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ENERGY RECOVERY THROUGH UTILIZATION OF THERMAL WASTES IN AN ENERGY-URBAN-AGRO-WASTE COMPLEX

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ABSTRACT

A quantitative description of the inter-relationships between energy production and conservation, agriculture and waste treatment are given. This area of study, more conveniently referred to as the energy-urban-agro-waste complex is an emerging technology which is stimulated by the realization that there are finite limits to material, energy and land resources.

Solid, liquid and thermal waste contain sizeable amounts of energy which, if properly harvested, can provide new sources of energy as well as alleviating certain disposal problems. The genesis of the modeling stems from the needs of the community or population center, which requires energy and food, and gives off solid and liquid wastes.

The analysis procedure provides the capability of analyzing the fact that wastes generated by one system could become part of the feedstock for other systems. The details of the material and energy balance are given for two possible configurations of the energy-urban-agro-waste complex. In one configuration, the heat rejected from a power plant is utilized by an evaporative pad greenhouse agricultural system as well as for thermal maintenance of sludge digesters. The products from waste processing are returned back to the power plant as an energy source.

Other by-products such as CO_2 from digestion are utilized for agro enhancement. Agricultural wastes are also recycled as an energy source. The other configuration, which was investigated involves the use of waste heat in the production of algae for animal feed as well as deriving other products from the cellulosic content of the waste stream.

INTRODUCTION

The needs of a community to provide important services in light of dwindling supplies of energy, raw materials and land have motivated the study of the elemental relationships within an energy-urban-agro-waste complex. The underlying approach used in this study consists of simulating the integration of a community with its electric generating stations, its liquid and solid waste treatment plants, and its food production facilities such that the outputs from a given plant are in a form that can be readily used by the community or by other plants. Traditionally, the various demands of the community have been serviced by separate and often competing facilities. For example, energy is typically supplied by a power plant which utilizes virgin natural resources and discharges its waste heat in a manner which burdens the environment. Similarly, waste treatment systems have often relied on land disposal which requires certain energy inputs and produces no net useable products even though the entering material stream has a certain hierarchy of values. Agricultural systems required to meet the food requirements of humans and animals are often separated from the community and require their own energy inputs.

A characterization of the energy and food requirement, in terms of protein, as well as liquid and solid waste generation levels and the potential energy content recoverable from these wastes are shown in Table I as a function of residential population. An analysis of the information contained in Table I indicates that a population size of 500,000 will require energy and waste treatment facilities of a typically produced capacity consistent with good economies of scale. For example, the size of the power plant required is on the order of 1000 MW, while 1125 TPD and 50 MGD solid and liquid waste treatment facilities would be needed. Further, the potential energy which could be extracted from the solid and liquid wastes in the form of refuse derived fuel (RDF) and methane would account for about 8.1% of the energy requirements of the power plant. Protein requirements on the order of 38.5 TPD would also be required.

Depending upon the nature, needs, and geographical location of the community or population center, a variety of configurations of an energy-agro-waste complex are possible. Two basic systems of a general nature were selected for modeling. Each system shown schematically in Figure 1 and 2 contains a conventional power plant, sewage treatment facility and a refuse processing facility capable of recycling solid waste into materials and energy. The heat rejected from the power plant is subjected to various dispersal systems such as wet and dry cooling towers and spray and cooling ponds as well as useful aspect system involving biological process such as agriculture, anaerobic digestion, algae production, and aquaculture. The latter were selected not only because they offer flexibility in system planning but more importantly, because of their compatibility with the temperature of condenser cooling water typically discharged from power plants.

SYSTEM COMPONENT MODELS

A description of the models used to characterize the elements of the energy-agro-waste complex follow:

Power Plant Model

This model, developed by Olszewski [1], utilizes a value for the condenser effectiveness to obtain the turbine exhaust pressure. Pressure and heat rate are then used to calculate the power production, from which a generator efficiency is obtained followed by the gross power plant output. With regard to the heat rejection system, this model requires only the total condenser flow rate and the temperature of the incoming cooling water.

Wet Cooling Tower Model

The design of this model was such that the same cooling characteristics would be obtained irrespective of flow rate. The underlying assumption was that a cooling tower can be designed and built to achieve a certain degree of heat rejection from a predetermined quantity of cooling water for a given set of climatic conditions. The design approach for the cooling tower was 14°F; and the design wet bulb temperature, 76°F.

Cooling Pond Models

The thermal performance and mass transfer, evaporation and drift, are computed with this model after specification of the pond size, circulating water flow rate, and ambient conditions of temperature, humidity, wind speed, and solar day and radiation. In the case of the spray pond, the overall pond spray nozzle efficiency must also be specified along with a relation for the drift characteristics as a function of wind speed. The energy balance relation consists of solar, convective, radiative, evaporative, and spray energy transfers and energy storage due to pond heat capacity. This relation together with the mass balance yields values of the pond temperature and inventory. The model can be used in either mode and also in an intermittent sense when the spray is turned on or off to accommodate the specification of maximum and minimum pond temperatures. The details of these models appear elsewhere [2,3,4,5] and are verified by experimental results.

Anaerobic Digester Model

In the thermal model for the anaerobic digester, the feed (at a known average temperature) is circulated through a heat exchanger, where it is heated by a portion of the hot effluent from the power plant. The temperature increase of the digester feed is calculated, using the heat exchanger effectiveness. Subsequently, the average gas production is calculated in terms of ft^3/lb. VS added based on the feed temperature and on data obtained in the previous digestion studies [6,7,8]. The number of digesters, their volumes, and feed flow rates must be known. Knowing these, the amount of condenser effluent diverted to the digesters may be varied, such as to maintain the digester contents at temperatures close to optimum.

Evaporative Pad Greenhouse

Agricultural production of food is considered in terms of the use of a modified-evaporative pad greenhouse as conceived by Beall and Samuels [9,10]. In essence, their system consists of a standard commercial greenhouse (with a double roof) equipped with fans and aspen fiber pads. Warm condenser cooling water is allowed to flow through the pad. The condenser water is cooled as it passes through the pad, thereby controlling the temperature within the house. In this manner, the greenhouse is used as a heat rejection system during both summer and winter operations. In the summer, the fans draw ambient air through the pads into the house. The air flows through the growing section and is finally forced back to the outside. In this mode the greenhouse functions in a manner similar to that of a wet cooling tower. In the winter, the louvers for allowing ambient air to enter and leave the house are closed. The house then acts as a closed system, and air is circulated through the space between the ceiling and the roof (attic). During winter operation, water condenses in the attic. The condensed water is collected and recirculated, thereby minimizing make-up water requirements.

A thermal model considers the details of the heat and mass transfer within the pad as well as the house [11,12]. By inputting the meteorological conditions, air and water pad flow rates and pad water inlet temperature, the ambient conditions within the house can be predicted as a function of time. This greenhouse model has been verified with actual operating data [11,12]. The house configuration used here consisted of a floor area of 50 x 100 ft, heights of 8 ft and 14 ft in the growing section and overall respectively, and a pad volume of 66 ft^3.

Waste Treatment Systems

The models for material and energy recovery were developed from fundamental investigations conducted at both the 5 TPH refuse processing facility located at the University and also at large scale commercial installations. The details of how the solid waste stream can be processed into heavy and light fractions resulting from shredding and air classification have been previously presented [13,14]. Basically, ferrous, aluminum and glass can be recovered from the heavy fraction while mixed paper waste, fibre, or refuse derived fuel in a fluff or densified form (RDF or dRDF) can be obtained from the light fraction. Certain materials such as putrecibles and other light fraction rejects of an organic nature can be used as feed stock for methane gas production via anaerobic digestion. The condition used for the treatment of liquid wastes via algae production are consistent with those given by Oswald [15], that is, average temperatures on the order of 68°F are needed. An optimum temperature of 85°F was selected for aquaculture systems.

NATURE OF SYSTEMS ANALYZED

The pathways for the flow of energy and materials within each of the two systems selected for analysis are diagrammed in Figures 1 and 2. Basic elements such as the power plant, refuse processing facility, and sewage treatment plant are common to both systems. The basic difference between the systems is in the manner in which the thermal effluents are handled; namely, in system 1, the primary mode of power plant reject heat dispersal is through some conventional cooling and the evaporative pad greenhouse while in system 2, ponds for aquaculture and algae, production are substituted for the agricultural complex. Specifically, the following pathways are delineated: a) the major avenues of energy flow which include, i) electrical energy production, ii) energy contained in thermal effluents which enters the so-called useful aspect systems, and iii) energy contained in the waste stream which is eventually utilized for primary electrical energy production; b) treatment of waste disposal encompassing the refuse processing and wastewater treatment facilities and agricultural wastes; c) materials recovery from the solid and liquid waste streams; d) food production; and e) other secondary flows such as the use of CO_2 produced in the digester gas for agricultural enhancement in the greenhouse, production of soil conditioners from digested sludges, etc.

In this particular study, emphasis was placed on the detailed consideration of the thermal dissipation and utilization aspects. The refuse processing facility and the wastewater treatment system were considered as being passive; that is, their quantative interaction in the previously described flow pathways is governed by the population size described in Table I. Calculations are performed on the basis of a diurnal cycle for both summer and winter operating conditions predicated on the requirement that the power plant is always able to meet the 1000 to 1100 MW requirement. After climatic conditions are selected, changes in water flow rate allocation to various elements within the system will ultimately be registered as affecting the power plant condenser temperature. The selection of the climatic conditions used in this study were influenced by the results of a previous feasibility study [16] which showed that agro systems of the type considered here were better suited to certain climatic, hence geographical, conditions than others. Consequently, the climatic conditions of Phoenix, Arizona, which also corresponds to a population size on the order of 500,000, were used in study of the two systems.

SIMULATION RESULTS

Systems 1 and 2 were studied under various conditions which are given in Tables II and III respectively.

System 1

System 1 was subjected to four cases which illustrated the effect of a) changing the condenser flow rate (cases I and II) and b) changing the flow rates to various sub-systems for constant condenser flow rate (cases III and IV). At the high condenser flow rate, the power production was essentially unaffected during summer and winter operation while at the lower flow rate a slight drop, from 1108 MW to 1089 MW, occurred as a result of seasonal operation. As shown in Figs. 3 and 4, the condenser cooling water temperature difference increased from 17.5°F to 26.5°F with decreased condenser flow.

Ten digesters having a 30 ft height, 100 ft diameter, 737 GPM sludge flow rate, and a 9000 GPM heating water flow rate were used in the models. Sludge was considered to enter at a constant temperature of 55° in the winter and 65°F in the summer. Using an exchanger effectiveness of 0.9, digester temperatures of 96°F and 73°F could be maintained a high condenser flow rate during summer and winter operation respectively. The relative gas production at these temperatures were 0.55×10^7 and 0.30×10^7 ft^3/day. Reducing the condenser flow rate caused the average digester temperature to increase to 104°F and 81°F for summer and winter operation respectively with corresponding gas productions of 0.46×10^7 and 0.40×10^7 ft^3/day. The temperature difference of the circulating flow through the digesters is shown in Figs. 3 and 4 on a diurnal basis for summer and winter operation respectively. It should be noted that only about 1% of the total condenser flow rate would be required to maintain the digesters at or near optimum temperature levels.

Reducing the flow rate to the evaporative pad greenhouses from 450,000 GPM to 300,000 GPM caused the number of houses in the complex to be reduced from 3,750 to 2,500 consistent with a 90 GPM individual house flow rate. When the total condenser flow rate is decreased, the temperature of the water entering a greenhouse pad increases by about 8°F for both summer and winter operation under the conditions stated above. The temperature of the heated condenser effluent entering and exiting the pads is plotted in Fig. 3. As it is shown in Fig. 3, during the summer the inlet temperature fluctuated between 95°F and 101°F while the outlet temperature varied between 65°F and 77°F. The inlet and outlet temperatures for winter operation are plotted in Fig. 4. The results show that the temperature of the condenser water entering the pads fluctuated between 72°F and 78°F. The temperature of the water exiting the pad decreased from 2 to 4 degrees. The temperature to note that during the winter, some ambient air must be allowed in the house in order to reduce the relative humidity. The corresponding mass evaporation rate changed from an average of about 1250 lb/hr to 1600 lb/hr in the summer and from about 50 lb/hr to 100 lb/hr during the winter.

For cases I and II the pond thermal performance did not change considerably as it is shown in Figs. 3 and 4. During summer operation, the average temperature discharged from the pond was about 75.4°F and 73.7°F for the high and low condenser flow rates while the temperature remained nearly constant at 51°F during winter operation. Evaporation and drift losses were on the order of 0.54×10^7 lb/hr and 0.36×10^7 lb/hr for summer and winter conditions respectively and did not change appreciably under the range of flow rate variation considered here.

In cases III and IV the flow rates to the various sub-systems were changed for a constant condenser flow rate of 900,000 GPM. The average power output remains essentially constant. Since the digester flow rate remained at 9000 GPM, the digester temperatures were similar to those previously given; specifically, temperatures of 97.6°F and 74.8°F were obtained in case III and 95.3°F and 71.1°F in case IV for summer and winter conditions respectively.

Evaluation of the greenhouses indicates that the average temperature drop from 102°F to 100°F occurs when the total flow to the complex was reduced during summer conditions. During winter operation, the temperature of the incoming water to the pad in case III was about 4°F higher than that in case IV; consequently, the average temperature leaving the pad was 74.4°F and 70.7°F for the two cases respectively.

The spray pond behaved similar to that previously described. Pond temperature around 78°F occurred for cases III and IV during summer and about 71.5°F for both cases during winter. Water loss proportional to those previously given occurred.

System 2

A description of the combination of conditions investigated for system 2 are given in Table III. In this system configuration all the ponds are operated as cooling ponds. Since one set of ponds was used for aquaculture and the other for algae production, it was important to ascertain the conditions of temperature stability for both summer and winter operation which can be achieved by seasonally varying the flow rates to each subsystem.

When the system is operated under the conditions of case V, the average power production is about 1100 MW and the average sludge temperatures in the digesters are about 101°F and 78°F for summer and winter operation respectively as demonstrated in Figs. 5 and 6. Average summer and winter temperatures of 83°F and 67°F occurred in the algae pond at the 100,000 GPM flow rate; diurnal temperature changes for both summer and winter are plotted in Figs. 5 and 6. The elevated summer temperature produced evaporation rates of about 0.83×10^6 to 0.18×10^7 lb/hr. As shown in Figs. 5 and 6, the average temperature of the aquaculture ponds for summer and winter was about 85°F and 68°F.

After these results were obtained, the remaining two cases were concerned with varying the subsystem flow rates in order to achieve constant seasonal temperature. Under these conditions, a wet cooling tower large enough to accommodate peak flow rates would be necessary. Reducing the flow rate to the aquaculture pond to 20,000 GPM only reduced the summer pond temperature to about 78°F; approximately 10°F higher than optimum. At the 100,000 GPM flow rate, thermal conditions near optimum are maintained during winter. In general, flow rates to the aquaculture pond on the order of 150,000 to 200,000 would be sufficient to keep the pond at near optimum temperature levels during summer whereas flow rates of about 600,000 GPM would be required for winter operation.

It should be noted that because of the fact that certain subsystems did not experience large temperature changes, diurnal temperature variations were given for cases I and V only. A more detailed description of the results obtained for all the cases studied can be found in Reference 17.

CONCLUDING REMARKS

Although this study is only an initial step, the results indicate that a combination of ponds, evaporative pad greenhouses, digesters and cooling towers can provide sufficient cooling for a 1000 MW power plant without large losses in power production. However, safety reasons and land requirements make it necessary to keep a cooling tower in the system. The data show that anaerobic digesters are not effective as heat rejection systems, since it would require only about 1% of the total cooling water flow from a complex to maintain the digesters at an optimum temperature level.

These results also indicate that the energy rejected in the cooling water of an electric generating station can be used to maintain optimal thermal environments for various biological processes such as algae production, agriculture, aquaculture, and anaerobic digestion. The feasibility of maintaining these processes in their thermal "optimal" zone is demonstrated. Further, the effect of fluctuations in ambient conditions can be reduced simply by varying the amount of cooling water diverted to each sub-system.

By using the global approach, the efficiency of energy and material utilization can be maximized while reducing detrimental ecological effects. Complete utilization of the models requires the consideration of the dynamics of all system elements along with economic considerations.

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LIST OF TABLES

TABLE I

ENERGY AND PROTEIN REQUIREMENTS AND LIQUID AND SOLID WASTE GENERATION FOR VARIOUS POPULATIONS

Population	Total(1) TPD	Organic Fraction(2) TPD	Sewage(3) MGD	Sludge(4) TPD Dry	Sludge(4) TPD Wet	Average(5) Daily Electrical Energy Requirements $\frac{\text{BTU}}{\text{day}}\times10^9$	Fossil(6) Fuel Requirements For Power Plant $\frac{\text{BTU}}{\text{day}}\times10^9$	Waste Heat From Power Plant $\frac{\text{BTU}}{\text{day}}\times10^9$	Energy(7) Recoverable From Solid Wastes $\frac{\text{BTU}}{\text{day}}\times10^9$	Protein(8) Requirement Tons/day
50,000	112.5	22.5	5	5.9	146.3	3.51	10.63	7.12	0.863	3.85
100,000	225.0	45.0	10	11.7	292.5	7.01	21.25	14.24	1.727	7.70
150,000	337.5	67.5	15	17.6	438.8	10.52	31.88	21.36	2.591	11.55
200,000	450,0	90.0	20	23.4	585.0	14.03	42.50	28.47	3.455	15.4
250,000	562.5	112.5	25	29.3	731.3	17.53	53.13	35.60	4.319	19.25
300,000	675.0	135.0	30	35.1	877.5	21.04	67.75	42.71	5.183	23.1
400,000	900.0	180.0	40	46.8	1,170.0	28.05	85.00	56.95	6.91	30.8
500,000	1,125.0	225.0	50	58.5	1,462.5	35.07	106.26	71.19	8.638	38.5
600,000	1,350.0	270.0	60	70.2	1,755.0	42.08	127.51	85.43	10.366	46.20
800,000	1,800.0	360.0	80	93.6	2,340.0	56.10	170.01	113.91	13.821	61.6
1,000,000	2,250.0	450.0	100	117.0	2,925.0	70.13	212.52	142.39	17.277	77.0

(1) 4.5 lbs/capita-day
(2) Segregated at processing plant
(3) 100 gal./capita-day
(4) 2340 lbs. of dry solids/10^6 gals (primary and activated)
(5) Based on 70,130 BTU/day
(6) Assuming a thermal efficiency of 33%
(7) RDF at 6700 BTU/lb and CH_4 at 1000 BTU/ft^3
(8) Based on recommended daily allowance of 0.154 lb/capita

Case No.	I	II	III	IV
Condenser Flow Rate (GPM)	900,000	600,000	900,000	900,000
Wet Cooling Tower Flow Rate (GPM)	450,000	300,000	600,000	300,000
Digesters Flow Rate (GPM)	9,000	9,000	9,000	9,000
Greenhouses Flow Rate (GPM)	337,500	225,000	225,000	180,000
No. of Greenhouses	3,750	2,500	2,500	2,000
Spray Pond Flow Rate (GPM)	450,000	300,000	300,000	600,000
Pond Area (Acres)	1,020	1,020	1,020	1,020

TABLE II

Cases Analyzed for System 1

Case No.						
Season	Summer	Winter	Summer	Winter	Summer	Winter
Condenser Flow Rate (GPM)	900,000	900,000	900,000	900,000	900,000	900,000
Wet Cooling Tower Flow Rate (GPM)	600,000	600,000	650,000	400,000	730,000	200,000
Spray Pond Flow Rate (used as cooling pond) (GPM)	200,000	200,000	200,000	400,000	150,000	600,000
Spray Pond Area (Acres)	150	150	150	150	150	150
Digesters Flow Rate (GPM)	8,000	8,000	8,000	8,000	8,000	8,000
Cooling Pond Flow Rate (GPM)	100,000	100,000	50,000	100,000	20,000	100,000
Cooling Pond Area (Acres)	150	150	150	150	150	150

TABLE III Cases Analyzed for System 2

LIST OF FIGURES

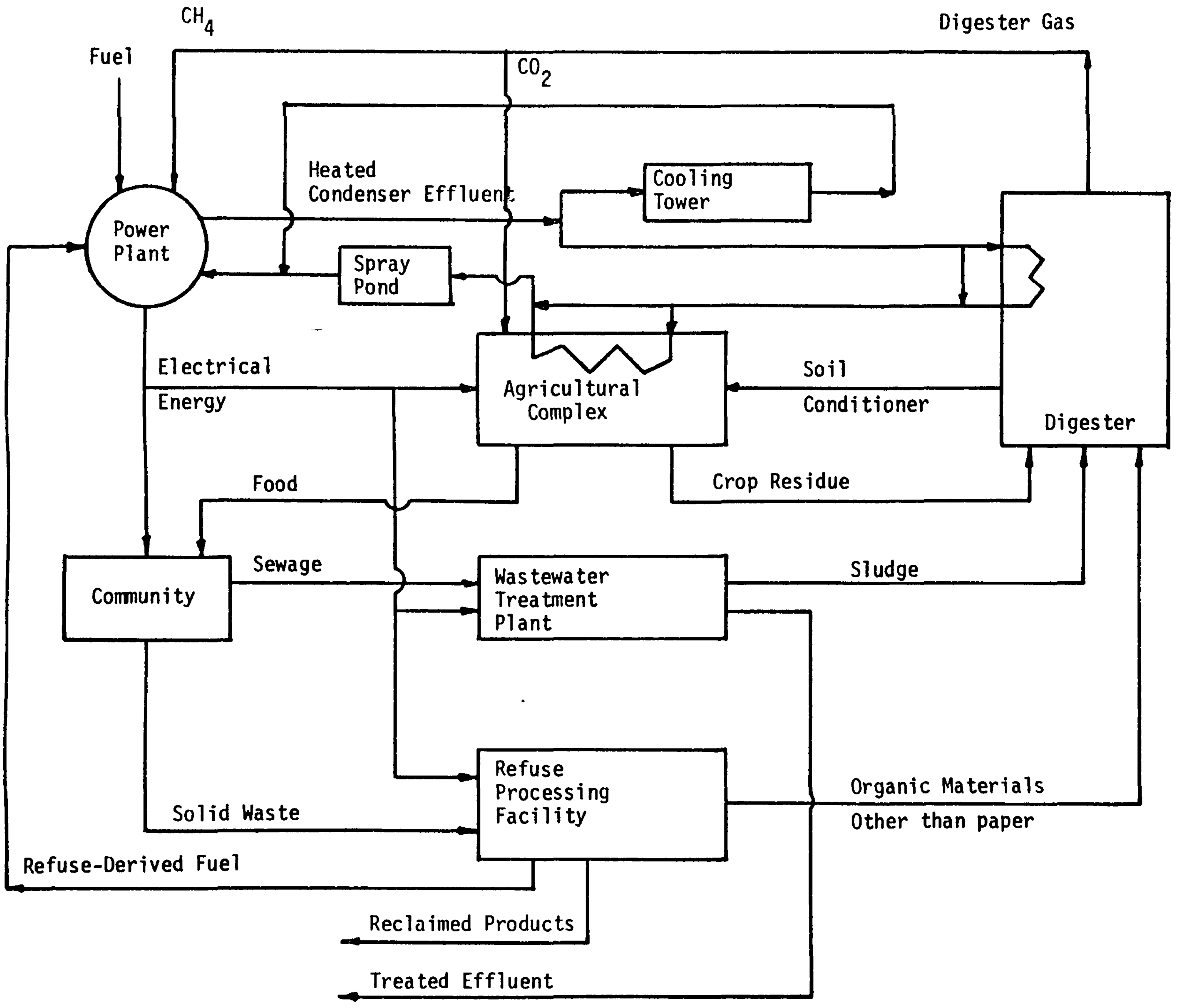

Fig. 1   Schematic Diagram of System 1

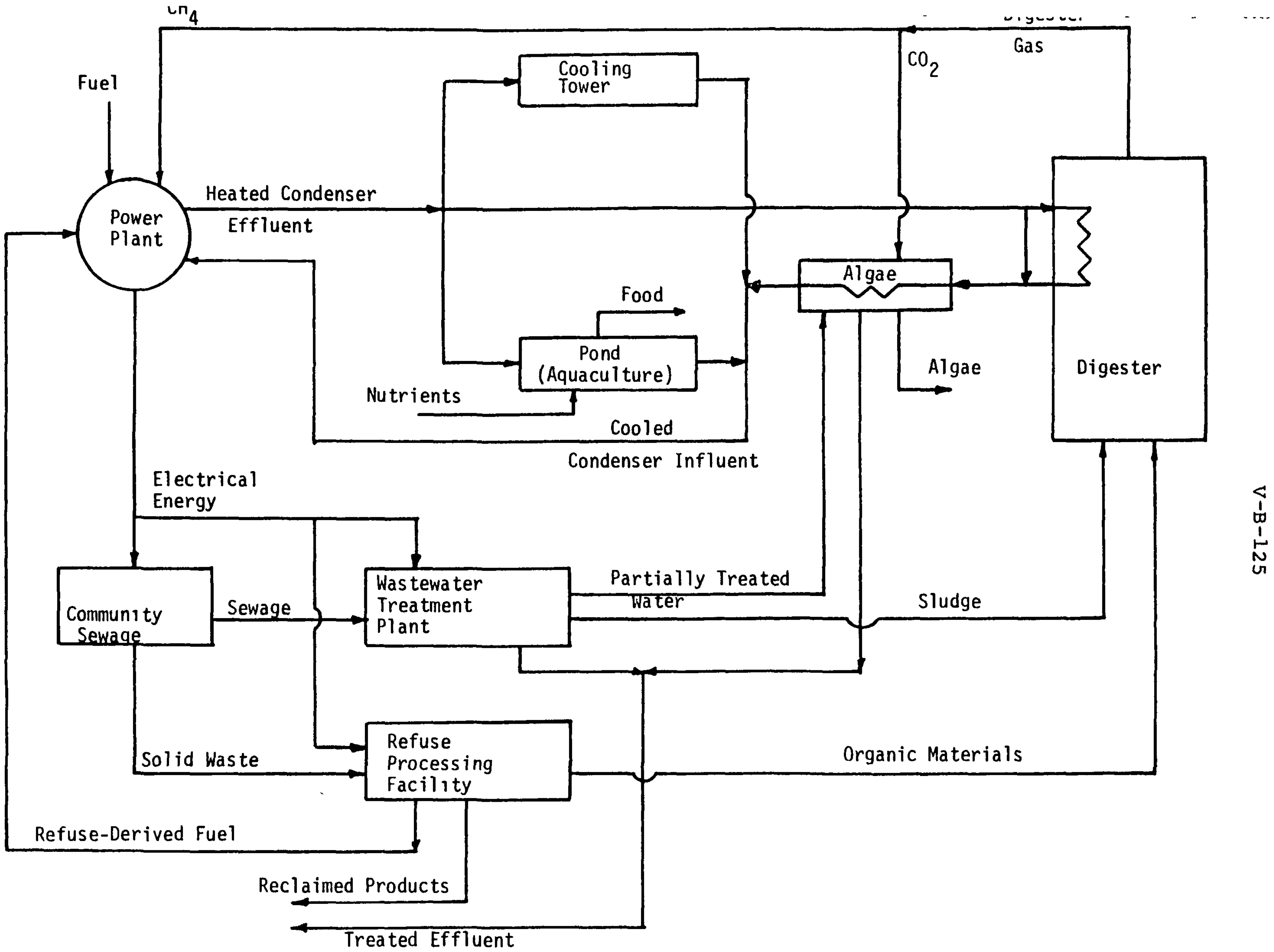

Fig. 2 Schematic Diagram of System 2

Fig. 3 Circulating Water Temperatures in the Subsystems of System 1 under the Conditions of Case I - Summer Operation

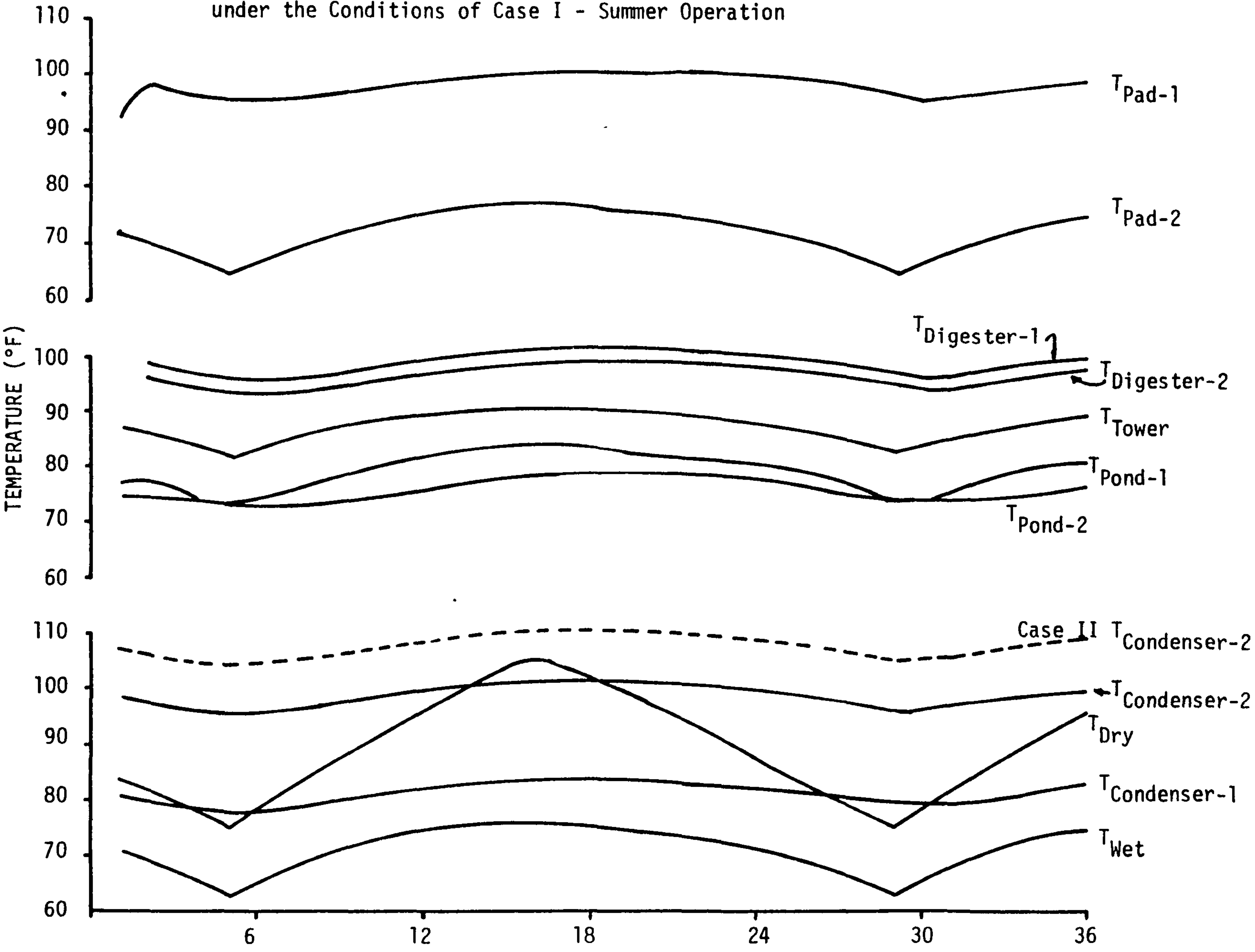

Fig. 4 Circulating Water Temperatures in the Subsystems of System 1 under the Conditions of Case I - Winter Operation

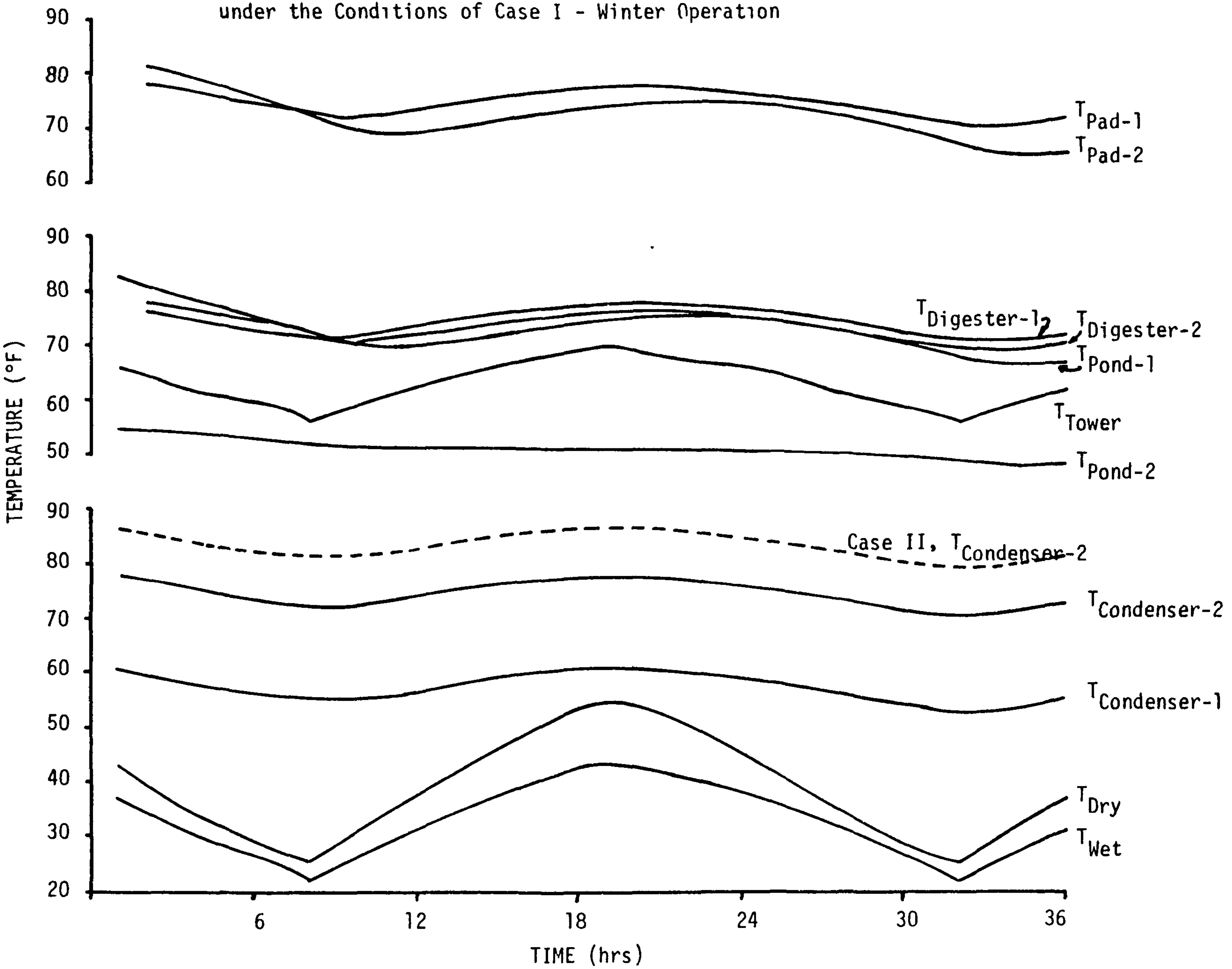

Fig. 5 Circulating Water Temperatures in the Subsystems of System 2 under the Conditions of Case V - Summer Operation

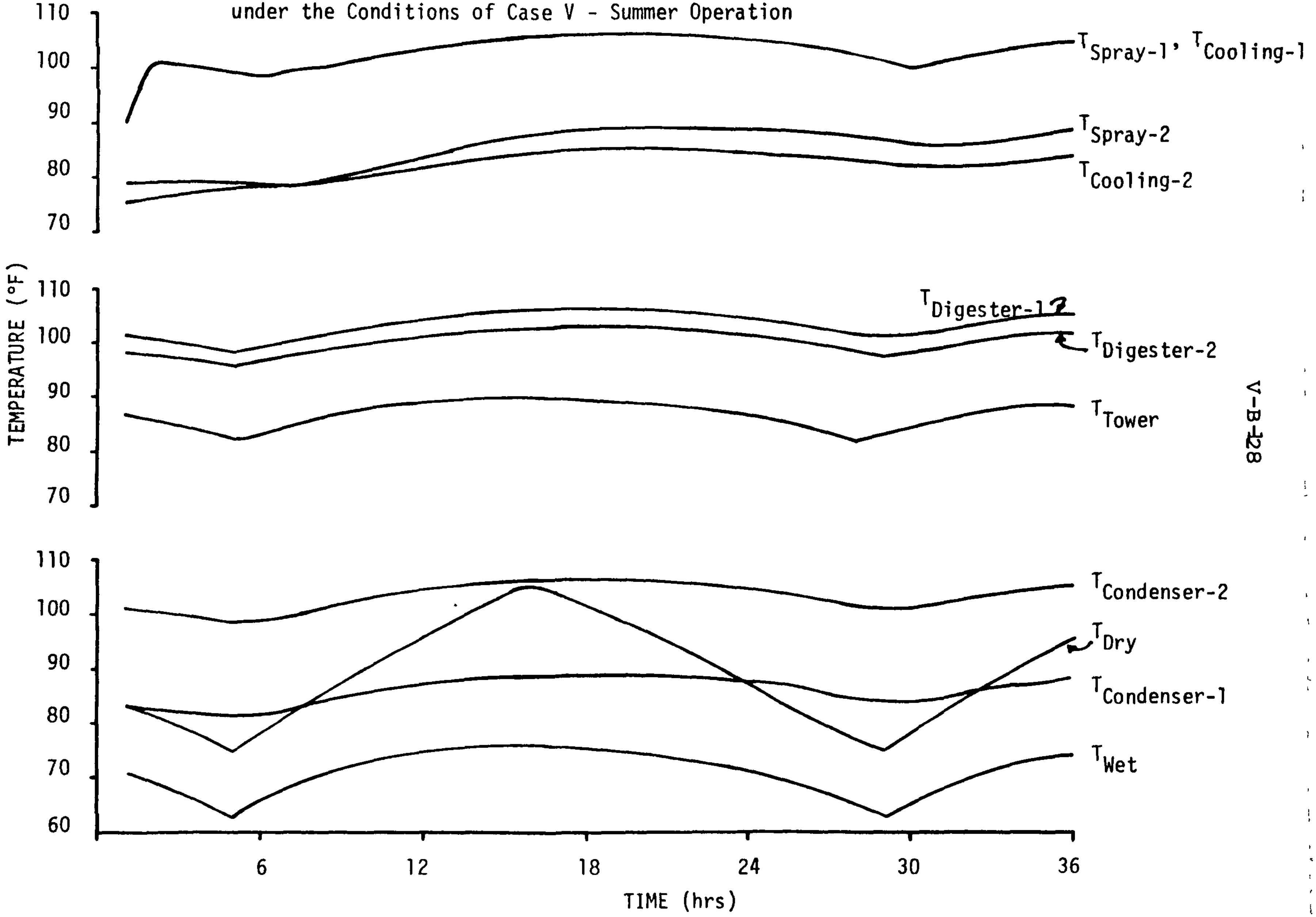

Fig. 6 Circulating Water Temperatures in the Subsystems of System 2 under the Conditions of Case V - Winter Operation