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FINAL REPORT

USES OF WARMED WATER IN AGRICULTURE

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INTRODUCTION

Increasing demands for electrical power impose stresses on our national resources. Additional energy sources must be tapped; sites for additional power plants must be selected; and additional resources of cooling water must be identified. These problems could be reduced by increasing overall efficiency of energy utilization. Large quantities of energy currently rejected in cooling water by power plants are a financial burden, an environmental hazard, an inefficiency in energy utilization, and in many cases, a heavy consumer of precious water supplies.

This project was an attempt to identify potential uses in agriculture* for direct application of warm water such as the effluent from a power plant and establish conditions for matching uses to sources. If uses can be identified which can practically and economically utilize the warmed water effluent, several benefits may be realized. Chemical and biological activity frequently accelerate at elevated temperatures; thus agricultural productivity may be increased with the utilization of warmed water. Because many agricultural processes currently utilize water in the same temperature regime as power plant effluent, it may be possible to conserve energy by utilizing the power plant effluent, either directly or through heat exchangers. Possibil-

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*Agriculture is interpreted in broad terms to include animal and plant production in open fields and enclosures, aquaculture, and processing of food products.

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ities for multiple land use may be realized by a combination of agricultural enterprises with electrical energy production. Perhaps most importantly, however, direct utilization of power plant effluent by agriculture--also a large consumer of water--may result in substantial savings in water through multiple use.

Extensive attention has been devoted to the problem of utilization of waste heat from power plants. Research projects in many different locations have studied technical feasibility of various potential uses through theoretical model study, laboratory experiments, and demonstration projects. Combinations of uses into integrated systems have been modeled and studied with regard to economic feasibility. Stiles (1975), speaking on future developments in waste heat utilization at a national workshop, concludes "there has been a considerable amount of work done on a relatively small scale which has been useful and productive, but there still remains a big gap between what use has been made so far of heated water and the total waste heat output of even a single 1000 MWe plant. I believe that we have reached the point in time when we should sit down and review where we have been, where we are, and where we are going." In the same spirit, a study of the literature on uses of warmed water, conducted in the course of this project, prompted a re-analysis of the problem.

SOURCES OF WARMED WATER

Energy in the form of warmed water is available from several sources. Studies concerned with the utilization of warmed water have directed their attention to the condenser cooling water from fossil fuel or nuclear electric power generating facilities. Geothermal power plants are another potential source of warmed water. They could produce warmed water from: (1) the condenser cooling system, (2) secondary heat exchangers used to extract heat from spent geothermal fluids, and (3) steam condensate. Geothermal energy may also be obtained by direct tap of low temperature geothermal water resources. Spent steam and cooling water from industrial processes is another source of energy in the form of warmed water.

CHARACTERISTICS OF SOURCES

Volume of warmed water available

The volume of warmed water effluent from a power plant depends upon its output and on the thermal efficiency of power generation. Fig. 1 shows the relationship between waste heat and plant output for several different efficiencies. Fossil fuel and nuclear plants are in the range of 1000 MWe and operate at efficiencies between 30-35%. Geothermal plants would operate at around 10%, depending on resource temperature. The waste heat output corresponding to efficiencies of 30-35% would be about 2000 megawatts (7 billion Btu per hour). Increases in efficiency to 60% are possible in the future through the use of a high temperature reactor heat source and a gas turbine topping unit combined with a Rankine steam-type base unit (Brown, 1975). Such increases in efficiency would reduce the energy rejected by a power plant to about 700 megawatts (2.4 billion Btu per hour), but the resulting quantity is still large. Energy parks with capacities of 4,000, 12,000 and 26,000 MWe have been suggested. The quantities of warmed water which would result from such installations stagger the imagination. A portion of the rejected heat in fossil fuel plants is dissipated through the stack; however about 85% goes into the condenser cooling water. In nuclear plants, about 95% goes into the cooling water (Gillham, 1974).

The rate at which water would be evaporated in consumptive use cooling to dissipate the waste heat is shown in Fig. 2. Also shown in Fig. 2 is the condenser flow-rate required to dissipate waste heat through incremental increases in cooling water temperature. Considering a power plant producing 1000 MWe with 2000 MW waste heat, the flow rate to replace evaporative cooling losses would be up to 0.8 M^3/sec (approximately 13,000 gpm or 20,000 acre-feet/year). For once-through cooling by a 10°C (18°F) incremental increase in cooling water temperature, the condenser flow rate would be 46 M^3/sec (approximately 750,000 gpm or 1,200,000 acre-feet/year).

An important consideration related to the volume of warm water effluent from power plants is the variability of flow rates. Variations can occur due to daily cycles in power generation, annual cycles, and long-term variations in the load assigned to a particular power plant. New, efficient plants are frequently used as base generating facilities with high load factors, whereas older, less efficient facilities are used to supply peak load power and as standby facilities. In addition to these cyclic and long-term variations in warmed water effluent, complete interruptions in flow can occur as the result of planned maintenance or unplanned equipment failures. Facilities with multiple sources of warmed water (e.g., multiple generator plants) obviously reduce the probability of total interruption of flow.

Temperature regime

Condenser cooling water effluent from electric power plants varies widely in temperature depending on plant location, season of the year, type of cooling system, and water flow rate. To increase electric generating efficiencies, the cooling water temperature should be as low as possible. Generally effluent temperatures range from 25 to 40°C (approximately 80-100°F). In mid-summer, some locations may produce warmed water effluent with temperatures as high as 50°C (approximately 120°F). DeWalle et al. (1974), considering the effects of varying input temperature of condenser cooling water in a system to optimize power generation efficiency with a system for land disposal of waste heat, show that under some specific conditions, a fuel penalty cost for operating at reduced efficiencies but with increased effluent temperatures, can be offset by reduction in costs associated with the cooling system. Conceivably, these fuel penalty costs could also be offset if effluent of higher temperature were valuable as an energy resource.

The use of condenser cooling water from geothermal power facilities would be comparable to other power plants. However, there is considerable attention being given to the possibilities of utilizing hot waters from goethermal sources directly. A report edited by Howard (1975) explored uses for water ranging from 50-160°C (approximately 120-320°F).

During load valleys, high energy steam could be made available from properly designed electric power plants to augment reductions in warm water flow or to provide a more valuable high temperature flow.

Water quality

According to the California Department of Water Resources, about 90% of California's thermal power plants use once-through cooling with saline or brackish water (Roberts and Hagan, 1975). Rochow and Hall (1975) point out that, through various treatments to the condenser, chemical impurities and solids accumulate in the cooling water. These include chlorine and chemicals to inhibit corrosion. Such waters would not be suitable for direct use for most agricultural operations. There is also some concern that the direct use of cooling water from nuclear power plants could result in some buildup of radionuclides in foods. Boersma (1975) concludes that it would generally not be desirable for condenser cooling water to mix directly with a biological system. Still, there have been numerous examples of systems in which cooling water is used directly. Whether or not it can be depends both on the quality of the effluent and the tolerance of the use. Even if the water quality is objectionable, it may be possible to devise heat exchangers to extract useful heat from the water for agricultural uses.

CLASSIFICATION OF USES

The discussion in this section is intended to bring into perspective the general attributes of uses of warmed water which may help to classify them and to aid in identifying those uses compatible with a particular source of warmed water. Specific agricultural uses will be discussed in later sections.

Degree of need for warmed water

Some uses have a current need for warm water in the temperature regime that can be obtained as effluent from other processes. For those applications currently producing and using warm water, the value of a warmed water supply can be determined. Other applications currently using cold water could use warmed water and derive some small benefit, but the economic value of the warmed water may be too small to consider or too intangible to determine. Still other applications can tolerate warmed water with no detrimental effects, but with no benefit.

Volume of warm water needed

Brown (1975) classifies reject heat-utilization systems into "those systems which attempt to utilize a major fraction of the reject heat output from a five hundred to 1,000 MWe plant and those whose goal is to produce an economically feasible product, but not to utilize any significant fraction of the reject heat output." His statement implies two different classification schemes. One scheme would separate systems on the basis of quantity of warmed water required into large and small users.

Primary objective to use warmed water

Another classification scheme implied by Brown's statement would separate those uses having the primary objective of reject heat dissipation from those uses having a primary objective of economical production of a product. The former group is considered an alternative method of disposing of the heat in warmed water. Any other benefits derived from that operation are secondary. This does not imply that those benefits are unimportant, but the system is operated with the objective of heat dissipation predominant. The latter group of uses has the primary objective of production with heat rejection as an secondary benefit. The primary objective of the system utilizing warmed water is extremely important regardless of whether that system is a large or small user in terms of the quantity of warmed water.

Consumptive use of water

Some processes consume large quantities of water; other processes pass most of the water through the system with minimal consumptive use. It is important to identify changes in the amount of consumptive use that would result from use of warmed water in a particular process. In general, evaporative losses from open water surfaces will increase as the temperature of the water increases.

Temperature of water needed

The temperature regime appropriate for a process using warmed water is perhaps the most important criteria. An optimal temperature range should be identified along with maximum and minimum permissible values and, where important, a maximum rate of change in water temperature. There may also be time-temperature relationships that are of importance. Such information will be helpful in evaluating the potential impact of changes in the temperature of the warmed water supply.

Timing of need

Information on daily and seasonal demand cycles for warmed water is essential in determining peak demand, in identifying compatible uses with dovetailing demand cycles, and in identifying points in time where the supply of warmed water may be interrupted for routine maintenance.

Cyclic fluctuations may well occur not only in the volume of water needed, but also in the degree of need, the temperature required and the consumptive use.

Quality of water needed

The quality characteristics of water which are important differ between processes. Where water is being used to irrigate plants, the concentration and proportion of sodium present as soluable salts is of primary importance. This attribute is expressed either in terms of parts per million of soluble salts or specific electrical conductivity, millimhos. Presence of trace elements such as boran are also of concern. In aquaculture systems other trace elements such as copper become of concern along with a host of other parameters: pH, dissolved oxygen, ammonium and nitrate ion concentration, and biological and chemical oxygen demand. Suitable values for all of these parameters depend on the specific use. There is no uniquely "good" water quality.

Land resources needed

Because of problems of conveying warmed water from a source of supply to a potential use and the inevitable heat loss involved in the process. It is desirable that the use and source be located in close proximity to each other. This requirement may pose serious limitations on the quantity and quality of land and perhaps even on the air quality and aesthetic requirements adjacent to the source of supply.

Investment resources needed

The amount of capital expenditure needed to develop a use of warmed water in proximity to a warmed water source, to move an existing enterprise, or to convey the warmed water resource, is important. In the case of developing new enterprises, market sensitivity to changes in supply are particularly important. To a lesser extent, market sensitivity is also a proper consideration where utilization of warmed water will increase the production quantity of an existing enterprise or shift the production season.

Technical competence needed

Where consideration is being given to integration of various uses of warmed water into a complex system, it is important to consider differences in technical competence required for each of the component enterprises. The more differences in technical competence required, the more difficult will be the communication of needs and objectives. Optimization of a complex system requires a well identified overall objective and may require component enterprises to operate at sub-optimal levels.

AGRICULTURAL USES

Many agricultural processes perform best at temperatures in the same regime as the effluent from electric power plants. Several crops have been shown to respond to warming of the soil above natural temperatures and systems for using warmed water to heat the soil have been designed and evaluated by several researchers. The same crops and aquacultural animals that respond to warm water may experience little growth, and in some cases, detrimental effects when subjected to the lower temperatures of the magnitude desired for input to power plant condenser cooling systems. Furthermore, while most crops are reasonably tolerant to variations in temperature and special varieties can be selected for use in higher or lower temperature conditions, for any particular field small variations in the microclimate between adjacent rows or plants within a row can cause non-uniformities in growth rate which are undesirable and sometimes intolerable. Because of these requirements for uniform temperature within an agricultural enterprise, it is not likely that the effluent from such an enterprise would be of low enough temperature for immediate recycling to a power plant condenser, additional cooling would be required. Thus, while agricultural enterprises may derive some benefit from the use of warmed water, they are not likely to replace temperature dissipating devices.

The demand for warm water is variable for most agricultural enterprises, some applications are strictly seasonal. Others can conceivably dispose of the rejected heat in warmed water on a continuous basis; but the benefits derived from that warmed water may still be seasonal. Because of the competitive nature of agricultural enterprises, in general the effects of the market for any product of changing the level of production of that product places limitations on the size of an enterprise and hence on the quantity of warmed water that can be utilized. The investment and competition involved in agricultural systems generally precludes their operation solely for reject heat dissipation. They must be operated for economical production of a product.

While agricultural enterprises differ widely in the quality of water acceptable, they are in general sensitive to the quality of the water they use. Crops and varieties have evolved in areas where water conditions are appropriate. Some adjustments can be made to changes in water quality, but sudden changes would undoubtedly cause problems.

Water passing through agricultural and aquacultural systems will generally increase in salinity, in nitrate concentration, and in the amount of sedimentary and organic material in suspension. Such water may not be suitable for reuse in a condenser cooling system without treatment.

Agricultural enterprises have become increasingly specialized. The problems that are likely to occur with culture at elevated temperatures will undoubtedly call for additional expertise. Experiences in catfish culture, for example, have shown that the same conditions that are ideal for catfish growth also promote disease.

If warmed water becomes a resource input to an agricultural system, the agriculturist will demand a dependable supply because of biological sensitivity to large temperature changes that could result from interruption of the supply and because of the importance of timeliness in agricultural systems. It may be that the benefits from the use of warmed water occur only at specific stages in the biological process. There is some possibility that the use of warmed water in agriculture may permit an intensified operation on less land area and with less water consumption than is normally required for an economically viable enterprise. Because of the importance of suitable land and water to agriculture, conservation is very important.

In the following sections several potential agricultural uses for warmed water are discussed with reference to the classification characteristics identified in the previous section. This discussion is based largely on a review of the literature of previous studies; a definitive classification would require more detailed information, much of it specific to a given site.

Aquaculture

Considerable research is in progress to determine requirements for culture of various species. Extensive work has dealt with catfish, lobsters, and prawns. These three species will be discussed individually.

Catfish

Catfish need warm water. Optimum growth occurs at about 30°C (85°F), and growth effectively stops at temperatures below 15°C (59°F). The catfish industry has developed in southern regions where ponds remain above 21^{o}C (70^{o}F) for a period of at least 180 days (Grizzel, et al. 1969). The use of warmed water effluent could conceivably extend the region where catfish culture could be practiced, and perhaps lead to year-round production. If a culture operation were developed where thermal effluent was used to provide the appropriate temperatures, that culture system would have a strong but perhaps seasonal need for the warmed water. Catfish culture systems should be able to use or at least tolerate warmed water even during warm seasons, provided effluent temperature is not excessive. Growth rate of catfish drops off at temperatures above 34^{o}C (93^{o}F) and the upper lethal temperature is about 39^{o}C (102^{o}F).

Rapid temperature fluctuations can impose stress on fish. Catfish seem to be fairly hardy in this regard. Daily temperature cycles of 3 to 4^{o}C (37 to 39^{o}F) were reported in the Gallatin catfish project without adverse affects (Goss, et al. 1973). Tests to determine the lethal limiting temperature for fish frequently employ rates of change up to 1^{o}C per minute.

The quantity of warmed water required for catfish culture will not only depend on the scale of the operation but also on the type of culture used. In pond culture a water source of .0039 M^{3}/sec per hectare (25 gpm per acre) of pond surface is generally recommended. In the Gallatin project, raceways 1.2 M wide by 15.2 M long (four feet wide by 50 feet long) were supplied with warmed water at rates up to 0.0063 M^{3}/sec (100 gpm). Ten such raceways had a net annual production of 27,198 kg (81,000 lbs) under experimental conditions. Ponds stocked with 3,700 15-30 cm (6-8 in.) fingerlings per hectare (1,500 per acre) could expect a yield of about 1134 kg (2,500 lbs) during a 210 day growing season in unheated water. The production from one hectare (2.5 acre) of raceways using heated water would be equivalent to about 30 hectare (74 acres) from pond culture. A system large enough to make use of effluent from one 1000 MWe power plant would have a production output equivalent to 9,105 hectare (22,500 acres) of ponds--one third of the estimated catfish market in the U.S. of 1977. Catfish aquaculture is not likely to utilize major fractions of the warmed water effluent from power plants.

Water for catfish culture should be maintained with a dissolved oxygen content greater than 3.0 parts per million and with a pH of 6.5 to 8.5. Water hardness should be in the range from 20 to 200 ppm. Beasley and Allen (1974) characterized the effluent from commercial catfish ponds by measuring COD, BOD, total solids, total volatile solids, suspended solids, suspended volatile solids, total coliform, fecal coliform, ammonia nitrogen, nitrites as nitrogen, nitrates as nitrogen, and total phosphorous, in addition to pH; but they did not establish optimal or limiting values of these parameters. While catfish are generally considered a hardy species, water quality becomes increasingly important as stocking density increases.

Lobster

Lobster growth has been shown to be accelerated substantially in warmed water at a temperature of 22°C (72°F). Lobsters can reach a mature 0.45 kilogram (1 lb.) size in as little as two years, compared to six to eight years in the naturally cool ocean water. Van Olst and others (1976) have used warmed water effluent from a power plant as culture water for experiments with lobster. Several other researchers have also investigated the problems of lobster culture (Conklin, 1976), but no active industry has been developed.

The quantity of warmed water required by a commercial lobster culture facility will depend on the amount of treatment and recirculation employed. There is some indication that the likelihood of disease causing pathogens will require water treatment and hence encourage recirculation.

Krage (1975) hypothesized a lobster facility capable of producing one million lobster per year. Criteria for the design of such a facility is still the subject of investigation; however, at the present stage of technology, it could only be an expansion of the facilities that have been used to culture laboratory animals. Researchers at the University of California Bodega Marine Lab have used trays measuring 122 x 244 cm (48 x 96 in.) with compartments 10, 20, and 30 cm (4, 8, and 12 in.) square. In the anticipated commercial system, animals would spend 300 days in each size compartment, reaching marketable weight in 900 days. Flow rates of 0.000252 M^3/sec (4 gpm) have been supplied to each tray. A commercial system to produce one million lobsters annually would require total water flow on the order of 15.77 M^3/sec (250,000 gpm). It is likely that new technology will result in lower water flow requirements before commercialization takes place.

Optimal temperature for lobster production is $22^{o}C$ ($72^{o}F$) and a commercial system would require a constant year-round flow. A lobster culture facility would need to be located close to a warm water source to minimize temperature loss in the water and to reduce pumping costs. While land quality would not be critical, the terrain should be reasonably level. A system making use of trays spread out in a single layer would require on the order of 100 acres of land. Systems are being studied which would reduce the land requirement by stacking the trays or using three dimensional arrays in deep tanks. Investment in a lobster facility would be relatively large. Consumer acceptance for the product is good; hence, market sensitivity should not be severe if costs can be kept competitive with those for lobsters caught in the wild. Technology for producing lobsters is not fully developed, but it is highly specialized.

Prawns

Yates (1977) has developed a scenario for prawn aquaculture which appears to be feasible in the central valley of California. It assumes that year-round brood stock maintenance, larval culture from mid October to mid January, and juvenile grow-up from December through mid May will take place in enclosed areas with controlled water temperature. Large juveniles would then be planted in outdoor ponds for grow-out from mid May through mid October. Temperature tolerance from prawn juveniles ranges from 14 to $35^{o}C$ (37 to $95^{o}F$) with optimal growth demonstrated between 28 and $31^{o}C$. Based on experiences in Hawaii, production from ponds of 111,200 N (2,500 lbs/

acre) can be anticipated, thus a 4,448,000 N (1,000,000 lbs) per year operation would require 162 hectare (400 acres) of ponds. An additional 40.5 hectares (100 acres) would probably be required for brood stock and larval culture and associated facilities. Ponds would require relatively flat areas with soil having a high clay content to facilitate sealing of the bottoms. A production facility of that type would require water flow on the order of 0.50 M^3/sec (8,000 gpm).

Larval culture requires brackish water with salinity on the order of 12 to 15 parts per thousand. Once the young reach the post larval stage, they are transferred to fresh water ponds. pH should be maintained at about 7.8, dissolved oxygen greater than four parts per million and NO_2 less than one milligram per liter.

Technology for rearing prawns is still under development (Knight, 1976). It appears that a system combining juvenile grow-up in intensive systems with pond grow-out should have moderate investment requirements. Market acceptance for prawns is good; the market should not be unduly sensitive to introduction of new culture facilities. Large quantities of prawns and shrimp are imported into this country and supplies from the wild are diminishing.

Irrigation

Rice

About 202,000 hectares (500,000 acres) of rice are grown in California, predominately in the Sacramental valley, using irrigation water from the Sacramento River. River water temperature is 10 and 18°C (50 and 65°F). A temperature of about 21°C (70°F) is the lowest that present varieties can endure without showing damage or seriously delayed maturity (Raney, et al., 1957). Lost stand due to low water temperature has been estimated at approximately 5% of the cultivated area. Furthermore, low water temperature tends to slow growth and delay harvest which can result in additional losses at harvest time. It appears that water to be used for rice irrigation can be used for power plant cooling before delivery to the farm with substantial advantage to the farming operation. There would, of course, be some additional evaporation loss because of increased temperatures of the water in distribution cannels.

Rice production requires application on the order of 150 to 210 cm (5 to 7 ft.) of water during the period from April through September with the largest amount required in April to flood the rice fields.

Use of warmed water for rice irrigation would require minimal changes in present practices.

Other Crops

While the need for warmed water for irrigation is not well established for other crops, experiences in desert regions such as the Imperial Valley where irrigation water temperatures are normally high, suggest that many crops could utilize warmed water with no adverse effects. Thus, it appears that warmed water effluent from power plants could still be used for normal irrigation water, provided the water is not contaminated in the power plant (Thompson, et al., 1975).

Soil warming

Several researchers have attempted to transfer heat from warmed water into the soil via underground piping networks (Berry and Miller, 1974; Decker, 1975; Sanders and Skaggs, 1975). Major advantages of soil warming are extending the cropping season into the early spring and late fall. This may permit multiple cropping and it may permit harvest at a time when market demand is high.

Some of the studies of the effects of soil warming on plant growth have been accomplished by using electrical heating cables to simulate warmed water pipes. This is unfortunate, because electric heating cables do not simulate heat transfer from warmed water pipes accurately unless flow rates in the water pipes are so high that temperature loss along the pipe is negligible (Shapiro and Roller, 1975). In any practical system, there will be a temperature loss along the pipe, and the changing heating flux will result in variations in soil temperature throughout the field. These variations can cause serious problems in crop uniformity.

Costs of underground piping and water pumping costs will be high; therefore, soil warming will be most suitable to high valued crops. These high valued crops tend to be highly competitive and the market is extremely sensitive to the available supply. High valued crops generally require high levels of technical competence and in many cases, large inputs of labor.

Space heating

Greenhouses

The effects of soil warming can be extended even further into the cold season by enclosing the culture area in greenhouses. Greenhouse temperatures should be maintained in the region of 20-30°C (68-86°F).

Berry and Miller (1974) placed a simple unheated greenhouse structure over an area of warmed soil to extend the period of benefits from soil warming. They found that under mild climatic conditions year around operation could be achieved.

Greenhouses are heated in many areas by water piped through the plant canopies. Water temperatures are generally higher than available from warmed water effluent sources, however.

Animal shelters

With a few exceptions, animal shelters in California do not require space heating. Swine farrowing houses do require heating, but that industry is not large in California. Poultry breeders require localized space heating and could perhaps make use of warmed water effluent. Their use of warmed water would be small.

Miscellaneous

Food processing plants use large quantities of water, much of it can be utilized at a temperature regime comparable to that available from power plants. The water must be of high quality and the demand tends to be seasonal with wide fluctuations in quantity required.

Methane generation of waste materials from animal production systems and food processing plants generally requires low quality heat (on the order of 32°C (90°F)) to reach optimum levels of gas production. Such facilities could conceivably be bathed in warmed water effluent from a power plant.

One way of making use of waste heat from power plants, which does not appear to have been given consideration in the literature, is to utilize warmed air obtained from dry cooling towers. This air could be useful for grain and fruit drying during much of the summer season, and for aeration of stored produce and space heating during the cool seasons. Dry cooling towers would also minimize the consumptive use of water by power plants. Use of the warmed air would improve the economics of using dry towers.

PROBLEM ANALYSIS

Possible advantages and disadvantages to warmed water sources of agricultural use

Some power companies have looked hopefully at possible agricultural uses of warmed water as a means of dissipating heat in waste water. Such heat dissipation, if achieved, would minimize the thermal pollution effects of discharging warmed water. As has been shown agricultural uses need water at the high range of discharge temperatures, but not at the low temperatures desired for ultimate discharge or for recycling as cooling water. Furthermore, agricultural uses need relatively uniform temperatures. High flow rates must be maintained with small drop in temperature of the warmed water as it passes through the agricultural system; cooling accomplished in the process must be minimized. Most agricultural uses can accommodate only a small portion of the total flow of power plant effluent and many agricultural uses have daily and seasonal fluctuations in demands. For all of these reasons, it seems highly unlikely that agricultural uses can be expected to provide significant heat dissipation for a power plant. Normal equipment for effluent cooling will still be necessary.

Other disadvantages include:

- Varying demands for effluent by agricultural users and concern of agricultural users for water quality will generate increased management problems and costs.
- Additional equipment and facilities will be needed to provide for distribution of warmed water to agricultural enterprises; hence, additional investment costs will be incurred. These costs cannot be offset by re-

ductions in investment costs for heat dissipating equipment.

- If the agricultural operations are carried out under the management of the power plant, significant problems of managing the agricultural enterprise can be expected. Agricultural enterprises are highly competitive and require careful management by highly skilled individuals. <u>Expertise for managing agricultural enterprises is considerably different from that needed for managing power plants</u>. If both managements are brought together under one overall enterprise management, conflicts of interests can be expected and some basis would have to be derived for optimizing the combined system.
- Investments in agricultural enterprises are often high, particularly for high intensity operations of the type that would be most likely to derive significant benefits from the use of warmed water.

Significant advantages for a power plant can be derived from the use by agriculture of warmed water effluent to specific agricultural enterprises. These benefits help to offset associated costs and disadvantages.

- Use of warmed water effluent may reduce demands for electrical energy particularly at peak power periods.
- Agriculture may be able to utilize idle land surrounding a power plant.
- Sociological and political benefits from conservation of the energy in warmed water are difficult to assess, but should not be ignored.

Possible advantages and disadvantages to agricultural enterprises of warmed water sources

There is a potential for increased profits from some agricultural enterprises provided with a reliable source of warmed water.

- Extended cropping seasons may allow multiple cropping patterns or shifts to more diversified or intensified cropping patterns.
- Minor shifts in cropping season can produce significant economic benefits by effecting the timeliness of harvest and by increasing yields.
- Operations currently using warmed water could benefit from reduction in cost of present energy sources.

There are also several concerns to agricultural enterprises regarding the use of warmed water.

- Water quality is a major concern and in many cases effluent from warmed water sources may not be usable directly.
- If heat exchangers are necessary, energy losses will occur in those heat exchangers and the cost of the heat exchangers must be offset by increases in profits.
- Perhaps one of the most critical concerns of agricultural operations is the reliability of the warmed water source. Agricultural operations can be very sensitive to temperature conditions. Loss of the warmed water source for a short period of time could conceivably result in catastrophic failure. Even under less severe conditions, loss of warmed water could effect the timeliness of an operation, with significant impact on profit potentials. If reliability of the source is questionable, it may be necessary to provide standby heating capabilities.

- If standby heating capabilities must be provided. the value of the warmed water source would be greatly reduced.

Interface between agricultural uses and warmed water supply

Several researchers have studied combined systems of agricultural uses with power plant operation. They have tried to demonstrate the feasibility of combining agricultural operations with power plants in order to utilize warmed water effluent (Price and Peart, 1973; DeWalle, *et al.*, 1974; and Bakker-Arkema, *et al.*, 1975). These analyses have generally favored such combinations and some researchers have tried to encourage investment in agricultural operations by utilities. However, management problems from an integrated system would be exceedingly difficult, because of the conflicting interests of warmed water suppliers and users and the need for a criteria on which to optimize an integrated operation. While this present analysis does suggest that certain combinations of agricultural uses may combine favorably with a warmed water source, the analysis also suggests a need to decouple the source of warmed water and the use.

All agricultural uses of warmed water studied must have as a primary objective economical production of a product if they are to be economically feasible. For most uses, sensitivity to temperature at critical times in the production cycle demands a reliable source of warmed water. If agricultural uses are supplied only reject heat, standby heating capabilities would be required.

Warmed water sources cannot count on heat dissipation from agricultural uses to reduce the need for cooling facilities. Thus, it is almost certain that a net cost will be incurred to supply warmed water to agricultural users. A value for supplying that water must be established.

Power companies are in the energy business. Many utilities combine the sale of natural gas and electricity. It seems logical that they could also sell warmed water at established rates and provide a reasonably reliable source of supply even though the demand is variable. In most cases the demand will be well below the total effluent available; but even if it is not, if rates are suitable, the power company should be able to generate warmed water on demand. Warmed water sources should consider the nature of the source with alternative delivery systems and attempt to establish costs to deliver a reliable source to users.

Some agricultural uses could derive sufficient benefits from an external source of warmed water to place a value on such a source. These potential users should consider the value of warmed water and likely demand patterns.

If a rate structure can be established for assured delivery of warmed water of particular specifications, potential agricultural users can decide whether the value to their enterprise exceeds the cost and warrants investment in the agricultural enterprise. Independent agricultural entrepenuers, each having skills appropriate for managing a particular agricultural enterprise, will eventually comprise a system making maximum potential use of the warmed water effluent available.

ENERGY SUPPLY SYSTEMS

Figure 3 shows a partitioning of the residual energy (1) from a power plant or other source of warmed water. In the absence of any use for the warmed water, the residual energy must be diverted to a cooling system which will remove the cooling energy (2). If a use for the warmed water is available, some effluent energy (3) may be routed to the energy user. In some cases, it may be necessary to add makeup energy (4) in order to provide the necessary supply energy (5). Some of the supply energy will be lost during transmission (6) and excess energy beyond that delivered to the user (7) must be disposed of (8), possibly by return to the cooling facilities.

The partition may be viewed as a model for operation of a warmed water energy supply system. The objective is to deliver energy in the proper flow and at the proper temperature. To do so it is necessary that the supply energy compensate for transmission losses. Transmission losses will depend both upon flow rates and temperature. Some disposal energy may be necessary to maintain proper temperature at point of delivery. If residual energy is at sufficiently high temperature, makeup energy should not be necessary. If residual flow temperature is too high, some of the flow can be diverted to cooling and the disposal flow reduced to allow transmission losses to reduce the temperature at point of delivery to the proper level.

Figure 4a shows a power plant operated with a bypass heating system to provide makeup energy for the supply flow in Figure 3. In reality the heater may represent a bleed of high energy flow from the plant itself. An alternate system shown in Figure 4b feeds disposal energy flow or a portion of the cooling energy flow back to the input to the power plant in a manner which maintains the proper residual energy in the output of the plant. While it is recognized that elevating the temperature of the cooling water inflow will reduce the generating efficiency of the plant, that loss in efficiency must be weighed against the cost of bleeding the boiler or other methods of providing makeup energy.

While knowledge of the probable demand patterns for uses of warmed water would obviously be desired for management of such a warmed-water supply scheme, a well-designed control system should be able to compensate for wide ranges of variation in demand. It should be possible, independent of the eventual users of warm water, to evaluate the cost to supply warmed water energy by such a system as a function of the total demand. Thus, rates could be established for warmed water and potential users could then compare those rates with the value they can anticipate deriving from the warmed water.

ENERGY USE SYSTEMS

Figure 5 diagrams the partitioning of energy flow in a typical agricultural operation. Again the energy flow at any point depends both on the flow of water and the temperature of the water. Cold inflow (1) is partially diverted (3) to a heat exchanger where energy (6) is added to the flow. The warmed water flow (7) passes through various processes (H) where it loses temperature (8). Some of the water is evaporated (9) and some water and energy is absorbed (10) by the material being processed. Water exiting the process (11) may be recirculated (4) or diverted to other lower temperature processes (12) or routed to the discharge (23). A portion of the cold inflow (14) is routed to cold water processes where the water may undergo a temperature change (16), be evaporated (17), or have water or energy absorbed (18). Effluent from the process (19) may be recirculated (20) or be combined with other plant outflow and discharged (23).

Figure 6 shows changes in this same agricultural enterprise when a source of warm inflow (2) is available. The amount of cold inflow diverted to the heat exchanger should be reduced and there should be a substantial reduction in the energy input (6) to the heat exchanger. All other parts of the operation should remain unchanged.

A complete analysis of the energy partitioning within a plant would require knowledge of temperatures and flow rates at each point. However, to determine the value of warmed inflow, it is only necessary to identify the change in energy input (6) and the change in cold inflow (3). If the rate of warm inflow varies according to time of day or season because of changes in demand for the warmed flow, the demand pattern of the agricultural enterprise must be evaluated and the rate function integrated to determine net value.

Capacity of the heat exchanger required for the agricultural process will depend somewhat on the temperature and reliability of the warmed water inflow. Decisions regarding the value of warmed water inflow should also consider trends in costs and availability of the energy input to the in-house heat exchanger and possible alternate sources for that energy.

SUMMARY

A re-analysis of the characteristics of possible agricultural uses of warmed water has revealed the need to decouple considerations of warmed water sources from those of warmed water users. Conflicting objectives and managerial requirements seem to preclude an integrated system approach. Rather an interface must be established with separate costs and benefits identified for a reliable warmed water source and for its various potential uses. These costs and benefits can be utilized as a basis for decisions separately by the energy supplier and the prospective energy users.

A method of classifying uses of warmed water according to need, volume, objective, temperature, and quality has been presented and preliminary classifications have been discussed for several potential agricultural uses of warmed water.

FUTURE RESEARCH

The principal thrust of future research has been suggested in previous sections.

- Costs to a power plant to provide a reliable source of warmed water need to be established and appropriate control systems designed.
- The potential for savings in energy costs to agricultural uses that may result from warmed water inflow should be established. These values are likely to be specific to particular localities and will depend on the temperature and quality of the effluent water.
- Research on techniques for designing low-cost heat exchangers for agricultural use of water may be warranted where water quality is not acceptable for direct use.
- Possibilities of utilizing warmed air from dry cooling towers should be investigated.

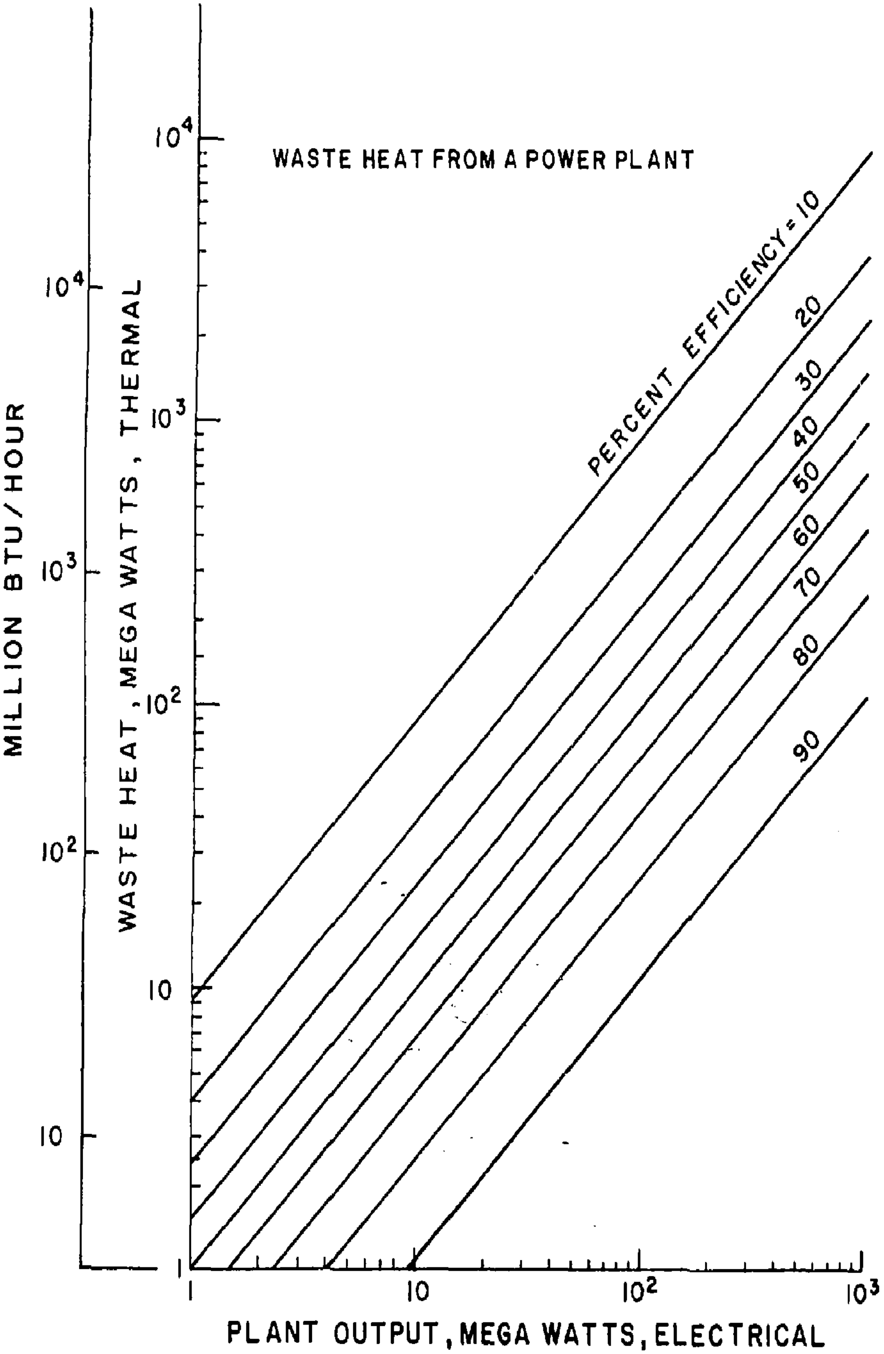
WASTE HEAT FROM A POWER PLANT
MILLION BTU / HOUR
10
10²
10³
10⁴
WASTE HEAT, MEGA WATTS, THERMAL
1
10
10²
10³
10⁴
PERCENT EFFICIENCY = 10
20
30
40
50
60
70
80
90
1
10
10²
10³
PLANT OUTPUT, MEGA WATTS, ELECTRICAL

Figure 1

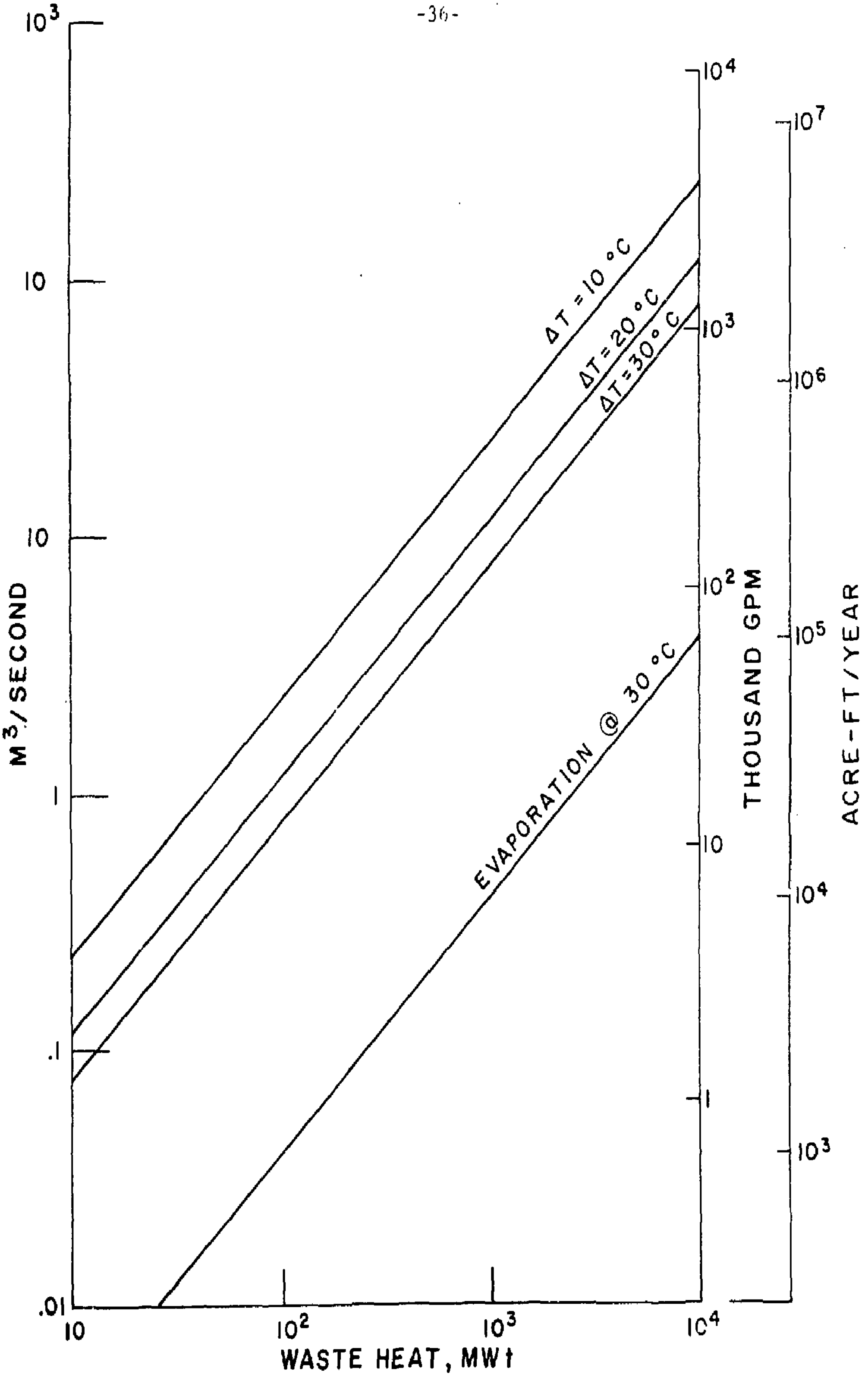
M^3/SECOND
10^3
10
10
1
.1
.01
$\Delta T = 10$ °C
$\Delta T = 20$ °C
$\Delta T = 30$ °C
EVAPORATION @ 30 °C
THOUSAND GPM
10^4
10^3
10^2
10
1
ACRE-FT/YEAR
10^7
10^6
10^5
10^4
10^3
10
10^2
10^3
10^4
WASTE HEAT, MWt

Figure 2

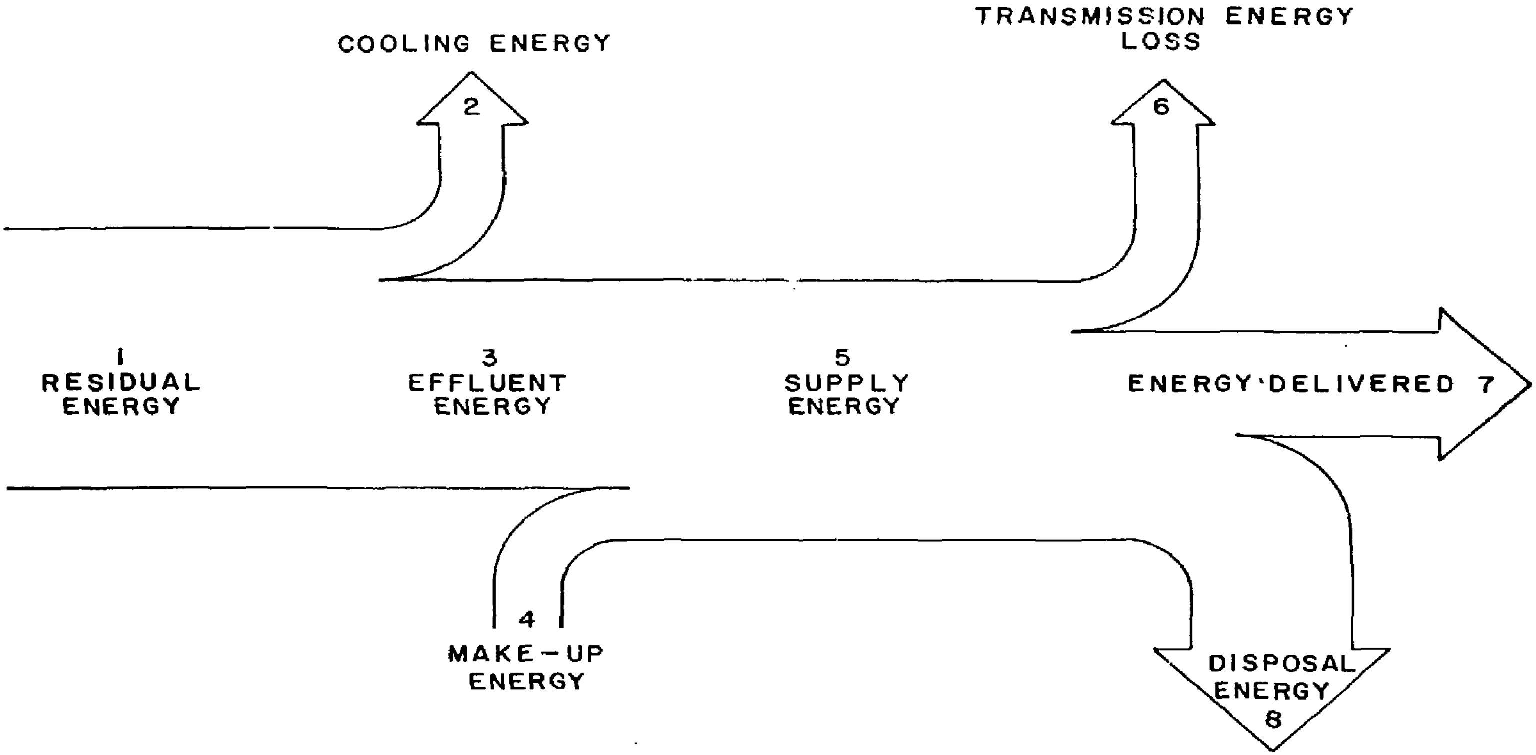

Figure 3. Partitioning of residual energy from a power plant.

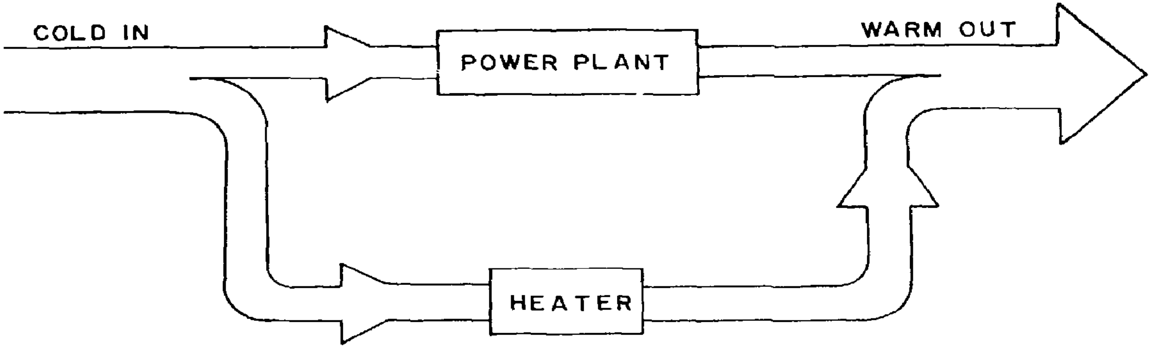

Figure 4a. Bypass heating to maintain output energy.

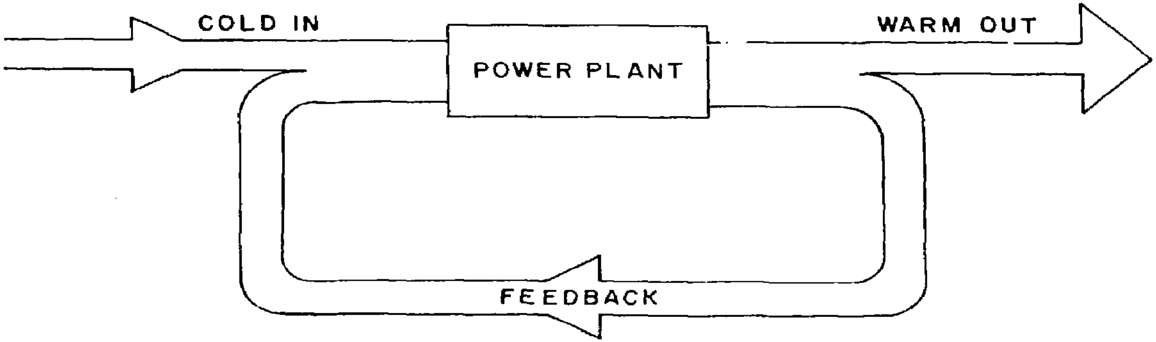

Figure 4b. Feedback to maintain output energy.

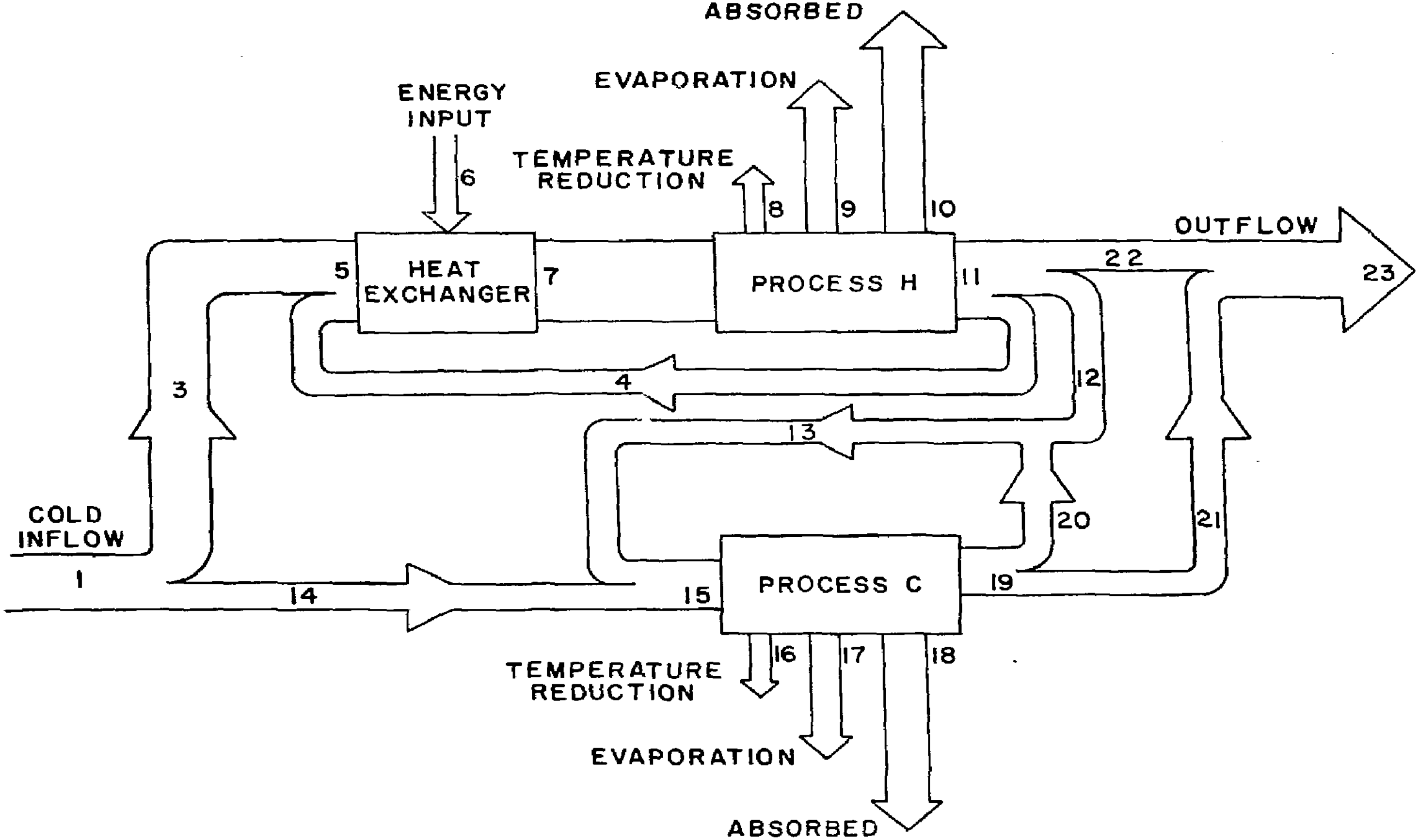

Figure 5. Partitioning of energy flow in a typical agricultural operation.

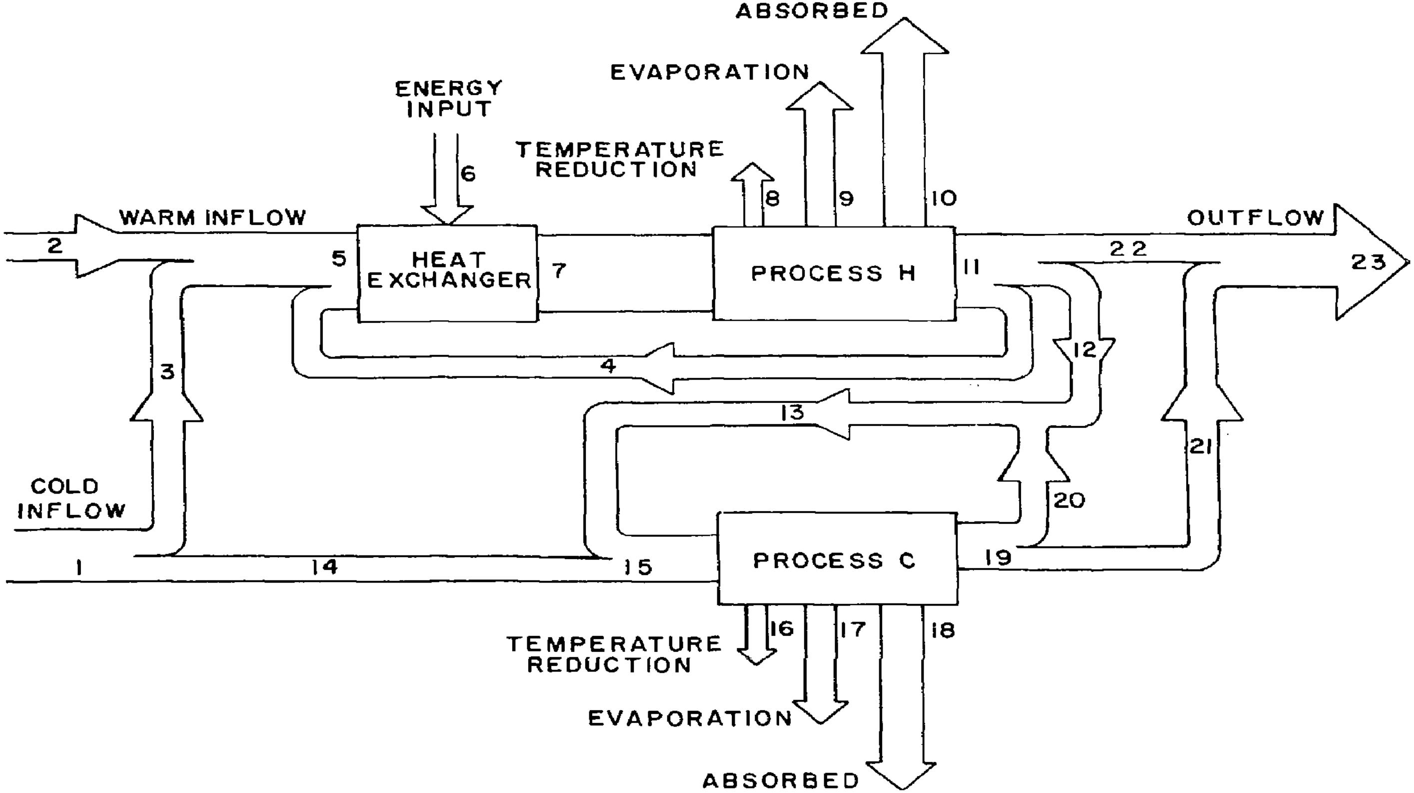

Figure 6. Partitioning of energy flow in agricultural operation with warmed water supply.

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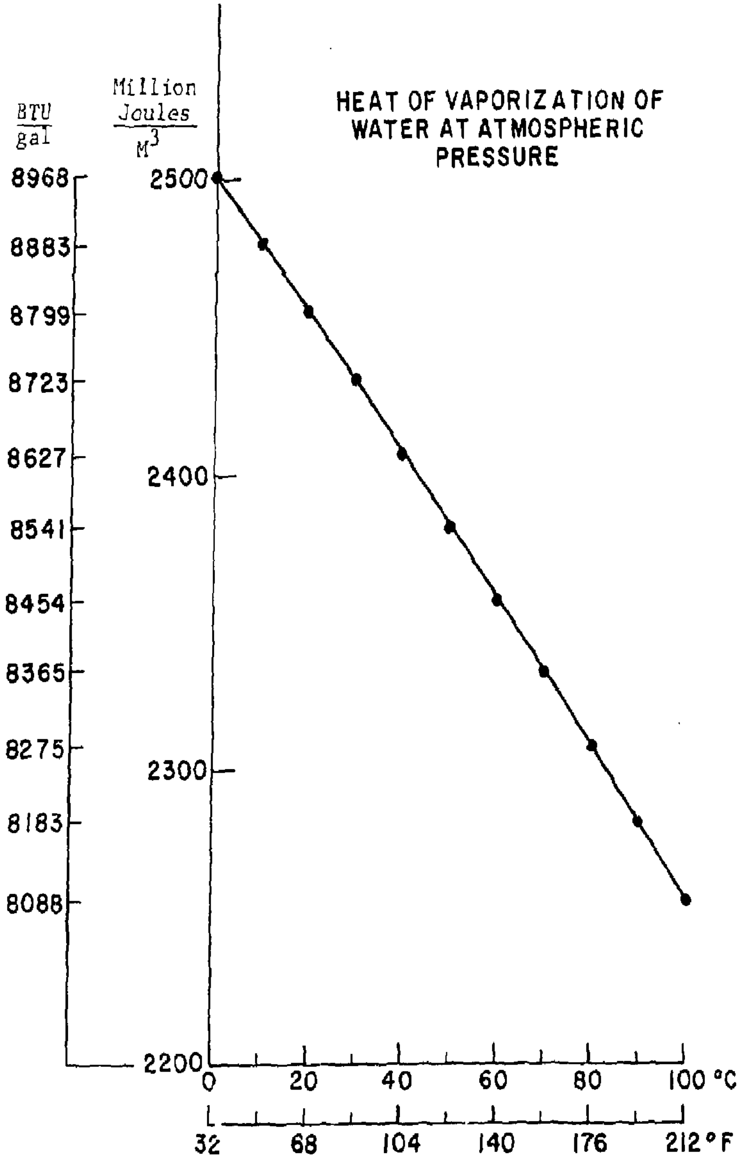
Appendix 1

CONVERSION FACTORS

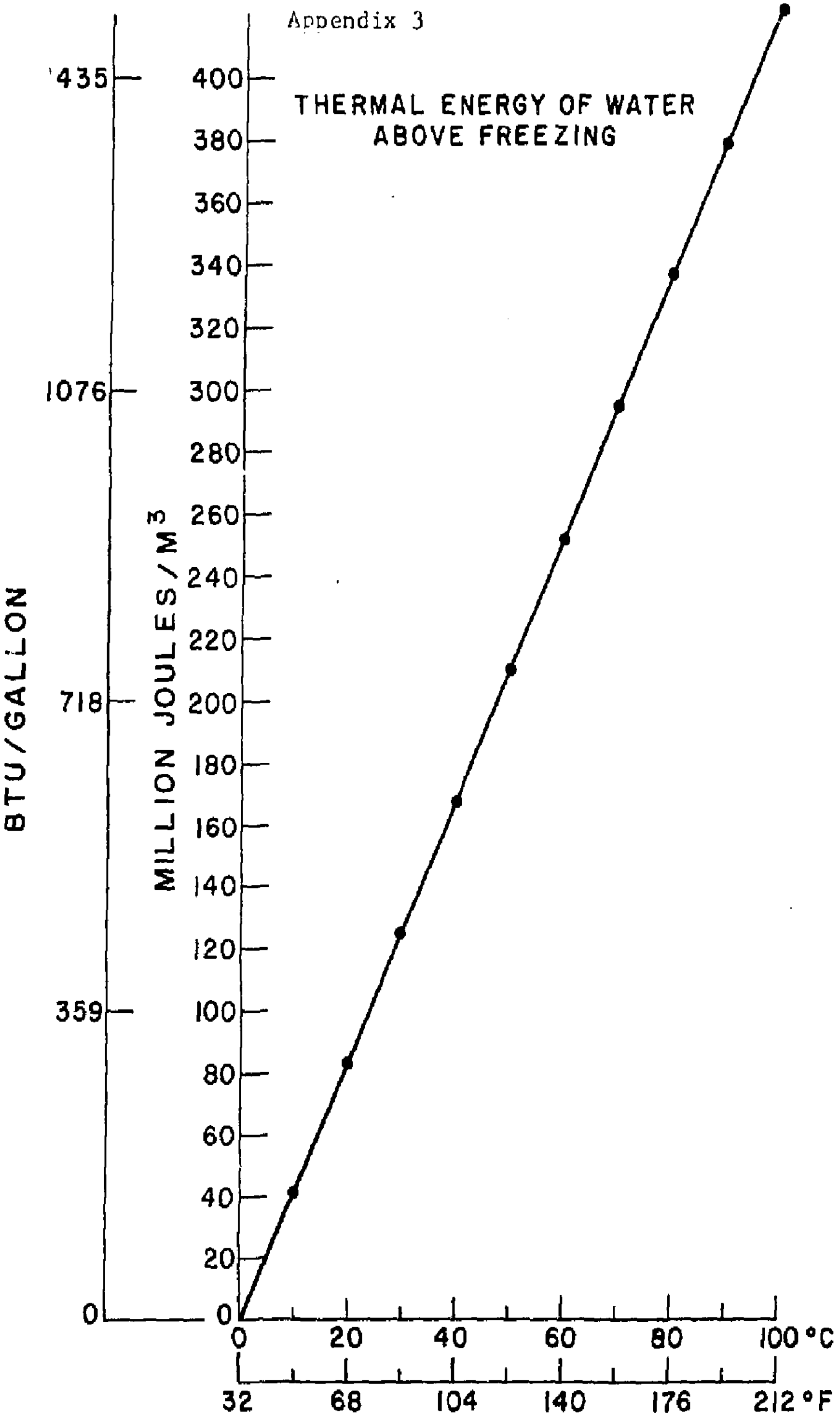
Multiply	→	By	→	To Obtain
BTU/hr		2.930711E-01		Watts
gpm		6.309020E-05		M^3/sec
acre-feet/year		3.911346E-05		M^3/sec
feet		3.048000E-01		M
inches		2.540000E-00		cm
gpm/acre		1.558993E-04		M^3/sec-hectare
acre		4.046856E-01		hectare
lbs		4.535924E-01		kg
To Obtain	←	By	←	Divide

$^{o}C = (5/9) \quad (^{o}F - 32)$

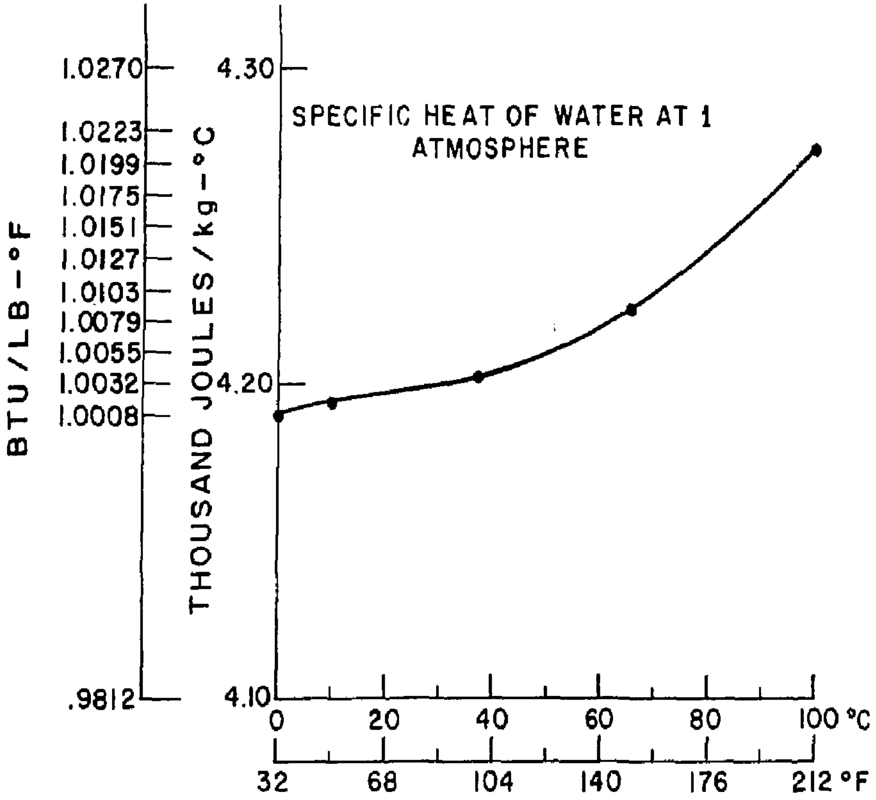
Appendix 2


HEAT OF VAPORIZATION OF WATER AT ATMOSPHERIC PRESSURE
BTU/gal
Million Joules/M3
8968
8883
8799
8723
8627
8541
8454
8365
8275
8183
8088
2500
2400
2300
2200
0
20
40
60
80
100 °C
32
68
104
140
176
212 °F

Appendix 3


THERMAL ENERGY OF WATER ABOVE FREEZING

Appendix 4


SPECIFIC HEAT OF WATER AT 1 ATMOSPHERE
BTU / LB - °F
THOUSAND JOULES / kg - °C
1.0270
1.0223
1.0199
1.0175
1.0151
1.0127
1.0103
1.0079
1.0055
1.0032
1.0008
.9812
4.30
4.20
4.10
0
20
40
60
80
100 °C
32
68
104
140
176
212 °F

Appendix 5

FACTORS TO BE CONSIDERED IN CLASSIFYING USES OF WARMED WATER

USE: Catfish Culture Water; Raceway

Volume of warmed water and degree of need:

	Need	Use	Tolerate
Large			
Small	X		
	Production	Dissipation	
Objective	X		

Consumptive use of water: minimal

Temperature of water needed:

Optimum	22-34°C
Maximum	39°C
Minimum	15°C
Maximum rate of change	

Timing of need: year around

Quality of water needed:

mmhos	20-200 ppm
pH	
DO	6.5-8.5
NH_3	
NO_2	
BOD	
COD	
Other	

Land resources needed:

Quantity	order of 4 hectare (10 acres)
Quality	not critical
Proximity to warmed water source	close

Investment resources needed:

Size of investment	moderate
Market sensitivity to product	high

Technical competence needed: Highly specialized

FACTORS TO BE CONSIDERED IN CLASSIFYING USES OF WARMED WATER

USE: Lobster Culture Water; Flow Through

Volume of warmed water and degree of need:

	Need	Use	Tolerate
Large	X↓		
Small			
	Production	Dissipation	
Objective	X		

Consumptive use of water: minimal

Temperature of water needed:

Optimum 22°C
Maximum
Minimum
Maximum rate of change

Timing of need: year around

Quality of water needed:

mmhos
pH
DO
NH_3
NO_2
BOD
COD
Other

Land resources needed:

Quantity	order of 40 hectare (100 acres)
Quality	not critical; terrain fairly level
Proximity to warmed water source	close

Investment resources needed:

Size of investment	large
Market sensitivity to product	moderate

Technical competence needed: Highly specialized

FACTORS TO BE CONSIDERED IN CLASSIFYING USES OF WARMED WATER

USE: Prawn Culture Water; Flow Through

Volume of warmed water and degree of need:

	Need	Use	Tolerate
Large			
Small	X		
	Production	Dissipation	
Objective	X		

Consumptive use of water: minimal

Temperature of water needed:

Optimum	28-31°C
Maximum	35°C
Minimum	14°C
Maximum rate of change	

Timing of need: primarily May-Nov.; some year around

Quality of water needed:

mmhos	fresh for growout, brackish for larvae 12-15 ppth
pH	$6.5 < 7.8 < 8.3$
DO	> 4 ppm
NH_3	
NO_2	< 1 mg/ℓ
BOD	
COD	
Other	

Land resources needed:

Quantity	200 hectare (500 acres)
Quality	heavy clay, flat terrain
Proximity to warmed water source	close

Investment resources needed:

Size of investment	moderate
Market sensitivity to produce	moderate

Technical competence needed: Highly specialized

FACTORS TO BE CONSIDERED IN CLASSIFYING USES OF WARMED WATER

USE: Rice Irrigation Water

Volume of warmed water and degree of need:

	Need	Use	Tolerate
Large	X		
Small			
	Production	Dissipation	
Objective	X		

Consumptive use of water: 2.8 x 10^5 acre-ft/year irrigation water; some additional evaporation loss

Temperature of water needed:

Optimum	75-85°F
Maximum	
Minimum	70°F
Maximum rate of change	

Timing of need: Apr.-Sept.

Quality of water needed:

mmhos	< 750 (K x 10^6)
pH	
DO	
NH_3	
NO_2	
BOD	
COD	
Other	Born < 1 ppm S.A.R. Index < 10.0

Land resources needed:

Quantity Quality	Rice productions areas mainly in Sacramento Valley
Proximity to warmed water source	moderate distance

Investment resources needed:

Size of investment	minimal to some reduction
Market sensitivity to product	no change in production anticipated

Technical competence needed: Knowledge of rice production

FACTORS TO BE CONSIDERED IN CLASSIFYING USES OF WARMED WATER

USE: Greenhouse Heating

Volume of warmed water and degree of need:

	Need	Use	Tolerate
Large			
Small	X		
	Production	Dissipation	
Objective	X		

Consumptive use of water: none

Temperature of water needed: preferred higher than normally available from effluent sources

Optimum 210°F
Maximum
Minimum
Maximum rate of change

Timing of need: fall and spring

Quality of water needed: immaterial unless used as irrigation water

mmhos
pH
DO
NH_3
NO_2
BOD
COD
Other

Land resources needed:

Quantity < 40 hectare (100 acres)
Quality high quality agricultural soil
Proximity to warmed water source close

Investment resources needed:

Size of investment high
Market sensitivity to product high

Technical competence needed: high

FACTORS TO BE CONSIDERED IN CLASSIFYING USES OF WARMED WATER

USE: Soil Warming

Volume of warmed water and degree of need:

	Need	Use	Tolerate
Large			
Small	X		
	Production	Dissipation	
Objective	X		

Consumptive use of water: minimal

Temperature of water needed:

Optimum
Maximum
Minimum
Maximum rate of change

Timing of need: spring and fall

Quality of water needed: immaterial unless used as irrigation water

mmhos
pH
DO
NH_3
NO_2
BOD
COD
Other

Land resources needed:

Quantity	< 40 hectare (100 acres)
Quality	high quality agricultural soil
Proximity to warmed water source	close

Investment resources needed:

Size of investment	high
Market sensitivity to product	high

Technical competence needed: high

FACTORS TO BE CONSIDERED IN CLASSIFYING USES OF WARMED WATER

USE: Animal Shelters

Volume of warmed water and degree of need:

	Need	Use	Tolerate
Large			
Small	X		
	Production	Dissipation	
Objective	X		

Consumptive use of water: none

Temperature of water needed: preferred higher than normally available from effluent sources

Optimum 99°C (210°F)
Maximum
Minimum
Maximum rate of change

Timing of need: year around

Quality of water needed: immaterial

mmhos
pH
DO
NH_3
NO_2
BOD
COD
Other

Land resources needed:

Quantity < 40 hectare (100 acres)
Quality immaterial
Proximity to warmed water source close

Investment resources needed:

Size of investment	high
Market sensitivity to product	high

Technical competence needed: high