-ha pond, which will be built in approximately 2 years to test a scaled-up system. This unique facility will be available to other researchers and industry for studies on microalgae productivity.

AN OUTDOOR TEST FACILITY FOR THE LARGE-SCALE PRODUCTION OF MICROALGAE

INTRODUCTION

The worldwide energy shortage and Arab oil embargo of the early 1970s encouraged many nations to look for new sources of oil, electricity, and gas. Resources such as biomass were often viewed as attractive solutions to the energy problem because of their nondepletable, renewable nature. The first biomass sources considered, such as wood or corn, were readily available, but it was apparent that new biomass sources should also be developed, including aquatic species.

Oil imports are expected to increase 138% by 2010 while domestic production is expected to decrease by 40%. The United States currently imports $50 billion of oil each year. By 2010 the cost of imports will have increased to $195 billion. Technological advances in biofuels could make biofuels competitive with petroleum-based fuels. The current U.S. Department of Energy (DOE) emphasis is placed on developing technology for our future energy supplies rather than finding more commodities (2).

One technology option being explored is the DOE/Solar Energy Research Institute (SERI) Aquatic Species Program to develop the technology base for large-scale production of oil-yielding microalgae and for conversion of the oil into gasoline and diesel fuels. These fuels should be cost-competitive with petroleum-derived fuels by the year 2010.

Microalgae are small, unicellular plants that range in size from 1 to 200 μm. Their productivity rates are higher than those of most other plants. Table 1 shows the productivity rates of many other plants and indicates the order of magnitude greater productivity that we expect can be obtained in microalgae outdoor culture ponds. Microalgae are also unique organisms in that they can accumulate storage lipid in large quantities within their bodies (up to 65% of their total biomass). Historically, microalgae have been grown in mass culture for food production and waste treatment (1).

Table 1. Comparative Productivity Rates in Different Plant Communities (adapted from Ref. 6)

Plant Community	$g\ m^{-2}\ yr^{-1}$
Continental:	
Tropical rain forest	2200
Temperate deciduous forest	1200
Woodland and scrubland	700
Desert and semidesert scrub	90
Cultivated land	650
Marine:	
Open ocean	125
Continental shelf	360
Algal beds and reefs	2500
Microalgae ponds	12,500

Following the energy crises of the 1970s, the possibility of using algae as a source of energy received widespread attention. Microalgae can be grown in large outdoor ponds, using the resources of sunlight, saline water, nitrogen, phosphorus, and carbon dioxide to produce proteins, carbohydrates, and lipids. In the process, they can double their biomass one to two times a day in large outdoor ponds. After a rapid growth phase, the algae can be transferred to induction ponds where, under nutrient limitation, many algae stop growth and division and use all their energy to make lipids as storage products for survival. Once the cells have accumulated lipids, they are harvested, and the water is recycled back into the growth ponds. The harvested cells are subjected to an extraction process to remove the lipids, primarily triglycerides with fractions of isoprenoids, glycolipids, and hydrocarbons. Lipids contain more oxygen and are more viscous than crude petroleum. The two most promising fuel conversion options are transesterification to produce diesel fuels and catalytic conversion to produce gasoline. Although microalgal lipids represent the premium energy product, the energy trapped in the other biomass constituents can also be used; e.g., the cell residue after lipid extraction can be digested anaerobically to produce methane and carbon dioxide. The carbon dioxide can be recycled for use in the algae production system.

The emphasis of the program at this time is on developing a mass culture technology for cultivating oil-yielding microlagae using saline groundwater in desert regions. The largest constraint to this technology is the economical production of an oil-rich microalgal feedstock. In addressing this constraint, the Aquatic Species Program has concentrated research on (1) selecting fast-growing, high-oil-yielding microalgae species; (2) improving the most promising species; and (3) developing the best culture and management methodologies.

In the past 7 years, the Aquatic Species Program has operated several different outdoor facilities in California, Hawaii, and Israel. Each facility was to test algae, which had already been screened in the laboratory, under outdoor conditions for high growth rates and lipid (oil) yield. In 1986 it became apparent that the program needed to consolidate into one outdoor test facility in the geographical area for which this technology was being developed. In addition, it was apparent that the size of the previous test facilities (approximately 25 - 50 m) was no longer adequate to meet program goals. The very high productivity rates seen in the small outdoor ponds needed to be confirmed in larger ponds; engineering scale questions needed to be resolved, and large amounts of biomass would be needed for the program to begin conversion research of algal lipids to liquid fuels.

SITE SELECTION AND DESIGN

Growth conditions in algae mass cultures can be divided into two categories: those dictated by the location of the culture and those based on culture management strategy. Location-related variables include insolation, evaporation, rainfall, temperature, and wind velocity. Variables that can be managed include salinity, nutrient concentration, carbon dioxide concentration, culture mixing, culture aeration, and residence time of the population.

Growth conditions dictated by location are among the prime considerations in siting the production facility. The DOE/SERI program has been based on the assumption that it will be necessary to locate a production facility in an area that receives large amounts of sunlight and has relatively warm temperatures. To have the best success, the facility must be located in an area that receives 5000 kcal m^{-2} d^{-1} and has more than 180 frost-free d yr^{-1}. This limits large-scale production to the southern United States (Figure 1).

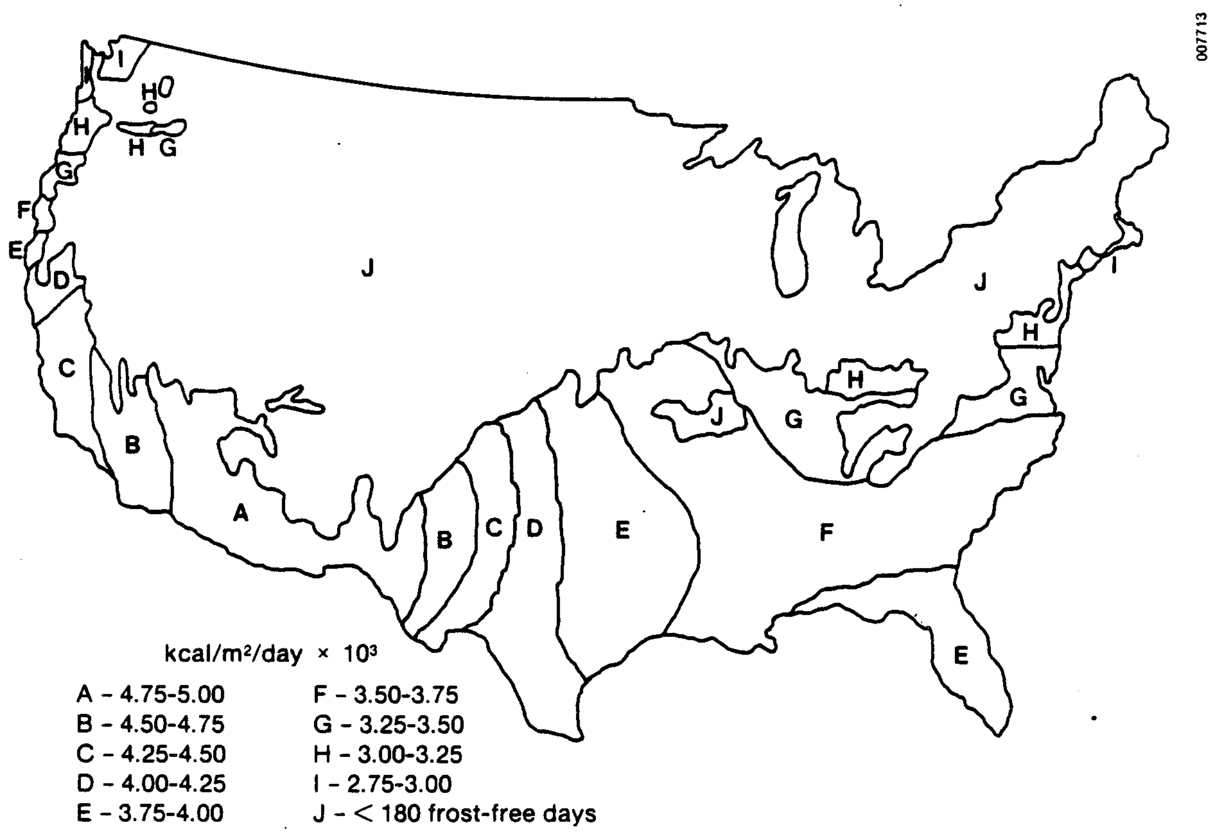

Figure 1. Solar Radiation in the United States Where There are More than 180 Frost-Free d yr^{-1}

However, it is also necessary to consider the trade-offs involved in locating in an area of high insolation. If the costs of land, raw materials, or operation are significantly increased at a location with high insolation, siting solely by the solar input may be disadvantageous.

Roswell, N. Mex. was chosen as the location for the Outdoor Test Facility (OTF). Roswell is 170 miles southeast of Albuquerque. The site meets the insolation and temperature requirements plus there is an abundant saline water supply and a large amount of existing infrastructure. Roswell is the site of a former Department of Interior desalinization plant that has been given to the town for water research purposes. There are offices, laboratories, large indoor working bays, and three 30-acre evaporation ponds. This infrastructure greatly decreased the additional government funds needed to start up the OTF.

Many other production conditions in outdoor systems are dictated by the engineering design and the management strategy. Three designs were examined in FY 1984 for the large-scale production of microalgae--open ponds, raceways, and enclosed tubes. The proposed costs for construction and operation of these three systems are shown in Table 2. All costs need to be kept to a minimum if the feedstock is to be produced inexpensively, thereby producing an economic liquid fuel, so open-pond systems were chosen as the facility plan for outdoor production (Figure 2).

Table 2. Capital Construction Costs for Three Different Algal Production Systems

Engineering Design	Cost ($/ha)
Open ponds	76,000
Raceways	161,000
Enclosed tubes	348,000

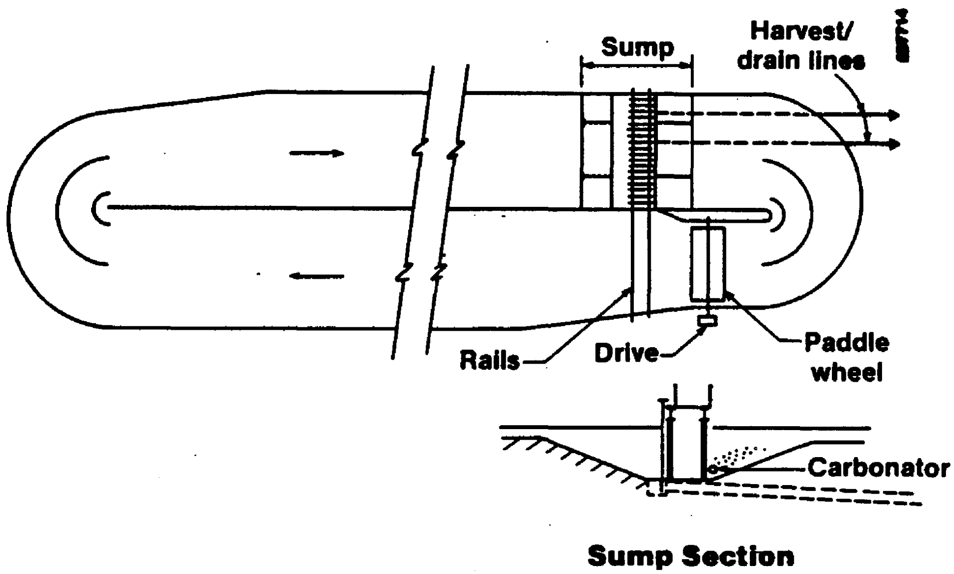

Figure 2. Open-Pond Design for Large-Scale Microalgae Production (from Ref. 4)

The OTF design plans include a small-scale system composed of six 3-m^2 ponds, a 50-m^2 inoculum pond, two 0.1-ha growth ponds, and one 0.5-ha pond. The sizes of the ponds were determined by optimizing research benefits with construction and operating costs. Programmatic objectives and economic constraints were also major factors in the size determination. The larger the pond, the higher the operating costs; thus, it was important to determine what sizes were needed and suitable to answer the biological and engineering questions.

SMALL-SCALE SYSTEM

The small-scale system was designed for the purpose of evaluating the growth performance of microalgae. It is necessary to determine optimum conditions (pH, carbon supply, culture density, mixing speed, temperature, etc.) in order to maximize each successful laboratory strain for yield, lipid production, and culture stability under outdoor conditions. To meet these objectives, it was necessary to have replicate ponds. Economic constraints dictate that this be done at the smallest practical scale. Both construction and operation costs are minimized at a scale of 1.5 to 10 m^2. However, sidewall shading becomes very important at sizes smaller than 3 m^2. Therefore, a pond size of 3 m^2 was chosen to minimize cost while not adding additional variables to the research. Six ponds were installed to provide for multiple experimental capability and also to provide replicability (see Figure 3).

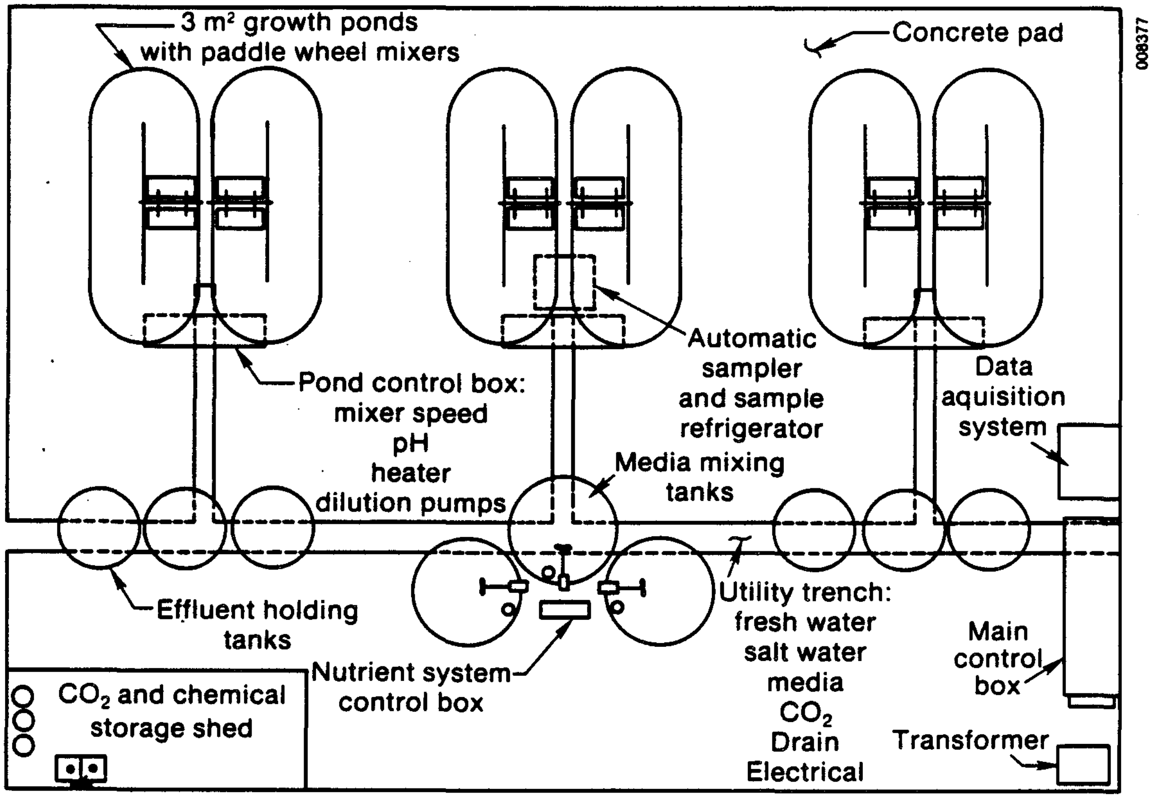

Figure 3. Design of the Small-Scale Microalgae System

Each pond can be operated at depths of 15 to 20 cm. Each pond is stirred by paddle wheels, which are made from clear Plexiglas to reduce shading. Mixing speed, pH, temperature, and salinity are maintained constant. Samples are taken automatically and refrigerated. The ponds are monitored with an automated data acquisition system. There are media mixing and holding tanks and effluent holding tanks so the systems can be operated as batch, semicontinuous, or continuous cultures. The small-scale system is located in the southeast corner of the Roswell Test Facility.

Construction of the small-scale systems was completed in July 1987. At this time screening began to test under outdoor conditions microalgae that had grown well in the laboratory. Figures 4 and 5 show the prime climatological factors affecting microlagae productivity: light and temperature from August through November. These initial data provide an indication of the range of the dominant variables as the seasons change from summer to winter. Insolation decreased from 6000 kcal m^{-2} d^{-1} in August to 3500 kcal m^{-2} d^{-1} in November. Minimum and maximum pond temperatures from August through November are shown in Figure 5. As expected, temperature decreased with the onset of winter from 32° to 20°C maximum and 20° to 0°C minimum. In November the ponds froze solid for one week. The ponds were operated in pairs, and one of the ponds was heated during the day beginning in late September. Most algae strains grow better under warmer temperatures.

During July and August a fast-growing, warm-water strain of diatom, *Cyclotella cryptica*, was grown in two of the ponds under identical conditions. Dilution was semicontinuous until August 5 and continuous thereafter. Approximately 45% of the pond volume was harvested each day. Productivity rates for *Cyclotella* are shown in Figure 6

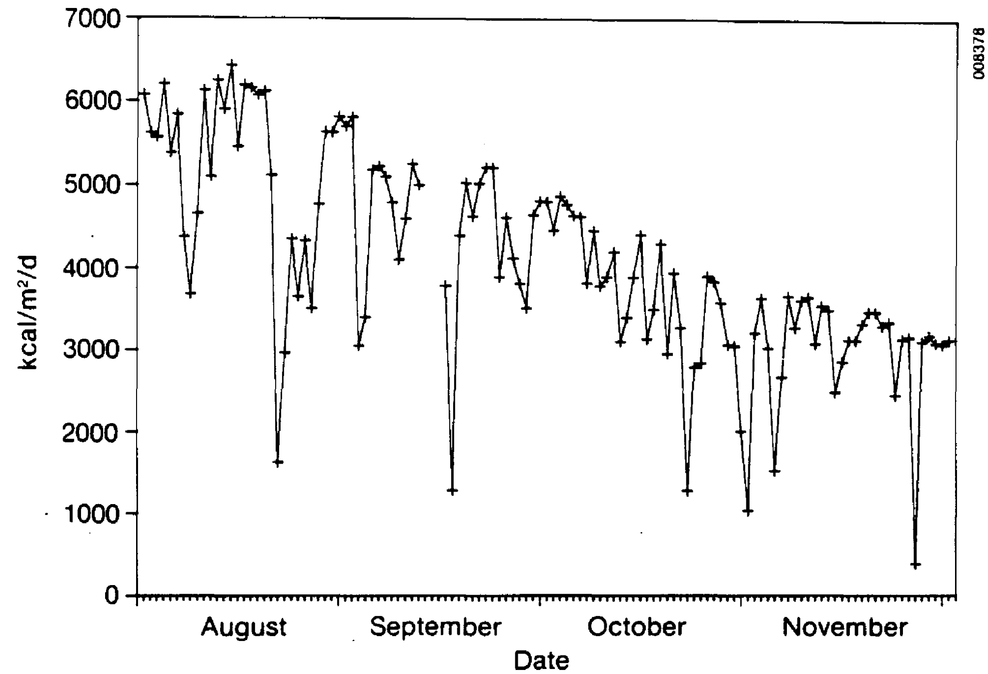

Figure 4. Daily Total Insolation at the Outdoor Test Facility

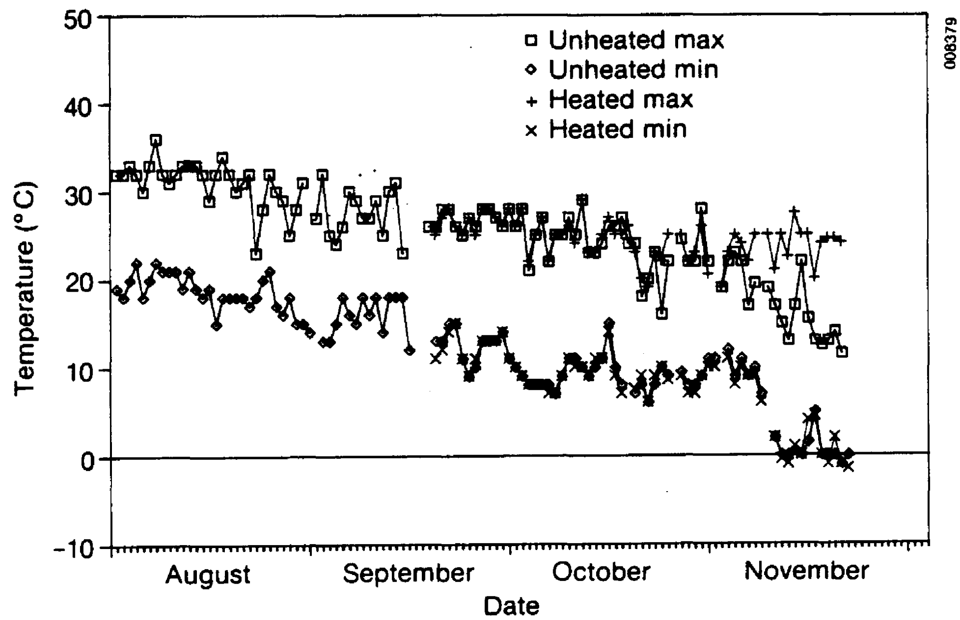

Figure 5. Maximum and Minimum Pond Temperatures in Heated and Unheated Ponds in the Small-Scale System

for these 2 months. Productivity averaged 24.7 g m^{-2} d^{-1} in Pond 1 and 29.0 g m^{-2} d^{-1} in Pond 2. In mid-August Pond 1 was invaded by another diatom species *Amphora* and the experiment in this pond was discontinued. As one can see from the figure, there was very good reproducibility between the two ponds until this time. During late August Pond 2 exhibited very high productivity rates of 56 g m^{-2} d^{-1}. It is unknown what caused these high uields, but we are encouraged that the current target program goal of 50 g m^{-2} d^{-1} can be reached.

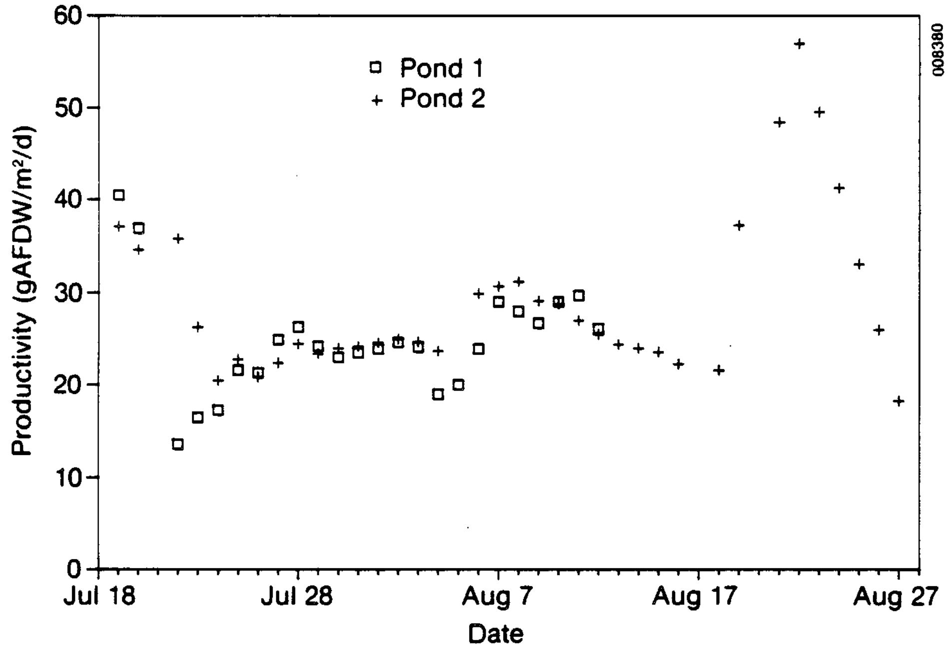

Figure 6. Productivity of *Cyclotella cryptica* in the Small-Scale System

During the colder months, a green microalgae, *Monoraphidium*, was tested for growth in the ponds. Productivity rates of 7 g m^{-2} d^{-1} were expected during this time (5). However, productivity rates averaged 15.7 and 16.8 g m^{-2} d^{-1} in Ponds 1 and 2, respectively (Figure 7). Pond 2 was heated during the day, but there was very little difference in production in the two systems. During December, the unheated pond froze solid and when it thawed a week later, the algae continued to grow. This has a major impact on the economics of large-scale production, since if a freeze does occur in the large ponds, they do not require reinoculation, which is an expensive process.

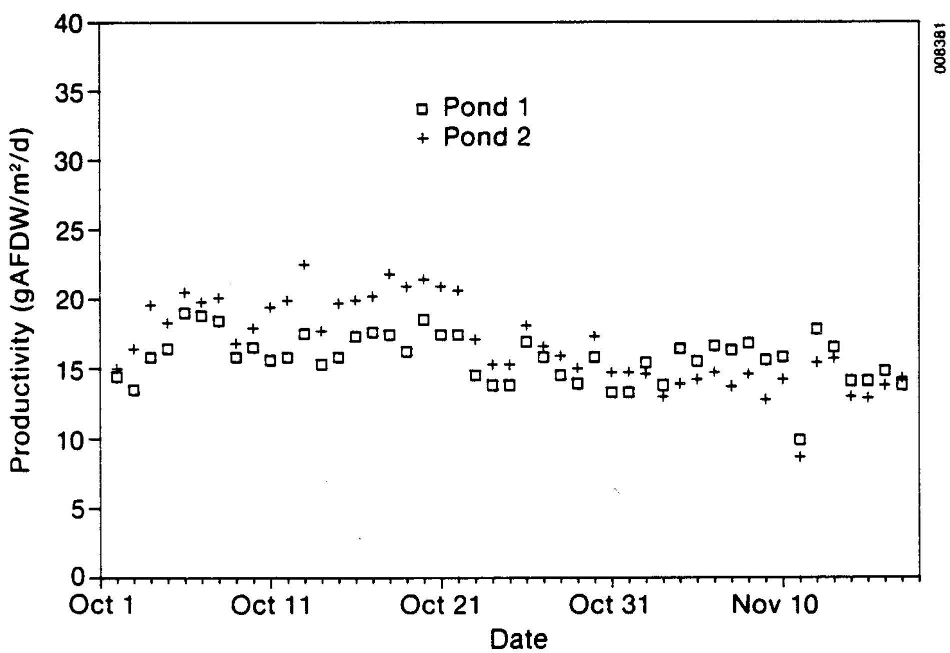

Figure 7. Productivity of *Monoraphidium minutum* in the Small-Scale System

These small-scale systems will be the workhorse of the microalgae OTF. They will be used to screen outdoors for productivity (i.e., minus any potential scale-up limitations), lipid production, and optimal culture managements strategies. In addition, the types of invaders, predators, and potential disease organisms will be monitored. If organisms that grow well in the laboratory do not grow well under outdoor conditions at Roswell, they will be sent to SERI for testing and optimization in 1.5-m^2 greenhouse ponds where conditions can be better controlled. After optimal growth conditions are identified, the strain will be sent back to the OTF for further testing.

The first phase of the large-scale system was completed in December. Two 0.1-ha ponds have been built approximately 1 mile from the Roswell Test Facility (Figure 8) in

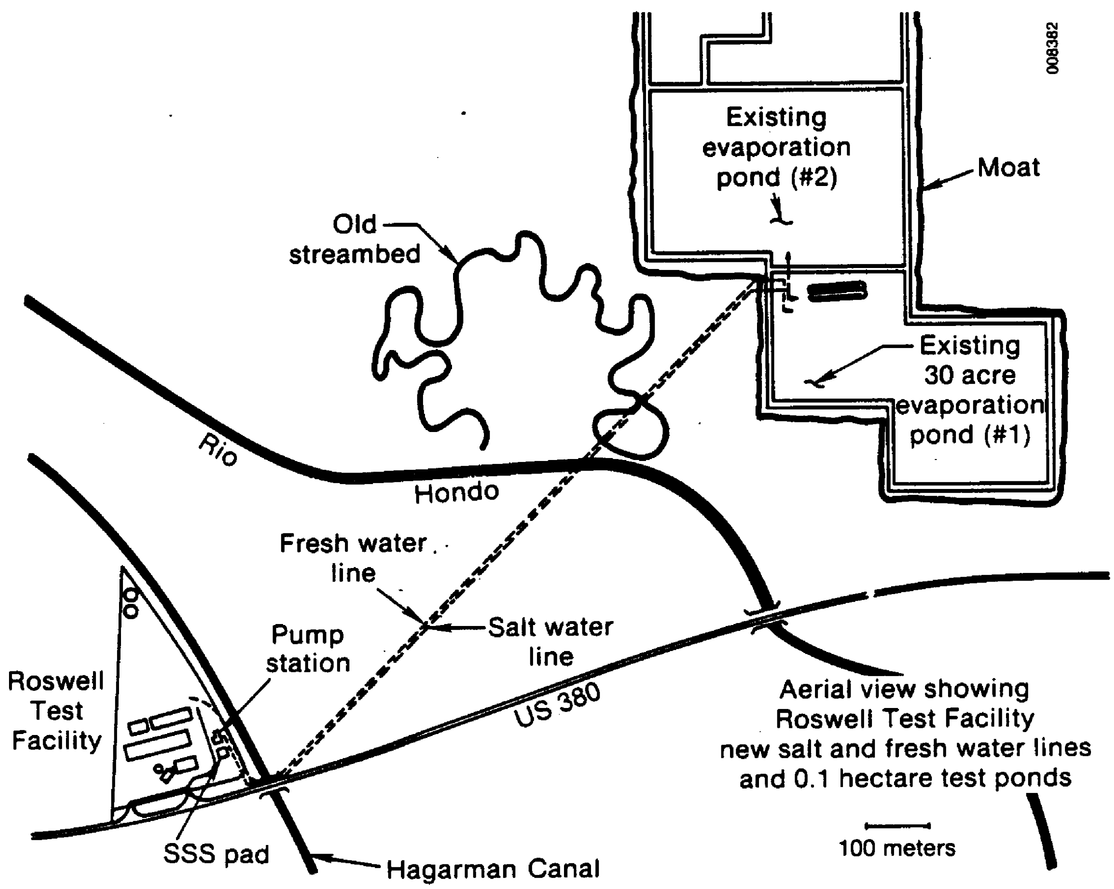

Figure 8. Aerial View of the Outdoor Test Facility

LARGE-SCALE SYSTEM

the southern 30-acre evaporation pond. These ponds are the open-pond design shown in Figure 2. In addition, fresh- and salt-water lines were run from the Roswell Test Facility to the ponds. One-tenth hectare ponds were chosen for the first scale-up size because (1) significant economy is realized in the construction of 0.1 - 0.2-ha ponds compared to the smaller ponds, and (2) operating costs are decreased by \$6,000 - \$10,000 by having a 0.1-ha pond rather than a 0.2-ha pond. These two ponds are not identical. One pond is lined with inexpensive earthen materials, and the second is lined with higher cost plastic.

FUTURE ACTIVITIES

A 50 m^2 inoculum pond will be built this spring to provide inoculum for the large-scale system. In addition, a series of hydraulic measurements will be made and studies done on injecting the carbon dioxide in the two 0.1-ha ponds. Velocity, pond roughness, paddle wheel efficiency, and outgassing will all be measured. After these are calculated and optimized in the two ponds, the best organisms from the small-scale system results will be inoculated into the large-scale system, and a year of productivity and economic data will be collected. Neenan et al. (3) estimated the relative costs of building and operating a microalgae outdoor test facility (Figure 9). Measurements made at the OTF for the cost of constructing and operating the large-scale system will be used to compare and update the model developed by Neenan et al. Results from this study will determine the future research priorities for the aquatic species program to further lower the cost of large-scale microalgae production.

Future plans call for the construction of a 0.5-ha pond in 1989 or 1990, based on available funding. This pond will be used to extrapolate the performance from the smaller systems and test the credibility of the hydraulic results. This size should also give data that can be extrapolated with confidence to a final operation size of approximately 5 ha.

This unique facility will be available for other researchers and industry for studies on microalgal productivity, harvesting, engineering design, or conversion. As long as the research project does not affect the ongoing research but can supplement or occur simultaneously, the facility will be available for use. Office and laboratory space is also available.

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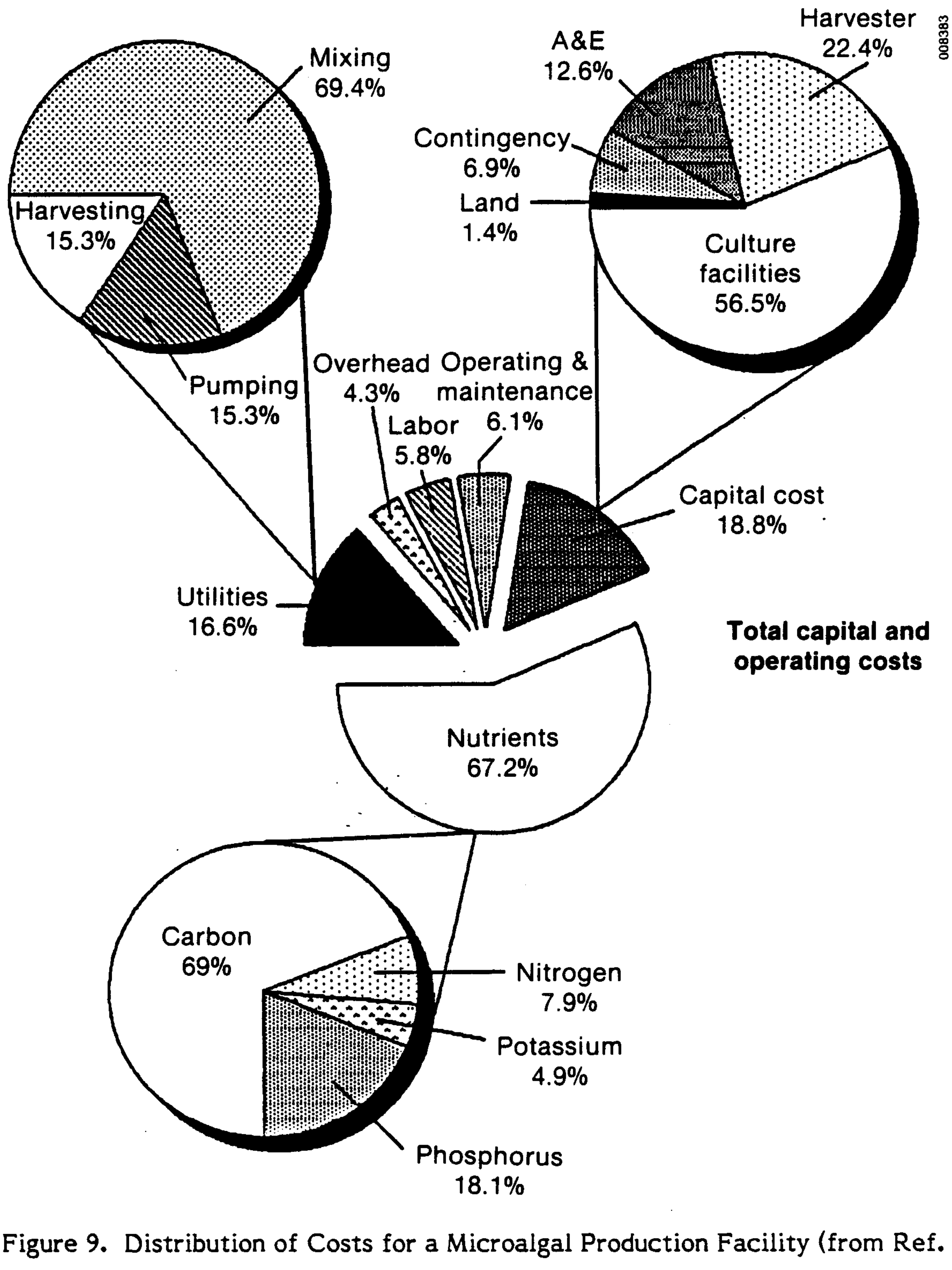

Figure 9. Distribution of Costs for a Microalgal Production Facility (from Ref. 3)