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CONTENTS

PREFACE

This report on productive uses of waste heat represents the results of an intensive effort over a limited time period to collect information on the subject topic. We recognized that within the time period allotted for this effort, it would not be possible to include *all* relevant information on heat utilization, but an effort was made to present information on the primary identifiable uses. The work benefited from the experience on the subject of a number of the contributing authors, and particularly from the many review comments of S. E. Beall of ORNL. This report is confined to discussions of waste heat uses only. In the report, we address principally the use of heat rejected from large central station electric generating plants. The coupling of heat utilization applications with smaller integrated utility systems is recognized as having significant potential advantages, but these systems are not extensively treated in this report. The section on Considerations in Implementing Waste Heat Use draws liberally from ideas, discussions, and information presented at The National Conference on Waste Heat Utilization held in Gatlinburg in October of 1971.*

*Proceedings of the National Conference on Waste Heat Utilization, October 27–29, 1971, Gatlinburg, Tennessee, Report Number CONF-711031. (Available from Dept. of Commerce, National Technical Information Service, Springfield, Virginia 22151.)

SUMMARY

Present steam power plants in the United States discharge as waste heat, energy equivalent to approximately twice their total present electrical generating capacity (~300,000 MW(e)). Because this energy is degraded in temperature it is difficult to use. It represents a necessary, but unwanted, by-product of the energy conversion process for generating electricity.

Because of the growing quantities of waste heat discharged and the increasing national concern with energy growth, energy utilization and thermal discharge problems have stimulated an examination of methods for productively using energy presently wasted to the environment.

The productive use of waste heat from steam electric plants that substitutes for heat energy which would otherwise have to be generated, results in a net improvement in our efficiency of energy use, and in energy conservation. Using a steam electric plant to supply both heat and electricity improves energy utilization. It is important to note that improving energy utilization in this fashion may be as effective as improving electrical conversion efficiency.

All energy ultimately appears as low temperature heat; indeed, low temperature heat has been aptly called "the ultimate waste." It would be wrong to suggest that waste heat is "used" and that after use it disappears from the environment. The term "utilization of waste heat" refers to the performance of useful functions with the heat before it is discharged to the environment. Even though *all* energy ultimately appears in the environment as heat, the energy may move from a highly concentrated point source to a widely dispersed geographic area where it may be environmentally more acceptable.

There are relatively few applications where serious consideration has been given to the use of reject heat from steam electric power plants. These include: the use of heat for food production in agriculture and aquaculture; the use of heat for urban and industrial applications; and the use in specialized processes. No one of these individual uses would be expected, by itself, to have a very significant effect on energy utilization and conservation at any single plant site. However, combinations of the various uses selected for a particular site could have a significant effect at that site.

Agriculture

Agricultural operations can use waste heat from power plants without reducing electrical energy production. While these uses will not solve the problems of thermal discharge, they may, in particular locations, reduce the impact of thermal effluents on the local ecology, conserve energy resources, and be profitable to both the electric utility and the farmer.

Thermal effluents from power plants potentially can be used in open-field agriculture to promote rapid plant growth, improve crop quality, extend the growing season, and prevent damage due to temperature extremes. Water, used for both irrigation and heating, can be applied through nozzles (spray irrigation) or through subsurface porous pipes. With these systems the farm acts as a large, direct-contact heat exchanger for the power plant, while the utility provides irrigation water to the farmer.

This heat is important for only a small portion of the year (early spring and late fall). During the remainder of the year, water is needed for irrigation, but not for heating. However, most power plants are sited near urban centers and most urban centers are in areas where rainfall is sufficient to obviate the need for irrigation. The long-term implications of waste heat applications for soil management, disease and pest control are not yet known. Thus the justification for the capital costs required for open-field agriculture requires careful study at each site.

The use of power plant waste heat for warming and cooling greenhouses can improve crop growth and yield and reduce operating (fuel) costs by as much as \$4000–6000/acre. This use appears especially attractive for large growers to locate near power stations. Greenhouses may eliminate or reduce the need for cooling towers in certain instances.

Research at the University of Arizona, University of Sonora, and the Oak Ridge National Laboratory suggests that using waste heat for greenhouse climate control is both feasible and economically attractive. However, no large-scale field demonstrations or operations are currently underway in this country.

Waste heat also could be used to provide optimal temperature control in swine and broiler houses. In addition to reductions in heat costs, savings in feed costs should result from improved feed efficiency under controlled environmental conditions. To date, no detailed studies have been performed to determine the technical and economic feasibility of such systems.

The fraction of the total waste heat produced in the U.S. that might reasonably be used in agriculture is quite low, probably less than 10%. Additional study is required to determine the limitations imposed by

climate, geography, product marketing, waste heat reliability, animal waste disposal, effects of biocides and corrosion inhibitors in the cooling water, and consumer acceptance of products grown using cooling water from nuclear plants. These problem areas should be thoroughly investigated before a commitment is made to large-scale agricultural applications of waste heat. In some "local" situations, agricultural applications seem to offer significant economic value.

Aquaculture

The use of heated discharge water to improve the yields and productivity for fish and seafood species is receiving attention in this country and abroad. Basic data indicate that catfish grow three times faster at 83°F than at 76°F. Similarly shrimp growth is increased by about 80% when water is maintained at 80°F instead of 70°F. Though few experiments in thermal aquaculture (the culturing of aquatic species using heated water to achieve near optimum water temperatures) have been carried out, studies indicate that maximum yield may be achieved in facilities employing flowing water channels where control is exercised over water temperatures. Control of dissolved oxygen and the buildup of wastes, as well as controlled feeding of a nutritionally balanced food will be essential to achieve maximum yields. The few operations conducted in this country and abroad have produced equivalent annual fish yields above 100 tons/acre.

The use of heated discharge water for aquaculture will have essentially no impact on the total quantity of heat discharged at the power plant. The discharge temperature, however, may be reduced somewhat by blending ambient water with the heated discharge water during the summer to prevent over-heating the culture facility. Unless fish wastes are removed, particularly in channel culture, water quality leaving the facility may be degraded in oxygen content because biological oxygen demand is increased and this in turn may degrade water quality in the receiving water body. Ameliorating these problems is technically difficult and costs for doing so have not been studied.

The development of extensive thermal aquacultural facilities appears to have the potential for revolutionizing the production of fish and seafood in much the same manner as has been done in the poultry industry. The economic potential appears attractive. As with agriculture, however, the fraction of the total waste heat from power plants which is used may be small. This fraction would be sensitive to the growth in consumption of seafood in this country, and localized applications may be the first to evolve. Aquaculture may offer an answer to the major problem foreseen by the seafood industry – a scarcity of supply from natural sources.

Studies, to date, have presumed direct cooling systems where discharge water from the plant would be used for agriculture or aquaculture en route to the receiving water body, but systems operating with cooling towers might also be feasible. Operating water temperatures with cooling towers are higher and this may increase the flexibility of operations. Water quality considerations, however, in closed cycle cooling tower systems will require careful attention in the design of such applications.

Implementation

The application of existing technology to the large scale use of waste heat requires the consideration of many problems of implementation.

Most modern steam power plants discharge much more waste heat than may conveniently or economically be used at one location, thereby presenting problems of matching the supply of waste heat with the demand. The investment in facilities at a single site to use all the waste heat produced would be very large, while the use of only a fraction of the waste heat produced may preclude an effective substitution for the cooling methods originally proposed. Solutions to problems such as these must be achieved before widespread use of waste heat is possible.

Utilities are concerned about how expenditures on research and development for using waste heat will be treated by rate regulating agencies. Questions arise on whether utilities marketing heat at profit will have to credit the profits against electrical production costs and therefore be penalized on their permissible electrical rates. The position taken by regulatory agencies will be strongly influenced by the specific arrangements between the utility and the waste heat entrepreneur. The position taken by the regulatory agencies will affect the decisions of the utility on marketing of waste heat. Side benefits accrued by the utility, such as a reduction in heat dissipation equipment costs, may encourage the utility to offer heat at very low cost.

The trend toward increasingly restrictive water quality standards may affect the development of certain uses of waste heat. Imposing very low temperature rise limits in receiving water bodies, for example, may pose serious problems to developing a viable aquaculture operation. In some heat use applications, such as open-field agriculture, water is consumed and in most states water laws restrict the permissible quantities of water that can be removed but not returned to the water bodies. These restrictions may preclude certain uses of waste heat.

The waste problems created by the use of heat for agriculture and aquaculture must be examined and defined in sufficient detail so that the environmental effects do not negate the advantages gained by combining the application of heat use with power production. Problems associated with animal waste from areas of high density animal production (cattle and poultry, for example) are well recognized. Little information exists on the waste problem from aquaculture facilities, but this topic should be carefully considered.

Heat applications should be considered in the power plant site selection process. This may facilitate the use of waste heat and can effect the water use rights established for the power plant facility.

The real and imagined problems associated with the use of heat from a nuclear power plant cannot be ignored. Food produced in or very near the exclusion area of a nuclear plant may be held suspect by the public. The degree of public acceptance must be determined. Even heat supplied from a nuclear power plant to an urban area may suffer from public skepticism. These and other problems need to be addressed before widespread use of waste heat will become a reality.

AGRICULTURAL AND AQUACULTURAL USES OF WASTE HEAT

M. M. Yarosh E. A. Hirst J. W. Michel B. L. Nichols W. C. Yee

INTRODUCTION

Few will dispute the importance of abundant energy in our national development. Through its massive energy capacity, the United States, with 200 million people, marshals the equivalent manpower effort of 100 billion individuals. Abundant energy has enabled the production of goods and materials and the establishment of a standard of living which would otherwise be unattainable. Through inescapable byproducts, however, the rapid growth of energy has had increasing impact on our society in ways that were previously unforeseen. One of these byproducts is low-temperature energy in the form of heat. We sometimes find this heat difficult to discard, and because of its low temperature, always difficult to use.

The principal energy consumption sectors in this country include transportation, industry, residential and commercial uses, and the generation of electricity. Of these, the last is the fastest growing consumer. While our population doubles approximately every 50 years, our consumption of electrical energy doubles approximately every 10 years.

A basic principle of nature (enunciated as the second law of thermodynamics) is that ultimately all energy (mechanical, electrical, nuclear, chemical, etc.), when converted, appears as heat. For example, a nuclear power plant operating at 33% efficiency requires 3 kWhr of nuclear energy to produce 1 kWhr of electrical energy. The remaining 2 kWhr appear as thermal energy in the condenser cooling water and are discharged to the environment. Ultimately, however, the 1 kWhr of electricity also is degraded to heat. The energy supplied by the electricity may be used to operate air conditioners, water heaters, television sets, washing machines, for industrial and other applications, and then appear as heat at these individual sites. Thus, even though the power plant is capable of converting nuclear and fossil fuel energy into electrical energy, eventually all the energy appears as heat.

Availability of Waste Heat

In modern plants electricity is generated with efficiencies ranging from about 33 to 40%, depending principally on the age and type of the power plant. The water-cooled nuclear plants presently being built have efficiencies of about 33%, while modern fossil-fueled plants are near 40% efficient. Projections for advanced gas-cooled reactors and breeder reactors show efficiencies of near 40%. Significant quantities of waste heat are also available from smaller energy sources such as those employed for industrial applications or small system applications as in shopping centers. Indeed the smaller system sources provide a means of achieving a better match between available heat and potential uses. Unfortunately, efficiency has been increasing only very slowly over the past two decades, so the waste heat produced has been increasing almost linearly with the growth in electrical generation; this is shown in terms of heat rate and efficiency in Fig. 1.

Compared with other energy conversion processes, the generation of electricity is efficient. The internal combustion engine, for example, converts chemical fuel to mechanical energy with an efficiency of about 15%. Electrical generation, however, is carried out in large plants, and thus large point sources of waste heat are produced that must be dissipated at or near the point of electrical generation.

Over the past two decades, the capacity of electrical power plants has increased significantly, as shown in Fig. 2. In 1950 the size of the average unit placed in operation in the U.S. was only 48 MW(e), but by 1970 the size of the average nuclear plant scheduled for operation was over 700 MW(e). Also the construction of multiple units at a given site has further increased the difficult task of handling the large, but local, sources of waste heat. In 1970 the electrical generating capacity of steam-electric plants in the United States was approximately 265,000 MW. These plants annually produce about 5×10^{15} Btu of waste heat.

The generation of large quantities of waste heat at point sources requires the development of techniques for safe disposition of this heat. The traditional method of handling it has been to discharge it to a nearby natural or artificial body of water. When adequate cooling water is not available, evaporative cooling towers are used for discharging the heat to the atmosphere. Because of the increased size of power plants and the consequent increased waste heat load, adequate cooling water supplies for heat dissipation are becoming difficult to find. Commonly for direct water cooling, between 1.2 and 1.8 cfs of water is required per megawatt of electrical power generation. The amount is dependent on plant efficiency and condenser water temperature rise. Power plant sites of more than 3000 MW of capacity are becoming more common. Thus for large plant sites several thousand cubic feet per

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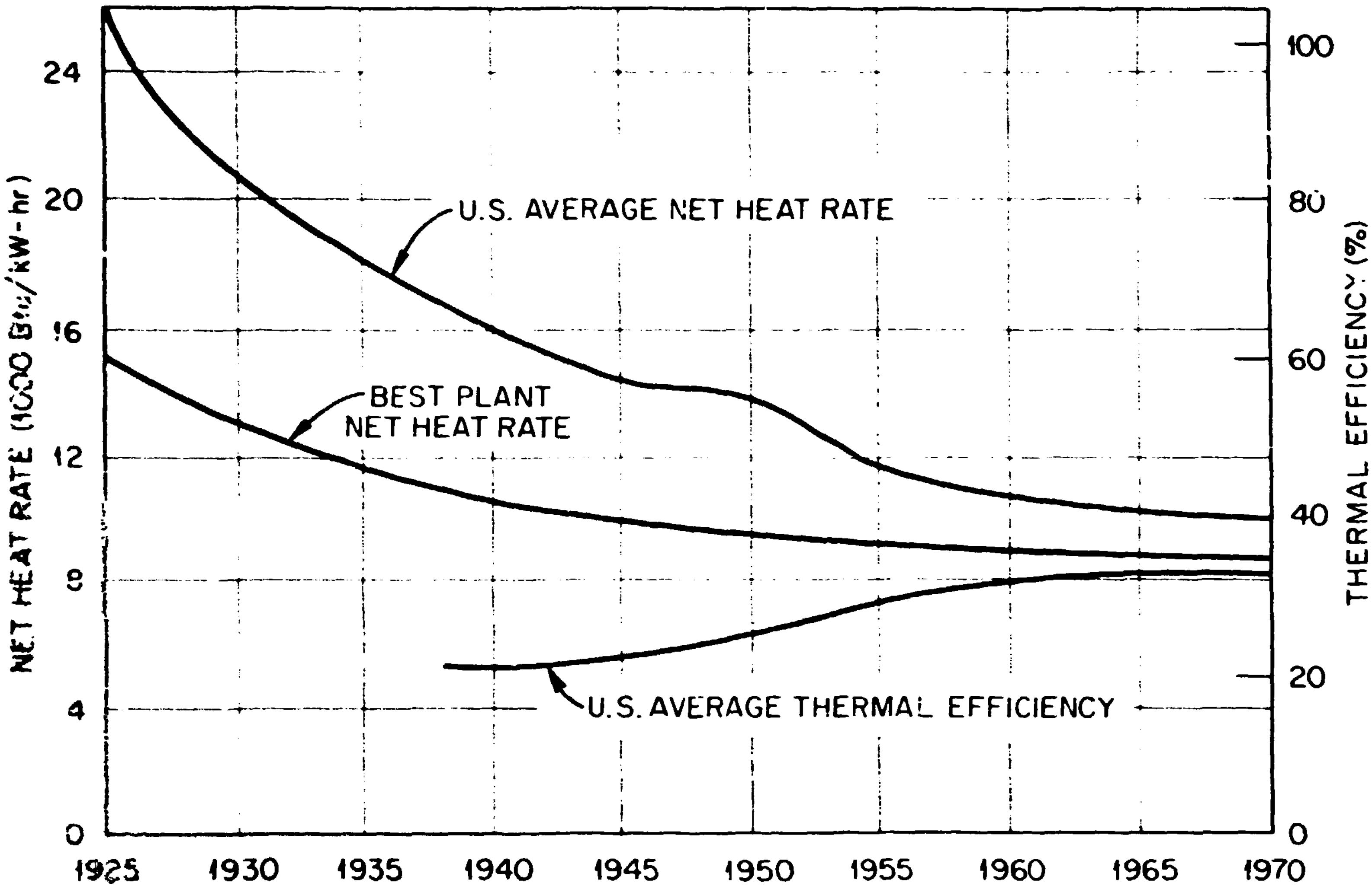

Fig. 1. Heat rate and thermal efficiency of steam generating plants.

second of water elevated perhaps 20°F in temperature above normal ambient is discharged from the power plant.

Plant thermal efficiency is often expressed in terms of the plant "heat rate," which is the number of BTU's of energy required to produce a kilowatt hour of electricity. As efficiency increases, the plant heat rate decreases.

Incentives for Using Waste Heat

The discharge of large quantities of heat to a body of water may alter the temperature of the receiving water sufficiently to cause unacceptable changes in the aquatic biota. As a result, increasingly stringent standards on acceptable temperature alterations to such water bodies are being imposed by state and federal regulations.

Disposition of the heat to the atmosphere through cooling towers may produce undesirable meteorological effects. Cooling towers also impose extra equipment costs on the plant operator and reduce plant cycle efficiency. Ultimately, of course, all net heat loss is transferred through the atmosphere to the ultimate heat sink – space.

These factors have increased interest in methods for utilizing the rejected heat from power plants. The utilization of waste heat might, in some cases, afford the opportunity to reduce the adverse environmental impact of waste heat discharge, reduce the cost of handling thermal discharges, and will improve overall energy utilization.

It is important to define waste heat and distinguish it from low-temperature heat. "Waste" heat designates energy which is so degraded in temperature that its uses are limited, and usually it is considered practical only to discharge it directly to the environment. Typically, such energy appears in the large quantities of cooling water used for condensing the steam discharged at the turbine in steam-electric power plants. Typical outlet temperatures for such cooling water are in the range 60 to 95°F, depending on the ambient water temperature, the quantity of water circulated, and other factors. For those power plants that have evaporative cooling towers the outlet water temperature would be increased by 15 or 20°F (i.e., to the 75 to 115°F range), while for dry cooling towers it would be increased by 20 to 40°F (80 to 135°F range).

"Low temperature" designates heat that has not been degraded to waste heat temperature levels. For example, the extraction of steam from a turbine before it has reached waste heat levels permits utilization of the heat extracted for functions requiring higher than waste heat temperatures. Typically, low-temperature heat is in the temperature range 100 to 400°F. Utilization of this heat from the turbine permits better utilization of the energy remaining in the steam, but it also reduces the efficiency of the turbine cycle. Low-temperature heat may be typically used in space heating and cooling for urban applications. The use of this heat will not be discussed in this report.

Waste heat, as discussed in this report, can be used for heating greenhouses and animal shelters, for providing frost protection in open-field agriculture, or to maintain optimum temperature for the culture of aquatic organisms such as shrimp or fish in aquaculture.

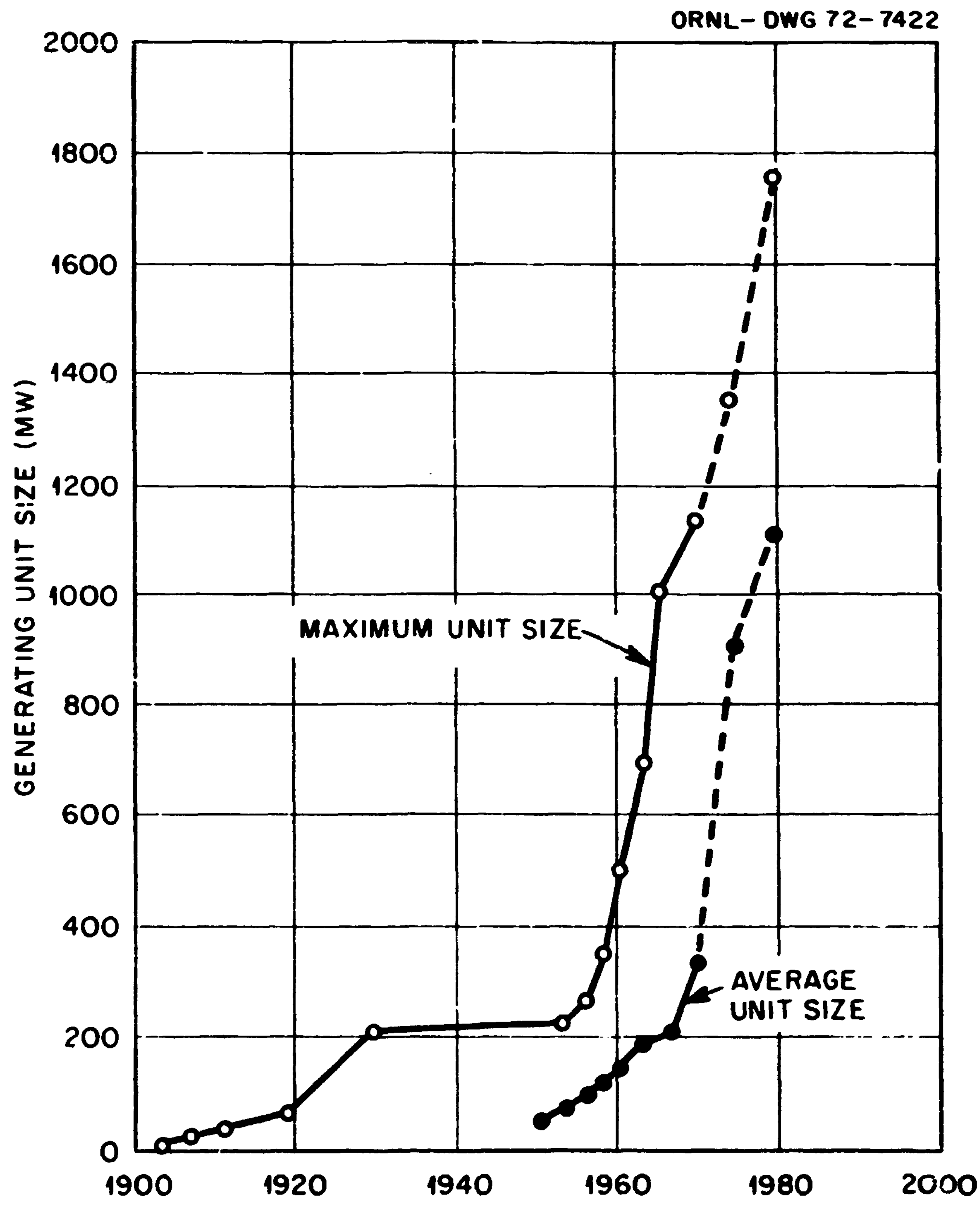

Fig. 2. Steam generating plant unit size.

At present, the waste heat from power plants represents an unpurchased product. If this heat could be marketed, the power plant owner could realize an additional return from his operation. In view of more restrictive regulations on the discharge of heat to the environment, this might provide the best opportunity for both a reduction in impact and in cost to the power producer.

The user of heat might benefit from the opportunity to purchase heat at a lower cost than is otherwise possible. In cases such as the heating of greenhouses, heating costs range from $4000 to $12,000 per acre per year, depending on the crop and the location. Energy costs of fuel vary from 40¢ to $1.50 per million Btu, and the lower energy costs possible from the use of waste heat could provide for considerable savings. Comparable savings might be possible for other uses. Total integrated waste heat utilization designs for power plants would allow use of the heated effluent during the entire year. Even if heat were sold only during the winter, however, the savings to the power producer could reduce the "add on" costs which result from requirements to provide treatment of the heated effluent coming from the power plant.

This report is intended to provide a survey of some of the possible uses for waste heat from steam-electric plants. The state of technology for use of this heat and the primary applications are discussed. This report also attempts to answer the more likely questions on waste heat use and provides references to additional information.

The methods described in this report cannot reduce the total thermal energy dissipated from power plants per unit of electricity generated. However, these processes can provide ways in which this heat can be *substituted* for the heat consumption of other energy sources. In this way energy and fuels can be conserved and thermal discharges reduced on a national and global scale. These processes may also permit the introduction of heat into the environment in a more acceptable manner and reduce other environmental insults. Though individual uses may be small, integrated waste heat use for several purposes could provide for better use of energy and increase the total use of the site.

It should be recognized that no single solution exists to the problems of waste heat discharge or to the increasing difficulties in finding sites for steam-electric power plants. However, under some circumstances these problems may be partially alleviated by methods employing heat utilization. No single method for heat use may, by itself, represent a significant outlet for waste heat. The total energy use (hence, energy savings), however, for a variety of heat applications can be significant. If it were possible to use only 10% of the heat rejected from the generating stations to be built over the next 30 years, the net effect would be to use more rejected energy than the equivalent in electrical energy generated today [~300,000 MW(e)]. On the other hand, it must be recognized that the economic utilization of large quantities of energy at low temperature is a difficult task, which otherwise would have already been solved. The incentives for solutions to waste heat utilization have increased, however, and seem likely to continue to increase in the future.

The opportunities that exist for utilizing waste heat are just beginning to be explored in this country. Because it is important to recognize the role that heat utilization may play in the generation of electrical energy, this report summarizes the methods available and the status of their application.

The use of *low-temperature heat* from electrical generating centers is not discussed in this report. Nonetheless, such use also permits the application of heat energy in a manner which improves overall energy utilization and contributes to energy conservation. This energy conservation should become a national goal – so many people think.

AGRICULTURAL USES OF WASTE HEAT

In contrast to many urban and industrial heat applications which require heat at temperatures higher than is normally wasted from electric generating or other steam process plants, several agricultural uses (e.g., spray irrigation, soil heating, and environmental control of animal shelters and greenhouses) offer a way to use the thermal discharges without reducing electrical energy production. (For example, steam or hot water at 300°F is needed for the various urban energy requirements currently under consideration. If steam from back-pressure turbines is extracted at 300°F rather than at 100°F, the *gross* turbine cycle efficiency is decreased from 47% to 30% for a modern fossil-fueled plant, and from 33% to 18% for a light-water reactor nuclear plant.[1]) Power plants with cooling towers are normally designed so that the temperature of condenser effluent is between 80 and 120°F; plants with once-through cooling operate near these temperatures much of the year but may discharge water as low as 55 or 60°F in the winter. In many locations these temperatures are high enough to provide satisfactory thermal environments for many plants and animals. Thus, agricultural operations which can be located close to the power station may truly be considered potential *waste* heat users

Spray irrigation and soil heating can be used to lengthen the growing season and provide frost protection in certain regions. Maintaining animal shelters at the proper temperatures can increase growth rates and feed efficiencies; this is particularly important for the smaller animals, such as poultry and swine. Greenhouse production of both flowers and vegetables is critically dependent on artificial heating and cooling, and the use of waste heat from condenser cooling water can significantly reduce fuel costs to greenhouse operators.

In spite of these obvious benefits from the use of waste heat for agricultural applications, several potential obstacles exist. Most important, the current level of agricultural production is such that only a small fraction of the waste heat discharged from power plants can be used profitably, and the projected growth patterns suggest that this picture will not improve in the future. In addition, the use of waste heat is strongly dependent on geography, climate, and season. The size of the greenhouse, poultry, or swine operation required to use a reasonable fraction of the waste heat generated by a typical power plant is an order of magnitude larger than any installations in the U.S. today. However, several foreign countries do have greenhouse operations that could use all the exhaust heat from a several hundred magawatt electric plant. Future greenhouse operations in the U.S. may be able to use the waste heat from power plants to replace the dependence on gas and other fuels which are in short supply. Such large operations, however, may introduce new problems in management, disease control, and waste disposal. Also for some operations, temperature control is not a controlling cost, and the lure of cheap (or even free) heat may not be sufficient to attract agricultural operations to power plant sites. Finally, certain problems may arise in coupling the power plant operation and the agricultural operation. The utility may be reluctant to have a second party on its cooling system or to obligate itself to supply the warm water from a nuclear plant where concern on the liability for radioactive contamination may be a problem.

Nevertheless, agricultural uses of waste heat are sufficiently attractive, under certain conditions, to warrant serious consideration. While these uses will not solve the "thermal pollution" problem, they can, in particular locations, reduce the impact of thermal effluents on the local ecology, conserve energy resources (reducing demand for fossil fuel heat), and save money for both the electric utility and the agricultural operator. The potential and problems associated with the use of waste heat for open-field agriculture, greenhouses, and animal shelters are discussed in the following sections of this chapter.

Open-Field Agriculture

Throughout the history of agriculture, man has generally been at the mercy of nature and has adapted to or accepted the vagaries of the weather or climate in his particular area. Control of temperature in agricultural activities was initiated only recently and is still limited primarily to greenhouse horticulture and poultry operations. The importance of environmental control has long been recognized and studied, but the high cost of heat and equipment has limited its application to a few high-income crops.

Considerable study has been devoted to the effects of irrigation water (and soil) temperature on crop production and, of course, to the technical aspects of design and operating techniques intended to minimize the temperature changes.[2] It is, however, important to recognize that much additional work is required as evidenced by the following statement, "Knowledge of how root temperature affects plant growth is woefully incomplete, partly because critical experiments are few and partly because of ignorance about root function."[3]

The idea of using waste heat from power stations for agricultural purposes was suggested at least as early as 1957,[4] but it is only recently that several investigators have begun to study and evaluate the potential benefits, costs, and problems. As a consequence, little information in the literature is specifically directed toward the productive use of waste heat in field agriculture. Nevertheless the use of warm water for field irrigation through subsoil or sprinkler application techniques represents potential applications for the waste heat in discharge water.

Incentives for Use of Waste Heat in Open-Field Agriculture

Both plants and animals respond to specific environmental conditions that are conducive to optimum growth. Although these conditions vary considerably among species and at different growth stages, it is seldom that optimum values are maintained in nature. One of the important variables influencing plant growth is the temperature of both soil and air, and although this discussion deals primarily with temperature, it should be recognized that many other critical environmental factors interact with temperature and may require simultaneous adjustment as the temperature approaches an optimum level. These factors include soil moisture, air humidity, plant nutrition, and soil-air and atmospheric-air composition. It is known that within certain temperature ranges, biologic activity essentially doubles with each temperature increase of 10°C, but that too low or too high temperatures are lethal to plants.[5]

Potential benefits of temperature control to open-field agriculture include the following:

1. prevention of damage caused by temperature extremes,
2. extension of the growing season,
3. promotion of growth,
4. improvement of crop quality,
5. control of some diseases and pests.

Prevention of temperature extremes. Perhaps the most obvious and the most easily adapted use of waste heat in the form of warm water is in frost protection, particularly to tree crops. Frost protection by sprinkler application depends on the "heat of fusion," that is, the release of heat by water as it freezes. A critical factor in this technique is the proper management of water application to preclude limb or stalk breakage from ice formation, which can cause losses that exceed the losses caused by frost. The use of warm water in the spray system can alleviate this problem.

Warm water can also be used to cool plants during the hot, dry summer months when atmospheric humidities are low. In such a situation it has been demonstrated that warm water applied through a sprinkler system attains ambient temperature by the time it reaches the soil surface.[6] Heat loss results from evaporation, cooling both the plants and the water supplied through the sprinkler.

The use of warm water for the purpose of controlling crop damage due to extreme temperatures, while of vital agricultural importance, generally is required only a few hours during a few days of a year. Thus, this application requires a highly reliable heat source which is used at a very low load factor, and would present problems in capital cost amortization, unless the warm water can be distributed through an irrigation system which would have been needed anyway.

Expansion of the growing season and promotion of growth. Temperature is one of the most important factors governing the germination of seeds. Germination, emergence, and early growth of plants are intimately related to soil temperature. The effects of weather are probably more critical during germination and early seedling development than during any other stage of vegetation growth. Unfavorable soil temperatures at seeding time often produce a poor stand and consequently a reduced yield. Retarded growth of young seedlings may not only further reduce yield but also adversely affect the quality of the crop produced.[7] Favorable temperatures at the seedling growth stage may enhance growth sufficiently to provide the possibility for producing two or more crops per year, and thus greatly increase farm income. Also, achieving earlier crop maturity can give a large marketing advantage, particularly for high-value crops.

As indicated above, basic knowledge of the relationship of soil temperature to plant growth is limited. Some literature is available on this subject, although much of it is related to plant growth in the noneconomic sense, that is, rate of net photosynthesis, total dry matter accumulation, time of (or percent) seed emergence, root volume, etc. There is, however, some literature that discusses yields. In one experiment, rice (grain) yields were increased from 32% to 55% by increasing the root temperature from 18°C to 30°C.[8] Corn yields (silage) increased by 68% when the soil temperature was increased from 12°C to 27°C, while for potatoes (tubers) the yield increased by 47% for a soil temperature change from 12°C to 20°C, but then decreased by about 40% when the temperature was further increased to 27°C.[9] Table 1 summarizes some recent data based on field experiments by Boersma.[10]

While all yields obtained in these experiments were depressed by water shortage, the growth in the heated corn plots was particularly restricted by insufficient irrigation. Based on the observed rate of yield increase and past experience of corn silage production potential in this region, yields of 13 to 15 tons/acre of dry matter are considered attainable. Soil warming also added to the quality of the product, and the nitrogen content in the silage was increased.

Table 1. Results of field experiments[a] designed to measure the effect of warming the soil above its natural temperatures (ref. 10)

Crop	Yield (tons/acre)		Yield increase (%)
	Unheated	Heated	
Corn			
Silage	5.5	8.0	45
Grain	3.2	4.3	34
Tomatoes	32.1	48.3	50
Soybeans, silage	2.25	3.74	66
Bush beans			
First planting	6.44	7.80	21
Second planting	3.30[b]	5.70	73
Total	9.74	13.50	39

[a]Conducted during 1969 near Corvallis, Oregon.
[b]Did not mature.

Two crops of bush beans were grown in succession on the same area, but the second crop on the unheated area did not mature. The beans harvested on the unheated plots were extremely small and could not have been sold commercially. On the other hand, the second crop on the heated plots was of the same quality as the first. Based on these observations, bean yields of 12 to 15 tons/acre, or more than twice the unheated yields, are considered feasible. Even higher yields probably can be obtained by using optimum practices and high density planting.

Improved crop quality. Crop quality is believed to be, in part, a function of the overall plant growth cycle, and therefore control of the environment over the plant's lifetime should improve the final product. Little is known, however, about the specific effect of elevated root temperature in commercial crop production.[2] Crop quality may not necessarily be increased, since plant production of certain materials is not assumed to be a single-valued function of root temperature over the whole range of plant growth temperatures.

Control disease and pests. Cool soils tend to encourage certain diseases, particularly in cotton, and coolness also adversely affects the quality of the fiber. The use of water heated above the temperature usually considered in the "waste heat" range, has been proposed for soil sterilization. For example, the golden nematode (and its eggs) are killed by 5 min exposure to water at 125°F (49°C).[11] With lower temperature exposures (105 to 110°F) it may take 20 to 60 min to be lethal.[12]

Current Research Programs and Applications

The importance of soil temperature to plant growth has long been recognized, and research studies of this factor have been in progress since about 1905. A review by Richards, Hagan, and McCalla[7] summarizes knowledge of soil temperature as a biological factor up to 1952, and Neilsen and Humphries extend this review to 1966.[3] An extensive bibliography (1152 references) on the general subject of soil temperature was prepared by the U.S. Agricultural Research Service in 1964 (W. O. Willis, "Bibliography on Soil Temperature, through 1963, U.S. Agricultural Resources Service, Sec. 41-94, 1964). The USDA is continuing to sponsor work at several universities and area experiment stations. The work at the Ohio Agricultural Research and Development Center on The Relation of Soil Temperature to Growth and Mineral Absorption by Plants[13] is particularly pertinent, as is the work at Oregon State University on Control of Soil Temperature with Reactor Cooling Water.[14]

The states of Washington and Oregon have a number of programs investigating the agricultural use of warm water from power generating stations. Boersma of Oregon State University has proposed the system shown schematically in Fig. 3 for utilizing (and dissipating) power plant waste heat.[10] This system includes two primary means for heat dissipation, soil warming and evaporative cooling. The power plant turbine-condenser water cooling loop would be a closed recirculating system giving up heat through a pipe wall to either the soil and/or to water in the evaporative cooling basin. One use proposed for the heated water from the basin is for treatment of animal waste with algae production which, in turn, would be recycled as animal feed supplement. In the summer the waste stream could be used for field crop irrigation, and thus many nutrients could be returned to the soil. Alternatively the waste could form the basis for an aquaculture activity.

In a current experimental project supported by the State of Oregon, the USDA, and the Pacific Power and Light Company, electric heating cables are used instead of buried pipe for soil heating.[10] Preliminary crop response data are reported in Table 1. Based on projected yield improvement and double cropping of some of the land, a benefit-cost analysis indicates that this system or modification of it using warm water may be extremely attractive. In an example analyzed, cooling water from a 1000-MW(e) reactor power station was assumed to heat the soil on a 5000-acre farm and to provide the water for a 500-acre evaporative cooling system.

In a separate program a 170-acre demonstration farm project has been operating for three years at Springfield, Oregon, sponsored by the Eugene Water and Electric Board and managed by Vitro (Division of Automation Industries).[15] Primary emphasis in the experimental program is on evaluation of the use of warm water (90 to 130°F, obtained from a nearby pulp and paper plant) for frost protection, plant cooling, and irrigation.[16] In tests conducted over three full growing seasons using heated waste water from the industrial plant for spraying of fruit and nut trees, no crop losses occurred from temperature damage (frost) on the test fields, while adjacent fields not being sprayed suffered crop losses up to 50%.[16] A considerable improvement in maturity dates, yields, and quality of several fruits and vegetables has been demonstrated.

Economic studies are in progress at Washington State University to evaluate the potential benefits to be derived from soil warming and from irrigation with warm water.[17] The study is in three parts, of which the first will assess and chart irrigable land areas and then

ORNL-DWG 72-7427

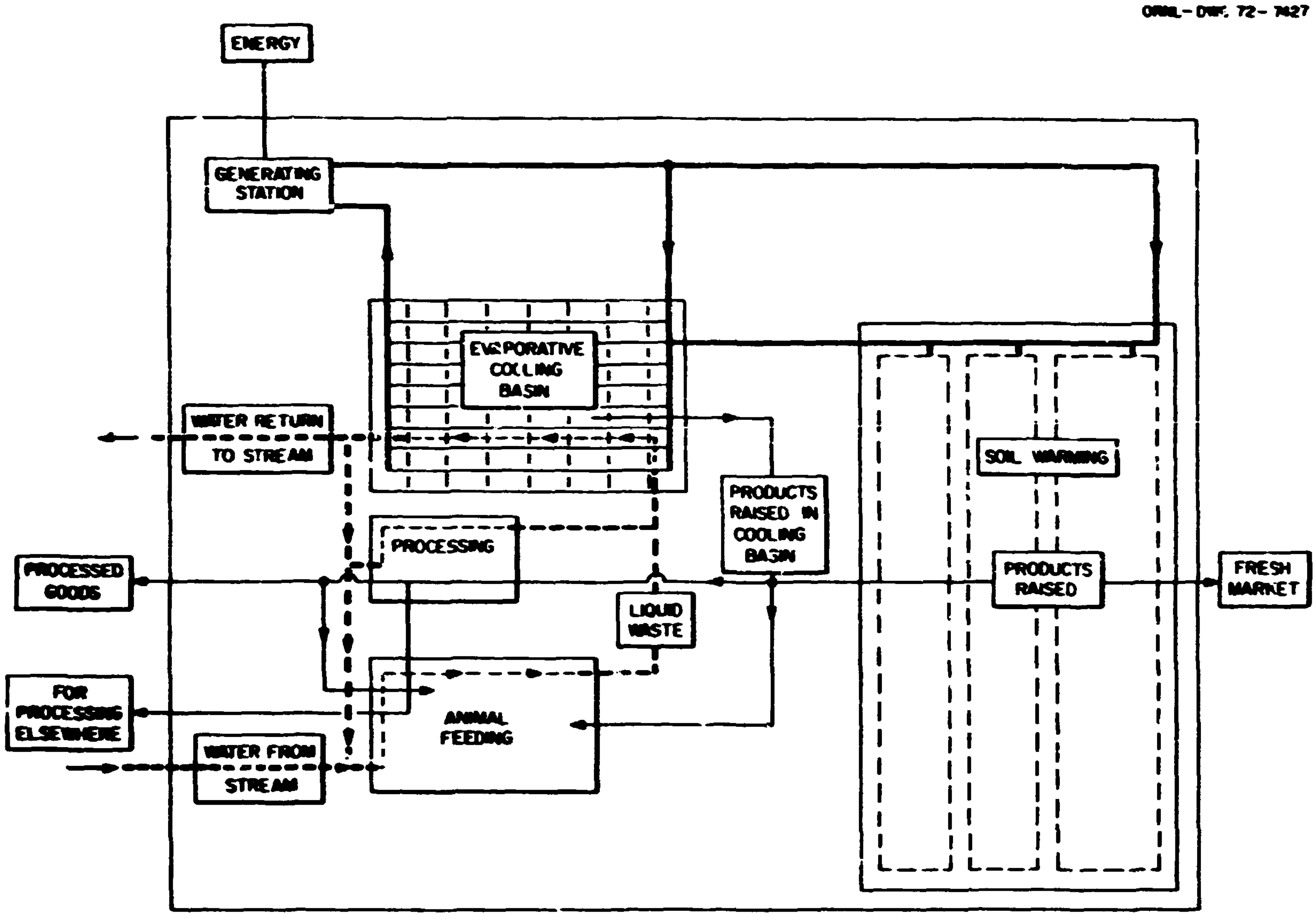

Fig. 3. Schematic diagram of an agricultural industry developed around a power generating station for the purpose of using the waste heat commercially.

establish cost-benefit ratios for irrigation. The second part of the study will predict environmental impacts of warm water additions to land masses. Part three will be a systems analysis of an integrated multiple-use water program.

Theoretical investigations are being carried out at the University of Arkansas to analyze the simultaneous movement of heat and moisture in soils.[18] One potential problem in heating soils with buried pipes is that as the soil temperature around the pipe rises, the soil dries out. The drying decreases the soil thermal conductivity and effectively insulates the pipe; this further reduces heat transfer. If the heating could be combined with subsurface irrigation, this problem might be alleviated. The Western Washington Research and Extension Center is starting an experimental project to study subsurface heating and subsurface irrigation. This work is sponsored by Puget Sound Power and Electric Company.

Field experiments are being initiated by North Carolina State University at Raleigh to evaluate the use of waste heat for soil warming in the southeast section of the U.S.[19] This project has the objectives of determining the feasibility of transferring waste heat to the soil system without crop damage during the hot months and determining the extent to which the soil environment can be modified and plant yields increased during the cooler periods of the year.

As part of the Tennessee Valley Authority's program on waste heat utilization, tests have been conducted on subsoil heating and irrigation to extend the growing season. Heating the soil more than doubled the yield of string beans on both irrigated and nonirrigated soils, and yields of sweet corn were almost doubled.

Potential Problem Areas

Most of the incentives for controlling soil temperature and the resulting benefits are of considerable significance. A basic problem exists in the economic risks due to the undemonstrated techniques and crop yields on large farms over extended operating times; that is, the overall economics have not been established, particularly with regard to the high initial investment where irrigation would not normally be needed. Also, long-term testing may reveal problems in soil management or plant disease and pest control, although there is presently no indication of such problems.

A significant question appears to exist in the breadth of application of waste heat from power stations for soil temperature management or irrigation. Most power stations are located relatively near population centers in areas of adequate rainfall where irrigation is only supplemental. On the other hand, many power stations are located in the higher latitudes where the soil warming feature could be advantageously used. Generally, the western part of the U.S. is deficient in rainfall, and particularly in parts of the Northwest both soil warming and irrigation appear to offer good potential for the use of waste heat from power plants.

There are also problems in continuously utilizing the entire flow of warm water [a 1000-MW(e) power station would continuously discharge 500,000–700,000 gpm] on nearby farms. However, even if the entire flow could not be distributed continuously, the careful selection of sites in regions of arid agriculture could benefit large farming areas. Since irrigation results in some consumption of water by evaporation and transpiration, the use of condenser water on previously unirrigated land might be objectionable. Such a use and its benefits would have to be weighed against the alternate choice of wet cooling towers and their water makeup and blowdown requirements, and the comparison of pumping and piping cost would have to be determined for soil irrigation cooling. In the western states, the availability of water would have to be determined, and legal restrictions would have to be defined.[20]

There may also be questions raised on the direct agricultural use of cooling water from nuclear plants from the standpoint of potential radioactive contamination.[21] Special precautions may be necessary to prevent this problem from occurring.

Problems of power plant operation, refueling, shutdowns, and effect on the power conversion cycle efficiency have not yet been adequately analyzed, and additional costs or areas in which research is needed may be revealed.

Conclusions

While agricultural uses for power station waste heat appear to be beneficial, especially for arid areas where water quality standards prohibit the return of heated water to streams, the current state-of-the-art for open-field use is quite limited. Most of the required research and development areas have been identified, and initial results are encouraging. However, areas in which work may be needed are: (1) induced power-station problems such as increased pumping costs, siting restrictions, etc.; (2) the economics of the total operation, including marketing and projected price structure of agricultural products; (3) overall ecological effects; (4) additional legal restrictions resulting from the combination of power production and irrigation. Since several of the research and development projects mentioned are being sponsored by power utility companies, it would be expected that these problem areas are receiving attention, but as yet they have not been discussed in the literature.

Greenhouses

The utilization of waste heat for greenhouse operation has been suggested in several studies[1,22] and papers[23-26] recently. Since an exclusion area is required for nuclear power plants, it has been suggested that greenhouses might be constructed on this idle land adjacent to nuclear plants to use the waste heat from the power plants and under certain circumstances might conceivably replace cooling towers which would otherwise be required.[23] In areas where the heating costs amount to from 10 to 30% of the operating cost (or $2000 to $11,000/acre) for greenhouse production of vegetables, the potential reductions in cost of heating provide a considerable incentive to develop large greenhouse operations in conjunction with power plants. This arrangement would allow the use of otherwise wasted resources (heat and land) without reducing the efficiency of the power plant. The increasing difficulties in obtaining natural gas (a primary fuel for heating in greenhouses) provide additional incentive for looking to the use of waste heat for heating and cooling of greenhouses.

Crop yields can be greatly improved through the utilization of heat, in controlled-environment glass or plastic houses, providing an added incentive for the use of waste heat. However, because the amount of heat available from large power stations is so great, it is not likely that the construction of greenhouses would be practical for the dissipation of all the waste heat produced by the power plants being constructed today.

Incentives for Using Waste Heat in Greenhouses

The use of greenhouses for the culture of vegetables enables larger crops and crop yields (up to 10 times the open-field output) to be realized with small amounts of land area. In addition, the ability to culture crops the year round allows more uniform productivity and permits the matching of crop harvest with periods of high demand and high price. Providing plants with the optimum temperature can reduce the time required to produce a crop and can greatly improve the yield per plant. Optimum temperatures vary with the species. Vegetables cultured at warm daytime temperatures of 80 to 100°F and nighttime temperatures of 75 to 80°F include squash, watermelon, cantaloupe, and cucumbers; those cultured at daytime temperatures of 75 to 85°F and 60 to 65°F nighttime temperatures are tomatoes, peppers, okra, eggplant, and onions. At low daytime temperatures of 70 to 80°F and nighttime temperatures of 50 to 60°F, spinach, radishes, cabbage, broccoli, carrots, beans, beets, lettuce, and cauliflower are cultured.[24]

Although many crops can be grown in greenhouses, the differences in value tend to encourage intensive production of only a few species. These include tomatoes, cucumbers, and lettuce. Growth curves for these three plants are shown in Fig. 4. The costs of producing vegetables in greenhouses vary with location, but the largest items in the operating costs are always labor and fuel.[27,28] In Ohio,[28] Michigan,[29] Illinois,[27] and Ontario,[30] the heating costs represent $2000 to $11,000/acre, or 10 to 30% of the operating cost (depending on location and crop species). With heating costs reduced, the profits may be increased, or more money may be available to pay for increased costs of labor or materials. The use of waste heat from steam-electric power plants therefore appears promising as a source of low-cost heat for use in greenhouses,

Fig. 4. Idealized growth curves for several crops (Ontario Department of Agriculture and Food – Publication 526).

especially if the plants have cooling towers with wintertime operating temperatures of 60°F or higher.

Commercial cultivation of tomatoes is usually profitable with heat from fossil-fueled sources at $1 to $1.50/million Btu. If reactor heat at 20¢/million Btu were available, operating costs in some parts of the country could be reduced by $4000 to $6000/acre.[31] Capital costs to deliver the heat from the reactor and to provide the necessary emergency heating are estimated at $28,000/acre (for each 100-acre installation), as compared with the normal capital investment in heating equipment of $15,000 to $25,000/acre.[23] If the heat in warm water from power plants could be sold at 20¢/million Btu to a 500-acre greenhouse installation, an operating profit to the power plant of $500 thousand to $1 million/year could be realized.[31]

The extensive use of greenhouses in or near areas of high population density would permit supplying food to nearby markets at seasonably favorable periods. Labor is considered the greatest single problem in the industry, and it may limit extensive use of greenhouses in some areas.[31]

Current Greenhouse Practices and Designs

Current greenhouse operations employ either glass or plastic-covered houses. Recent interest in plastic-covered houses results from their low capital and construction costs and their tax advantage.* Developments in plastics and the use of twin-layer plastics for greenhouses have reduced the heating costs by reducing the heat losses through the roof. Wittwer notes that double-layer plastic houses require only ⅝ the amount of heat required for glass houses. Detailed discussions of greenhouse design are available in refs. 33–35.

Greenhouses have been heated with hot water for many years by using radiators or finned tubes. In addition, water is often used for cooling with evaporative pads and fans. Studies have shown that warm water in the pad and fan system, in conjunction with finned tubes, can be used for *both* summer cooling and winter heating.[31]

The best documented studies of the use of waste heat in greenhouses involve the joint efforts of the University of Arizona and the University of Sonora at Puerto Penasco, Sonora, Mexico.[22] At Sonora the waste heat of diesel engine–generator sets is used in a desalting

*Annual replacement of the plastic is an operating cost, and the lower capital cost results in lower real estate taxes. In some states plastic houses are not taxed because they are not considered permanent structures.

plant and the growing areas of the controlled-environment greenhouses. Environmental control is provided in the University of Arizona experiment by use of a direct-contact heat exchanger in which air is forced through packed columns into which seawater is sprayed at the rate of 120 gpm. Variation in flow rate is used to regulate the temperature. When warmer temperatures are required, the 94°F blowdown water of the desalting plant may be used instead of seawater. In this system the humidity remains at nearly 100%, and the air temperature is close to that of the water passing over the packed-column heat exchangers. Approximately 20,000 cfm of moist air is circulated for ventilation and temperature control in the greenhouses. Warm water from power plants and other industrial processes could be used for such agriculture.[24]

A preliminary feasibility study of the use of warm water for heating and cooling greenhouses in the Denver area was carried out by Oak Ridge National Laboratory.[31] The study showed that the cooling tower planned for the 330-MW(e) Fort St. Vrain nuclear plant of the Colorado Public Service Company could be replaced with low-cost (relative to cooling tower capital cost) evaporative heat exchangers located in the greenhouses.** For the design wet bulb temperature in the Denver area (65°F), calculations indicated that the greenhouses could be cooled to at least 75°F in the summer by evaporating 92°F water (available from the turbine condenser) with once-through air, the heat being discharged to the outside. By recirculating the greenhouse air through the evaporative pads during the winter, the air temperature could be maintained above 65°F with a 0°F outside temperature. In either mode of operation, heat dissipation is constant and "full load."

In the ORNL design, water is circulated through evaporative pads as shown in Figs. 5 and 6. Air passing through the pads is evaporatively cooled during periods of high ambient temperature and heated during periods of low ambient temperature. To maintain the humidity at levels under 80%, finned-tube heat exchangers are placed downstream of the evaporative pads so that dry heat could be added to reduce the air humidity. (Discussions with plant physiologists and horticulturists suggest that plants are more prone to fungus and disease at humidities above 85%; hence the need for humidity reduction. However, the University of Arizona experiments have been with nearly saturated air.) The water returning to the condenser approaches the wet bulb temperature of the air during operation, and the water heats or cools the air moving through the pad, depending on water temperature and entering air temperature conditions.

Figures 7 and 8 show the greenhouse arrangement. Except for the plastic sheet used for the attic to permit air recycling, the arrangement is fairly typical of large greenhouse units that use evaporative pads for summer cooling. During the summer, air enters the greenhouse through the pads and exhausts at the opposite end. As outside temperatures drop, the discharge louvres close and force the air to recycle through the attic and subsequently through the evaporative pads. During cold nights the relative humidity of the air leaving the pads is nearly 100%, and the finned-tube heat exchanger is used to heat the air to reduce the humidity in the greenhouse to 80–90%.

Table 2 gives the calculated air and water conditions for several summer operating cases, with evaporative

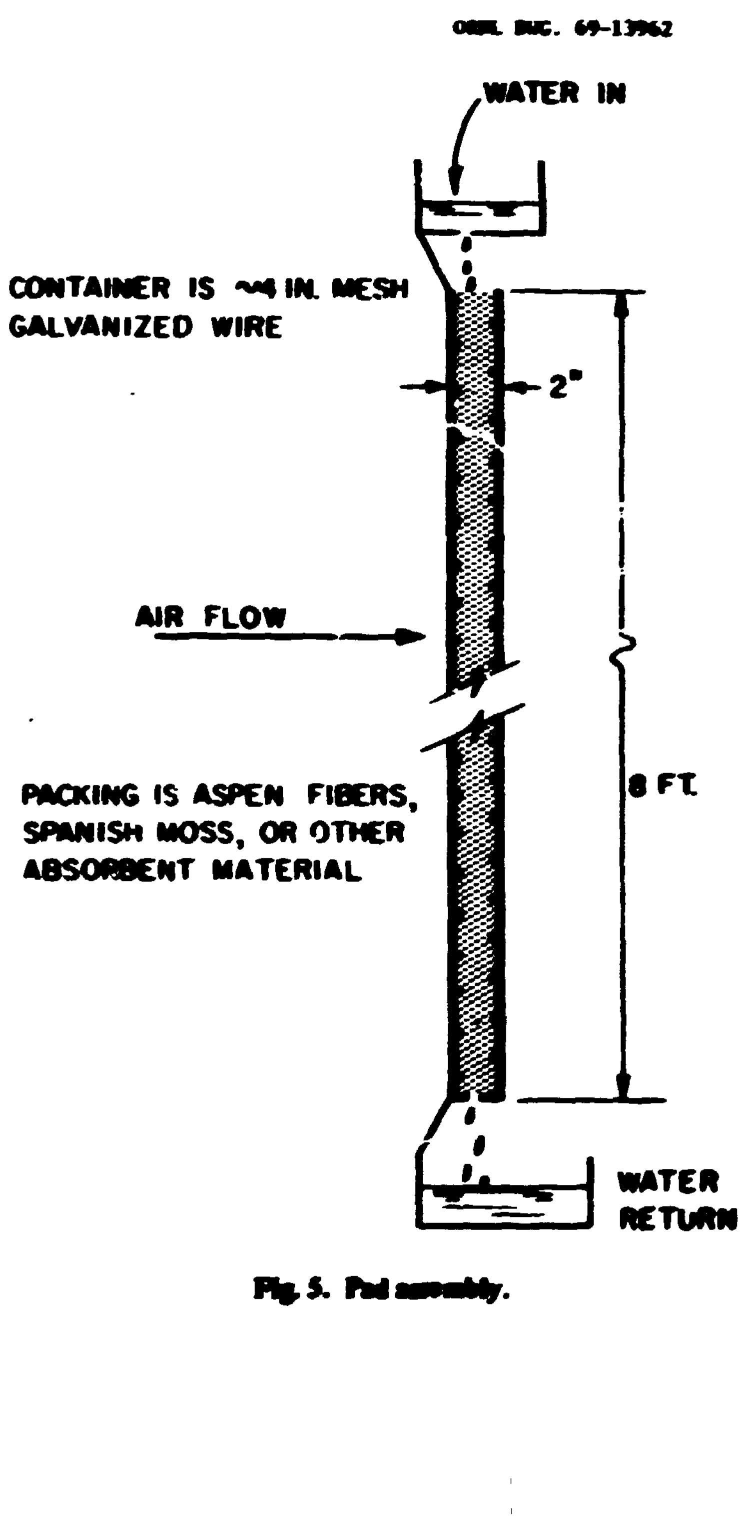

Fig. 5. Pad assembly.

**Gulf General Atomics, designer, and Public Service of Colorado, owner of the plant, granted permission for the ORNL study, but there are no plans to build such a greenhouse facility.

Fig. 6. Pad and finned-tube system for evaporative cooling. The pads are on the right, and the finned-tube heat exchanger is on the left. Air flow is from right to left.

pads replacing the cooling tower of the Fort St. Vrain plant.[31] It was assumed that hot water from the condenser would be piped directly to the greenhouses. The flow rates expressed are for each 50 X 100 ft greenhouse. In all cases the range of the temperature is 22°F, the same as for the Fort St. Vrain plant, which has design temperatures of 80 to 102°F.

Table 3 gives similar data for winter operating conditions.[31] Data for wind and sky conditions are also given in the table, and the relationship between the air, water, and roof temperatures is shown. The heat available from the Fort St. Vrain plant would be enough for 250 to 300 acres of greenhouses. During the summer, water returning to the power plant from the pads would be cooler than would normally be delivered by the existing cooling tower and therefore would increase the efficiency of the plant during hot weather.

Summer cooling conditions are favorable for the Denver area, because of the design wet bulb temperature of 65°F. It should be noted that the water temperature from the pad approaches the wet bulb temperature of the air within 3 to 5°F. In areas having a high wet bulb temperature, the cooling effectiveness would be less than in areas with a low wet bulb temperature.

Current Development Programs

While there are no large greenhouse operations in this country using low-level heat from power plants, experimental work is being carried out which could lead to large-scale use in the future. As mentioned earlier, the

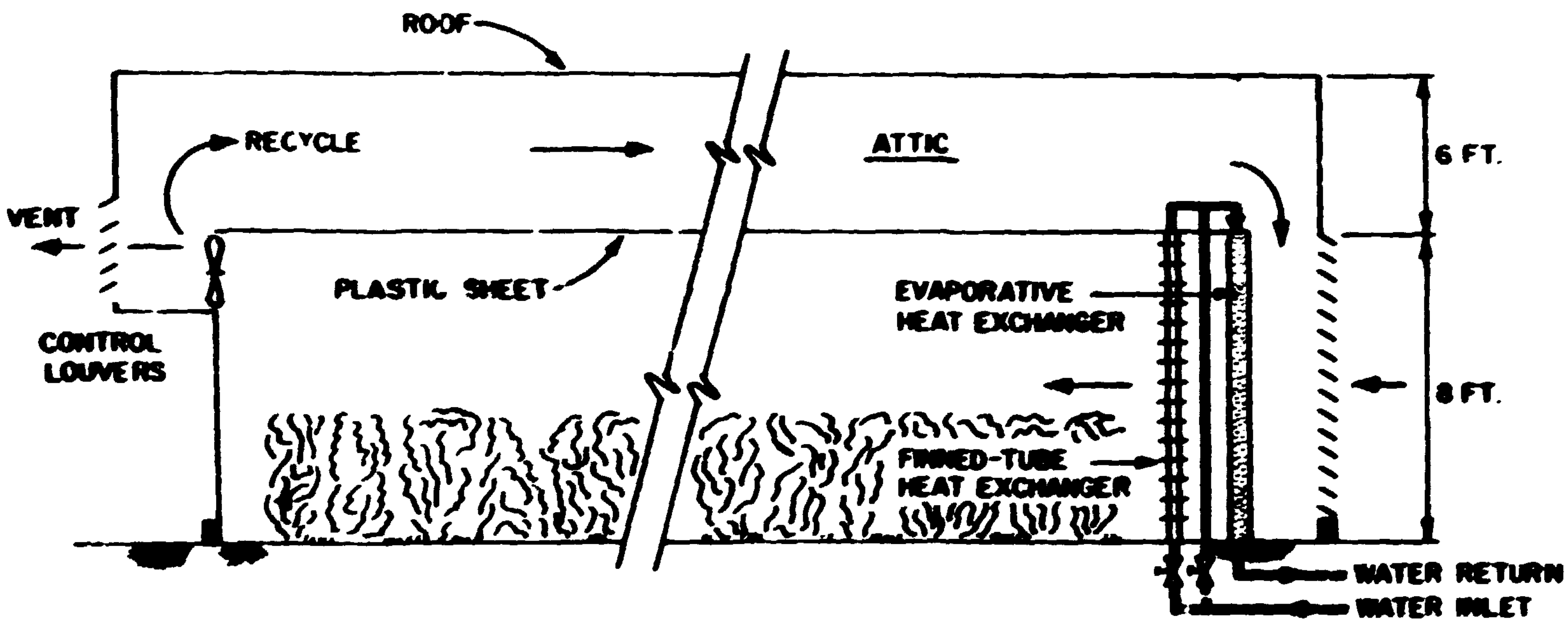

Fig. 7. Typical greenhouse with air and water flow system.

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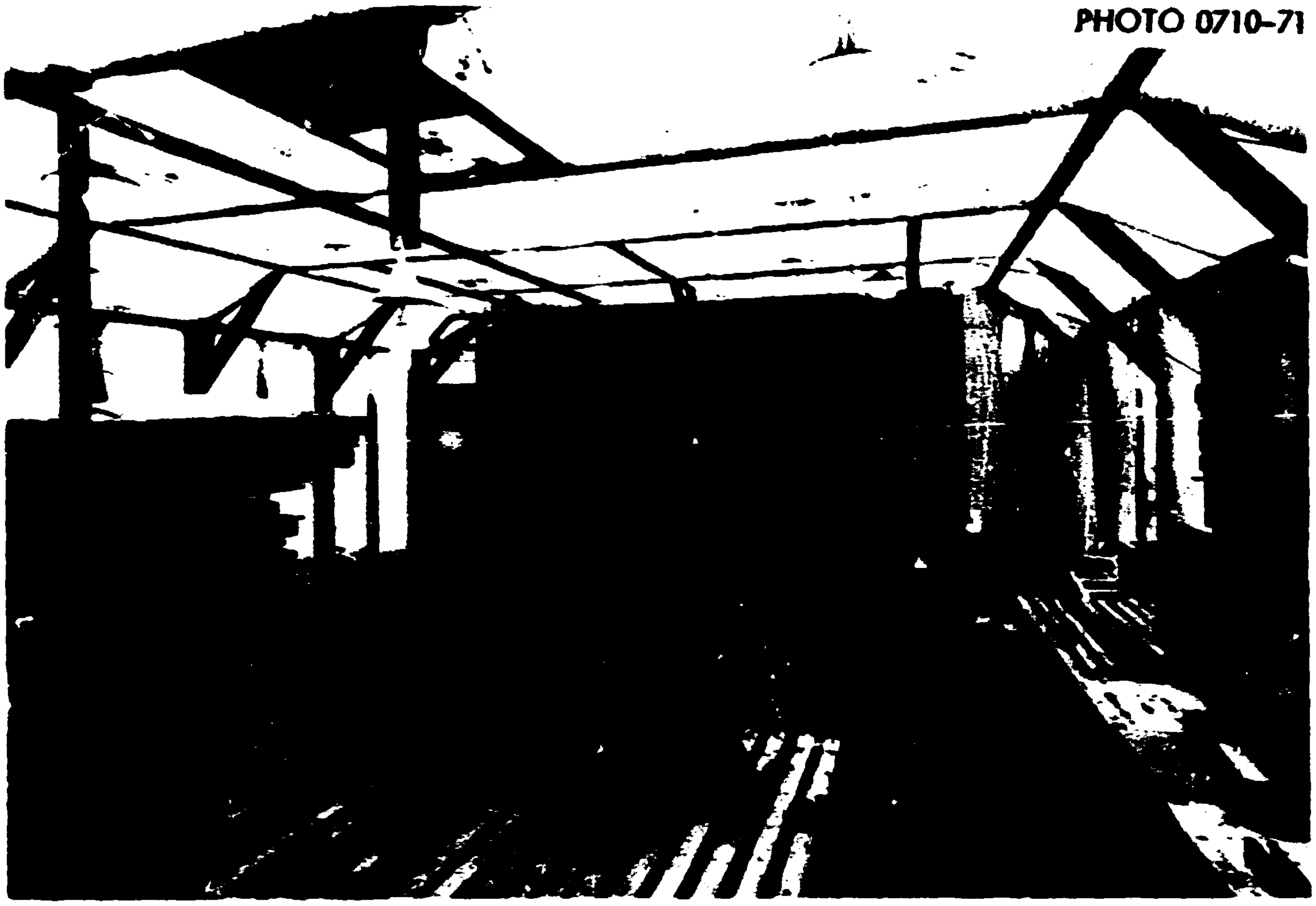

Fig. 8. Interior of the ORNL experimental greenhouse showing the finned-tube heat exchanger. The pads are behind the finned tubes.

Table 2. Greenhouse conditions for summer operation* (ref. 31)

Case	Ambient conditions		Air flow rate (lb/hr)	Water flow rate (lb/hr)	Range of conditions in greenhouse		Range of water temperature (°F)
	Dry bulb temperature (°F)	Relative humidity (%)			Temperature (°F)	Relative humidity (%)	
1[a]	95	16	306,000	88,200	76–86	80–67	67–89
2[b]	50	73	306,000	88,200	~58	~95	51–73
3[b,c]	50	73	153,000	88,200	~67	~100	57–79
4[d]	95	16	306,000	44,100	71–81	85–71	64–86
5[e]	50	73	306,000	44,100	~53	~90	48–70
6[f]	50	73	153,000	44,100	~57	~100	50–72

*Data are for each 50 X 100 ft greenhouse.

[a]Summer conditions for Denver (64°F wet bulb) and 500 MW of waste heat dumped to 100 acres of greenhouses.

[b]Moisture in air assumed to remain same as for day conditions, but dry bulb temperature dropped to 50°F.

[c]Air flow rate reduced by one-half.

[d]Conditions same as in case 1, except that 200 acres of greenhouses were assumed and the water flow rate was reduced by one-half.

[e]Similar to case 2, with 200 acres of greenhouses and water flow rate reduced by one-half.

[f]Similar to case 3, with 200 acres of greenhouses and water flow rate reduced by one-half.

Table 3. Greenhouse conditions for winter operation* (ref. 31)

Wind velocity: 15 mph
Effective sky temperature: −100°F
Greenhouse area: 200 acres

Outside air temperature (°F)	Water flow rate (lb/hr)	Air flow rate (lb/hr)		Air temperature (°F)		Range of water temperature (°F)	Mean roof temperature (°F)
		Recycle	Vent	Over plants	Through attic		
−30	44,100	153,000	0	72	72–65	66–88	1
−15	44,100	153,000	0	76	76–69	71–93	15
0	44,100	153,000	0	80	80–74	75–97	26.5
0	44,100	148,400	4,600	72	72–65	66–88	21
0	44,100	141,400	11,600	63	63–56	56–78	15
0[a]	26,500	153,000	0	56	56–50	51–73	12
0[a]	26,500	148,400	4,600	51	51–44	45–67	8.5

*Data are for each 50 × 100 ft greenhouse.

[a]Emergency conditions: reactor shut down and an emergency heater being used to supply heat at the rate of 1.5 MW/acre.

University of Arizona and the University of Sonora are using heat from diesel generators to provide heat for greenhouses at Puerto Penasco, Sonora, Mexico, where crops have been grown at near 100% relative humidity.[22,26] The success led to a request from the Shaikhdom of Abu Dhabi for construction of a 5-acre facility on the island of Sa'Diyat in Abu Dhabi, and this system is now in operation.[26]

One of the unique features is the ability of the facility to conserve water through collection of the condensate which occurs on the plastic roof. It is reported that each 4600-ft² greenhouse will yield up to 1500 gal of water per day during periods when the exterior temperatures are low enough to result in condensation on the inside of the plastic roof.[26] Since this is distilled water which can be recovered and used for makeup water, during the winter there would be a potential recovery of water amounting to ≅14.2 thousand gallons per acre of greenhouse per day. This water could also go to supplying the approximately 10 thousand gallons per acre per day irrigation needs of the crops being raised, and to provide high-quality makeup water for the power plant cooling system.

Although the ORNL feasibility study[31] described earlier indicates that several advantages exist for using greenhouses to cool reactor condenser water, no plans exist to indicate that greenhouses will be built in the U.S. to use a sizable portion of power plant waste heat. However, regardless of whether the power plant is cooled significantly, even a fraction of the heat should be an attraction to a greenhouse operator because of low heat costs. Furthermore, there are many industrial processes and cooling towers wasting heat which could be used in greenhouses at a small expense to the grower. Recently, an experiment was started at Oak Ridge to determine the actual operating performance of a pad and fan system for use in heating and cooling greenhouses. Waste heat in the water from a building air-conditioning system is being used for temperature control in a small plastic greenhouse. Preliminary results thus far have revealed small differences between the theoretical calculations used in the feasibility study and the pad performance, but additional work is required to prove details of the system. The Tennessee Valley Authority is planning a pilot test of the "Oak Ridge System" of heating and cooling in a joint TVA-ORNL program.[25]

Each of the systems mentioned involves the flow of water from the power plant to the greenhouse, where the water is cooled and sent back to the power plant or discharged to surface waters. The systems available for blending and controlling the water to maintain certain temperatures require conventional engineering. The use of greenhouses in series or parallel with cooling towers, cooling ponds, or other systems could afford increased flexibility for waste heat use.

Although work is being conducted throughout the United States on design of greenhouses, greenhouse equipment, and on growing methods, little work having direct applicability to the utilization of waste or low-temperature heat from power plants is currently under way. Sufficient information exists to design a greenhouse system to use waste heat. However, the integrated performance of large complexes may require on-site demonstration facilities before many questions can be answered.

Economics of Greenhouse Operation

Incentives for the utilization of low-temperature heat from power plants include the legal restraints on heated discharge water to water bodies, the economic potential to the utility for the sale of heated effluents, and the reduction in heating costs to the greenhouse operator. For the nation, such use could result in some improvement in national energy utilization.

The economic and marketing incentives for greenhouse products deserve some attention. Current greenhouse tomato production is distributed in the United States as shown in Fig. 9. Most production is in areas having high population densities and represents greenhouse operations of 5 acres or less, with an average being about 1 acre.

The costs and net return for greenhouse tomato production are illustrated by the data in Tables 4 and 5, which are for operations in the U.S.,[27,29] Canada,[30] and Great Britain.[36] Table 6 illustrates the investment, production costs, and returns for flower production.[37] In the data presented, the investment and operating

Table 4. Approximate annual operating costs to produce two tomato crops per acre

Illinois[1]	Labor	$ 4,800–6,720
	Fuel	2,500–3,500
	Total[4]	$ 9,025–12,700
Ontario[2]	Labor	$ 7,730
	Fuel	5,957
	Total[4]	$19,320
Great Britain[3]		
	Total[4]	$14,520–21,780

[1] Courter (1965).
[2] Fischer (1966).
[3] Sheard (1970).
[4] Represents total operation expense, not just the sum of labor and fuel.

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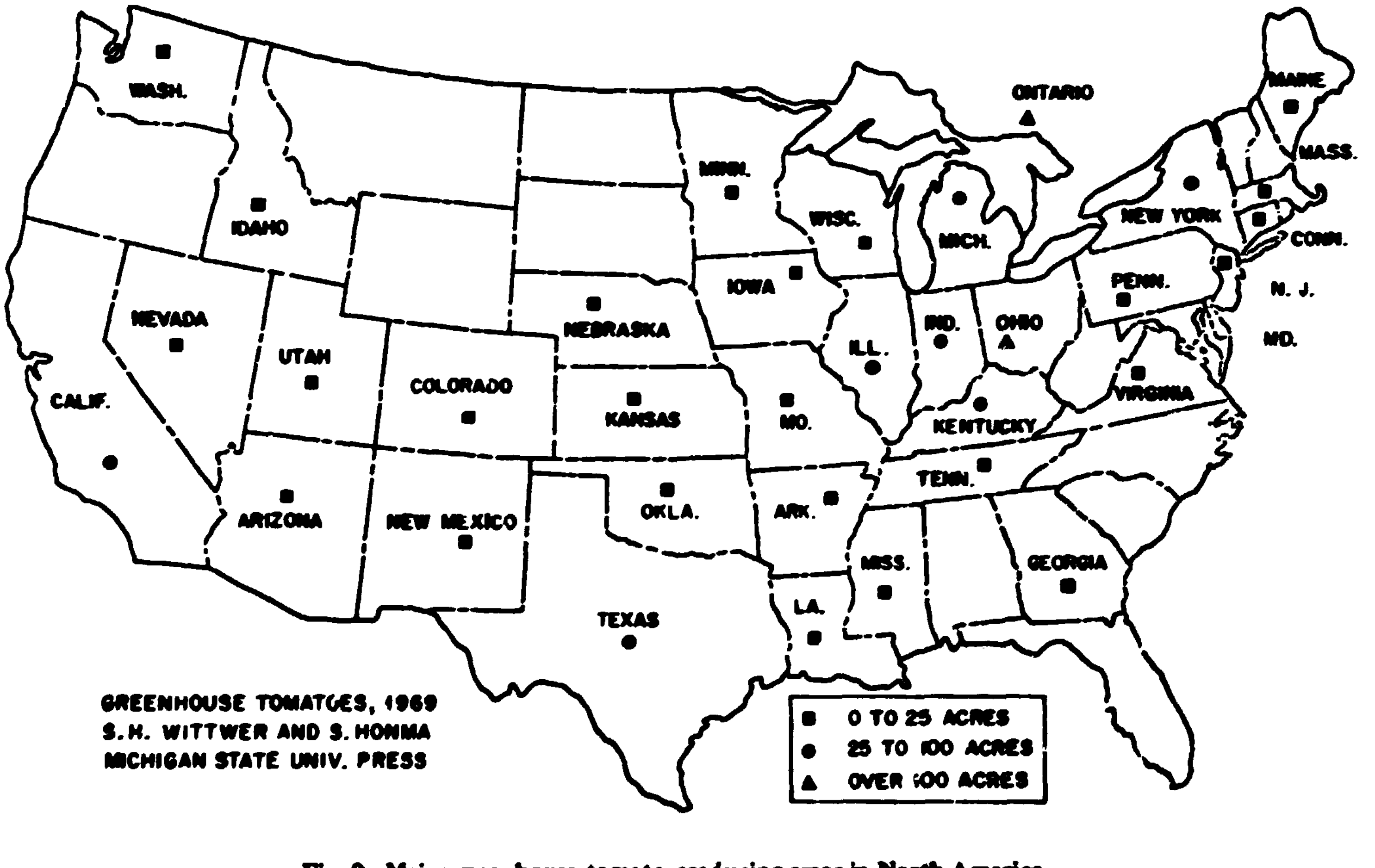

Fig. 9. Major greenhouse tomato-producing areas in North America.

Table 5. Estimated net returns for labor and management for production of 1 acre of greenhouse tomatoes*

Item	Glass	Semipermanent plastic	Temporary plastic
Fixed costs	$ 8,175–11,150	$ 7,325–9,050	$ 6,000–8,650
Operating costs	9,025–12,790	9,025–12,790	9,025–12,790
Total costs	$17,200–23,940	$16,350–21,840	$15,025–21,440
Gross cost returns less direct marketing costs[a]	$27,940–33,000	$27,940–33,000	$27,940–33,000
Net returns to labor and management	$ 4,000–15,800	$ 6,100–16,650	$ 6,500–17,975

*Courter (1965).

[a]Calculated for a production of 20 lb per plant, for total production from two crops per year, at an average price of $1.75 to $2.00 per 8-lb basket.

Table 6. Greenhouse flower production costs and returns by years in Ontario per acre, 1966 and 1968–1969*

Labor costs	1966	$31,076
	1968–1969	31,697
Heating	1966	8,496
	1968–1969	9,941
Total costs	1966	88,140
	1968–1969	85,744
Net returns	1966	2,167
	1968–1969	3,252

*"Report of Greenhouse Flower Production in Ontario – Production Costs, Returns and Management Practices." 1970. Farm Economics, Co-operative and Statistics Branch, Ontario Department of Agriculture and Food, Chatham, Ontario.

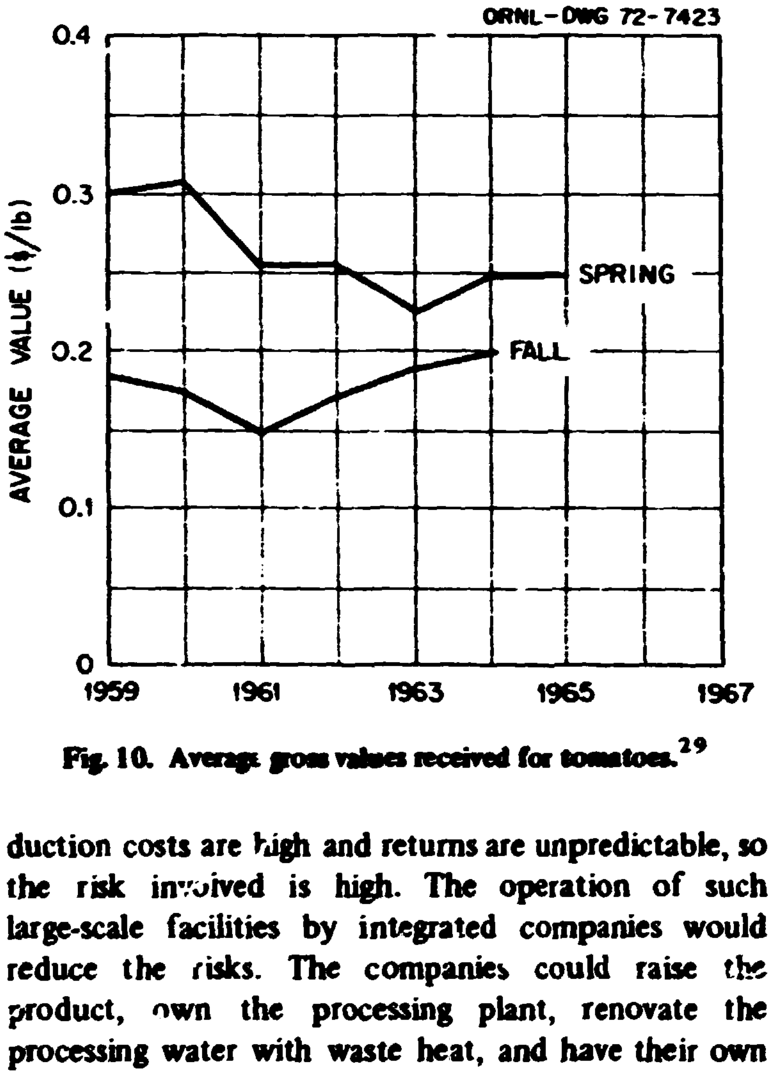

Fig. 10. Average gross values received for tomatoes.[29]

expenses to provide heat represent sizable fractions of the total expense.

An examination of the data from experiments at Puerto Penasco[22,24,26] indicates that annual yields in greenhouse culture are as much as 10 times greater than for open-field culture; prices fluctuate, however, and the profit from a crop is determined not only by the yield and the value per unit but also by the expense of production. Fluctuation in the value of tomatoes is illustrated by Fig. 10. For the large-scale greenhouse facilities considered in the ORNL study of Fort St. Vrain,[31] a proposed mixture of crops that might be raised was suggested and is shown in Table 7. Also shown are potential yields and crop value.

Reasonable profits can be realized from large-scale greenhouse vegetable operation; however, current production costs are high and returns are unpredictable, so the risk involved is high. The operation of such large-scale facilities by integrated companies would reduce the risks. The companies could raise the product, own the processing plant, renovate the processing water with waste heat, and have their own market outlet.

Evaluation and Summary of Use of Waste Heat for Greenhouses

A principal advantage of using waste heat from power plants for greenhouses is that it does not require

Table 7. Possible mixture of crops for controlled-environment greenhouse complex

Crop	Days required per crop	Yield per crop-acre[a]	Crops per year[c]	Yield per acre-year	Wholesale value per acre-year[b]	Acres assigned	Total value
Cucumbers	100	144,000 lb	3.6	518,000 lb	$31,080 at 6¢/lb	50	$ 1,554,000
Eggplants	130	24,000 lb	2.7	67,500 lb	5,400 at 8¢/lb	50	270,000
Lettuce (leaf)	40	84,000 heads	9	756,000 heads	37,800 at 5¢/head	100	3,780,000
Bell peppers	146	30,000 lb	2.5	75,000 lb	9,000 at 12¢/lb	50	450,000
Radishes	30	40,000 bunches	12	480,000 bunches	24,000 at 5¢/bunch	5	120,000
Squash	105	22,200 lb	3.6	80,000 lb	12,000 at 15¢/lb	50	600,000
Tomatoes	140	92,000 lb	2.5	230,000 lb	25,300 at 11¢/lb	100	2,530,000
Flowers	180	40,000 plants	2	80,000 plants	20,000 at 25¢/plant	50	1,000,000
Strawberries	180	40,000 lb	2	80,000 lb	17,600 at 22¢/lb	50	880,000
						505	$11,184,000

Projected average value: $\frac{\$11,184,000}{505} = \$22,146/\text{acre}$

[a]Winter season, Puerto Penasco Experiment Station, Sonora, Mexico.

[b]1970 wholesale prices, mostly from U.S.D.A. Vegetables – fresh market, 1970 Annual Summary. (Acreage, Yield, Production, Value. These represent the amount received for outdoor crops.)

[c]For areas of the country having high light intensity, low cloud cover, and near uniform day length.

modification of the plant and does not reduce power cycle efficiency. The application is one of several options available for the dissipation of waste heat produced during the production of electric power or other industrial processes. However, if all of the commercial greenhouses existing in the United States today used waste heat, they would consume only a few percent of the heat being wasted from existing power plants. Since the growth rate for power plants exceeds the present growth rate for greenhouses, it is questionable whether more than 1–5% of the total waste heat could be utilized by greenhouses, and therefore the primary incentives must be economic rather than a solution to the thermal discharge problem.

Although a large amount of water would be consumed in greenhouse operation, water losses would be less than for cooling towers if the water condensing on the greenhouse surface were collected and returned. As described earlier, during recirculation in winter, most of the water could be recovered from condensation in the attic.

In the studies at Puerto Penasco,[22,16] the closed environment itself greatly improved the yields of a wide variety of crops even though relative humidity was nearly 100%. Most successful varieties were those developed in hot humid areas. Tomato varieties such as Floradel, N-65, and Tropic did well, while varieties such as Michigan-Ohio, Wolverine 119, and Tuckcross-O did not. Whether operation at 100% humidity is possible, in colder cloudy areas of the country and with other varieties, remains to be seen. High humidity at night can result in the collection of water on the leaves of plants. This may result in growth of fungi and the spread of bacteria which are likely to be detrimental to the plant.

During winter the greenhouse operator must depend on a reliable supply of heat. At power sites with multiple units the reliability of the heat supply should be high. During scheduled or unscheduled outages of a unit, heated water would be available from alternate operating units. Base-load nuclear plants with high reliability seem aptly suited to the greenhouse requirements. Nuclear stations are equipped with a fossil-fired heater of 100 MW or more, which would provide additional reliability. In some cases a separate emergency heating unit would have to be provided.

The use of low-temperature heat therefore represents a potential way of significantly reducing operating expenses and increasing profit for the grower. A very large greenhouse operation could in turn reduce the capital investment and operating expense of the power plant operator by providing a substitute heat rejection system and a market for previously wasted heated water. Thus gains might be realized by both parties in a greenhouse operation large enough to use a sizable fraction of the waste heat from a power station, but the investment required would be large. For example, glass houses which used one-fourth of the waste heat from a 100-MW(e) power plant would require a capital investment of approximately $25 million and occupy about 250 acres. Although no such large installations are expected for many years in the United States, it is reported that single operations of 250 acres exist in Hungary.*

Little work has been done to date on the evaluation of the market for greenhouse-produced crops at the scale necessary for using such massive quantities of waste heat. Most of the existing data are extrapolated from small-scale operations of 5 acres or less.

There are many unanswered questions concerning the use of waste heat from power plants. Chemicals such as chromates used for water treatment in the cooling water system might affect the plants in a greenhouse. Similarly, the pollen from the greenhouse could possibly affect the cooling system. The determination of whether such effects will occur requires experimental studies. In the case of nuclear plants the real and imagined hazards of radioactivity must be considered, and public acceptance of products produced in such greenhouse complexes would have to be analyzed. Potential sources of activity in the cooling water would have to be considered and measuring devices installed to continuously monitor the water for radioactivity.

The most difficult questions to resolve appear to be those of institutional arrangements necessary for the financing and operating of such an enterprise in conjunction with the operating of a power plant. The organization and training of the greenhouse operating teams, agreements with the utility on shutdown schedules, provision for auxiliary heat supply, and protection of the power plant coolants from loss or fouling are several of the important problems. If risk insurance is common to greenhouse operation, the degree to which it might be affected by coupling to a power plant for heat would have to be determined.

All of these questions point to the necessity of conducting research or studies to resolve uncertainties which now exist. Although engineering questions can be resolved fairly easily, these and the biological and economic questions require demonstration projects with crops in a greenhouse facility.

Marketing data, legal restrictions, economic incentives, insurance, and other questions need extensive probing before the full potential can be ascertained. Labor is considered the number one problem.[32] Problems of providing the large skilled staff necessary for a successful operation must be investigated and solved.

Conclusions

Adequate engineering information is available to allow the design and operation of a heating and cooling system for greenhouses utilizing waste heat from steam-electric power plants. Prospects and incentives exist for the coupling of greenhouse vegetable operation with electric power production. The principal uncertainties are in the marketing problems related to high production rates, institutional arrangements for implementing such a program, and the problem of public acceptance of the product.

Presently there is need for detailed examination of the operation of a large-scale greenhouse complex in order to resolve these questions.

Animal Shelters

The feed efficiency (pounds gain/pound feed) and growth rate of some farm animals are strongly dependent on environmental temperature. Proper temperature control can decrease feed consumption and increase productivity. This is particularly important for small animals (with a large surface area to volume ratio) such as poultry and swine, and considerably less important for cows. Because the production of other farm animals (e.g., sheep, goats) is small, only poultry and swine production will be discussed here.

Poultry Operations

During the past several decades, broiler production has become concentrated in fewer, but larger, farms.** A typical operation today might produce 40,000 to 100,000 birds annually. Broiler production has grown spectacularly in recent years, from 6 billion pounds in 1960 to 11 billion pounds in 1970, an increase of 80%.[38] In recent years, broiler prices have decreased; see Fig. 11.

Table 8 lists the eight leading states in broiler production. Production is heavily concentrated in the Southeast; almost 60% are grown in Georgia, Arkansas, Alabama, North Carolina, and Mississippi. The reasons for this geographic concentration are probably related to low labor costs and a warm climate.

*Personal communication, J. A. Daum (Voskamp En Vrejland N.V. The Netherlands) to S. E. Beall (ORNL), 1971.

**Egg-laying hens are not discussed here because their supplemental thermal requirements are so low.

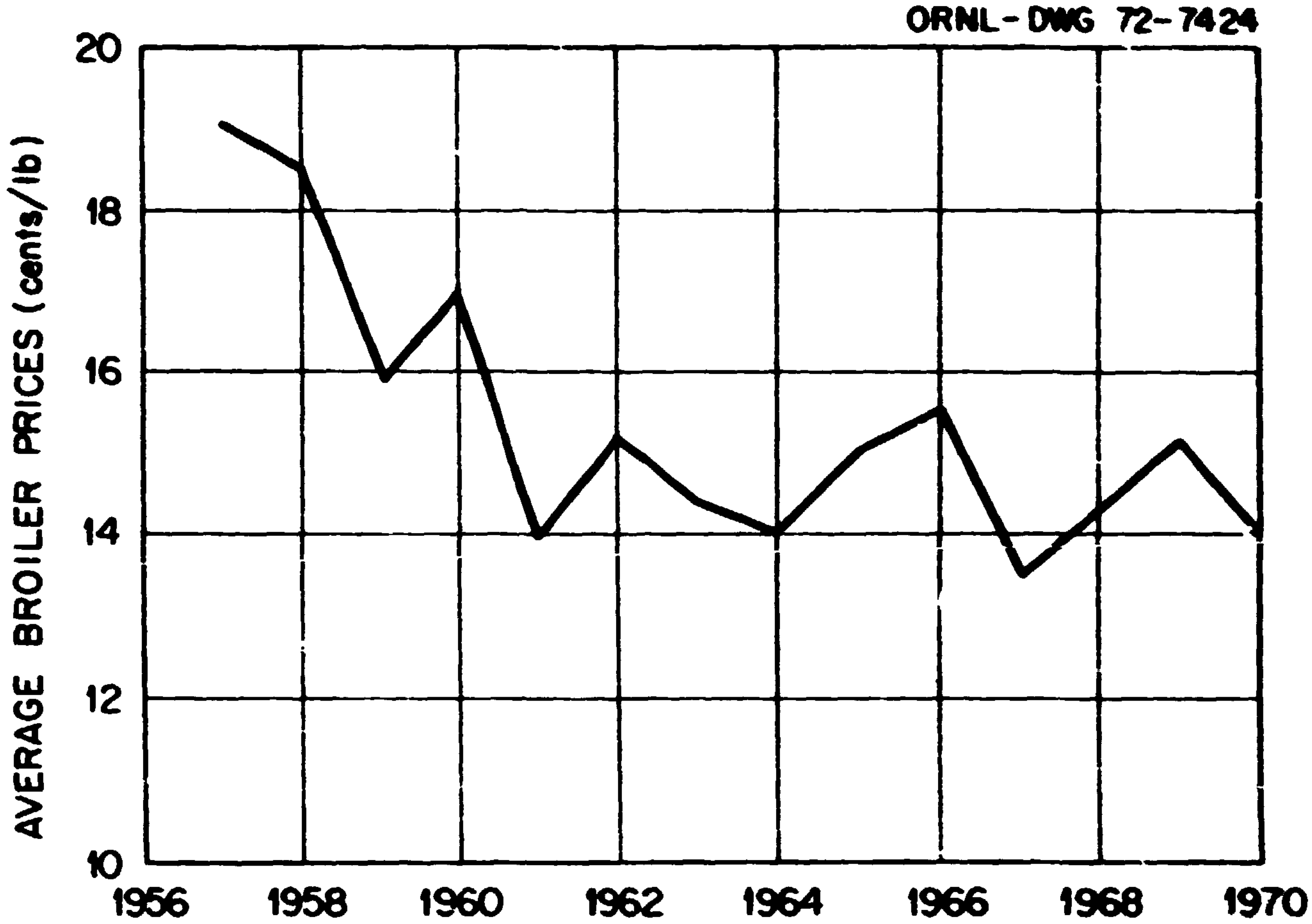

Fig. 11. Broiler prices received by farmers as a function of time.[38]

Table 8. U.S. broiler production[39] (1969)

	10^6 lb	Percent of total
Georgia	1,548	15.4
Arkansas	1,410	14.1
Alabama	1,235	12.3
North Carolina	1,038	10.3
Mississippi	774	7.7
Maryland	680	6.8
Texas	597	5.9
Delaware	521	5.2
Rest of U.S.	2,243	22.3
Total	10,046	100.0

Typical costs to the farmer of producing broilers are tabulated in Table 9, from ref. 40. This table shows the importance of maintaining high feed efficiency. Feed accounts for 62% of the total cost of raising broilers. The figures presented in Table 9 are in good agreement with more recent USDA figures.[41]

Poultry physiology. The value of a controlled environment for broilers has been recognized for some time. Numerous experiments have been conducted which show that feed efficiency and growth rate can be improved by properly adjusting the temperature, humidity, and ventilation within poultry shelters.

Barott and Pringle[42-44] demonstrated the importance of temperature control for young chicks. Their experiments indicate that maximum growth rates occur when the air temperature starts at 95°F on the day of hatch and drops continuously to 80°F on the 18th day and 65°F on the 32nd day. Figure 12 shows the effect on growth rate of changing air temperatures.

Tests conducted in Maryland[45] showed that maximum growth rate and feed efficiency occur between 60 and 70°F for broilers four weeks of age and older. These results are summarized in Fig. 13. Prince et al.[46] showed that the feed efficiency was 11% higher for broilers housed at 65°F than for broilers at 45°F.

Figure 13 shows that increasing the temperature from 40° to 60°F increases broiler growth rate by 14% and feed efficiency by 11%. This suggests that proper temperature control can reduce feed costs (improved feed efficiency) and reduce per unit labor and capital costs (higher growth rates).

This shows that broilers grow best when the temperature is maintained within the appropriate temperature range, assuming the humidity is maintained between 50 and 70%.[47-49] Adequate ventilation is required to remove moisture and odors, and to provide a uniform temperature distribution and adequate oxygen. Ventilation rates should be about 1 cfm/lb in winter and 2 cfm/lb in summer.[50]

Current shelter engineering practices. A well-insulated house can cut fuel costs by a factor of 4 compared with an uninsulated house.[51,52] Research demonstrated that energy requirements per broiler ranged from 20,000 Btu in the summer to almost 60,000 Btu in the winter with an uninsulated house for a full eight-week period, that is, from birth to market. These figures were reduced to 5000 and 13,000 Btu for an insulated house.

Drury[53] compared several different kinds (coal, gas, and electric) of brooders. Some were operated in a warm room, the purpose of which was to maintain comfortable conditions throughout the house so the chickens could keep warm with less feed. In cool-room brooding, only the area near the brooder is kept warm. The temperature in the rest of the house fluctuates with the ambient.

Table 9. Broiler production costs[48]

	Cents/lb sold	Percent of total cost
Fixed costs: depreciation, interest, taxes, insurance, maintenance	1.0	5.7
Chicks	3.1	17.6
Feed	11.0	62.5
Labor	1.4	8.0
Fuel	0.6	3.4
Miscellaneous	0.5	2.8
Total cost	17.6 cents[a]	100.0

[a]These costs are based on 1962 data for the New England area, which may not be representative of current national costs.

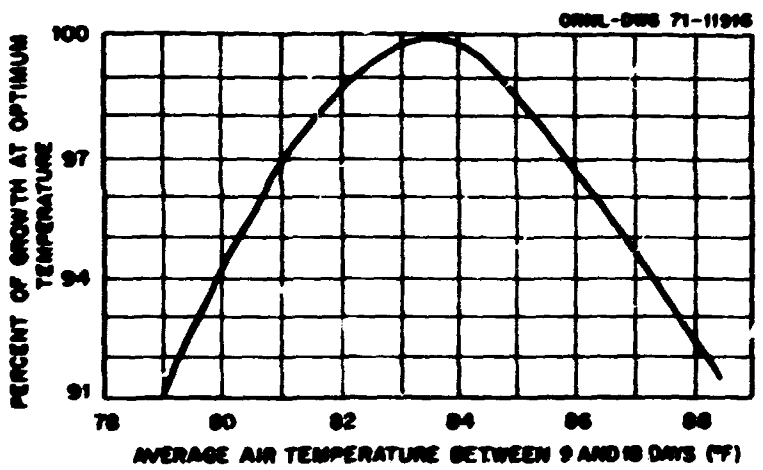

Fig. 12. Effect of temperature on the growth of chicks between the ages of 9 and 18 days.[43] Air temperature was always 87°F on the 9th day.

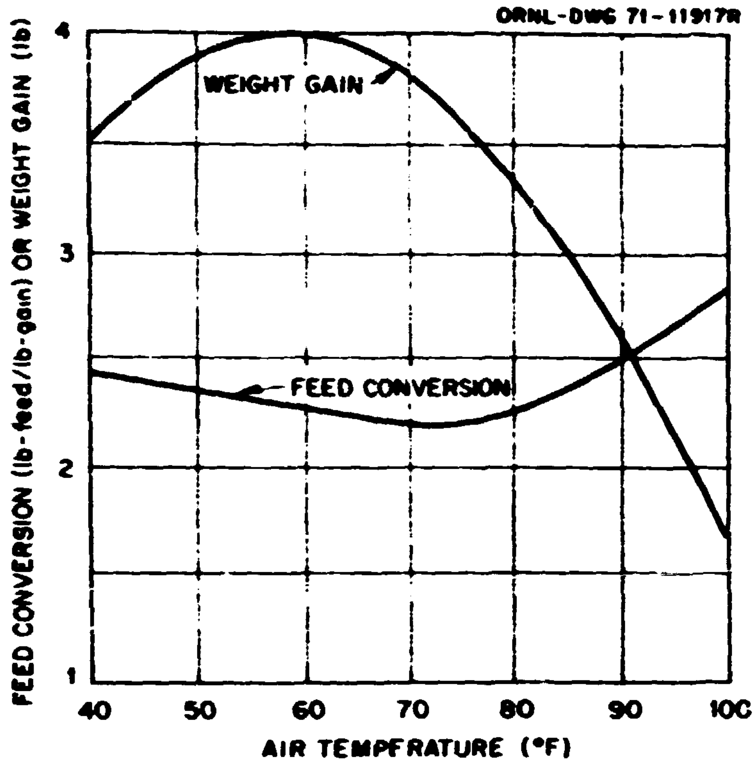

Fig. 13. Feed conversion (lb-feed/lb-gain) and weight gain (lb) for 4- to 8-week-old broilers.[45]

Under winter conditions, costs range from 4 cents/bird with warm-room coal heaters (60,000 Btu/bird) to 0.5 cent/bird with cool-room electric heaters (7500 Btu/bird). In summer these figures are reduced by a factor of 3 to approximately 20,000 Btu/bird with coal and 2500 Btu/bird with electric heating.

The use of evaporative coolers for poultry is still quite controversial. Drury,[54] in Georgia, expressed doubt that the operating costs of the equipment would be offset by the increased production. On the other hand, Longhouse and Garver[55] note that evaporative cooling is successfully used in Texas for broilers, where the wet-bulb depression is 20 to 30°F during midday. Ota[56] pointed out that evaporative cooling can be used in the Southeast during the warmest part of the day, because then the wet-bulb depression is greatest. In almost all cases, dry-bulb temperatures above 80°F occur with wet-bulb temperatures below 60°F.[47,*] Table 10, from ref. 47, shows the inside conditions to be expected with evaporative cooling. If the inside humidity is to be maintained below 80% (a reasonable upper limit), then the outside relative humidity must be lower than 50% in order for evaporative cooling to be effective.

Current design recommendations for broilers include proper ventilation, adequate insulation, and the use of

*The design wet-bulb temperature is usually higher, around 75°F.

Table 10. Temperatures and relative humidities inside evaporatively cooled buildings, for several outside conditions[a] (ref. 47)

Relative humidity of outside air (% RH)	Dry-bulb temperature of outside air (°F)											
	85			90			95			100		
	Tb	Tc	RHc	Tb	Tc	RHc	Tb	Tc	RHc	Tb	Tc	RHc
20	65	68	72	68	71	73	72	75	70	75	78	71
30	68	71	75	72	75	75	76	79	73	80	83	73
40	71	74	79	75	78	79	79	82	78	83	86	78
50	74	77	82	78	81	82	82	85	82	87	90	81
60	76	79	86	81	84	84	85	88	96	90	93	85
70	79	82	87	83	86	87	88	91	90			

[a]Tb = dry-bulb temperature of air as it leaves the cooler; Tc = dry-bulb temperature of diffused air inside the building; RHc = relative humidity of diffused air inside the building.

brooders for young chicks. Installed brooder capacity ranges from 15 to 30 Btu/hr-bird, depending on insulation and geographic and climatic conditions. Summer cooling is usually accomplished with increased ventilation rates, although evaporative cooling is used in some locations.

Swine Operations

Hog production has remained fairly constant over the past several years, increasing only slightly from 96 million in 1955 to 102 million in 1970.[38] Hog prices received by farmers have varied erratically over the past 15 years, as shown in Fig. 14, ref. 57; however, the trend seems to be toward an increase in hog prices.

Table 11 lists the eight leading hog-producing states.[58] Hog production is very concentrated; 70% of the hogs produced come from the eight midwestern states listed in Table 11. Production is concentrated in these states because of the availability of inexpensive feed, primarily midwestern corn.

Currently, a large hog operation produces about 5000 pigs/year. In the past, hogs have been grown in two annual shifts – a spring and a fall crop. Recently, the trend has been to year-round growing to make better use of the farrowing houses.

Economic data concerning hog production is quite scanty. Table 12, based on information in refs. 59 and 60, shows that feed accounts for 65% of the costs in raising hogs. Fuel accounts for about 4% of this cost.

Swine physiology. Heitman, Kelly, and Bond[61] studied the influence of ambient air temperature on the growth rate of swine; see Fig. 15. The optimum temperature for hogs varies from 73°F for 100-lb pigs to 65°F for 250-lb pigs. The growth rate drops off sharply on either side of the optimum temperature and even becomes negative at high temperatures. For example, above 95°F larger pigs begin to lose weight. This occurs because of depressed appetites and increased respiration. The growth rate of a 200-lb pig decreases by 33% if the temperature is more than 13°F higher or lower than the optimum (69°F).

Warwick,[62] Sorensen,[63] and Mangold et al.[64] present results which confirm Heitman's data and show that the

Table 11. U.S. hog production[58] (1970)

	10^3 head on farms 12/1/70	Percent of total
Iowa	16,322	24.2
Illinois	7,468	11.0
Indiana	5,129	7.6
Missouri	5,120	7.6
Minnesota	3,692	5.5
Nebraska	3,691	5.5
Ohio	2,838	4.2
Kansas	2,202	3.3
Rest of U.S.	21,078	31.1
Total	67,540	100.0

Table 12. Approximate distribution of hog production costs[59,60]

	Dollars/hog sold	Percent of total cost
Buildings, equipment	$ 3.60	18
Feed	13.00	65
Labor	1.60	8
Fuel	0.80	4
Veterinary medicine, miscellaneous	1.00	5
Total cost	$20.00	100

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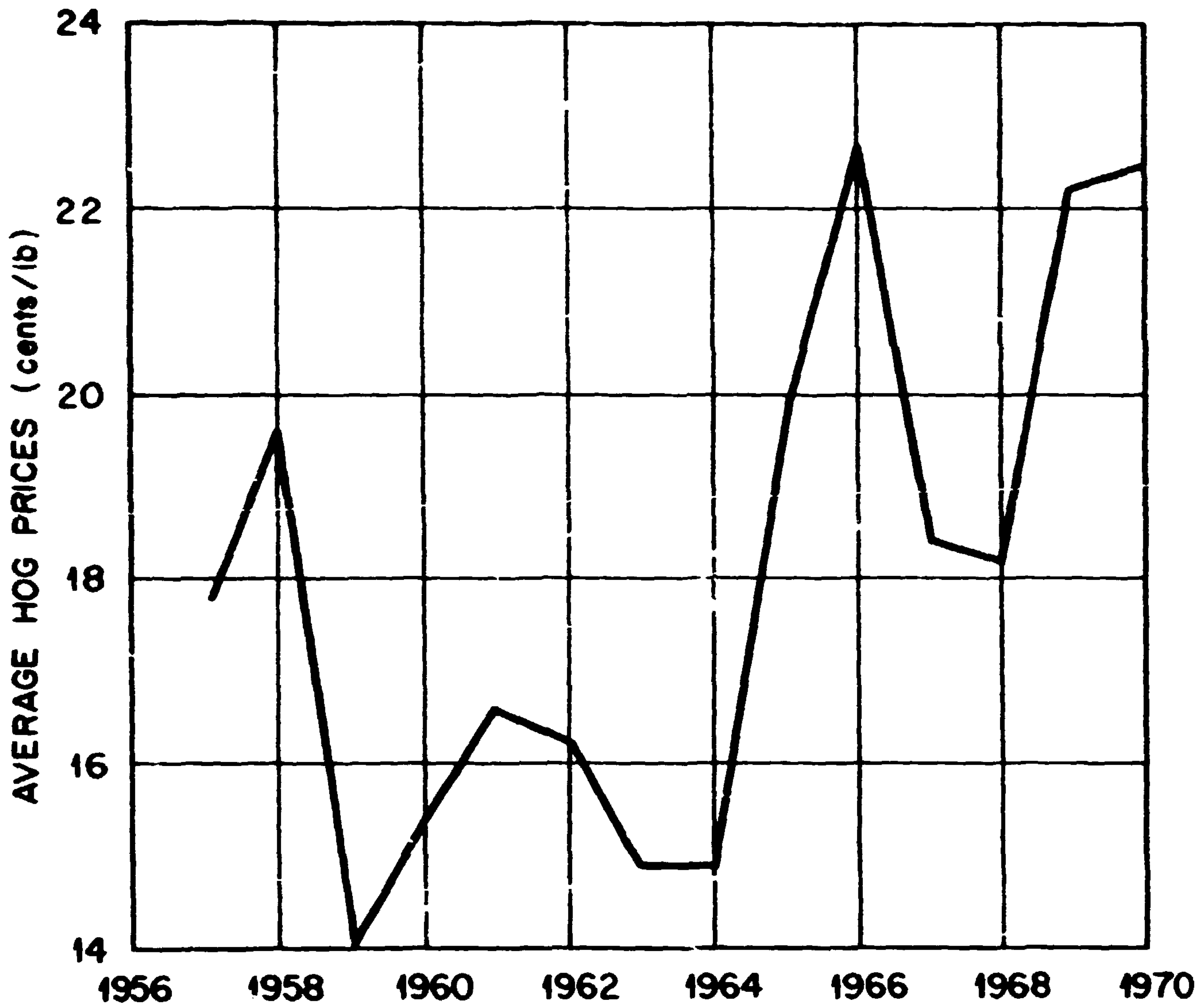

Fig. 14. Hog prices received by farmers as a function of time.[56]

temperatures for optimum feed efficiency are nearly identical to the temperatures for maximum growth rate. These results are well summarized in Figs. 16 and 17, from Dale.[65] Figure 16 shows that the optimum temperature for feed efficiency decreases with increasing hog weight, in agreement with the data shown in Fig. 15 for daily weight gain.

Figure 17 shows how temperature influences the time to market a 240-lb pig. As the daily weight gain increases, the time required decreases. Both the total feed consumption and the time required are a minimum between 60 and 70°F.

The effect of humidity on swine was investigated by Morrison et al.[66] In general, both feed efficiency and weight gain decrease with increasing humidity. Weight gain drops approximately 0.1 lb/day (~5%) with an increase in humidity from 45% to 95%. Despite the adverse effects of high humidity, the authors conclude that "evaporative cooling of hot dry air at the expense of increasing the humidity is desirable, since the benefit of lower air temperature would more than offset the possibly small detrimental effect of the higher humidity."

For example, evaporative cooling of ambient air from 90°F and 30% RH to 74°F and 70% RH will increase daily weight gain almost 60%. Thus, evaporative cooling would increase weight gain by more than 0.5 lb/day under these conditions.[67]

The optimum temperature range for pigs is between 60 and 70°F, and the relative humidity should be maintained between 50% and 75%.[47,68] Ventilation rates vary from 50 cfm for a sow and litter, and 20 cfm for a finishing hog in winter, to 200 cfm for a sow and litter, and 100 cfm for a finishing hog in summer.[59]

Current shelter engineering practices. Traditionally, environmental control in hog houses has been limited to ventilation and insulation. Several USDA publications[69-71] on swine shelters were issued in the late 1950's and make no mention of supplemental heating or cooling for noninfant swine. Infrared brooders were

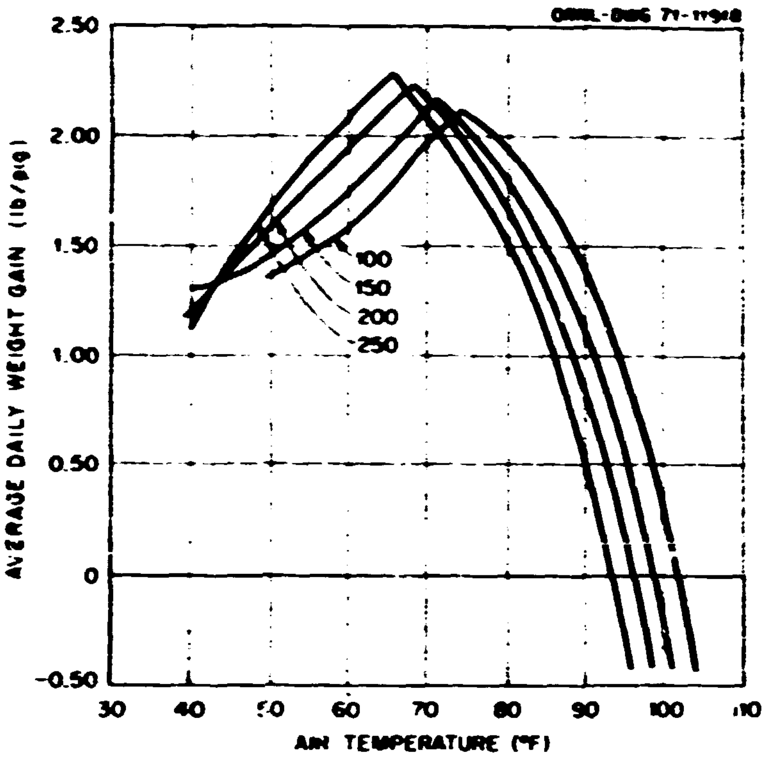

Fig. 15. Daily weight gain as a function of air temperature for different pig body weights.[61]

recommended for warming baby pigs, and shades and wallows were suggested for cooling pigs in summer.

More recently, supplemental heating has been recommended for all swine in winter[59] to improve weight gain and feed efficiency. Heater capacities of 2000 to 5000 Btu/hr for a sow and litter, and 100 to 500 Btu/hr for a finishing swine are suggested.[59]

Experiments performed in South Carolina[72] using electrical strip heaters showed an average (based on a year's operation) supplemental heating requirement of 1400 Btu/hr for a sow and litter confined in the heated pens for 21 days.

Shades, wallows, sprinklers, and drinking water offer considerable relief from high temperatures for swine.[73-74] Garrett et al.[75] compared the effects of mechanical air conditioning with those of a shaded water wallow on hog performance. While feed efficiency and growth rate were improved with air conditioning, air conditioning is generally uneconomical; that is, the capital and operation costs of air conditioning exceed the value of increased weight gain. However, mechanical air conditioning is useful for spot cooling of lactating sows.[76] Cooling only the sow, rather than the entire building, reduces the required capacity by a factor of 10.

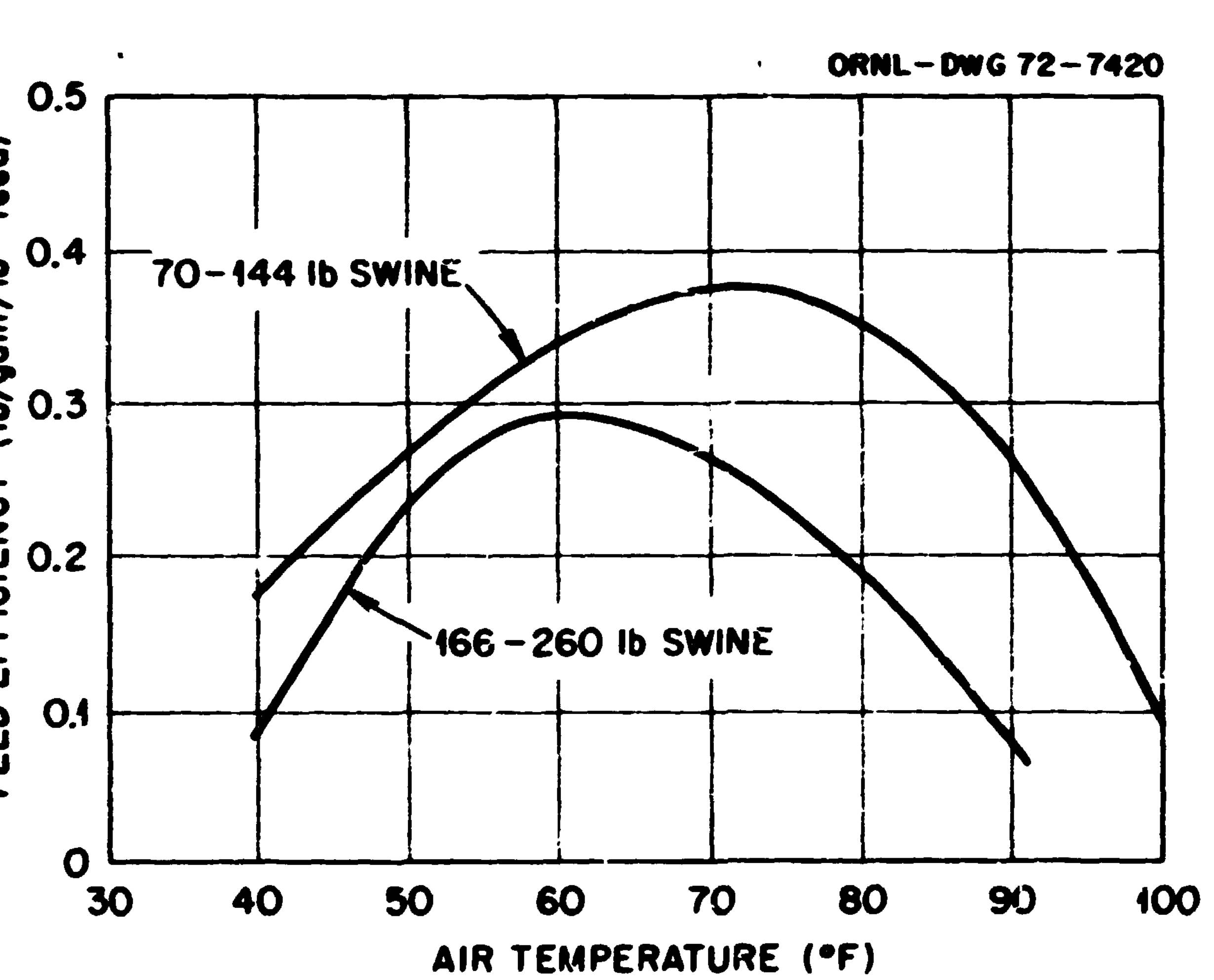

Fig. 16. Effect of air temperature on swine feed efficiency.[65]

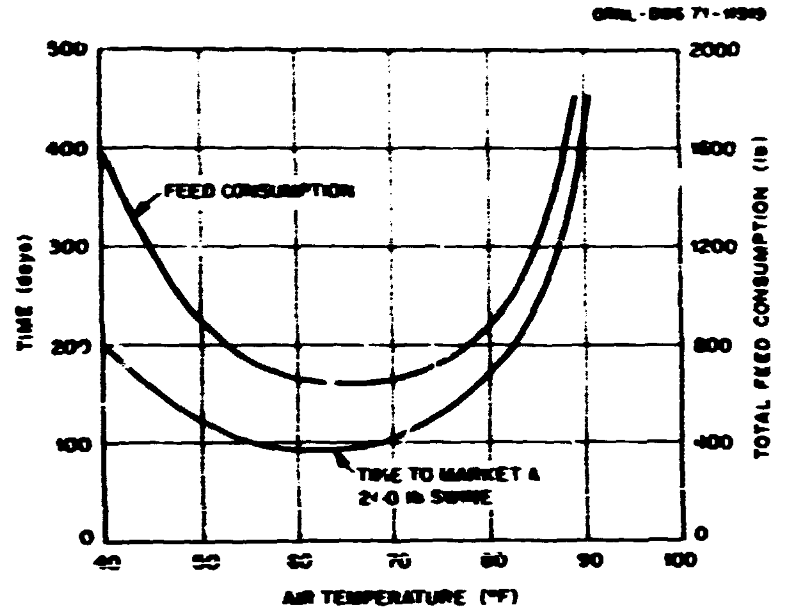

Fig. 17. Effect of air temperature on swine feed consumption and time to market.[65]

Hazen and Mangold[68] suggest that evaporative coolers are useful only in arid regions. Where the wet-bulb depression is slight, evaporative cooling may even be detrimental, because hogs cool themselves in warm weather by increasing evaporation through higher respiration rates. If the humidity is increased, then lung respiration is less effective. These conclusions, however, conflict with the results obtained by Morrison et al.[66,67]

Thus, current trends in hog production are toward greater environmental control. Specifically, some form of supplemental heating (under-floor or hot air) is becoming increasingly prevalent for both farrowing and finishing operations. Protection from thermal stress in the summer is normally obtained by high ventilation rates, proper insulation, and drinking water. Neither mechanical air conditioning nor evaporative cooling appears to be widely used.

Potential Benefits of Waste Heat Utilization

It is of interest to compute the fraction of waste heat produced by steam-electric power plants which can profitably be used for temperature control of swine and poultry shelters.

Approximately three billion broilers were grown in the U.S. in 1970.[38] Since broilers are grown year-round, the average energy required to brood all these chicks can be taken as 10,000 Btu/chick for a well-insulated house.[51] Thus approximately 0.3×10^{14} Btu/year are required to brood all the broilers currently grown in the U.S., using current data. With low-cost waste heat available from power plants, heat use might be higher since the economic penalty of providing optimal thermal conditions would be greatly reduced.

Jimeson and Adkins[77] estimate that 5.3×10^{15} Btu/year of waste heat was rejected from power generating stations in 1970. Thus, about 1% of the total waste heat generated could be used for raising broilers – under current conditions if all the broilers were raised using waste heat from power stations. In the winter, broiler heating could use almost 2% of the waste heat discharged, but in the summer it could use only 0.5% of this heat.

Hazen[78] estimates that 5000 Btu/hr are desirable for a sow and litter during a typical Iowa winter. This heat would be used for the equivalent of 50 days at the above rate. Assuming 5 million litters/winter implies that 3×10^{13} Btu would be required for heating all the sows and litters produced in winter. This compares quite well with 0.7×10^{13} Btu suggested by data obtained in the much warmer climate of South Carolina.[72]

In addition, approximately 300 Btu/hr are required for finishing pigs. Using the same 50-day full use factor and 50 million pigs per winter gives 1.8×10^{13} Btu required for the finishing operation in winter.

Thus, about 5×10^{13} Btu/winter are required to supply the current winter heating needs of American hog production. This is 1% of the total waste heat generated and about 3% of the winter heat generated. During the summer, very little waste heat would be required, just enough to keep the litters warm at night. The thermal requirements of hog production are slightly greater than those of broiler production. However, broiler heat requirements are not so concentrated in the winter.

The use of waste heat can reduce fuel bills and increase feed efficiency and growth rate for both hogs and broilers by providing optimal temperature conditions. A pad and fan system, in conjunction with a finned-tube coil (system described later), can provide *both* winter heating and summer cooling while, at the same time, cooling the condenser water.

If heating costs \$1/million Btu, then the maximum potential savings for broiler and hog growers are about \$3 million/year (\$0.01/broiler) and \$5 million/year (\$1/hog) respectively. This assumes that 10% of American broilers and hogs are grown using *free* waste heat, before incremental costs are subtracted. Alternate computations of the fuel savings using data from refs. 40, 41, and 60 give figures in reasonable agreement with those above.

Thus, the use of waste heat for warming animal shelters might save poultry and swine operators \$8 million/year in fuel costs based on *current* fuel consumption figures. However, since current practice does not maintain optimal temperatures, the potential savings may be higher than indicated here because of improved feed efficiency and increased growth rates. Feed accounts for over 60% of the total cost in both broiler and swine operations.[40,41,59]

For example, ref. 45 shows that increasing the ambient temperature from 60° to 70°F increases the feed efficiency for broilers by at least 0.05 lb-feed/lb-gain. With feed at $0.05/lb (and production of 11 billion pounds of broilers annually) this represents a savings of $2.7 million/year ($0.0075/broiler) when applied to 10% of broiler production.

Similarly, increasing the air temperature from 60° to 65°F for swine reduces the total feed consumed by 20 lb/hog;[65] see Fig. 17. This represents a savings of $7 million/year ($0.70/hog) with feed at $0.035/lb and production of 100 million hogs annually. Again, a 10% application factor is used. Thus, even slight changes in ambient temperature can significantly reduce feed costs.

The Evaporative Pad and Fan System

The system envisioned for heating and cooling animal shelters involves the use of conventional pad and fan systems with finned-tube coils; see Fig. 7 and the discussion on greenhouses in this report. Pad and fan systems are currently used in many greenhouses and in some poultry and swine operations for cooling purposes. The pad and finned-tube system used in the ORNL experimental greenhouse is shown in Figs. 6 and 8.

The pads (see Fig. 5) are typically filled with a semipermanent fibrous material. Condenser cooling water flows onto the pads from a trough at the top and drips vertically down along the fibers. Air flows horizontally across the pads and is heated or cooled depending on the ratio of sensible to latent heat transfer. The cooled water is collected at the bottom of the pads and in a closed system would be pumped back to the condensers.

Warm water from the condenser may also be pumped through the finned-tube coils, located downstream of the pads.* The air coming from the pads is heated and dried by the transfer of sensible heat across the fins. By varying the relative fractions of water pumped through the pads and the coils and the air flow rate, the temperature and humidity of the air entering the animal shelter can be adjusted over wide ranges. This system can be used for both summer cooling and winter heating. The heated (or cooled) air passes through the house and out the other end through exhaust fans. Automatically controlled louvers would permit recirculation under conditions of extreme cold.

With this system the environment within the animal shelter can be maintained near the optimum. Simultaneously, the power plant condenser water is cooled, approaching the ambient wet-bulb temperature. Thus, the animal shelter serves as a horizontal cooling tower. The engineering details of this system are described by Beall and Samuels.[31]

Problems

A significant obstacle to the use of waste heat for animal shelters is insufficient knowledge. Further studies are needed to determine the technical and economic feasibility and desirability of such a system.

Using current figures, broiler houses and swine shelters could use about 2% of the total waste heat generated at steam-electric power plants if all present animals were raised using such heat. The generation of electricity has been doubling every ten years for the past several decades and will probably continue to do so for some time. The growth rate in swine production is considerably lower, only a few percent per decade. Broiler production has increased rapidly, about 80% during the past decade. However, this growth rate is also slower than the growth in electrical generation. Thus, it appears that in the future, animal shelters will require an even smaller fraction of the waste heat generated – assuming current trends continue.

Geographic concentration is another factor which may inhibit the use of waste heat for animal shelters. Hog production is very concentrated in the Midwest, and broiler production is concentrated in the Southeast. Power plants in these areas may be able to couple their operations with agricultural enterprises, but throughout most of the country, broiler and swine production are so low that they will be unable to use more than a small fraction of the power plant waste heat. However, it is possible that the lure of cheap (even free) heat may induce broiler and swine production to shift geographically. For example, New York produces only 0.1% of American broilers[39] but probably consumes 5–10% of the total production. If the use of waste heat can lower production costs sufficiently, New York may be able to grow its own broilers.

In order to minimize pumping and piping costs, the broiler and swine operations would have to be located

*Alternately, the warm water could be run through pipes embedded in the floor of the shelter.

adjacent to the power plant (within the exclusion area for a nuclear plant). The waste heat from a 1000-MW(e) plant is sufficient to brood almost one billion broilers a year or farrow and finish about 10 million hogs a year. As indicated earlier, a typical broiler operation currently produces about 50,000 birds annually, and a large hog operation produces about 5000 pigs/year. Thus, current operations are *two or three orders of magnitude smaller* than would be required to use 10% of the waste heat from a modern power plant.

Several problems may arise with large operations such as disease, odor, and waste disposal, and these have not yet been resolved. In particular, waste disposal may be a major problem with hog operations. Current legislation and regulations require improved waste treatment, and the resulting economic penalty may inhibit the development of larger operations. However, future technological developments may eliminate this problem.

Similarly, hog operations require a considerable amount of land. Hazen[85] estimates that a 1000-hog operation requires about 30 acres. This includes hog housing, feed storage, and waste disposal facilities for a controlled-environment operation. Linear extrapolation indicates that 30,000 acres would be required to produce a million hogs/year [enough hogs to use 10% of the waste heat from a typical 1000-MW(e) plant].

The capital costs of the pad and fan and finned-tube coil system plus the pumps and piping are higher than the costs of conventional brooders and space heaters. These additional capital costs must be compared with the reduction in operating costs due to the use of waste heat. In many locations (e.g., the South) the additional capital expenses may not be justified.

The demands for heat in animal shelters are quite seasonal – considerably higher in the winter than in the summer. Yet it is during the warm summer months that thermal pollution problems are most severe. In the summer the animal shelter would serve as a horizontal cooling tower, with little advantage to the farmer. In fact, the high humidities and temperatures associated with this operation may be detrimental in certain regions of the country where the wet-bulb depression is small.

Variations in electrical generation may seriously hamper the use of waste heat for heating animal shelters. If the power plant shuts down for a long time during a period when heat is required, alternate means must be provided for warming the chicks or pigs. The cost of installing a backup heating system must be compared with the savings from the use of waste heat. This would not be a problem at multiunit power plants.

Biocides and other toxic substances are usually added to condenser cooling water to prevent the growth of algae within the condenser tubes and accessory piping. Carry-over from the evaporative pads may be harmful to poultry and swine.

During the winter, when air is being recirculated within the animal shelters, high dust levels may accumulate on the pads and in the cooling water. This dust buildup may block airflow, reducing heat transfer, and may also change the chemical quality of the cooling water sufficiently to aggravate corrosion problems.

The condenser cooling water circulated through the pads in the animal shelter is cooled largely by evaporation. This represents a consumptive use of water, amounting to about 2% of the total flow rate. In arid regions this water loss may be unacceptable. However, the water losses are no higher than they would be with an evaporative cooling tower.

Climatic variability is another factor which may inhibit the use of waste heat in animal shelters. Only certain regions of the country have climatic conditions suitable for the use of waste heat. The Midwest is a good candidate for waste heat applications, because the winters are cold and the summers are cool, with reasonable wet-bulb depressions. The Southeast, on the other hand, has warmer winters and a very small wet-bulb depression. So heat utilization will probably be minimal in the Southeast.

Concern about radioactivity may make people reluctant to buy pork and broilers grown in a reactor exclusion area. This problem can probably be overcome with a suitable public education program.

Figures 11 and 14 show the annual average prices for broilers and hogs over the past 13 years. Broiler prices have steadily declined, while hog prices have increased erratically. These fluctuations in the *average* prices show that broiler and swine operations are somewhat risky. This risk and the low return on investment may hamper the expansion of these operations into areas of waste heat utilization.

Conclusions

The use of waste heat for environmental control of animal shelters has the potential for reducing costs and minimizing environmental impacts at certain locations. Potential fuel savings are about $8 million/year for the industry, and the potential reduction in feed costs are in the same range. However, various problems exist which might inhibit such uses. Studies are needed to determine the technical, economic, and environmental desirability of such a system. Research is needed in several areas to better define the problems and potential associated with waste heat utilization in animal shelters.

Technical questions concerning the actual performance of pad, fan, and finned-tube systems remain. Preliminary work at ORNL suggests that this system can provide adequate environmental control in many parts of the country, but applications to commercial operations must be demonstrated.

The problems associated with economics and management have not yet been addressed. Research is needed to answer the following questions: Can feed efficiencies be further increased or are current practices nearly optimal? What are the problems associated with very large broiler and swine operations? Are such large operations economically viable? Are the savings in fuel costs worth the additional capital expenses associated with pumps and piping? How should the capital costs be apportioned between the utility and the farmer? Will cheap heat reduce the riskiness of these farm operations?

If research suggests that such systems for animal culture are feasible and desirable, then a pilot-plant program should be initiated to obtain field data. Ideally, the field trial should include greenhouse, poultry, and swine operations. In preliminary trials the size of the operation should be kept small, but in later tests these operations should be significantly increased to about 50 acres of greenhouses, 500,000 broilers/year, and 50,000 hogs/year to reveal the problems caused by larger agricultural operations.

Summary

Agricultural operations are capable of using low-temperature (waste) heat from power plants without reducing electrical energy production. While these uses will not solve the thermal pollution problem, they can, in particular locations, reduce the impact of thermal effluents on the local ecology, conserve energy resources, and save money for both the electric utility and the farmer.

Thermal effluents from power plants can be used in open-field-agriculture to promote rapid plant growth, improve crop quality, control pests and disease, extend the growing season, and prevent damage due to temperature extremes. Water, used for both irrigation and heating, can be applied through nozzles (spray irrigation) or through a subsurface piping system. With these systems the farm acts as a large, direct-contact heat exchanger for the power plant, while the utility provides irrigation water to the farmer.

Several research projects are under way in the Pacific Northwest to investigate the feasibility and desirability of these systems. Some additional work is being performed in the Southeast.

This use of heat is of importance for only a few days of the year (early spring and late fall). During the remainder of the year, water is needed for irrigation but not for heating. However, most power plants are sited near urban centers where rainfall is sufficient to obviate the need for irrigation. Also, the long-term implications of waste heat applications for soil management and disease and pest control are not yet known.

The use of power plant waste heat for warming and cooling greenhouses can improve crop growth and yield while reducing operating (fuel) costs by as much as $4000 to $6000/acre. With approximately 7000 acres of greenhouse production today, this represents a total potential saving in fuel costs of $28 to $42 million annually on a national basis (10 to 30% of operating costs).

Research at the University of Arizona, University of Sonora, and the Oak Ridge National Laboratory suggests that using waste heat for greenhouse climate control is both feasible and economically attractive. However, no large-scale field operations are currently under way.

Waste heat can be used to provide optimal temperature control in swine and broiler houses. Fuel costs could be reduced by $8 million annually on a national basis. Additional savings in feed costs may result from improved feed efficiency under controlled environmental conditions.

Additional study is required to determine the limitations imposed on agricultural uses by climate, geography, product marketing, waste heat reliability, effects of biocides and corrosion inhibitors in the cooling water, and consumer acceptance of products grown using cooling water from nuclear plants.

It is essential that these problem areas be thoroughly investigated before a commitment is made to large-scale agricultural applications of waste heat.

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AQUACULTURAL USES OF WASTE HEAT

Aquaculture is an ancient art. It has been practiced for centuries in the Orient, particularly in the tropical and subtropical areas where framers raised fish in flooded rice fields to provide a protein supplement to their basic grain diet.[1,2] Yet the practice is also a new technology. A few fish species have been intensively cultivated in controlled environments, and yields of these species have been enhanced by the degree of management exercised over the operation.[3,4] In pond culture, for example, with nitrogen and phosphorus fertilization, yields for carp are 100–600 lb/acre-year at sites in Israel and Southeast Asia. With supplemental feeding, these yields increased to 1600–2400 lb/acre-year. Most impressive of all are the yields in running-water culture with intensive feeding as practiced by the Japanese. Yields of 0.8–0.3 million lb/acre-year for carp have been obtained.[5] Catfish culture in ponds under semicontrolled conditions may yield 2000 lb/acre-year,[6] while yields as high as 2 million lb/acre-year for catfish and trout might be achievable in intensive culture in a flowing stream with a relatively high degree of environmental control.[7] By contrast, fishing for wild species on the continental shelf by trawling and purse seining may yield only 20 lb/acre-year.[8]

Aquaculture is more like farming, whereas fishing is like hunting. While yields from aquaculture cannot be compared with yields from fishing for wild species, the contrast provides an insight into the potential for aquaculture in supplying future fish demands.

The methods described above are all seasonal activities. No attempt is made to maintain the temperature of the culture system in the optimum range for growth. Yet basic data on fish growth indicate the potential benefits of maintaining optimum temperature (Fig. 18). For example, shrimp growth[10] is increased by 80% when water is maintained at 80°F instead of 70°F, and catfish[11] grow three times faster at 83°F than at 76°F. Growth of both both aquatic species benefits appreciably more from temperature control than does growth of animals such as broilers, cows, and swine.

Heated discharge water from steam power plants represents a large thermal energy source for maintaining the temperature of a culture medium in a range that is optimum for the growth of some aquatic species. Also, electricity is available for pumping power, permitting greater environmental control over the water system. Thus, thermal aquaculture at power plant sites offers the potential of producing high-quality aquatic foods continuously in some locations, and the possibility of decreasing the present high variability in available supply due to the seasonality of such produce.

Temperature control alone, however, is not sufficient for optimum production of aquatic species. Dissolved oxygen content, biological oxygen demand of the culture system, fish waste control, and nutritional adequacy of the food diet are some of the other important variables that also influence yield.

Methods Used in Fish Culture

Of the 2500 known fish species, less than 1% of them have been successfully cultured at all, and probably less

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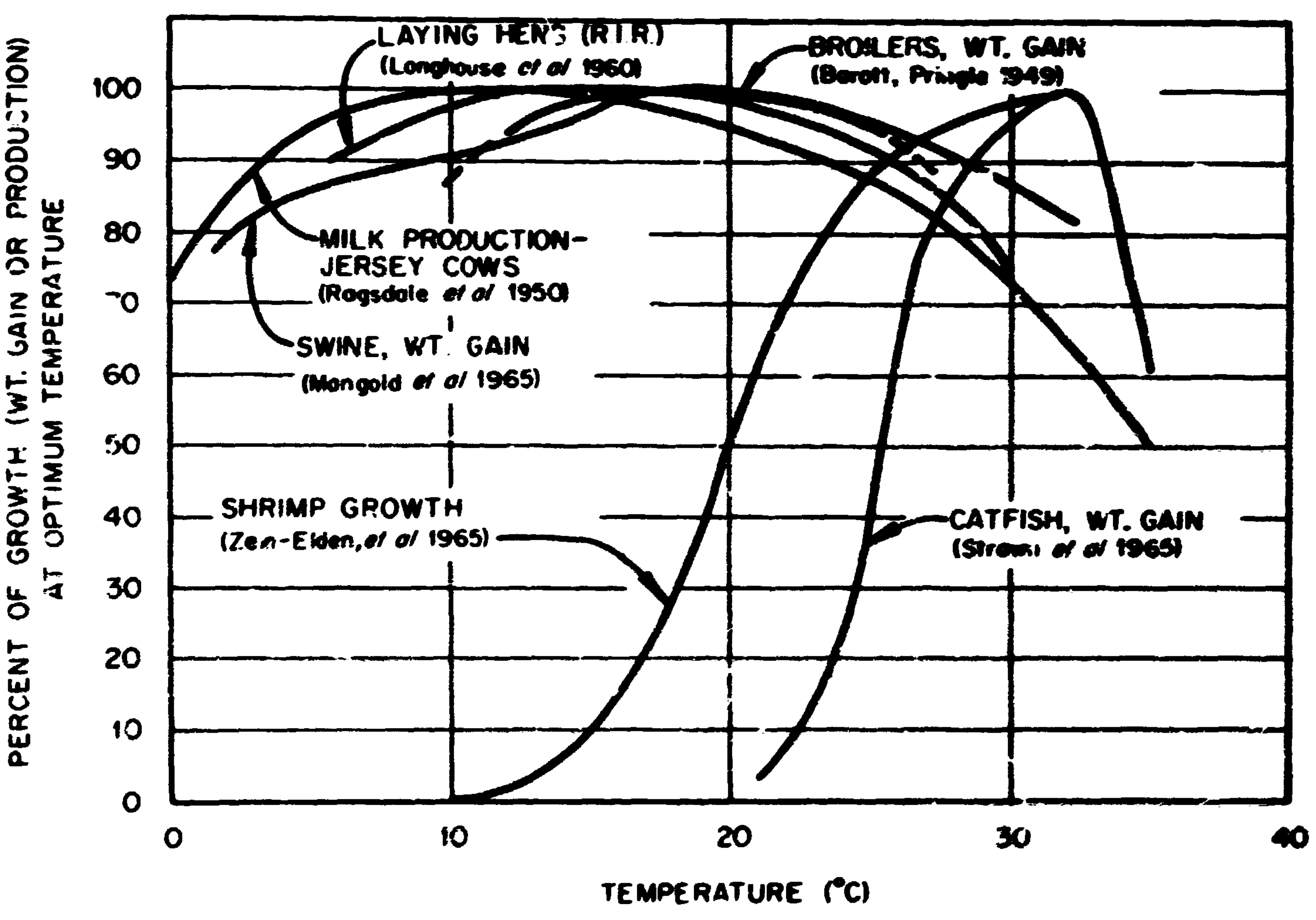

Fig. 18. Effect of temperature on growth or production of food animals.[9]

than 0.5% of them have been intensively cultured as in animal husbandry.[3,4] The simplest operation is pond culture,[1] in which environmental control is quite limited and variable. Here fish are simply stocked in a body of water. At low stocking rates (hundreds of pounds per acre), fish can exist on natural food in the water. As the stocking density is increased, nutrient levels of the pond have to be enriched by nitrogen and phosphorous fertilization and addition of supplemental foods. Aeration may become a necessity to satisfy the increased metabolic oxygen requirements. In addition, buildup of fish wastes and oxygen consumption by other aquatic organisms in the system become important factors in overwhelming the system.

In contrast to stationary ponds, dynamic systems of culture can offer a greater degree of environmental control. Fish can be confined in cages[12] (e.g., 30 ft long X 10 ft wide X 5 ft deep) and placed in a large volume of water such as natural lakes and streams, or cooling ponds or channels of coolant water. A greater water flow rate (increased number of volume changes) permits higher stocking density. Food is fed at regular intervals. Cage culture can result in disease problems when it is carried out in large bodies of water where wild fish populations exist and the fish in culture cannot be isolated.[12]

Flowing water culture is also practiced in multiple channels or raceways, each of which might be 100 ft long X 4 ft wide X 5 ft deep in a commercial operation.[13] Water depth and flow rates can be controlled. The water is utilized more efficiently and productivity (yield/acre) is enhanced. Fish population density can be high. With flowing water, environmental control is easier than in other systems; that is, dissolved oxygen is distributed more uniformly and biological oxygen demand is lower because fish wastes are flushed away. However, capital costs are about ten times that of the pond or cage culture.[4]

Current Techniques

Catfish is commercially the most widely cultured fish in this country (about 54 million lb in 1970).[15] This is a warm-water species whose optimum growth temperature is between 80 and 90°F. Seasonal culture is carried out largely in Arkansas, Mississippi, and Louisiana. Farmers usually fill their culture ponds in the spring, stock them with catfish fingerlings, feed the fish during the growing season, harvest them in the late fall, and sell them to processors who market the prepared product. However, this simple culture method is not without problems. High temperatures and low dissolved oxygen concentrations can result from solar heating of the ponds and pond stratification. Sudden algae blooms can increase biological oxygen demand in the pond system and cause oxygen depletion. Development cost for such ponds is about $400 to $1200/acre.[4]

Some of the newer commercial catfish culture projects are more sophisticated in design. Floating cages[12] have been placed in flowing water, or 70–75°F groundwater has been pumped continuously into circular tanks.[16] In both types of technology, yields up to 200,000 lb/acre-year or better have been reported.[12,16]

A successful commercial demonstration of intensive aquaculture is the Thousand Springs Trout Company in Buhl, Idaho.[7] This the largest farm of its kind in the world, supplying 30% of the U.S. market (4–5 million lb in 1969) for rainbow trout.[17] Yields of 200,000–400,000 lb of rainbow trout per acre-year are obtained, and each year shipments of 1.5 million lb of dressed trout are made to domestic and foreign markets. The year-round culture is made possible by a 250,000-gpm supply of constant-temperature (60°F) springwater that comes from canyon walls. One-fourth of this flow is diverted and distributed into channels where high-density culture is practiced. At a stocking density of 2 lb/ft^3 of water, the weight of rainbow trout supported is 16 lb/gpm of water flow. Nutritionally balanced pelletized food is fed at regular intervals, and an excellent feed conversion ratio of 1.5 lb of dry food fed per lb of wet fish produced is normally achieved. The commercial operation includes feed formulation and mixture, culture from the egg in the hatchery to growth in flowing water to a uniform marketable size, and processing of the harvested fish to a frozen packaged product. The uncommonly fresh taste and firm meat of this trout are attributed to the flowing water which flushes away ammonia and nitrogenous wastes. The average wholesale price for the product is in the middle to upper portion of the price range for rainbow trout, $0.85–1.15/lb (1971 price).

The technical success of this enterprise is probably due to the high-quality water at the culture site, coupled with sufficient knowledge about rainbow trout biology to make mass culture possible. There are relatively few sites with such a dependable source of water and only a very few aquatic species whose biological characteristics are known well enough to permit such an intensive operation.

A dependable market for the cultured product is essential to the financial success of the operation. There have been numerous instances of interprises which were technically successful but failed because of an inadequate marketing arrangement.[18]

Some seawater species have also been cultured on a seasonal basis. Raft culture of oysters and mussels has produced 2000–200,000 lb of product per acre of water surface along the shorelines of Australia, France, Japan, and the United States.[3,4] The most favorable sites for these rafts are areas where the nutrient concentrations are enriched by the drainage of rivers and estuaries and where large volumes of moving water are available to carry natural food supplies to the mobile rafts. Although no entirely suitable food formula has yet been developed for oysters or mussels, the nutrient content of the water can be further enriched by the addition of nitrogen and phosphorus fertilizers. Yields may be drastically reduced by predator attack (oyster drills and starfish) when the facility is not isolated from the sea. Four years of culture are normally required to produce a marketable oyster.

The Japanese are the foremost fish culturists in the world.[3,4] Along the bay areas of Japan's Inland Sea, finfish (yellowtail) is cultured in nylon net bags (cage culture) supported by bamboo frames. Oyster culture is an established industry of long standing; rafts are floated in bay areas, and wire strings of oysters are hung from a lattice work on each raft, where the oysters feed by pumping seawater and extracting the available nutrients. Shrimp culture owes much to the results of a 30-year effort by M. Fujinaga to perfect methods of induced spawning of gravid females and mass hatchery rearing of the larvae forms so that shrimp supplies would not be dependent on the catch of juveniles along the seacoast. Experimental culture of blue crab, abalone, and squid is also in progress.

Several varieties of seaweed (Nori) and algae (Undaria) are cultured by the Japanese for use as a condiment or additive to a variety of foods.[3,4] Both grow best in seawater that is in the range 50–70°F. Monospores cultured in indoor tanks are transferred to nets or strings suspended on bamboo rafts and allowed to grow during the late fall and early winter in shallow estuarine areas. The harvested product is processed into thin dried sheets and sold in packets of 6-in. sheets. In 1967, Nori production was 140,000 tons and Undaria was 67,000 tons.

Heat Utilization in Aquaculture

Thermal aquaculture involves the use of heated effluents (e.g., power plants or thermal springs) to maintain optimal temperatures for growth and produce high yields. Power plant coolant water has only recently been used for aquaculture. A commercial operation, the Long Island Oyster Farms of Northport, Long Island, utilizes the thermal effluent of Long Island Lighting Company for the early stages of oyster culture.[19] Normal growing periods of four years have been reduced to 2.5 years by selective breeding, spawning, larvae growth, and "seeding" oysters in the hatchery. This avoids reliance on variable natural conditions and permits accelerated growth in the thermal effluent discharge lagoon over a period of about 4–6 months, when the water would otherwise be too cold for maximum growth. Oyster culture is completed for market in the cold waters at the eastern end of Long Island Sound. The product is harvested, processed, and marketed for $15–20/bushel (1971), the upper end of the wholesale price range. About 20% of the oysters "set" in the hatchery result in a harvested product.

Catfish have been cultured in cages set into the thermal discharge canal of a fossil-fueled plant of the Texas Electric Service Company at Lake Colorado City, Texas.[20] During the winter of 1969–70, growth rates achieved were equivalent to 200,000 lb/acre-year. This is comparable to the yields of rainbow trout culture in flowing water. The Texas operation is now on a commercial basis.

A pilot research and development project is being conducted by Trans-Tennessee Industries (now Cal-Maine Industry) of Nashville, Tennessee, at the TVA steam plant in Gallatin, Tennessee.[21] Heated discharge water from the plant is circulated through nine of ten concrete channels each 4 ft wide X 4 ft deep and 50 ft in length. Algae formation is minimized by covering the channels and preventing photosynthesis. Presently, studies are being conducted at different stocking densities. Nutritionally balanced pelletized feed is fed to the catfish in culture. Extrapolated yields of up to 2,000,000 lb/acre-year have been obtained in several of their raceways. The company is planning a 230-channel facility that would supply cultured catfish to the nearby Nashville metropolitan area. The expanded facility would have a capacity for 60,000 lb of dressed catfish per week. With a continuous supply of warm water and a vertically integrated operation like that of the Thousand Springs Trout Company, Trans-Tennessee believes that it can supply the catfish demand of the Nashville area at costs considerably less than pond production costs for catfish.

Large feed production and animal processing companies in the agribusiness industry are considering utilizing waste heat for fish cultivation. Florida Power Corporation of St. Petersburg, Florida, has recently announced a joint five-year research effort with Ralston Purina Company to develop a satisfactory technique for culturing shrimp at the utility's Crystal River site.[22]

Armour and United Fruit have conducted a small research effort on shrimp culture in cooperation with the University of Miami at Florida Power and Light Company's Turkey Point facility.[23]

Smaller companies like International Shellfish Enterprises are developing methods for oyster culture in the thermal discharges canal of Pacific Gas and Electric's plant at Humboldt Bay.[24] Marifarms, Inc., of Panama City, Florida, is utilizing the warm water from the local power plant to maintain pond temperatures in winter so that mortality of shrimp in culture is minimized.[25] Experimental lobster culture using warm water is being considered by a few institutions, including a California group (San Diego Gas and Electric Company and Mariculture Research Corporation) and the Department of Sea and Shore Fisheries of the state of Maine.[26]

The Japanese[27] have led the way in demonstrating the benefits of waste heat utilization for aquaculture. Shrimp, eel, yellowtail, seabream, ayu, and whitefish are being cultured. Culture experiments started at the Sendai Power Plant in 1964. Five other demonstration programs have been established at fossil-fueled power generating stations. In pond culture at a power plant in Matsuyama, shrimp are cultured in thermal effluents blended with ambient water to maintain constant temperature. Summer growth under culture conditions was 1.2 times the growth of shrimp in natural summer water temperatures, while winter growth was 7 times that of shrimp in ambient temperature water.[28] Survival rates were about 50% in the summer experiment and as low as 30% in the winter experiment.[28] In flowing water, yellowtail cultured in constant-temperature water from October to June grew to a weight of 1.5 times the weight of fish cultured in natural water. No mortality or parasite problems were encountered.[29] At the Tokai-Mura Nuclear Power Station near Tokyo, a multispecies $575,000 demonstration program of thermal aquaculture has just been approved by the Japanese government.[30] The five-year program is to develop a facility consisting of 35 concrete channels of various sizes to demonstrate flowing water culture. Additional funding for the program is anticipated from the utility companies through the Japanese Atomic Industrial Forum.

The English[31] have had a small development program since 1966 on the culture of flatfish species, plaice and sole, at their nuclear plant in Hunterson, Scotland. The problem of free chlorine toxicity was avoided by the use of a continuous chlorination treatment of coolant water instead of the conventional batch treatment. This resulted in a residual of less than 0.02 ppm Cl_2. The problem can be further reduced if the power plant uses mechanical cleaning techniques. No radioactivity is allowed to be diluted into the coolant water stream used for aquaculture. Although culture of the flatfish species has been demonstrated, wide-spread culture has been restricted by low food conversion efficiency and high food costs. Low-value fish is used as feed, and a suitable low-cost, formulated food has not been developed. Flatfish are cultured in flow-through ponds near the shoreline. Since the system is not isolated from the sea, predator attack and disease are of concern.

Feasibility Study of Thermal Aquaculture

A thorough feasibility study of a conceptual design and the market potential for a shrimp culture facility has been performed.[14] The study used the published data on shrimp biology and technology to develop a conceptual design for continuous culture in a flowing stream. A cost estimate, a cost sensitivity analysis, and a market projection for the cultured product were developed. Sophisticated channel culture was proposed (Fig. 19) in which juvenile shrimp, cultured from the egg in a hatchery, would be raised in a series of pens of increasing surface area within a channel until the shrimp reached marketable size. The channel design (Fig. 20) is based on a generalized growth curve published by Lindner and Anderson.[32] This curve is divided into equal segments to allow six months of cultivation time after insertion of juvenile shrimp into the channel. Each pen area would be proportional to the area under each corresponding segment of the growth curve. Weight density would be maintained constant throughout culture by moving batches of shrimp to progressively larger pens at regular intervals as the shrimp increase in size. Shrimp would be harvested from the largest pen at the end of the cultivation period. Other shrimp in culture would be moved forward one pen, and shrimp from the hatchery would be inserted into the smallest pen at the beginning of the channel. When all the pens are operating, the culture system would be in equilibrium, and harvesting would be done on a weekly basis.

With year-round cultivation at optimum temperature, a shrimp yield of 20,000 lb/acre/year was projected. This would be four times the seasonal yields (lb/acre/year) that have been reported for Japanese shrimp culture in flowing water.[3] This is based on two crops per year instead of one and the doubling of weight density of shrimp in culture from 55 to 110 g/ft^2 of bottom area (shrimp are bottom dwellers). Weight densities up to 200 g/ft^2 have been reported for the culture of bait shrimp in aerated tanks.[33]

A detailed cost estimate was made for this integrated conceptual design and included feed preparation, shrimp culture from eggs and larvae in the hatchery to growth to a harvestable size in channels of flowing water, and processing to the frozen product. For the assumptions made, the calculations showed a yield of 10 million lb/year of shrimp which at 1970 market levels would have a wholesale value of $1.00/lb. Production costs were estimated to be about 80¢/lb.

The production cost was found to be most sensitive to feed conversion ratio and least sensitive to labor considerations; capital costs for site improvement were intermediate. Low-cost, nutritionally balanced feed is important to the economics of shrimp culture, because it constitutes more than 60% of the total operating cost. To date, no feed has been successfully tested for the mass culture of shrimp, although food formulation test programs are currently under way both in the United States and in Japan. In this country, formulated feed has been developed only for the mass culture of rainbow trout. This same feed, however, has been used for the mass culture of other fish. In Japan, shrimp in culture are fed low-value fish which give a food conversion of 10 lb of feed to 1 lb of flesh. It is economically feasible to do this, because retail prices for live cultured shrimp command a higher price in Japan than in the United States.[34]

Market Estimates for Cultured Fish and Seafood

The potential of thermal aquaculture is related not only to technical feasibility but also to markets for the products. There is little statistical data at present to indicate the extent of demand for cultured aquatic foods in this country. In Japan, fish is a prime source of protein, and the per capita fish consumption in 1967 was 120 lb/year, an order of magnitude above that in the United States. Aquaculture in Japan represents a significant tonnage and monetary value in the fisheries industry. In 1967, the total catch was 15.6 billion lb, with a value of nearly $2 billion. Aquaculture products totaled 940 million lb and were valued at nearly $300 million, about 6% of the total catch and 15% of the

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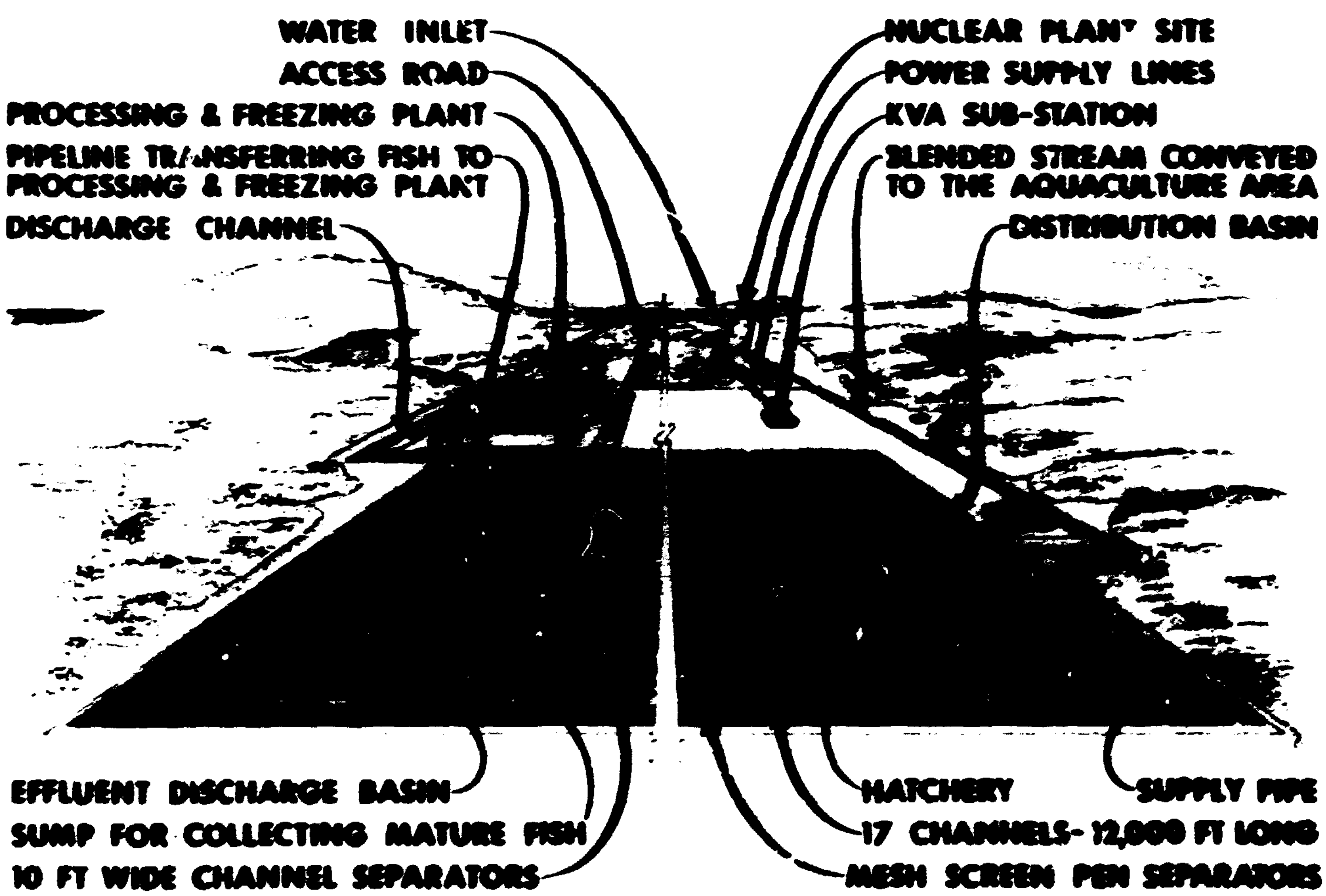

Fig. 19. Artist's concept of an aquaculture facility.

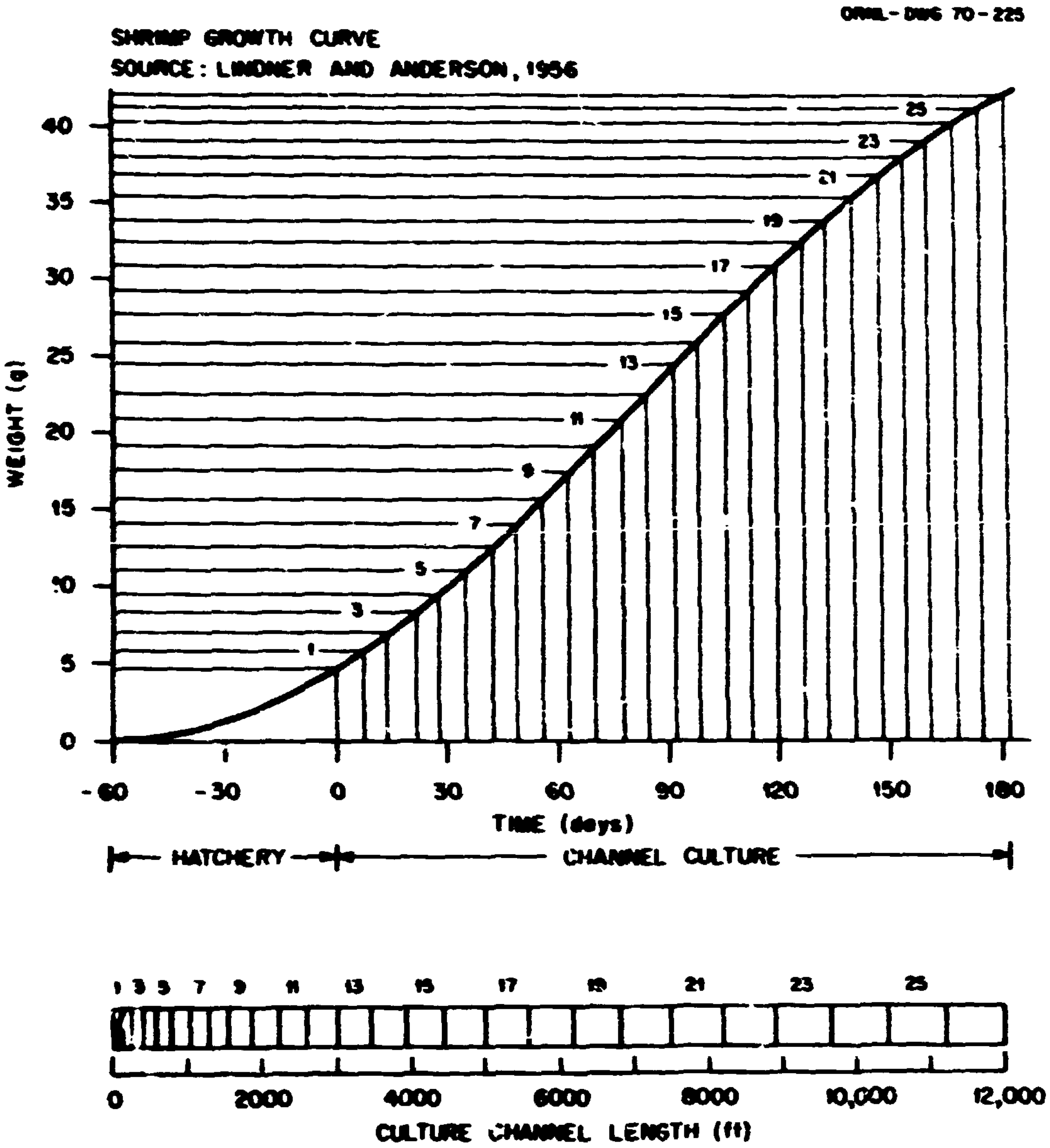

Fig. 24. Channel design based on shrimp growth.

total value. Certain cultured products can command luxury prices in Japan.

As mentioned earlier, the yellowtail fish of the tuna family has been cultured extensively in Japan. In 1963, 60% of the Osaka market for yellowtail was furnished by aquaculture. By 1965, production reached 36 million lb, but further production increases were threatened by a lack of natural supply of small fry. By 1968, artificial propagation was successfully developed so that future demands for the fry could be met.[35]

Present difficulties in providing a constant supply of fish have presented serious problems to the seafood industry in the United States, and the scarcity of certain seafoods is given as the most serious problem by the U.S. seafood industry.[36] On a world basis, seafood consumption represents the fastest growing food area, but world sustained yields from natural sources will be limiting for many species within the next few decades.[36] Culturing of fish and other seafoods would reduce this problem. In the United States, aquaculture is in its infancy. Statistical data[31] show that during the past decade total edible fishery products have risen from 4.3 to 6.2 billion lb. The domestic catch, however, has remained approximately constant at 2.0 to 2.5 billion lb, while the imported supply has increased from 1.8 to about 3.7 billion lb. Less than 1% of the total supply is furnished by fish culture.

However, statistical data provide an incentive for considering the culture of high-value fish species. For example, in the period 1950 to 1970, shrimp per capita consumption rose 160% from 0.8 to 2.0 lb, while total consumption of all seafoods remained relatively constant at about 10–12 lb.[37,38] Consumption of meat, poultry, and fish combined rose by 40% in this same period.[39] Although the domestic catch of shrimp is the largest in the world, imports constitute more than 50% of annual total supply in the United States. There is no import duty and no quota placed on the amount imported. The National Marine Fisheries Service has indicated that shrimp consumption is less sensitive to price changes than is beef and pork consumption. They predict that the annual per capita shrimp consumption will exceed 3.0 lb before 1980. They feel that the fraction of shrimp supply imported will have to increase to meet the added demand. By 1980, world shrimp demand will equal the world's estimated harvest potential, and they feel that beyond 1980, aquaculture will have to supplement world supply in order to continue to meet world demand (Fig. 21).[40]

In general it is speculated that the dollar value of fishery imports will rise faster than the annual tonnage imported, because a greater fraction will be high-value species.[41] Domestically cultured fish products can be substituted for some of these imports, provided the operation is economically viable.

Some food market analysts predict a growth in U.S. fish consumption through development of a new aquacultural industry based on advanced technology. This has occurred in the chicken broiler industry.[42] For the 30-year period 1939 to 1969, per capita consumption of chicken rose from about 1.5 to about 35.0 lb/year, while per capita fish consumption remained at 10 to 12 lb/year. In modern broiler technology, food conversion ratios improved from somewhat less than 5 lb of feed per lb of flesh to about 2 lb/lb.

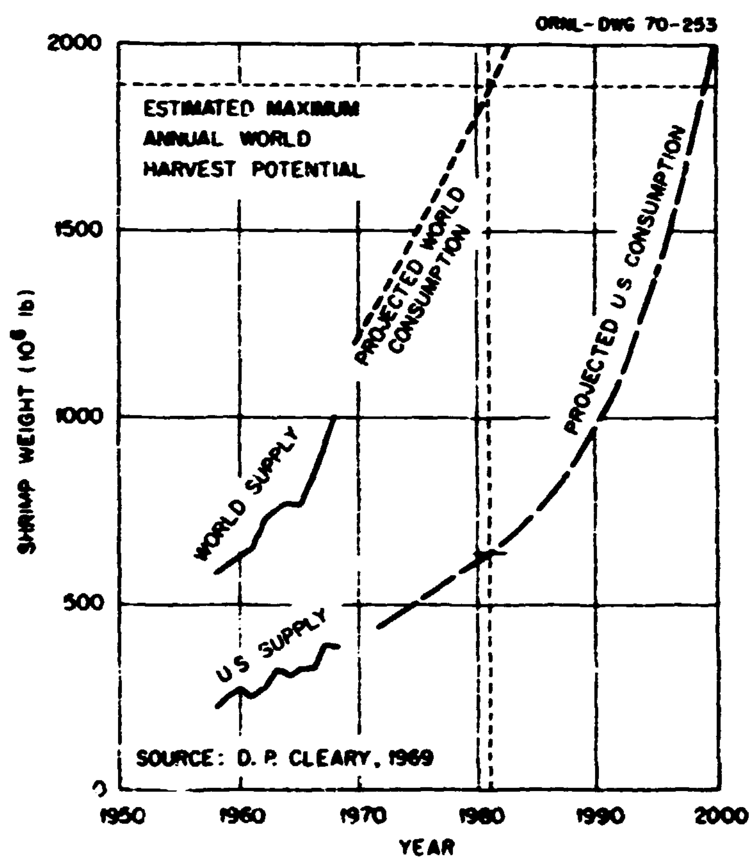

Fig. 21. Market projection on future U.S. shrimp consumption (heads-off shrimp).

Cultured species like catfish and rainbow trout under adequately controlled environments do convert nutritionally balanced feed to flesh as efficiently as in broiler production or better. For some other species like shrimp, food conversion efficiency is low because suitable food formulations have not yet been developed, and only natural foods like low-cost fish can be fed at this time. Food formulas are being evaluated now, and with other improvements including environmental control, a cultured product that is superior to the corresponding wild species could significantly alter the per capita consumption of fish foods in the future.

Potential for Heat Utilization

Fish culture facilities may be located at power plant sites to utilize land area surrounding the power plant. Power and water are available to blend water streams to achieve water temperature control. Flowing-stream thermal aquaculture may permit year-round intensive culture of some species, an improved product quality over that cultured in a pond on a seasonal basis, and a significant reduction in the costs of culture.

Estimates on the growth of thermal aquaculture in relation to waste heat are difficult. Few demonstration projects are available, and yield data are scarce. One may gain insight into the relationship between heated water availability at power plant sites and the potential for aquaculture from the following assumptions:

1. Water utilization. About 2000 MW of waste heat is generated for each 1000 MW of electricity produced. About 1000 million gallons per day (Mgd) of cooling water is required to dissipate this waste heat with a 20°F rise in water temperature. If the average ambient temperature of the inlet water is assumed to be 50°F for the colder half of the year and 70°F for the warmer half, and if 70°F is the temperature to be maintained for best growth, then heated effluent (at 70°F) would only be used for thermal aquaculture during the colder half of the year.* During the warmer half, ambient temperature water at 70°F would be used instead of the heated effluent at 90°F. Thus heated water would be used only half of the year. Even during this period the heat is not "consumed," and "thermal pollution" is not reduced significantly.

2. Fish yields. The 1000 Mgd (700,000 gpm) of water is distributed over 1000 acres of working water

*In reality, the source of water at each power plant site has its own seasonal temperature cycle. Winter water temperatures in many locations reach 35°F for a few months, and growth rates would be low during this period.

surface. This is about one-half the size of an exclusion area for a 1000-MW(e) nuclear power plant. At a fish yield of 10 tons/acre-year (a pessimistic value for intensive culture), an annual production of 4000 tons or 0.02 lb of fish harvested per 1000 gal of H_2O could be realized. This is less ambitious than the production rate at Thousand Springs Trout Company in Buhl, Idaho, where 60,000 gpm of water is distributed over 10 acres, and a harvest of 100 tons/acre-year or 0.06 lb of fish harvested per 1000 gal of H_2O is achieved.

For a U.S. population of 200 million and a per capita fish consumption of 10 lb/year, the national consumption of fish food would be 2000 million lb.[43] If 10% of this fish consumption were supplied by thermal aquaculture, the equivalent of twenty-five 1000-MW(e) power plant installations of the type postulated would be required. If per capita consumption increased to that in Japan (100 lb/year), the number of 1000-MW(e) power plant aquaculture installations needed would be 250. In terms of land requirements, 10,000 to 100,000 acres would be used.

Table 13 gives some extrapolations for the years 1970 to 2000 based on similar assumptions as given above. The figures show a decrease in the fraction of heated effluent utilized from 14% in 1970 to 2% in 2000. Changes in per capita consumption or the fraction of demand furnished by thermal aquaculture could significantly change the figures. In any case, only a small fraction of the waste heat available from steam power plants is required for aquaculture, and though aquaculture employs the ambient temperature of the water, the heat is, of course, not consumed. The production of this ambient temperature by other means, however, would require the expenditure of very large quantities of energy.

It is, of course, extremely difficult to predict a market for a new technology like thermal aquaculture, and a thorough market analysis is required. Further, the impact of thermal aquaculture on waste heat utilization should be considered on a site-by-site basis, because water quality is highly variable and the ambient seasonal temperature of water used for cooling purposes is important. Conditions in one section of the country may not apply to other sections. Even within a region, the temperature and quality of waters are highly variable. If, for example, water temperatures are lower in the winter than for the simplified case presented, then fish productivity would be adversely affected. Therefore, generalized projections on a national basis can be very deceptive.

Table 13. Thermal aquaculture land and waste heat utilization

Year	Population[1] (millions)	Fraction of heated effluent for thermal Aquaculture[2] (%)	Land for thermal aquaculture[3] (acres)
1970	200	14	10,000
1980	235	6.8	11,750
1990	270		13,500
2000	300	2.1	15,000

[1] Reference: National Academy of Sciences, *Resources and Man* (1969).

[2] Market assumptions: (1) per capita consumption of fish foods, 10 lb/year; (2) 10% of demand furnished by thermal aquaculture. Changes in consumer tastes could change these assumptions.

[3] Assumes 20,000 lb live product/acre-year.

Technological Problems and Development

The utilization of waste heat for aquaculture will have little effect on the amount of thermal energy to be dissipated. However, the waste heat can be used to increase food production. In some instances, fish production would result in a reduction in discharge temperature, since ambient temperature water would be blended with the warm effluent to maintain the optimum temperature range for fish growth. In this case the temperature of the return water stream would be reduced. Thermal plant cycle efficiency would only be affected if the winter discharge cooling water temperature were maintained above normal values.

Only once-through cooling has been studied to date. Aquaculture in conjunction with closed-cycle cooling towers has the advantage of higher available water temperatures but would require a feasibility study, because tower blowdown rates (which would remove wastes) are at least 20 times less than for a once-through system. The effect of particulates and increased dissolved solids in the blowdown as well as biocides added would have to be considered. Fish culture in the main recirculation stream could be a possibility, but fish wastes will have to be treated prior to recirculation to the power plant condenser. The adaptation would require further study.

Another possibility for using warm water from a cooling tower system is to circulate the water through a heat exchange system (such as that described earlier for greenhouses and animal shelters) to maintain the temperature of a building which houses aquaria or fish culture tanks. In this enclosed concept,[44] already in the demonstration phase, large tanks are stacked vertically on frames. Each tank contains sufficient water for 500 one-pound fish. The water is recirculated continuously through the tanks to filters and aerators. The amount of heat required to maintain the building temperature depends on the building surface area, insulation and climate, but would be in the range 0.25 to 0.5 MW per acre of space used.

Large-scale use of waste heat for aquaculture would probably not be considered until demonstration projects at existing sites indicate an economic viability. The projects mentioned earlier may serve this purpose.

Since the demonstration phase may occupy several years, it is unlikely that larger facilities will be planned soon for plants under construction or design. Although such facilities could be installed at a later time, it would be preferable to include the aquaculture facility in the original site selection and planning.

Engineering design and evaluation are needed for intensive aquaculture systems. Applied research and development work would be necessary to complement engineering tests. For a given species, mass culture techniques can be quite different from laboratory experiments. Flow rates for channel culture must be optimized so that energy spent on physical activity is minimized and food energy conversion into flesh is maximized. Aeration systems should be evaluated. Fish handling devices for transferring and harvesting in a flowing system need to be considered. Fish waste treatment systems need to be designed and potentially represent a significant problem. For the near term, wastes might be diluted by installing relatively small aquaculture farms at each power station, thus holding waste concentrations low, consistent with water quality standards. Low-cost nutritionally balanced feeds must be made available.

Selective breeding should be considered to produce species particularly amenable to intensive culture. Fish culturists must be able to furnish fingerlings the year-round in order to have truly continuous culture. Medicinal treatment methods must be available to treat fish diseases rapidly, particularly in intensive culture. Water quality must be satisfactory.

Other technical and nontechnical problems may include the following:

1. To increase the reliability of heated discharge water, it may be necessary to practice aquaculture at multiple-unit plants. Only a fraction of the total volume of heated discharge water would be used for aquaculture, so that in the event of an outage, a switch could be made from a nonoperating to an operating unit.

2. Even if multiple units are available, unprogrammed shutdowns could cut off the warm water supply suddenly. Such rapid temperature changes could be lethal, and, at least, fish growth rates would be lower until the power plant resumed operation. However, it might be necessary to provide for rapid valving to an alternate operating unit or an auxiliary supply or to stop the water inflow so that thermal shock is minimized as a result of the shutdown. Systems with large thermal inertia would be less affected. Sudden temperature changes on startup could be ameliorated also by gradual blending of heated discharge water with recirculated ambient water.

3. Batch chlorination of coolant water may result in a residual free chlorine concentration that is toxic; this may be prevented by aeration to drive out the gas, by reverting to continuous chlorination instead of the conventional batch treatment, or by substituting mechanical cleaning devices[45] or periodic thermal shock treatment of the cooling tubes of the condenser.

4. Increased copper concentrations occur in the discharge water from power plants when condensing temperatures above 100°F are employed. Copper tends to concentrate in oysters and causes a green coloration. Copper may not be a problem if the condenser steam temperature is held below 100°F.[46]

5. Nuclear plant thermal water used for aquaculture must be protected from radioactivity being discharged into the stream. Monitoring of activity in the cooling water would certainly be required. Fossil-fired stations would of course not have this requirement.

6. Fish wastes discharged from an intensive culture facility may have to be removed by acceptable waste treatment methods to minimize the BOD discharged to receiving waters and to meet water quality standards. The waste treatment plant size, design, and economics will have to be studied for each facility.

7. Legal and regulatory restrictions such as water quality, water rights, and prior appropriation (regulations on the total amount of water usable in a power plant) may influence the viability of the idea in certain regions, including many western states.[47]

8. Regulatory restrictions on the discharge of heated water may eliminate the once-through approach that has traditionally been used in hatcheries.

9. Insurance costs might have to be borne by a food cultivator to cover damages that might result from a sudden accidental release of radioactivity or chemicals from a nuclear or fossil power plant – a statistically low possibility but a real one.

Various types of integrated systems may be considered. Multispecies culture systems might be considered, including finfish in channels, conversion of fish wastes to algae, and intensive oyster culture fed on this algae.

Agriculture-aquaculture systems might be considered, particularly in the summertime when thermal effluent temperatures may be too warm for fish culture. Greenhouses might be used as cooling towers to extract heat from thermal effluents, and the discharge from greenhouses may be used for fish culture. This integrated system might permit the maximum utilization of waste heat for food production, and simultaneously incorporate aquaculture into a closed recirculating system instead of a once-through cooling system. However, fish waste treatment would be a necessary part of this system and may be expensive.

Demonstration of intensive culture using a culturable fish species and power plant thermal effluents is needed, and information is needed on the degree to which yields are improved by waste heat utilization in small pilot systems. The facility at the Gallatin Steam Plant should answer some of these questions for that specific site and species; work now being carried out by Long Island Oyster Farms, Inc., at Northport, New York, will provide additional information on oysters, clams, and scallops; and work in Florida, California, and Maine should provide information on other species. Additional demonstrations at other sites for other species, however, are still needed. Once the data are obtained, sufficient information will be available to determine the incentives for performing the engineering, biology, and chemistry necessary for thermal aquaculture on a commercial scale.

Summary

Thermal aquaculture is a method for using heated effluents productively, but it does not necessarily reduce the heat disposal problem of the power plant. Basic data show that warm-water fish growth rates could be increased by a factor of 2 to 3 by controlling the temperature of the water medium within the range 75–85°F. Yield potential can be optimized in flowing-stream aquaculture, employing nutritionally balanced feed and oxygenation of the water. Food conversion efficiency also improves with temperature control. With technical innovations, a significant reduction in production cost comparable to that already achieved in the chicken broiler industry could occur. Seafood consumed in this country is largely wild stock, and comparatively little effort has been expended to culture fish on an intensive basis as is done with land animals.

Waste heat is unlikely to be used in large-scale applications until successful demonstrations have been achieved. Therefore, the short-term impact of this activity on power plant siting should be small. Over the longer term, however, the possibilities for aquaculture should be considered during site selection. Site-oriented demonstration programs are needed to provide the technical data that will indicate the extent of improvement in quality and yield of culturable fish species through greater environmental control. These demonstration programs, some already in progress, will show the viability of thermal aquaculture.

Thermal aquaculture will not diminish the amount of waste heat to be rejected from a power plant. During the summer, to maintain optimum growth temperatures, it may be desirable or necessary to dilute the heated discharge water with ambient temperature water. To the extent that ambient temperature water for blending purposes is available, this dilution process will reduce the temperature of the water discharged to the receiving water body. The cost of this dilution would be borne by the aquaculture operator and the power producer. During the winter, ambient temperatures may not be as warm as desired, and this will reduce growth.

Unless it is removed from the culture stream effluent, fish waste could contribute to the pollution of the receiving water by increasing the biological oxygen demand. The cost of adding a treatment plant to take care of fish wastes, particularly in the effluent of an intensive culture facility, should be considered and evaluated as part of the economics of thermal aquaculture.

Legal and regulatory problems encountered in implementing thermal aquaculture will be discussed in the next section. These problems need to be resolved before commercial thermal aquaculture will become a reality.

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CONSIDERATIONS IN IMPLEMENTING WASTE HEAT USE

A review of the utilization of waste heat would hardly be complete if only technical aspects were considered. It is clear from an examination of waste heat use that many difficulties are associated with implementing the technology which already exists. The mismatch between the available heat and the needs for various potential applications, the traditional role of utilities as suppliers of electricity and the impact on this role of supplying waste heat, the arrangements required between entrepreneurs interested in using heat and utilities interested in supplying heat; all are important considerations. Similarly, the influence on rate structures for a highly regulated industry and the impact of increasingly restrictive environmental standards are additional important concerns.

The problems in implementing waste heat use were considered sufficiently important and sufficiently diverse that they served as the subject of a major portion of a National Conference on Waste Heat Utilization sponsored by the Electric Power Council on the Environment and held in October 1971.[1] The Conference explored many of the nontechnical impediments to heat utilization, and much of the material in this section is drawn from information presented at that meeting.

Matching Demand with Supply

Modern steam power plant generating capacities are large and thus make large amounts of waste heat available at the power plant. For example, a 1000-MW electric power plant produces approximately 5×10^{13} Btu/year of waste heat, and since the projected uses for heat are often not energy intensive, extensive facilities would be required to use amounts of heat comparable to that available from such large plants. Agricultural or aquacultural facilities for using all this heat would require an investment of many millions of dollars. Facilities capable of using large amounts of heat may in turn be poorly matched to the market potential for the products produced. (The potential for production of agricultural and aquacultural products as indicated earlier in this report can be a significant fraction of the total production from existing facilities in this country.)

The incentives for waste heat use in agriculture and aquaculture are sensitive to geographical location and climate. In regions where extensive heating is required, heating costs may make the availability of large quantities of low-cost waste heat an attractive incentive. In warmer climates where heating costs are substantially less, the incentive for waste heat use is correspondingly reduced. In any case, the fraction of heat that can be realistically used when compared with the amount of heat nationally available is likely to be small.

An attractive alternative for heat utilization not explored in this report may exist through the coupling of smaller heat emission sources from industrial or other activities with heat uses described here. Waste heat, for example, from a 5- or 10-MW self-contained generating facility or from an industrial waste heat source might prove to more closely match the quantity required by potential heat users and may allow production to be more compatible with surrounding area markets. However, use of even a fraction of the waste heat from a generating plant improves energy utilization and may supplant energy sources which would otherwise be needed for the application. A matching of waste heat use to waste heat available is not a requisite for heat utilization.

The use of waste heat will not alleviate problems of thermal pollution except in specific cases. For example, in aquaculture, actual temperature degradations which occur during the utilization process are slight. Similarly, the substitution of greenhouses for regular cooling towers may result in relatively little difference of impact on the environment from the discharge of heat. Such an energy use, however, may substitute for another energy source which would otherwise be required and thereby would eliminate pollution from that source.

At present, a large mismatch exists between the amount of heat available from steam power plants currently being constructed versus the reasonable quantity of waste heat that might be used at a given site. This mismatch may not impose any penalty on the potential user, but the ability of the utility to market only a small fraction of the heat produced may reduce the incentive for utility participation.

Considerations in the Marketing of Heat

Few steam electric power plants in this country market heat as a second product of their electrical power production. Yet the extensive use of waste heat from power plants will require the consideration of the steam power plants as a multienergy source producing both heat and electrical energy. Such a multienergy role for utilities, however, may initially generate problems as well as energy.

There are encumbrances to utility efforts at developing markets for waste heat, and these include a utility concern for the influence of profits from heat sales on the rate structures for electrical energy. This influence may be a function of the degree of success exhibited by the utility in marketing their waste heat product. Utilities question how their research expenditures for developing methods and applications for heat utilization will be treated in setting the rate structure on electrical energy sales. Unless opportunities exist for the utility to increase profits, there will be a reduced incentive for the utility to investigate means for heat utilization. Rate regulatory bodies might provide encouragement to utilities to develop systems which use waste heat in order to keep prices of electricity down. There is evidence that this is occurring.[4] The initiation of efforts for waste heat applications by potential extrepreneurs may provide one pathway and an incentive for stimulating investigative programs on heat utilization, but the success of such projects will require efforts by both the potential supplier and potential user of heat.

Under normal contract practice, utilities avoid responsibility for consumer losses because of loss of electrical power during unscheduled outages of the utility. It is almost certain that utilities would be loath to enter into agreements for supplying heat where loss of heat might reflect as a responsibility on the utility. Utilities are likely to seek agreements which preclude responsibility from power outages or which avoid increased restrictions on utility operations to better accommodate the entrepreneur in his utilization of waste heat.[2]

The extent to which a utility may modify operations to accommodate the requirements of the waste heat user, and indeed the operating relationship between the user and supplier of waste heat, must be carefully worked out. An example of a cooperative effort on waste heat utilization is illustrated by the agreement between the Ralston Purina Company and the Florida Power Corporation to conduct a mariculture research program and a commercial operation at the Crystal River site of the Florida Power Corporation.[3] In their agreement, Florida Power and Purina are sharing financial responsibility for research efforts necessary to the development of the commercial enterprise. Ralston Purina has almost total responsibility for securing the necessary local, state, and federal permits required for the proposed activities. Both Florida Power and Purina conducted extensive discussions with the state and federal authorities in their initial investigations of the feasibility of the project. Their agreement defines the extent of liability for each of the corporations in the enterprise. Florida Power will not be required to modify normal operation of the power plant for the production of electrical power in order to satisfy the needs for the aquaculture facility. The aquaculture facility will have to adapt to the requirements of the power generating station.

In order to ensure an active interest in the success of the venture, both corporations are investing in the research and construction program. The care and time devoted to reaching the agreement between the parties involved reflect the importance attached by both members of the agreement to the need for a clear definition of their relative positions.[3] The Florida Power–Purina venture, however, represents just one form of many types of arrangements that may be implemented.

Numerous questions have arisen on the role of the utility as a marketer of heat versus its traditional role as a regulated marketer of electricity. The attitude that regulatory agencies will adopt on the regulations required and the restrictions on utility operations is not clear. The regulation of the utility may strongly depend on the application and the customer.[4] A utility dealing with an individual customer (e.g., a greenhouse operator) might be free of regulations, while a utility marketing waste heat to a city or urban development may be under close regulation.

The influence of income from the sale of heat on the rate structure for the utility in the sale of electricity may be an issue of importance. The incentive for the utility in pursuing the marketing of waste heat may be strongly influenced by the regulatory decisions on such issues. Revenues, for example, from the sale of waste heat to a private entrepreneur might be credited against the cost of producing electrical power in much the same way that the sale of fly ash is credited against the cost of ash removal systems.[5] On the other hand, positive savings may occur through a reduction of heat dissipation equipment required by the utility, by marketing the heat to an entrepreneur who will return cooled water to the utility. The utility may therefore have an incentive to market the heat at very low cost or perhaps on a free basis in order to save capital equipment costs. Conceivably, the utility itself might even pay certain costs to supply the heat to an entrepreneur, and in this case, such costs could be credited against the cost of service in determining the rate structure.[5]

If the utility itself enters into a business, using waste heat, then costs associated with the enterprise, whether gains or losses, would be chargeable to the enterprise and ultimately to the stock holders.[5]

Few precedents exist which typify the relative relationship between the utility and the user and which give information on what the effect on rate structure might be. But as more arrangements such as the Florida Power Crystal River Project, the Long Island Lighting Company and Long Island Oyster Farms effort, and the TVA–Gallatin Steam Plant work come into being, precedents will be established on which additional enterprises might base their own arrangements.[3,6,7] Generally, state utility commissions are responsible for setting rate structures, and the specific agreements reached by the utility on heat utilization will strongly influence how the individual state commissions treat the costs and revenues associated with the project.[4] A high degree of variability may be expected in the various states.

Legal and Regulatory Problems

Fundamental problems relating to the right to use water as well as the right to increase the temperature of the water must be solved in order to facilitate the productive use of water. Legal problems of water rights vary with the areas of the country under consideration. In the eastern states, water rights follow the riparian doctrine, with or without regulation, while the western states subscribe to the appropriation doctrine (Colorado Doctrine) or to a combination of the riparian doctrine and the appropriation doctrine (California Doctrine).[8]

According to the riparian doctrine the owners of lands bordering upon a stream have a right to the reasonable use of the natural flow of the stream past their land, with the water undiminished in quantity and unimpaired in quality.[9] Therefore, diversion of water for open-field agriculture, or the use of water for aquaculture without the treatment of wastes, may represent uses of waste heat that present water rights problems if practiced in riparian states.

Where appropriation of water is practiced, the problem may be less serious, since the right to the water could be purchased to provide the necessary amount of water for utilization of waste heat in aquaculture or open-field agriculture.[10] In the case of aquaculture, however, other restrictions such as those imposed by water quality standards would determine the requirements to be met before discharging the water back into the stream.

Increasingly stringent water quality standards may influence waste heat utilization. Limitations on the allowable discharge temperature into receiving water bodies permit only a small temperature increase above ambient water temperature.[11] In estuaries and coastal waters, for example, allowable discharge water temperature increases above ambient range from 1.5 to 4°F, depending on the time of year. Such limitations can preclude certain operations such as aquaculture, unless downstream cooling or dilution is used, and this might be costly and impractical. On the other hand, as utilities are forced to cooling tower installations, the higher and less variable seasonal water temperatures make heat applications more attractive.

Under present regulations the use of warm water from a utility by an entrepreneur concurrently transfers to the entrepreneur the responsibility for meeting water quality standards. The possibility of performing a resource use cost benefit analysis as is now done for environmental impact statements might provide greater insight into the relative value of permitting the use of heated discharges for productive purposes. This might be developed, for example, if the heat resource use were controlled by governmental lease.

Legal questions exist concerning the ownership of heated water discharged from steam power plants. Such questions require resolution, but answers may be highly site dependent and determined by local regulations and statutes. Heat discharged into canals, for example, may belong to the utility, while heat discharged directly to a public stream may not.

The problems now facing Long Island Oyster Farms and the Long Island Lighting Company are indicative of the kind of difficulties that may face companies wishing to use the heated effluents from power plants.[6,12] In the case of Long Island Oyster Farms, which has been using the heated effluents of the Long Island Lighting Company's Northport Steam Electric Generating Plant, the new restrictions imposed by the New York State Water Quality Standards may threaten the viability of the project and prevent its continuation.

When the project was begun by Long Island Oyster Farms in 1967, the temperature limits for the Northport Plant restricted the maximum temperature of water discharged to Long Island Sound to 90°F. Since this maximum was near the optimum for the growth of young oysters, the use of the heated water by Long Island Oyster Farms allowed them to accelerate the growth of oysters, allowing harvesting in 2.5 years instead of the normal 4 years. By providing more favorable temperature conditions during the 4 to 6 months that would otherwise be too cold for growth, the heated effluent is productively used.

In September 1970, however, the state of New York notified Long Island Lighting Company that when Long Island's Unit 3 went on line at the Northport Plant, the discharge from the entire plant would have to comply with a summertime maximum increase in water temperature of 1½°F, measured at the surface 300 ft from the discharge. The only practical way to meet this restriction is through the use of a bottom discharge located approximately one mile from shore. If this type of discharge is used, it would no longer be practical to use the discharge lagoon, and there would be no place to practice oyster culture with the heated water.[6]

Problems such as this present situations where the restrictions imposed on the thermal discharge of the power plant may preclude the direct utilization of the heated water. Methods of utilizing waste heat therefore may depend on the ability to obtain heated waters while still allowing reasonable opportunities for the power plant or the entrepreneur to dispose of heated water in compliance with the water quality standards. The concept of providing water quality standards to maximize public benefit cannot of course be challenged. The issue of analyzing the true costs and benefits of heat energy use in conjunction with standards has not yet been addressed.

Site Selection and Environmental Considerations with Waste Heat Utilization

Early consideration of waste heat utilization will enable the utility selecting a power plant site to consider topography, site layout, and design requirements important for heat utilization. Such early consideration may facilitate the selection of a site compatible with a use of waste heat.[13]

The applicability of differing heat uses will be site sensitive. Closed-system agriculture, for example, may require extensive land areas surrounding the power plant with relatively level topography, while the use of heated water for open-field agriculture requires not only suitable terrain for water distribution, but a site where existing water law will not prohibit such use. High consumptive water use may be in conflict with water rights for many sites unless such rights exist or are procured.[9,10] In regions where water is short, consumptive use may be an unacceptable impact. If both heat and water are utilized at a level which resulted in no additional problem from consumptive use, then the environmental impact of the power plant supplying heat might be lessened by the utilization of that heat.

In using waste heat to heat and cool greenhouses, benefits accrue to the utilization of waste heat because it is possible to cool water from the power plant while conserving water.[14] Therefore, the impact of releasing heat to the environment is lessened while water is conserved. In this instance greenhouses are a means of reducing the impact to the environment as compared with the use of cooling towers. Animal shelters might use the same approach as greenhouses.

The consideration of the local water quality standards applicable to the receiving water bodies may also influence the location for the power plant site. The use of waste heat for aquaculture, for example, requires special environmental considerations. Where fish are cultured, the wastes produced by the fish may require special treatment to meet standards. For other culture, such as oyster culture, the problems are not as great. Similarly, problems of waste disposal from very intensive agricultural operations may require special treatment plants in order to meet water quality or other standards. The problem of waste handling from the concentration of large members of animals requires special consideration. Without the solving of this problem, the use of waste heat in shelters with high animal concentrations might present more serious problems than those of wasting the heat. The availability of large quantities of heat, however, may facilitate means for treating animal wastes at such installations.

It is in the nature of the use operations that intensive activities using relatively large quantities of heat may be required for economic viability. But these same intensive activities may create a high potential source for pollution. For each case where the utilization of waste heat is anticipated, there will be a need to evaluate the environmental problems associated with the use of waste heat at that location to determine whether the total benefits of using the waste heat exceed the total costs.

Health and safety considerations will arise particularly with respect to products using the effluent from nuclear power plants. For example, it is proposed that cooling water circulated through the condensers of a nuclear power plant be pumped through evaporative cooling pads in greenhouses located in the exclusion area of the nuclear plant. There must be assurance that products will be free of any radioactive contamination from the power plant. Monitoring systems may be required to ensure that safety considerations are adequately met. Questions of public attitude on plant and animal products produced in facilities adjacent to power plants will arise. Designs and operation for such systems will have to include procedures to be followed in the event of contamination of the cooling water.

Because of the costs of distribution systems and the fact that the temperature of waste heat is already low (~100°F), heat must be used as near the heat source as possible. The importance of plant site location for "low-temperature" heat use (see Introduction) has been studied extensively for urban uses, and many of the same considerations are applicable for waste temperature heat use.[15] Only a few studies have examined the problems with extensive heat use facilities located at the power plant site.[16]

It is possible that the additional requirements imposed by the consideration of waste heat use may make the site selection process even more difficult. For example, the additional consideration to locate sites near product markets, if possible, to facilitate the distribution of products would narrow the choice of suitable sites. On the other hand, the availability of large quantities of low-grade heat may provide an incentive for locating a power plant in certain areas. It seems unlikely, however, that in the developmental phase of waste heat utilization, significant weight will be given to heat utilization in the location of a power plant site. To date, consideration of heat use has been given only after site locations have been selected and often after actual construction of plants are under way.

Over the longer term it is likely that effective use of waste heat from power plants will require careful advanced planning during the site selection process, with participation of both the utility and the waste heat user, so that locations optimum for both electrical production and heat energy use are selected.

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