THERMAL GASIFICATION OF DENSIFIED SEWAGE SLUDGE AND SOLID WASTE

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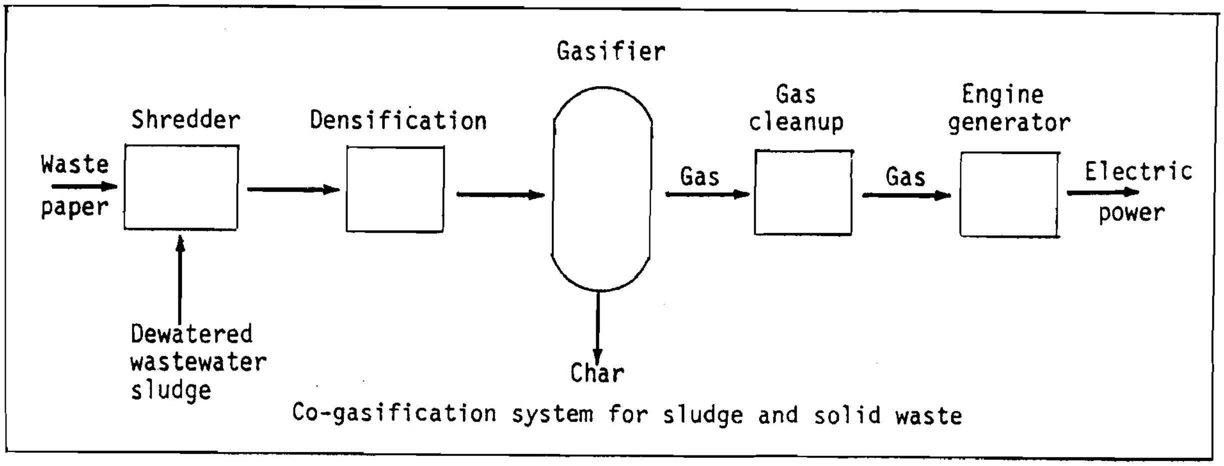
ABSTRACT

Disposing of sewage sludge in an economical and environmentally acceptable manner is a problem for all communities that have wastewater treatment plants. Similarly, many communities are having to dispose of increasing quantities of solid waste. These problems could be solved by co-disposal of sludge and solid waste in a common facility. This study, a condensation of the original report, presents results of an experimental program on the feasibility of gasifying densified sludge and source-separated solid waste.



Co-gasification system for sludge and solid waste

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INTRODUCTION

Background. Facilities for processing and disposing of wastewater sludges may account for up to 50% of the capital cost and up to 55% of the operating cost of a treatment plant. There are two basic ways to dispose of sludge: biological treatment, in which aerobic and anaerobic digestion is used to stabilize sludge, and thermal treatment, in which sludge is sterilized and reduced in volume through incineration (or pyrolysis), thermal gasification or liquefaction.

Biological processes are relatively simple, have proven performance, and, in the case of anaerobic digestion, have the potential for energy recovery. The end product is a wet slurry that usually can be dewatered for disposal. The end product of thermal processes is a dry, sterile ash or char. The principal disadvantages of thermal processes are their relatively high capital cost and their demand for fossil fuels.

Co-disposal of sludge and solid waste. Co-disposal in a common system would eliminate or reduce the need for fossil fuels used in incineration, while reducing landfill requirements for solid waste. There are no full-scale co-disposal systems in the United States, but several systems are being designed or constructed. There are two basic types of co-disposal: in the first, a mass-fired solid-waste incinerator is used to combust dried sludge that has been mixed with unseparated solid waste; in the second, a sewage-sludge incinerator is modified to accept refuse-derived (RDF) as a substitute for natural gas or oil.

An alternate method is co-gasification of sludge and source-separated solid waste. The system consists of a shredder to reduce the size of waste paper and to mix it with dewatered sludge, a densification system to convert the sludge/waste paper mixture into a dense fuel cube, a gasifier, a gas cleanup system, and an engine-generator to convert the gas to electricity.

Gasification. Gasification is an energy-efficient technique for reducing the volume of solid waste and recovering energy. The process involves partial combustion of a carbonaceous fuel to generate a combustible fuel gas rich in carbon monoxide and hydrogen.

Reactor types. There are four basic gasifier reactor types: vertical packed bed, multiple hearth, rotary kiln, and fluidized bed. The vertical-packed-bed reactor (VPBR) is simpler and less expensive than the others, although it is more sensitive to the mechanical characteristics of a fuel.

In the VPBR, fuel flows by gravity, with air and fuel moving concurrently through the reactor. At steady state, four zones form in the reactor. In the hearth, where air is injected radially into the reactor, exothermic combustion and partial combustion reactions predominate. Heat transfers from this zone upward into the fuel mass, causing pyrolysis in the distillation zone and partial drying of the fuel in the drying zone. Fuel gas is produced in the reduction zone, where endothermic reactions predominate, forming CO and H_2. The end products are a carbon-rich char and a low-energy gas.

Downdraft gasifiers are simple to build and operate, but they have exacting fuel requirements. Moisture content must be less than 30%, ash content must be less than 10%, and fuel must be uniform in size. Since waste can be dried before gasification, excessive moisture can be avoided. But ash content and fuel size are more difficult to manage. A suitable fuel can be made by mixing dehydrated sludge with the paper fraction of source-separated solid waste and densifying the mixture to produce a densified refuse-derived fuel (d-RDF) that has low moisture content, low ash content, and uniform fuel size.

Gas composition. When a gasifier is operated at atmospheric pressure with air as the oxidant, the end product is a low-energy gas (LEG) typically containing (by volume) 10% CO_2, 20% CO, 15% H_2, 2% CH_4, with the balance being N_2 and a carbon-rich char. The low-energy gas can be utilized in several ways. The simplest is to burn the gas with stoichiometric amounts of air in a standard boiler designed for natural gas. Another approach is to cool and filter the gas and use it as an alternate fuel for internal combustion engines.

Gasifiers also can be used to operate diesel engines.

EXPERIMENTAL APPARATUS, METHODS, AND PROCEDURES

An experimental gasifier was built, consisting of three subsystems: a batch-fed downdraft gasifier, data acquisition system and solid-waste shredding and densification machinery. Fig. 1 shows the pilot-scale batch-fed downdraft gasifier designed and constructed at the University of California, Davis.

The subsystem for data acquisition was an automated temperature measurement system. Temperatures were sensed with Type K thermocouples located as shown in Fig. 1. Additionally, a Type T thermocouple was used in the air inlet line, a Type K thermocouple was installed in the gas outlet pipe, and magnetically mounted Type K thermocouples were used to measure surface temperatures. The thermal emf from the thermocouples was converted to temperatures by a Digitec Model 1000 Datalogger. The channel number, temperature, and elapsed time were printed on the paper tape output of the instrument.

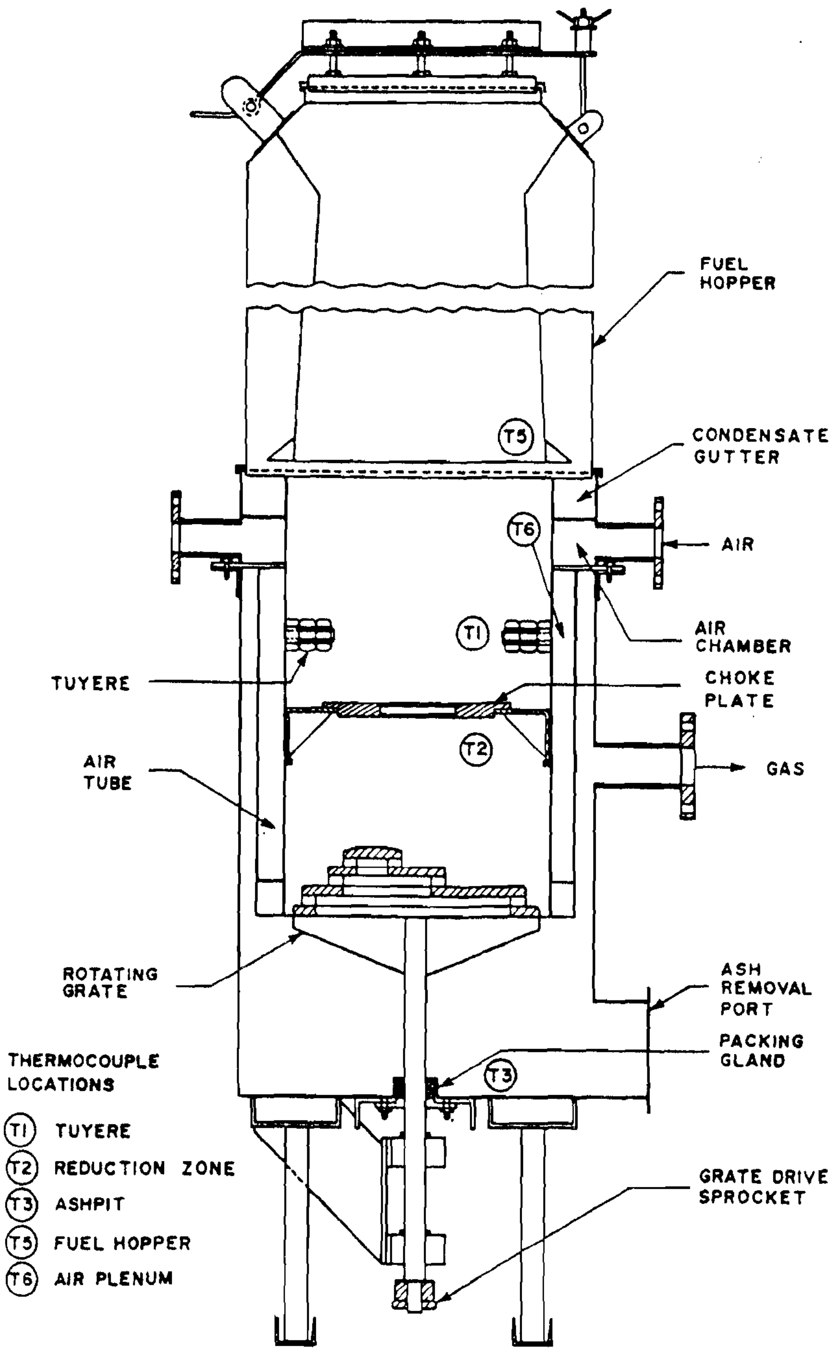

Fig. 3. Cross section - UCD sludge/solid waste gasifier.

Densified fuels are required for the operation of packed-bed gasifiers. The simplest type of densification system is a shredder followed by an agricultural cubing machine. Since the capacity of commercial densification systems is relatively large (1.8 to 4.5 metric tons per hour) compared to the gasifier (16 to 49 kg/hr), a densification system was not built especially for this project. Rather, systems on the university campus and the pilot plant densification system operated by the Papakube Corporation of San Diego were used.

Field testing. In addition to gasifier temperatures that were recorded automatically by the data analysis subsystem, the following data were recorded manually during test runs.

Air and gas flows--Measured using standard flange-mounted orifice plates in the air inlet and the gas flare line. Orifice plates were calibrated before and after runs.

Weight loss--The gasifier was mounted on platform scales and its weight recorded at 5-minute intervals. Since char accumulated in the ashpit, weight loss during the run was a direct measure of gas generation.

Pressure drop--Pressure

drop across the fuel bed was measured periodically. When it exceeded 5 cm of water, the grate was rotated, displacing char into the ashpit.

Char--Samples were collected on the day after each run to allow the gasifier to cool. Samples for analysis were collected from the reduction zone when the gasifier was partially disassembled for inspection after each run.

Condensate--Condensate was drained from the gasifier after each run, weighed, and a sample saved for analysis.

Slag--To assess the potential of sludge/waste paper cubes to cause slagging, the gasifier was partially disassembled after each run and residual char in the firebox removed and sifted for slag agglomerations.

Laboratory testing. Samples of gasifier fuels, chars, and condensate were tested. Grab samples of the low-energy gas also were analyzed. Proximate analyses of the fuel and char were made according to ASTM Standard Methods. Ultimate analysis for percentage of C, H, N, S, and O_2 for the fuel, char, and condensate were done by the Chemistry Department of the University of California, Berkeley. The energy content of the fuel and char was determined with a Pass Oxygen Bomb Calorimeter.

Gas samples were collected in Tedlar gas sampling bags and analyzed on a Leeds and Northrup process gas analyzer system. Percentages of CO, CO_2, O_2, H_2, and hydrocarbons were determined, as was moisture content.

Energy balance computations. In an energy balance, energy input into the gasifier is compared with energy output. Energy inputs include the sensible and latent heat of the air blast, and the sensible heat and heat of combustion of the fuel. Energy outputs include the heat of combustion and sensible heat of the dry gas; the sensible and latent heat of the steam in the gas, the sensible heat and heat of combustion of the char; the sensible heat, heat of combustion, and latent heat of the condensate; and convection and radiation losses.

EXPERIMENTAL RESULTS

Fuel characteristics. The gasifier was operated with four different mixtures of sludge and solid waste. Samples of lagoon-dried, mixed primary and secondary sludge (about 60% solids) from the university's treatment plant were collected and trucked to the Papakube pilot plant in San Diego. Five batches of cubes (about 200 kg each) were prepared by placing preweighed dried sludge and newsprint on the conveyer belt of the densification system. The violent mixing of the shredder, blower, and cyclone ensured uniform mixing of sludge particles and shredded paper. Mixtures of 10%, 15%, 20%, and 25% sludge (by wet weight) were prepared.

Fuel cubes were tested for proximate analysis, ultimate analysis, and energy content. Table 1 summarizes results of these analyses. In general, fuel cubes were relatively high in volatile combustible matter (VCM), low in fixed carbon (FC), and low in energy content (HHV), compared with coal, which has a VCM of 30% to 40%, a carbon content greater than 70%, and an HHV of about 30 MJ/kg.

Operational data. Test runs were conducted as close to the air flow rate as possible, $\approx 0.41/m^3/min$ (1 atmosphere, 0°C). Thus, the flow rate of fuel through the gasifier, the efficiency, and gas quality were a function of the gasification characteristics of the fuel. Fuel consumption rate is the primary measure used to compare the gasification potential of fuels. It is calculated as shown:

$$\text{Fuel consumption rate} = \frac{\text{Weight loss during run} + \text{Condensate removed} + \text{Char removed} + \text{Slag removed}}{\text{Net run time}}$$

Where: Net run time = Run time - (refueling time + other down time).

It was originally assumed that the fuel consumption rate was inversely related to bulk density. However, Tables 2 and 3 show that the densified fuel with the lowest consumption rate, 15% sludge, was among the least dense of the densified fuels. In both wood and coal gasification studies, it has been found that the surface roughness and porosity of fuels has a profound effect on the rate of gasification. Therefore it was assumed that these

TABLE 1. SUMMARY OF FUEL CHARACTERISTICS USED FOR GASIFICATION STUDIES

Item	RUN 09	RUN 10	RUN 11	RUN 12
Fuel description	10% Sludge Cubes	15% Sludge Cubes	20% Sludge Cubes	25% Sludge Cubes
Proximate analyses				
VCM, %	83.87	75.10	74.54	73.66
FC, %	8.19	12.19	13.05	13.70
Ash, %	1.11	2.62	3.07	4.08
Moisture, %	6.83	10.09	9.34	8.56
Ultimate analyses (Dry basis)				
C, %	46.46	45.99	45.24	45.27
H, %	5.98	5.89	5.81	5.77
N, %	0.19	0.19	0.13	0.42
S, %	0.14	0.10	0.11	0.16
O, %	45.33	44.83	46.81	44.18
Residue	1.90	3.00	1.90	4.20
Energy content, MJ/kg (Dry basis, HHV)	19.04	18.88	18.93	18.49

TABLE 2. DENSITIES OF GASIFIER FUELS

Fuel	Run No.	Densification process	Bulk density, kg/m^3	Unit density, kg/m^3
10% Sludge cubes	09	Papakube	374	738
15% Sludge cubes	10	Papakube	445	932
20% Sludge cubes	11	Papakube	536	1010
25% Sludge cubes	12	Papakube	486	1014

TABLE 3. OPERATIONAL SURVEY

Item	RUN 09	RUN 10	RUN 11	RUN 12
Fuel description	10% Sludge Cubes	15% Sludge Cubes	20% Sludge Cubes	25% Sludge Cubes
Fuel consumption rate kg/hr	21.4	12.3	17.5	16.3
Char production rate, kg/hr	1.15	1.40	2.47	1.71
Condensate production rate, kg/hr	0.58	0.82	0.50	0.73
Net run time, min.	251	407	265	262
Gas flare igniting time, min.	9	31	24	44
Air input rate, m^3/min. (0°C, 1 atm)	0.405	0.408	0.407	0.415
Gas output rate, m^3/min. (0°C, 1 atm)	N/A[a]	N/A	0.68	0.66
Average reduction zone temperature, °C	828.8	656.4	779.8	734.7
Average gas outlet temperature, °C	193.5	149.1	197.6	180.6
Volume reduction, %	81	73	64	74
Weight reduction, %	91	80	82	83

[a] Not available

properties are more important than fuel density.

In addition to gas flow measurements made with the flare stack orifice plate, gas flows were computed by mass and nitrogen balances. Gas flow was computed with mass balance by comparing air and fuel flow into the gasifier with gas, char, and condensate output rates. Gas flow was computed with the nitrogen balance by comparing nitrogen in the input airflow with nitrogen in the low-energy gas (nitrogen in the fuel, char and condensate was assumed to be negligible).

Weight reduction for sludge/solid waste cubes ranged from 91% to 83%, respectively, for 10% to 25% sludge mixtures. Similarly, volume reduction ranged from 64% to 81%, respectively, for 10% to 20% sludge mixtures.

Gas samples were collected for analysis during runs 9 through 12, but because of problems with the gas-sampling train, analyses are available only for runs 11 and 12. Table 4 summarizes dry-gas composition, gas moisture content, and gas energy content. Dry-gas compositions measured during runs 11 and 12 were within the normal range expected for air-blown gasifiers.

TABLE 4. COMPOSITION AND ENERGY CONTENT OF LOW ENERGY GAS

Item	RUN 11	RUN 12
Dry gas composition (By volume)		
CO, %	20.9	21.5
H_2, %	14.5	13.7
CH_4, %[a]	2.3	2.5
C_2H_6, %[a]	0.1	0.1
CO_2, %	11.9	11.0
O_2, %	0.3	0.3
N_2, %	50.0	50.9
Gas moisture content (By volume), %	14.15	12.31
Gas energy content MJ/m^3 (Saturated, 0°C, 1 atm)	5.11	5.17

[a] Measured as total hydrocarbons, CH_4, assumed to be 95% of THC, C_2H_6 assumed to be 5% of THC.

Char, condensate, and slag characteristics. Samples of char and condensate were collected after each run. Char remaining in the firebox was sifted for slag agglomerations.

Char. Proximate analyses indicated that chars were low in VCM and high in FC in comparison to the sludge/solid waste mixtures. In this respect, chars were similar to coal, which is also low in VCM. Ash content of the chars was high, ranging from 43% to 80%, which would limit their use as a fuel. Although the chars had relatively high energy contents, their high ash content seems to preclude their use as a gasifier fuel. Char could be blended into the fuel of later runs, but it may be more promising as a substitute for activated carbon in polishing wastewater treatment plant effluent.

Condensate. Detailed chemical analyses of condensate were not conducted, but ultimate analyses were done, as shown in Table 5.

Slag. The weight of ash in the fuel and char, and the amount of slag recovered after each run are summarized in Table 6. In all cases, ash recovered in the char exceeded the total ash theoretically contained in the fuel consumed during the run. This discrepancy probably was caused by sampling errors, since the amount of slag generated during a run is not precisely known.

Several methods control slagging. The easiest is to limit ash content of sludge/solid waste cubes by controlling the ratio of sludge to solid waste. Another method is to operate the gasifier with a steam/air blast instead of air. This reduces temperatures in the combustion zone below the point where ash is melted. A third technique is to operate the gasifier at high temperatures, producing a molten slag that can be tapped and drained off during the run.

Energy balances, runs 11 and 12. These are shown in Table 7. Results are given in energy units, MJ/hr, and percentages, assuming the fuel net energy as 100%. The gas chemical energy is the most significant energy output, ranging from 72% to 81% of the input net energy. Char energy ranged from 17% to 25% of the input net energy. Condensate energy was minor, varying from 0.9% to 1.3% of the input net energy. The negative energy losses shown are most likely due to errors made in determining the exact amount of char generated during the relatively short runs. This problem was corrected in subsequent test runs.

TABLE 5. SUMMARY OF CONDENSATE CHARACTERISTICS

	Ultimate Analyses, %				
RUN	C	H	N	S	O
09	7.56	10.25	0.25	0.08	81.86
10	7.12	10.31	0.07	0.10	82.40
11	6.06	10.24	0.09	0.07	83.54
12	7.55	10.37	0.12	0.05	81.91

TABLE 6. CHAR AND SLAG GENERATION

Item	RUN			
	09	10	11	12
Fuel				
Sludge content, %	10	15	20	25
Ash, %	1.1	2.6	3.1	4.1
Total fuel, kg	89.4	83.2	77.2	75.1
Total ash, kg	1.0	2.2	2.4	3.1
Char				
Ash, %	42.9	49.6	79.8	75.3
Total char, kg	4.8	9.5	10.9	7.5
Total ash, kg	2.1	4.7	8.7	5.6
Slag				
Total slag, kg	0.6	1.2	0.8	1.0
Totals				
Char ash + slag, kg	2.7	5.9	9.5	6.6
Char ash + slag/ fuel ash, %	270	270	400	213

APPLICATION OF GASIFICATION TECHNOLOGY TO MUNICIPALITIES

This project has demonstrated that densified sludge/solid waste mixtures can be gasified successfully.

Role of gasification in large cities. It makes economic and technical sense to couple treatment of a community's liquid and solid waste streams. The relative simplicity of gasification lends itself to satellite operations in larger cities. For example, source-separated solid waste (or sludge/solid waste mixtures) could be densified at a large central facility and trucked to satellite gasifiers in other parts of a city. In large urban areas with several landfills and wastewater treatment plants, complete co-gasification systems could be located at each site.

Role of gasification in small cities. Gasification in small communities requires several commitments: 1) economic and managerial cooperation between solid-waste and wastewater treatment divisions, 2) a community-wide source-separation system for production of gasifier fuel, and 3) the technical expertise to operate a co-gasification system.

Although a gasification system could be operated in a small community strictly with source-separated solid waste and sludge, a more cost-effective approach might be to incorporate gasification with other waste-generating activities. If a gasifier is located at a wastewater treatment plant, for example, the low-energy gas could be used to power pumps, blowers, and other equipment.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Conclusions:

1. The co-disposal of densified sludge/solid waste mixtures appears technically feasible.
2. Preparation of such mixtures at a full-scale pilot facility has been demonstrated.

TABLE 7. ENERGY BALANCES

Item	RUN 11		RUN 12	
	MJ/hr	%	MJ/hr	%
Gross energy, dry fuel	269.49		268.08	
Latent heat combined water	18.48		16.26	
Latent heat, fuel moisture	4.15		4.07	
Net energy, fuel	273.86	100.00	247.75	100.00
Gas chemical energy	197.15	71.99	199.93	80.70
Gas sensible heat	12.37	4.52	11.03	4.45
Heat loss condenser	21.16	7.73	19.27	7.78
Char energy	69.00	25.20	41.45	16.73
Condensate energy	2.38	0.87	3.33	1.34
Energy losses	-28.19	-10.30	-27.25	-11.00
Hot gas efficiency		76.51		85.15
Cold gas efficiency		71.99		80.70

3. Other than a lower gasification rate relative to biomass fuels, virtually no operational problems were experienced with sludge/solid waste fuels.
4. Co-gasification of densified sludge and source-separated solid waste may be a new approach to co-disposal that could be adopted by both large and small communities.

Key issues which must be addressed before co-gasification can be done routinely are:

1. What is the optimum fuel consumption, air flow, gas quality, and efficiency for gasifier operation?
2. What causes slagging? Slag control measures such as steam or water injection, or continuous grate rotation should be investigated.
3. What is the fate of heavy metals during gasification?
4. What is the mass emission rate and size distribution for particulates in the low-energy gas?
5. The economics of co-gasification for small communities must be known.
6. Manufacturers of co-gasification machinery must be identified.

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Additional information about the process can be found in the publications listed below.

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The UC Appropriate Technology Program was established by the California Legislature, through an item in the 1977-78 University budget, to fund research and disseminate results in "appropriate technology" areas. Presently, research is being conducted in the following areas: (1) energy production from renewable resources, (2) efficient end uses of energy, (3) climatically responsive architecture, (4) resource conservation and recycling, (5) organic agriculture, and (6) institutional factors affecting appropriate technologies. A list of final reports and further information on the Program can be obtained from the main office: Bldg. T-4, Rm. 100, University of California, Berkeley, CA 94720 (415) 642-8859.

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