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# ENERGY FROM AQUATIC PLANT WASTEWATER TREATMENT SYSTEMS

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## Introduction

Due to the inevitable depletion of the once vastly abundant fossil fuels, it is of prime importance to seek new sources of available energy. The U.S. Department of Energy (DOE) is presently considering the potential of cultivating plants on large-scale energy farms solely for the purpose of fuel production.[1] Among some fundamental questions that must be answered before serious consideration can be given to large-scale energy farms are: What plants should be grown, and will the plants chosen compete with our vital food, feed, and fiber-producing plants for land, water, and fertilizer?

In present agricultural practice a sustained photosynthetic solar conversion efficiency of 1% represents a high yield corresponding to an average U.S. production of 33 mt/ha/yr (15 t/ac/yr) dry weight.[1] Sugarcane and sorghum can be expected to double this annual productivity.[2] The highly prolific water hyacinth is expected to achieve a solar conversion efficiency of 4% or greater[3] and produce four times more biomass annually than average U.S. conventional agricultural crops.

Cultivation of higher plants for the specific purpose of fuel production is not economically feasible at present.[1] However, cultivation of higher plants for use in wastewater treatment, and incorporation of these plants into a system where the biomass is harvested for fuel production is economically appealing at the present time. Since this biomass is a by-product of wastewater treatment, it has a positive environmental impact, and thus poses no threat as a competitor to food, feed, or fiber-producing plants.

NASA has developed and is operating vascular aquatic plant wastewater treatment systems for both domestic and chemical wastes at the National Space Technology Laboratories (NSTL).[4-7] As a part of this program and a Life Sciences study, NASA has investigated a variety of plants which have at least one common characteristic, i.e., a high potential productivity when cultivated and harvested to achieve optimum growth conditions. During the past five years that these systems have been in operation, NASA has been continuously searching for the most productive means of using the harvested plant biomass. One such method of using the biomass by-product from aquatic plant wastewater treatment systems is the conversion of the plant material into methane through anaerobic digestion. For a review of anaerobic digestion see National Academy of Sciences[8], Johnson[9], and Singh.[10] The energy produced from biomass digestion can be used for aeration and other wastewater treatment energy requirements. The residual sludge from the digesters can also be used for fertilizer, feed products, etc.

NASA's original studies on the bioconversion of water hyacinths into methane in 1975 consisted of simple batch fermentations requiring long digestion periods of 90–120 days.[11] In an effort to minimize the digestion time, recent studies have focused on two-phase digestion chambers using the anaerobic filter concept first demonstrated by Young and McCarty[12] for reducing the biochemical oxygen demand (BOD) of wastewater. The first chamber contains the pulp (fiber), water and plant juices from the blending process. The second chamber is an anaerobic filter consisting of a vessel packed with inert pea gravel which provides an extensive surface area for receiving only liquids from the fiber containing chamber. Water hyacinth (Eichhornia crassipes), duckweed (Spirodela sp. and Lemna sp.), water pennywort (Hydrocotyle ranunculoides) were the aquatic plants used in this study. The highly prolific terrestrial plant Pueraria lobata, commonly referred to as kudzu, was mixed with duckweeds for increased methane production.

The kudzu vine is one of the most prolific terrestrial plants on earth and covers thousands of acres in southern and central states of the U.S. Kudzu possesses several characistics which make it an ideal candidate for energy farms. It grows rapidly by either vegetative means or seeds. Each vine can produce 1-1.5 feet of new vine each day. It is a hardy plant as evidenced by its resistance to eradication. Since the kudzu vine is a legume, it can thrive in poor soil that is useless for agriculture and actually improves the land by restoring nitrogen to the soil. Due to its long roots, kudzu can also withstand droughts.

## Materials and Methods

Water hyacinths, duckweeds, and water pennyworts used in these experiments were grown on sewage lagoons located at the National Space Technology Laboratories. Kudzu vines were collected from fields near NSTL. The whole plants were blended into a slurry with approximately one milliliter of tap water per gram wet plant and placed into an 8-liter glass vessel. This vessel contained small pea gravel, 9 cm deep, in the bottom. The 8-liter vessel was connected to a 730-ml glass vessel (anaerobic filter) which was filled with small pea gravel (see Figure 1). Fifty milliliters of bacterial seed solution from an on-going anaerobic digester was added to the initial start-up batch. Liquid from the 8-liter vessel was pumped through the anaerobic filter and recycled through the large vessel continuously 8 hours per day. The anaerobic filter was kept sealed as new batches of plant material were added to the digester. The digestion temperature was maintained at 37° ± 1°C using an incubator. Gas samples were taken through the rubber septum and analyzed with a Fisher-Hamilton Gas Partitioner Model 29. The total volume of gas produced was measured as the volume of water displaced. The initial plant samples were analyzed by Raltech Scientific Services.

## Results and Discussion

Eight experiments were conducted to determine the digestion times and the total volume of methane that can be obtained from water hyacinths, duckweeds, water pennyworts,

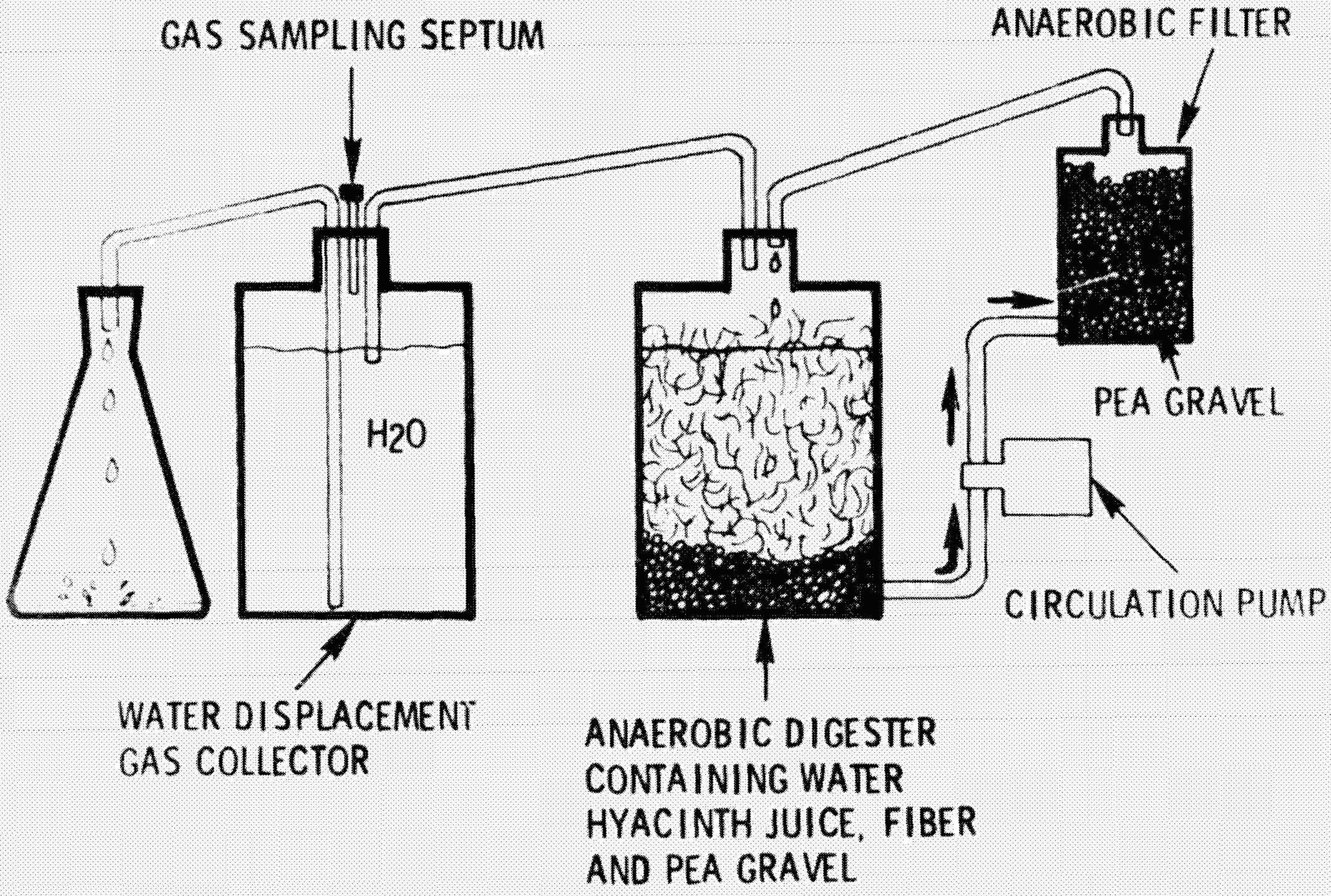

Figure 1. Two-stage anaerobic digester system for producing methane.

and combinations of duckweed/water hyacinth and duckweed/kudzu using the anaerobic filter technique. The age of the anaerobic filter was also noted in order to observe improvements in the efficiency of the methane production rates as a function of the anaerobic filter age.

The rates of methane production for the eight experiments have been graphically compared in Figures 2 through 4. Figures 2 and 3 show a definite improvement in the rate of methane production once the anaerobic filter has been matured through at least one digestion cycle. As shown in Figure 2 and Tables 1 and 2 for experiments 1 through 3, there was further improvement in the performance of the anaerobic filter during the third digestion cycle, thus indicating that the microbial balance in the anaerobic filter of the facultative, acid-forming, and methane-producing bacteria is still changing in order to achieve an optimum balance. After the anaerobic filter portion of the system has been sealed and matured, the filter should never be reopened and replaced unless by accident the bacterial balance is irreversibly upset.

The raw data for the total biogas and methane production is given in Table 1. The digestion time varied from 15 to 30 days with an average of 23 days. The digestion time has been dramatically reduced by approximately 75% from the previous batch digestions. Therefore, the size of the digestion chambers can be reduced accordingly in order to generate the same volume of biogas and methane.

The calculated results are shown in Table 2. The maximum volume of methane produced for water hyacinths and water pennyworts in this study was 0.198 $m^3/kg$ (3.17 $ft^3/lb$) and 0.146 $m^3/kg$ (2.34 $ft^3/lb$), respectively. Since the initial anaerobic filter age was approximately the same, results indicate that the water hyacinth is easier to anaerobically ferment than water pennywort. This observation is further substantiated by the data pre-

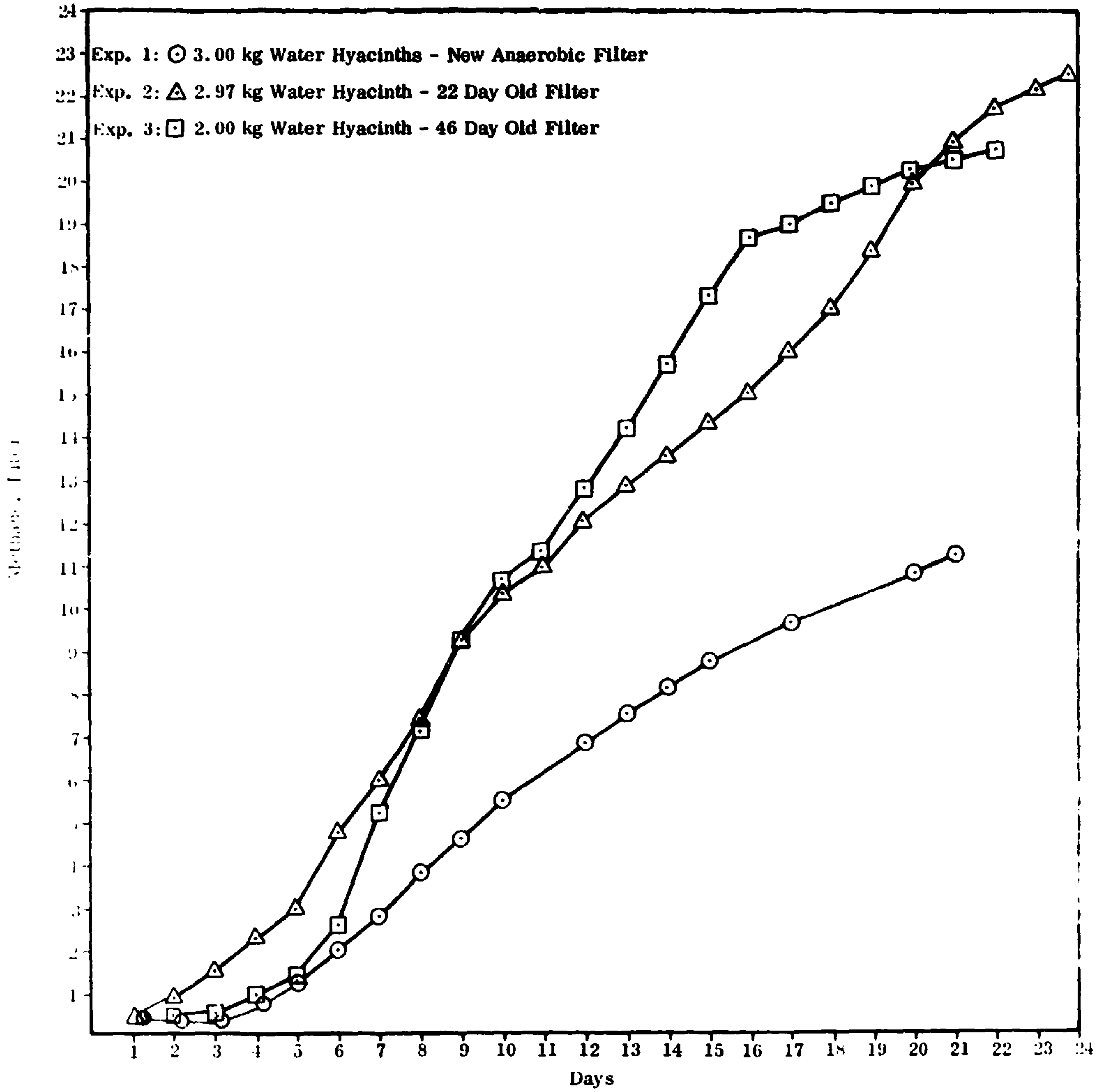

Figure 2. Comparison of water hyacinth digestion rates and anaerobic filter age.

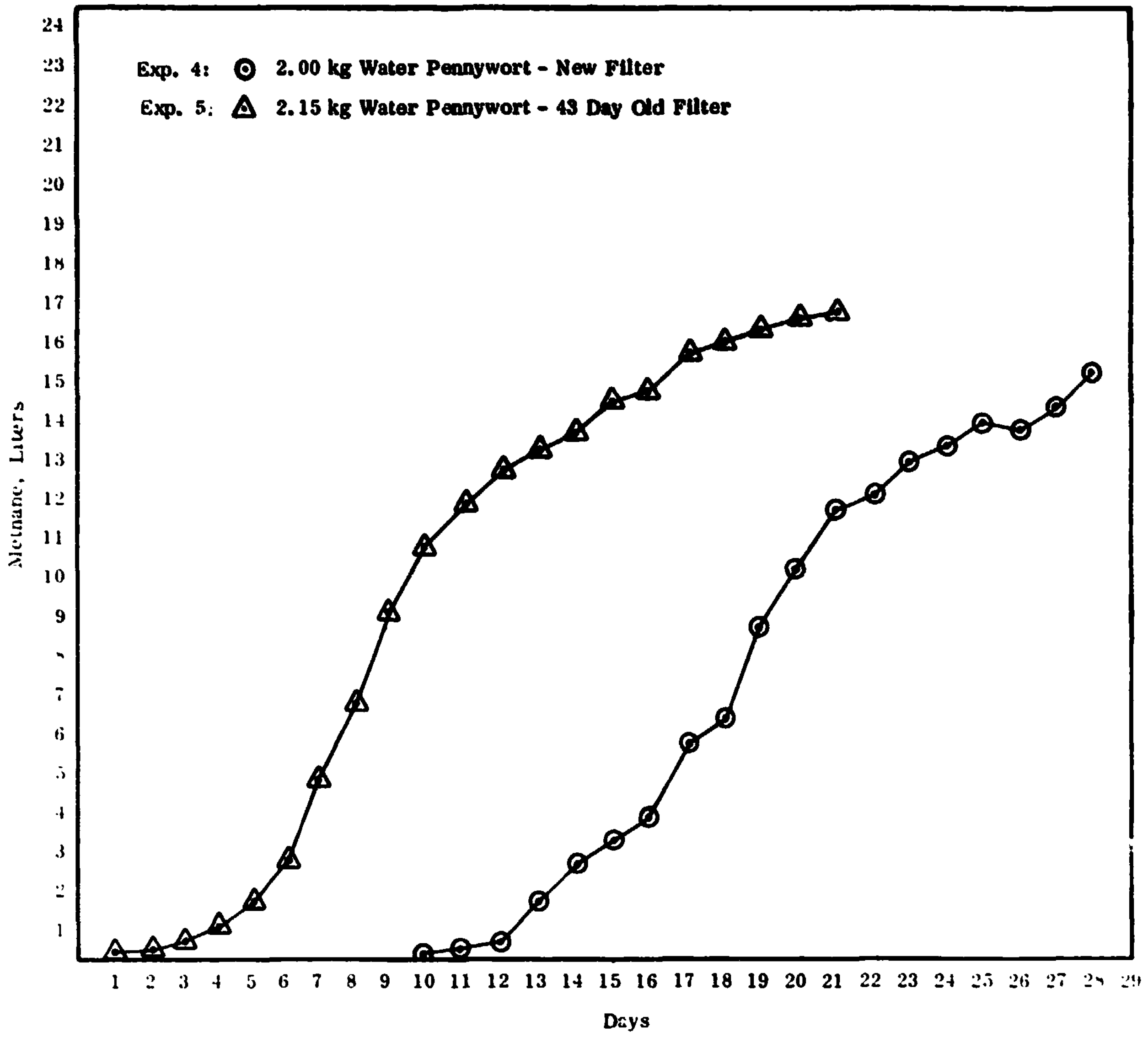

Figure 3. Comparison of water pennywort digestion rates and anaerobic filter age.

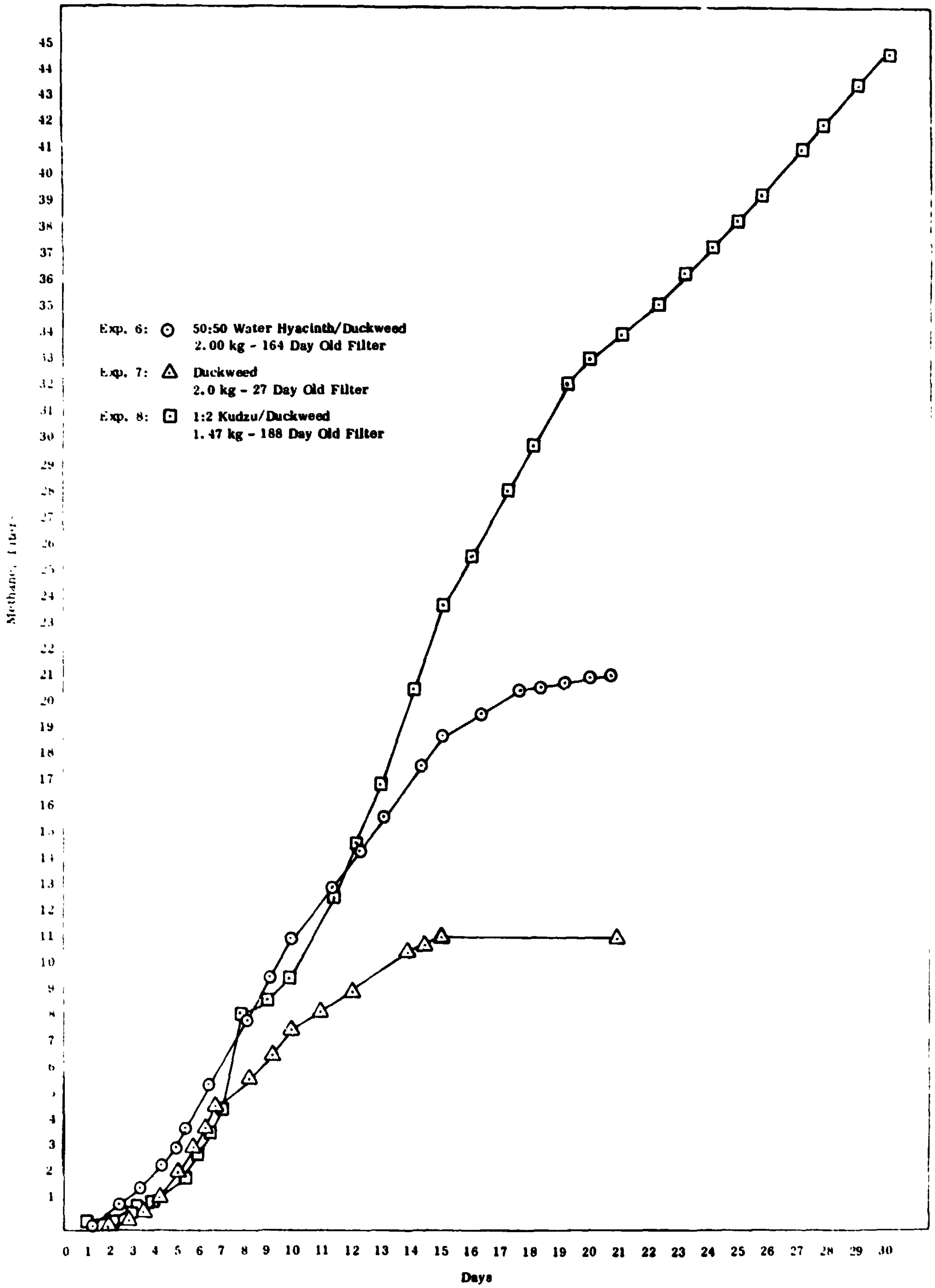

Figure 4. Comparison of digestion rates of duckweed, duckweed/water hyacinth mixture, and duckweed/kudzu mixture.

Table 1. Final results for experiments 1-8. (gas volumes as measured at 37°C)

| Exp. # | Plant | Wet Weight, kg | Dry Weight, kg | Total Biogas, liter | Total Methane, liter | Initial Filter Age, Days | Digestion Time, Days |
|---|---|---|---|---|---|---|---|
| 1 | water hyacinth | 3.00 | 0.150 | 35.28 | 11.1 | 0 | 21 |
| 2 | water hyacinth | 2.97 | 0.149 | 4.33 | 22.5 | 22 | 24 |
| 3 | water hyacinth | 2.00 | 0.100 | 37.5 | 20.8 | 46 | 22 |
| 4 | water pennywort | 2.07 | 0.105 | 33.1 | 15.1 | 0 | 28 |
| 5 | water pennywort | 2.15 | 0.108 | 28.7 | 16.6 | 43 | 21 |
| 6 | 50:50 water hyacinth/ duckweed | 2.00 | 0.100 | 40.1 | 22.6 | 164 | 21 |
| 7 | duckweed | 2.00 | 0.100 | 21.0 | 11.2 | 27 | 15 |
| 8 | 1:2 kudzu/duckweed | 1.47 | 0.150 | 71.7 | 44.5 | 188 | 30 |

Table 2. Calculated results of experiments 1-8. (all gas volumes corrected to 20°C)

| Exp. # | Total Biogas* | | % $CH_4$ | Total Methane* | |
|---|---|---|---|---|---|
| | $m^3/kg$ | $ft^3/lb$ | | $m^3/kg$ | $ft^3/lb$ |
| 1 | 0.222 | 3.56 | 31.6 | 0.070 | 1.13 |
| 2 | 0.276 | 4.43 | 52.0 | 0.143 | 2.30 |
| 3 | 0.356 | 5.71 | 55.5 | 0.198 | 3.17 |
| 4 | 0.299 | 4.80 | 45.6 | 0.137 | 2.19 |
| 5 | 0.253 | 4.05 | 57.8 | 0.146 | 2.34 |
| 6 | 0.381 | 6.11 | 56.4 | 0.215 | 3.45 |
| 7 | 0.200 | 3.20 | 53.3 | 0.106 | 1.71 |
| 8 | 0.454 | 7.29 | 62.1 | 0.282 | 4.53 |

* dry weight

sented in Table 3. The water hyacinth has approximately twice as much hemicellulose content as the water pennywort. Hemicellulose is a substance found in plant tissue that is more complex than a sugar but less complex than cellulose. Therefore, the hemicellulose is generally considered more amenable to bacterial degradation than cellulose. The lignin contents in the water hyacinth and water pennywort did not differ significantly. In fact the lignin contents of all four plants used in this study were low. In anaerobic digestion processes, lignin is considered to be a nonbiodegradable substance which reduces the availability of the cellulose to bacterial attack.

Duckweed alone only produced 0.106 $m^3$/kg methane (1.71 $ft^3$/lb). The water hyacinth/duckweed mixture produced an even higher amount of methane, 0.215 $m^3$/kg (3.45 $ft^3$/lb). However, it must be noted that the higher results with this mixture may be due to the anaerobic filter age of 164 days. The duckweed could also supply a more available form of nitrogen to the bacteria.

Very interesting results were obtained with the duckweed/kudzu mixture. Although the mixture required 30 days for digestion completion, it produced 0.282 $m^3$/kg $CH_4$ (4.53 $ft^3$/lb). The initial anaerobic filter age was 188 days. The promising results from this one experiment with kudzu could be due to the higher solids concentration because kudzu is approximately 20% dry matter as opposed to 5% for most aquatic plants. Further experiments and more detailed analyses are planned in order to further verify the results from experiment 8 and to determine the exact reason for the high methane production capacity from this terrestrial plant.

Table 4 shows the gross or proximate composition of the plants prior to anaerobic digestion. The duckweed had the highest crude protein content of 37% of dry weight. The

Table 3. Cellulose, hemicellulose, and lignin analyses.

| | %, Dry Weight | | |
|---|---|---|---|
| Plant | Cellulose | Hemicellulose | Lignin |
| water hyacinth | 21.5 | 33.9 | 6.01 |
| water pennywort | 15.7 | 15.1 | 7.28 |
| duckweed | 10.0 | 21.7 | 2.72 |
| kudzu | 26.2 | 20.8 | 10.5 |

Table 4. Proximate composition.

| | %, Dry Weight | | | | |
|---|---|---|---|---|---|
| Plant | Crude Protein | Fat | Fiber | Ash | Total Carbohydrate |
| water hyacinth | 14.7 | 1.59 | 18.6 | 11.1 | 54.0 |
| water pennywort | 23.4 | 2.19 | 11.8 | 17.4 | 45.2 |
| duckweed | 37.0 | 3.40 | 15.6 | 12.5 | 31.5 |
| kudzu | 16.3 | 2.11 | 31.3 | 8.2 | 42.1 |

Note: total carbohydrate = 100-(crude protein + fat + fiber + ash) kudzu had the highest fiber and the lowest ash content. Table 5 gives the nitrogen, phosphorus, and potassium contents of the plants on a dry weight basis. These elements are the most common ones noted in order to judge fertilizer value. During anaerobic digestion, some nitrogen is generally lost. The extent of denitrification is dependent on the method and care of the anaerobic digestion and also on the initial C:N ratio. The C:N ratios of the plants used in this study are given in Table 5. In general, the lower the ratio, the higher the nitrogen loss due to a surplus of nitrogen. However, all of the minerals such as potassium and phosphorus will remain in the sludge. In fact, these minerals will be more concentrated due to a reduction in the initial solids content from loss of nitrogen and carbon in the forms of ammonia, nitrogen gas, methane, and carbon dioxide during the anaerobic digestion. A small amount of sulfur will also be lost in the form of hydrogen sulfide.

Table 5. Miscellaneous elemental analyses.

| | %, Dry Weight | | | | |
|---|---|---|---|---|---|
| Plant | Nitrogen | Phosphorus | Potassium | Carbon | C:N |
| water hyacinth | 2.35 | 0.445 | 1.99 | 39.9 | 17:1 |
| water pennywort | 3.75 | 0.606 | 2.80 | 37.0 | 10:1 |
| duckweed | 5.92 | 0.955 | 2.91 | 43.7 | 7:1 |
| kudzu | 2.61 | 0.222 | 1.83 | 43.1 | 17:1 |

## Conclusions

1. Anaerobic filters reduce the total digestion time to an average of 23 days as compared to 90 days with simple batch digestion.

2. The maturity of the anaerobic filter is important to the overall efficiency of the system.

3. The descending order of anaerobic digestibility of the four plants used in this study is: kudzu, water hyacinth, water pennywort, duckweed.

4. Based on an estimated potential productivity of 154 mt/ha/yr for the water hyacinth grown in highly enriched lagoons,[3] one hectare of water hyacinths can generate enough biomass to produce at least 30,500 $m^3$ (1,076,000 $ft^3$) of methane by the anaerobic filter technique.

5. The kudzu vine demonstrated a high potential methane production per unit dry mass. These very promising results in conjunction with its high productivity and hardiness make it an ideal candidate for terrestrial energy farms on land that is not suitable for agricultural use.

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