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URBAN UTILIZATION OF EXTRACTED HEAT AND WASTE HEAT FROM CENTRAL STATION POWER PLANTS

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ABSTRACT

An analysis is presented of the feasibility of providing thermal energy as well as electricity to urban areas from central station steam-electric power plants. Consideration is given to the use of thermal energy for applications such as industrial processes, building space heating, air conditioning, sewage treatment, agriculture, and aquaculture.

The analysis shows that the use of dual-purpose plants significantly reduces the consumption of fuel and lessens the environmental impact of providing energy as compared to conventional systems. Areas of multifamily dwellings and other multistoried buildings could be served in new cities, or renewed old cities, at costs comparable to those incurred with more conventional separate systems. However, it would require more planning of facilities and coordination of diverse organizations than we normally employ. The costs and dislocations associated with retrofitting existing cities would cause each city to be a separate case.

Contributions to the analysis were made by some 25 members of the staff of the Oak Ridge National Laboratory, several people from other installations in Oak Ridge, and a few consultants.

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THE EFFICIENCIES OF THE PROCESSES used to generate electricity vary from about 25% (simple cycle gas turbines) to 40% (modern fossil-fired steam stations), and these operations resulted in a wastage of energy equivalent to over 200 million barrels of the oil, over 200 million tons of the coal, and 2600 billion cubic feet of the natural gas burned in U.S. power plants during 1970. Such losses of valuable resources are doubly damaging because the combustion products and heat from electric generating stations are a significant source of environmental pollution. Population growth and increased per capita consumption of electrical energy are the two forces driving the expansion of the electric generating capacity in the United States. The relationship of these factors is indicated in Table 1.

It is unfortunate for the environment that 60 to 70% of the energy released to generate electricity is disposed of at the generating station, while the 30 to 40% shipped out as electricity is released at scattered residences, offices, and industrial plants. In the last 15 years the size of the largest stations has increased by a factor of about 6, that is from 200 MW to nearly 1200 MW. This is especially important in terms of "energy concentration"; a typical 1000 MW(e) nuclear generating station would release about 2000 MW heat as a "point source" to air or water at the site, whereas the 1000 MW of electricity would be dissipated by a city of a million people occupying a space of many square miles. The 1000 MW(e) station would require a cooling water flow of about 700,000 gallons per minute if the temperature rise of the water were limited to about 20°F. With a 20°F rise across the condenser the outlet water temperature can be limited to less than 93°F on most streams and lakes. This is the limit which the Federal Water Quality Act permits for discharge to warm-water streams, but there are many environmentalists who favor less heat and lower temperatures.

Another cause of concern is the number of large power stations which must be built in the near future. The Federal Power Commission has estimated that 492 new power stations 500 MW or larger are planned during the next 20 years (1970-1990) and that 255 new sites must be selected (1).* Because of the difficulty expected in finding sites with suitable cooling

*Numbers in parentheses designate References at end of paper.

capacity, the report estimates that 32% of the new plants will be equipped with cooling towers. They, of course, are not without environmental effects. Their physical appearance and vapor plumes are objectionable to many people. Furthermore, they add significantly to the cost of electricity by reducing conversion efficiency and by increasing capital costs.

With these problems in mind, the Department of Housing and Urban Development approved a 1968 proposal by the Oak Ridge National Laboratory of the Atomic Energy Commission, to study the extent to which low-temperature heat from central station power plants might be used to replace urban fossil fuel consumption and thus reduce total fuel consumption, urban air pollution, and concentrated heat rejection at the power stations. Conservation of fuel resources, environmental impact and cost were the criteria for evaluation (2).

COMBINED HEAT-ELECTRIC SYSTEMS

There are two modes of making use of the heat from the steam electric plant — one at normal cooling-water temperatures in the region of 95°F for functions such as greenhouse heating, and the other by removal of steam from the turbine at higher temperatures (after it has made some electricity) in order, for example, to provide manufacturing process heat or for heating and cooling buildings. Figure 1 is a schematic diagram of a heat-electric system illustrating applications considered for a hypothetical new city.

Extraction of heat as steam from back-pressure sections of turbines or from variable extraction turbines is a typical heat-electric operation that is employed in some of the country's industries and larger district heating systems. Withdrawal of high-temperature steam does, of course, reduce the electrical efficiency of the plant, but of greater importance is the fact that it increases the overall efficiency of energy utilization. The effects of steam exhaust conditions on the gross steam cycle efficiencies of modern large fossil-fueled plants and nuclear-fueled plants are shown in Fig. 2. The reduction and elimination of thermal rejections at the condenser of these plants by use of the extraction and back-pressure systems are illustrated in Fig. 3.

Heat is also recovered from many small electrical plants using gas turbines, gas engines, or diesel engines. Such systems are being studied for the Department of Housing and Urban

Development at the Oak Ridge National Laboratory and at other locations but are not included in this paper.

UTILIZATION OF EXTRACTED HEAT

The amount of heat required for building services such as heating, air conditioning, and hot-water supply is appreciable by comparison with the quantities of heat released from plants generating electricity. The extraction of heat for such purposes from the turbines would result in significant reductions in waste heat emissions from steam-electric plants. Major amounts of steam are also needed for industrial processing. The seasonal and diurnal variations in the requirements of a city's buildings and in the industrial steam consumption would cause important variations in the extracted heat load. Also, the desalting of sewage plant effluent by distillation to provide potable water appears attractive, but such a process needs additional development (3). Distilled water in large-scale agriculture is a likely use and has been the subject of several studies at the Oak Ridge National Laboratory. Snow melting operations could also be carried out with heat from the energy center when large benefits would accrue in terms of heavy vehicle or pedestrian traffic usage, prevention of accidents, and a lessening of highway deterioration.

The temperature of steam or water provided for building services should effect a reasonable compromise between low heat distribution cost and reduced heat emission to the condenser at the energy center. Hot water at 300°F is a good heat-transfer fluid to deliver the heat from a power plant to city buildings. These buildings can also be air conditioned if water at a temperature as low as 240°F is used in commercial lithium bromide absorption air-conditioning equipment, but the resulting thermal emission to the biosphere from the air-conditioning process would actually be slightly more than from conventional electric air-conditioning practice (4). However, with the absorption system the entire heat release would occur at many sites within the city and relieve the problem of a large heat emission from electricity production at the power plant. Figure 4 compares the energy requirements of absorption air conditioning using 240°F water with those for steam turbine driven compressive air conditioning at the power plant and with electric compressive air conditioning. Although gross cycle efficiency is shown as the abscissa, the energy requirement is also a function of the steam cycle employed in the indicated plants.

WARM WATER FOR AGRICULTURE — There appear to be several attractive possibilities for increasing food production with warm water from the condensers of power plants in urban areas. The fresh vegetable, poultry (broiler and egg), pork and fish requirements of a city could be met with controlled environment structures heated and cooled with the warm water normally discarded from the condenser of its power station (5). Experiments at Oak Ridge have demonstrated the feasibility of using warm water (70 to 110°F) in film-type evaporative coolers to heat and cool air; these structures (greenhouses, etc.) perform as "horizontal cooling towers" to dispose of excess heat up to approximately 5 MW/acre in an average U.S. climate.

The cost of a system for conveying and using warm water in 200 acres of these structures appears to be about $2,000,000 greater than the cost of ordinary greenhouse heating-cooling systems. If the waste heat is available at no cost, the saving in heating costs (compared to usual greenhouse costs) would be $5,000 per acre/year or $1,000,000 per year for fuel. With the additional investment of only $2,000,000, the greenhouses could provide a 1000 MW(t) cooling for a 500 MW(e) power plant which would save the utility a capital cost of about $6,000,000 for ordinary cooling towers and their operating expenses of several hundred thousand dollars per year. Aside from these savings, other savings in food cost would accrue from integrating the food operations, such as recycling the animal waste to the plants and the plant wastes to the animals.

Irrigation with warm water has some advantages. The Eugene (Oregon) Water and Electric Board is financing three experimental farms (totaling 170 acres) to study irrigation with water as hot as 130°F. Their experiments designed by the Vitro Corporation (6) indicate that water at this temperature, sprayed from a height of 8 or 10 feet, will cool to ambient air temperature by the time it reaches the ground, and will not damage field crops in hot weather. Their spring and fall growing seasons have been extended past the light-frost periods as a result of this additional heat input. At Oregon State University (7), there is an investigation of the effect (on crop growth) of underground pipes heated with condenser discharge waters.

WARM WATERS FOR AQUACULTURE — Several studies have shown (8) that a combination of controlled warm temperatures and nutrient supply

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from animal wastes or city sewage effluent could produce heavy yields of algae -- up to 30,000 lb per acre. The algae can be centrifuged, dried, and used as food for fish, fowl, or animals. The University of California has a large-scale experiment on algae growth and use in progress.

Higher yields of fish, shellfish, and crustaceans have been demonstrated where optimum growth rates could be maintained with regulated water temperatures. The Long Island Lighting Company, at their Northport Long Island plant, is engaged in a commercial oyster culture operation with the Inmont Corporation.

Catfish or trout production is another application which appears attractive because the fish can grow year-round if the water temperature can be maintained in the optimum growth range. Japan is now cultivating 470,000 tons of fish annually. In flowing streams with temperature control, yields as high as 200,000 lb/acre have been demonstrated in the United States (9). The Tennessee Valley Authority and J. Butler, a Nashville entrepreneur, have a cooperative intensive catfish culture project in operation at TVA's Gallatin Plant.

REFERENCE CITY STUDY

GENERAL DESIGN – The purpose of studying a reference city (2) and variations in its parameters was simply to help synthesize and illustrate the ideas previously discussed. Therefore its design was only conceptual and provided just enough information to define a reasonable arrangement for analysis. There was no need or attempt to design a city per se.

The city was imagined as a new one with 390,000 people located in a geographical area having the climate of Philadelphia, Pennsylvania. The energy center was designed to produce the average amount of electricity forecast for a city of 390,000 people in 1980, except for a small reduction to compensate for the use of district heat for air conditioning and domestic hot-water production. The heat source consisted of two light water reactors. They were base loaded and fed a single shaft dual turbine with a condensing section and a back-pressure section similar to that illustrated in Fig. 1. The division of the steam supply between the back-pressure and condensing sections was varied in keeping with the heat demands. It was assumed that any excess or deficit of power could be fed to or drawn from the utility grid.

The industrial consumers of low-temperature process heat were located in close proximity to the energy center, and their process heat consumption conformed to the projected country average for a population of the chosen size in 1980. Since the effect of "country average" industrial consumers on heat rejection is small compared with that of providing building services, their nature was unspecified, and the industrial load factor was assumed to be unity. An installation for distillation of sewage plant effluent was also located at the energy center. There were also 200 acres of environmentally controlled greenhouses which utilized condenser cooling water for heating and evaporative cooling.

The residential and commercial areas of the city were all situated at a distance greater than five miles from the energy center, as illustrate in Fig. 5. The population at any distance from the energy center was less than that for the area surrounding the Indian Point reactor in 1980. The downtown area and an apartment house area were in one sector between 6 and 12 miles from the center, and they received 300°F water for building services. This section of the city that was supplied with district heat had a total area of 16 square miles. Of the 390,000 people who lived in the city, 260,000 of them resided in 12 square miles of apartment area. The downtown area was located in the remaining 4 square miles. The other 130,000 people lived outside the 16-square mile area at unspecified locations within the 5- to 12-mile annulus. All 390,000 people were supplied with electrical energy from the center.

The portion of the city supplied with thermal energy from the center was laid out in a fashion that allowed it to be characterized with relatively few parameters. After an economic analysis was made of its energy system, the effects of changing important parameters, such as population density, total population, dwelling space per person, and distance from the energy center, were readily estimated. The apartment buildings were assumed to be uniform and three stories high with 300 ft^2 of net usable enclosed space per person, including entrances, hallways, and stairways. The resulting population density in the apartment area is 21,500 people per residential square mile. In an alternate arrangement of apartment buildings that resulted in the same district heating cost, the 21,500 people were spread over a 1 1/2-mile area giving a population density of 14,333 per square mile in the apartment areas.

ENERGY REQUIREMENTS — A summary of energy production and consumption estimates is given in Table 2. The estimate of maximum heat to the condenser is based on the extreme assumption that the minimum district heat load could be zero.

The annual average reduction of heat to the condenser as compared to a single-purpose plant is about 36%. The heat rejection to the condenser cooling water during the hottest summer hour is very small. Even this could be used beneficially in approximately 200 acres of greenhouses (or in poultry houses, swine houses, or fish ponds) located at the energy center. Furthermore, the maximum heat disposal capacity of 200 acres of greenhouses is sufficient to dispose of the entire 1180 MW(t) at any time of the year. Thus no cooling towers or warm water discharge would be required if greenhouses were provided.

The total annual reduction in energy content of fuel used to supply the needs of the city is estimated to be 10^{13} Btu as compared to conventional systems. This is equivalent to a 334 MW(t) source.

COST OF ENERGY – The costs of energy for the city were estimated on a 1969 present-cost basis. Electricity generation costs were assumed to be those of a single-purpose 500 MW(e) plant. All costs above those incurred by use of such a plant were allocated to the cost of heat. The cost of heat production is shown in Table 3.

The cost of distributing heat to the city in conventional steel pipes and conduits (not plastic) 6 ft below ground surface is 106¢/MBtu. The sum of the heat production and distribution costs add up to the total cost of district heat for the buildings of the city. This is in the region of 106¢/MBtu for distribution plus 36¢/MBtu for heat production or approximately 142¢/MBtu. This is equal to the average cost of 142¢/MBtu for district steam in 43 cities of the United States in 1968. A study of reports from many apartment building owners indicated that in 1968 their average heat production cost was also about 142¢/MBtu. Space heating, domestic hot water heating, and air conditioning these buildings in the reference city affects the major portion of the reduction in heat emission to the energy center cooling water. The cost of providing this heat from the energy center as compared to other methods of serving the buildings is the dominant factor in assessing the economic feasibility of using heat from the steam-electric power plants for urban applications.

The cost of energy for air conditioning with 300°F delivered water and 240°F absorption equipment would be equivalent to a cost of 28.5 mills per kWhr for electricity for an electric-compressive system. With a charge of 79¢/MBtu

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for air-conditioning heat, the energy cost would be equivalent to 16 mills/kWhr for electricity for a compressive system. At the latter price the charge for heat for space heating and domestic hot water heating would have to be increased from approximately 142 to 198¢/MBtu. The air-conditioning charge would be defraying the cost of 300°F heat production plus somewhat more than the incremental distribution cost of heat for air conditioning. (In the largest U.S. district heating system the estimated peak load on a typical summer day in 1968 was equal to 65% of the measured winter peak for that year; this summer day load was chiefly due to steam required for air conditioning.)

Estimates were made of what the cost of heat would be if the apartment areas in the reference city contained a lower density of apartment buildings and had a correspondingly lower population density, thereby spreading their 260,000 inhabitants over a larger area within the city. Estimates were made for both the original 21,500 persons per square mile and 14,333 persons per square mile street configurations. The results are shown in Table 4. The listed cost of space heat is based on a charge of 79¢/MBtu for air-conditioning heat. It can be seen that the cost of heating multifamily dwellings in areas of rather modest population density is either less expensive or competitive with electric heating. The high incremental cost of heat for space heating for one-fourth mile of small consumers adjacent to the apartment area is shown in Fig. 6.

CONCLUSIONS

The analyses show that the use of extracted and waste heat from central station power plants reduces the consumption of fuels and thereby lessens the environmental impact of providing energy as compared to conventional systems.

With large new cities or renewed old cities having areas of high population density, or with large concentrations of low-temperature steam consuming industries close to the plant, the dual-purpose plant system would be economically attractive. Establishment of such a system would require more planning and coordination of diverse organizations than we normally employ. However, considering that the U.S. utilities are likely to have difficulty in finding 255 new power plant sites in the next 20 years, it would appear worthwhile to work toward the establishment of some dual-purpose plants and eliminate the heat rejection problems for those sites.

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From the standpoint of fuel consumption and air pollution, the use of extracted heat in existing cities would also be advantageous; but the retrofitting of existing cities is usually quite costly. Each city would have to be studied as a separate case.

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Table 1. Forecasts of U.S. Population Growth, Electrical Energy Consumption, and Cooling Water Requirements

	1970	1980	2000
Population[1]	205 million	232 million	300 million
Per Capita			
a. Energy Usage[2]	273×10^6 Btu	341×10^6 Btu	484×10^6 Btu
b. Electrical Usage[2]	6900 kWhr	10,777 kWhr	20,243 kWhr
Total Electrical Usage[3]	1400×10^9 kWhr	$2{,}500 \times 10^9$ kWhr	$6{,}100 \times 10^9$ kWhr
Total Generating Capacity[4]	320,000 MW(e)	570,000 MW(e)	1,393,000 MW(e)
Cooling Water Requirements[5]	125×10^9 gals/day	265×10^9 gals/day	677×10^9 gals/day

[1] Bureau of Census Publication Series P. 25, No. 448 ("C" Projection) March 1966.

[2] Averaged from several projections reported in "A Review and Comparison of Selected United States Energy Forecasts," PNL-Battelle Memorial Institute, December 1969.

[3] Multiply population by per capita electrical usage (kWhr).

[4] Capacity required to provide Total Usage at 50% Average Utilization.

[5] "The Nation's Water Resources," U.S. Water Resources Council, 1968. Includes both fresh and salt water.

Table 2. Energy Production and Loads for Reference City

Production capacity of heat source	2268 MW(t)
Annual average thermal power production	2041 MW(t)
Annual average net electrical power production	463 MW(e)
Annual average internal power consumption	29 MW(e)
Annual average district heating load	457 MW(t)
Peak summer district heating load	1144 MW(t)
Peak winter district heating load	1088 MW(t)
Minimum district heat load	0 MW(t)
Industrial steam load at 965 psig	43 MW(t)
Industrial steam load at 450 psig	251 MW(t)
Industrial steam load at 207 psig	74 MW(t)
Sewage distillation steam at 32 psig	90 MW(t)
Peak greenhouse heating	243 MW(t)
Annual average greenhouse heating	33 MW(t)
Annual average heat to condenser	634 MW(t)
Maximum heat to condenser	1180 MW(t)[1]
Heat to condenser at hottest summer hour	230 MW(t)

[1]To be disposed of by greenhouses.

Table 3. Unit Heat Production Costs for Reference City

	Heat Costs at Power Plant (¢/MBtu)	
	With Cooling Tower	With Greenhouses[a]
Industrial steam		
Prime (965 psig)	50.4	46.3
450 psig	43.8	40.3
207 psig	37.5	34.5
32 psig	24.3	22.3
District heat	36.5	34.6

[a]Assuming no thermal energy charge to greenhouses.

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Table 4. Heat Costs for Apartment Areas with Various Population Densities

Population Density (people/mi^2)	Average Cost of Heat (¢/MBtu)	Cost of Heat for Space and Hot Water Heating (¢/MBtu)
21,500	142.5	198
14,334	142.5	198
10,750	186	280
8,600	186	280
5,375	292	480
4,778	292	480

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Fig. 1. - Schematic Arrangement of a Heat-Electric System

Fig. 2. - Effect of Exhaust Temperature on the Efficiency and Ratio of Process Heat to Electricity for Several Power Plants

Fig. 3. - Reductions in Thermal Rejection at Condenser Based on Constant Electric Generation

Fig. 4. - Increase in the Plant Energy Requirements Resulting from Air Conditioning with Compressive Refrigeration and 240°F Hot-Water-Heated Absorption Refrigeration

Fig. 5. - Schematic View of Reference City and Energy Center

Fig. 6. - Average Incremental Cost of Space Heat for a One-Fourth-Mile Line of Consumers with a Peak Demand of 50,000 Btu/hr

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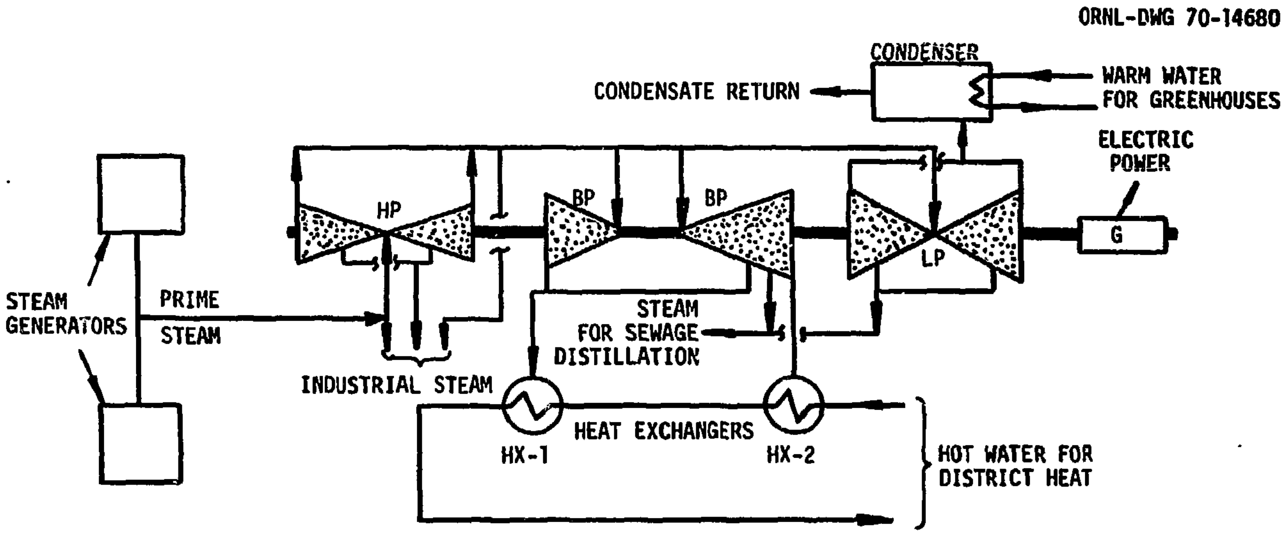
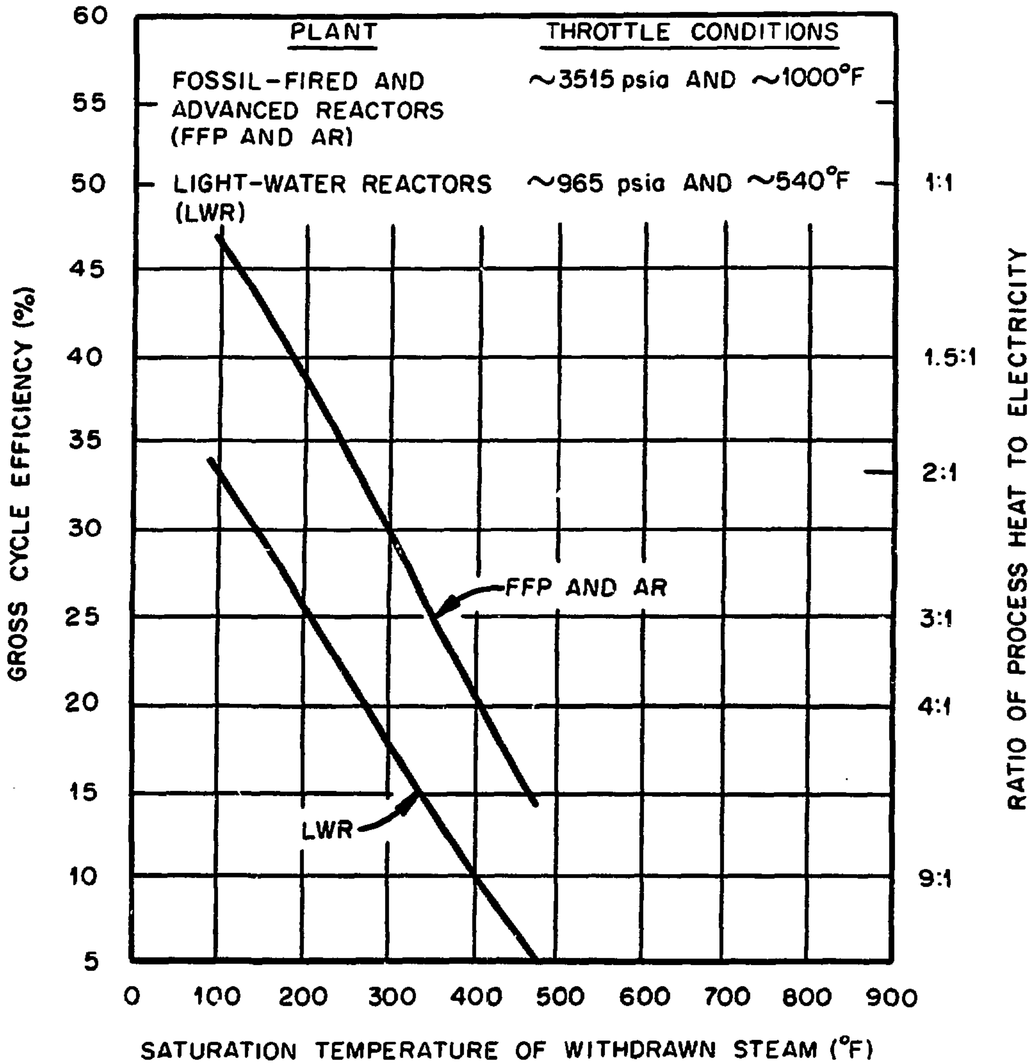
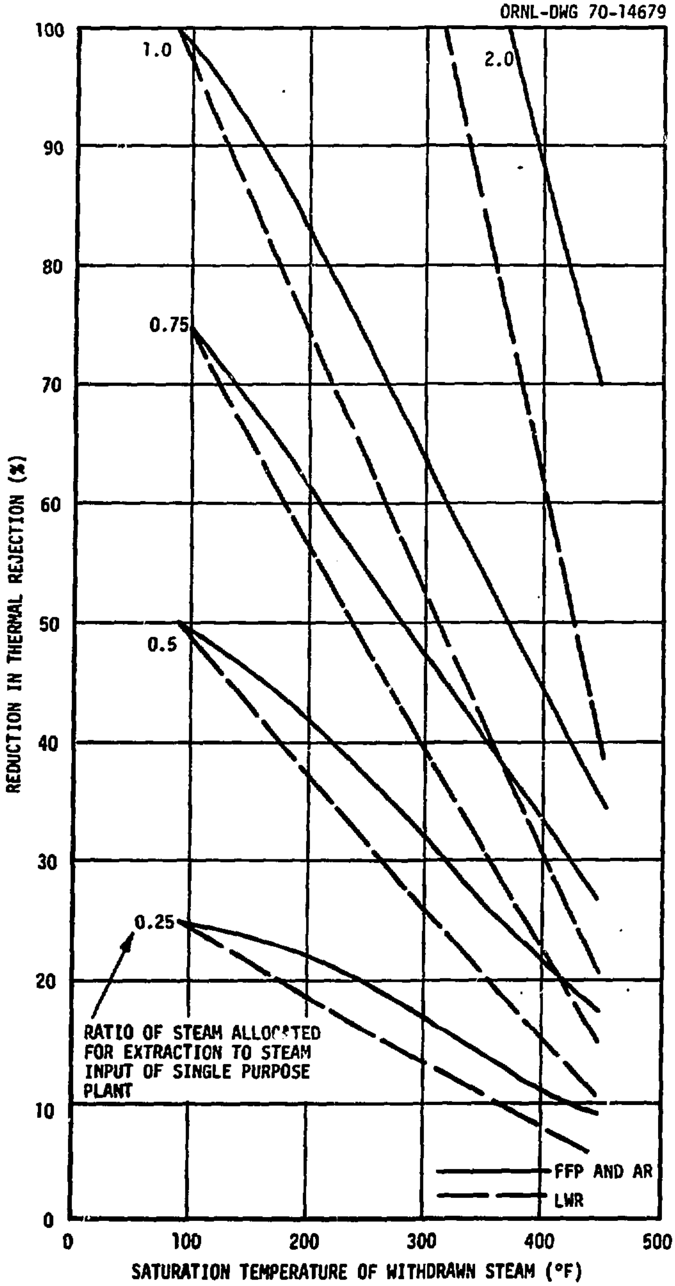
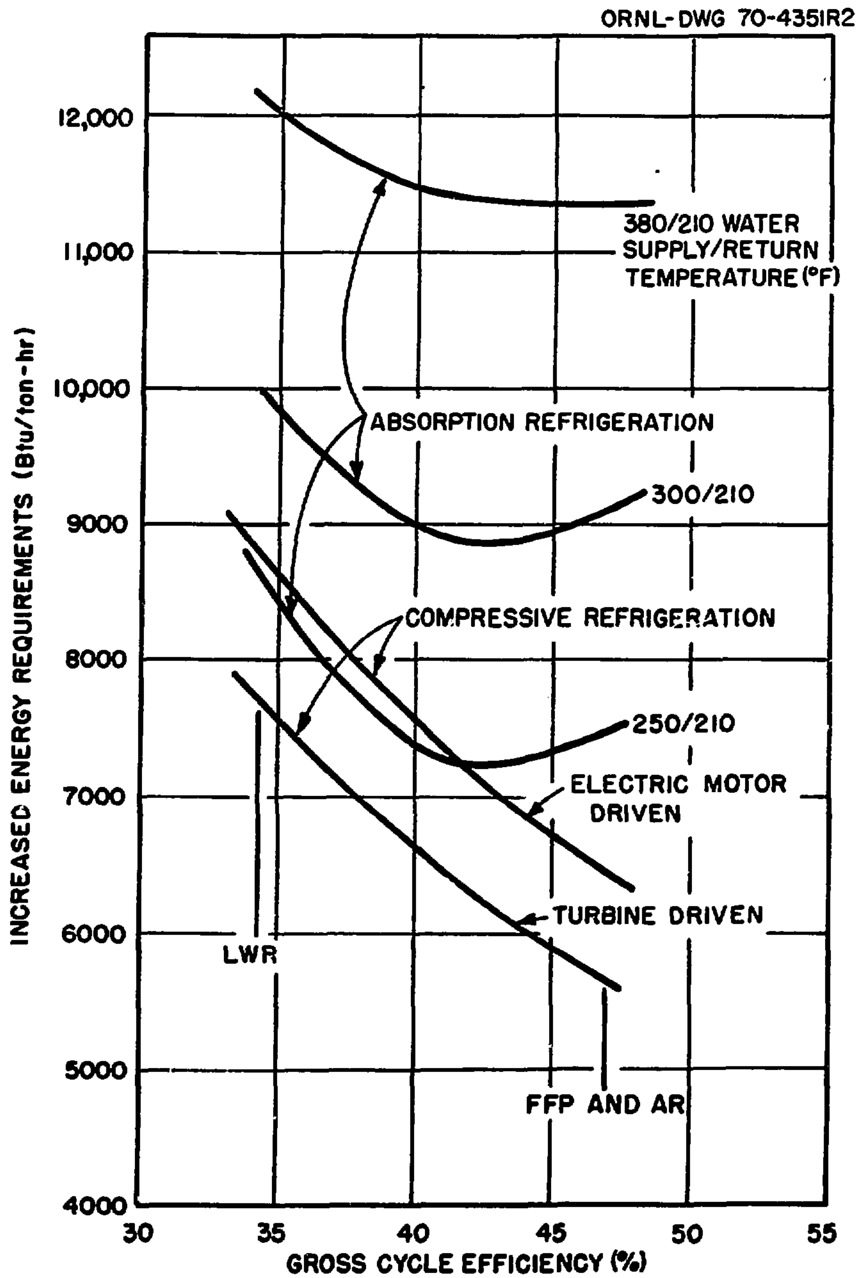


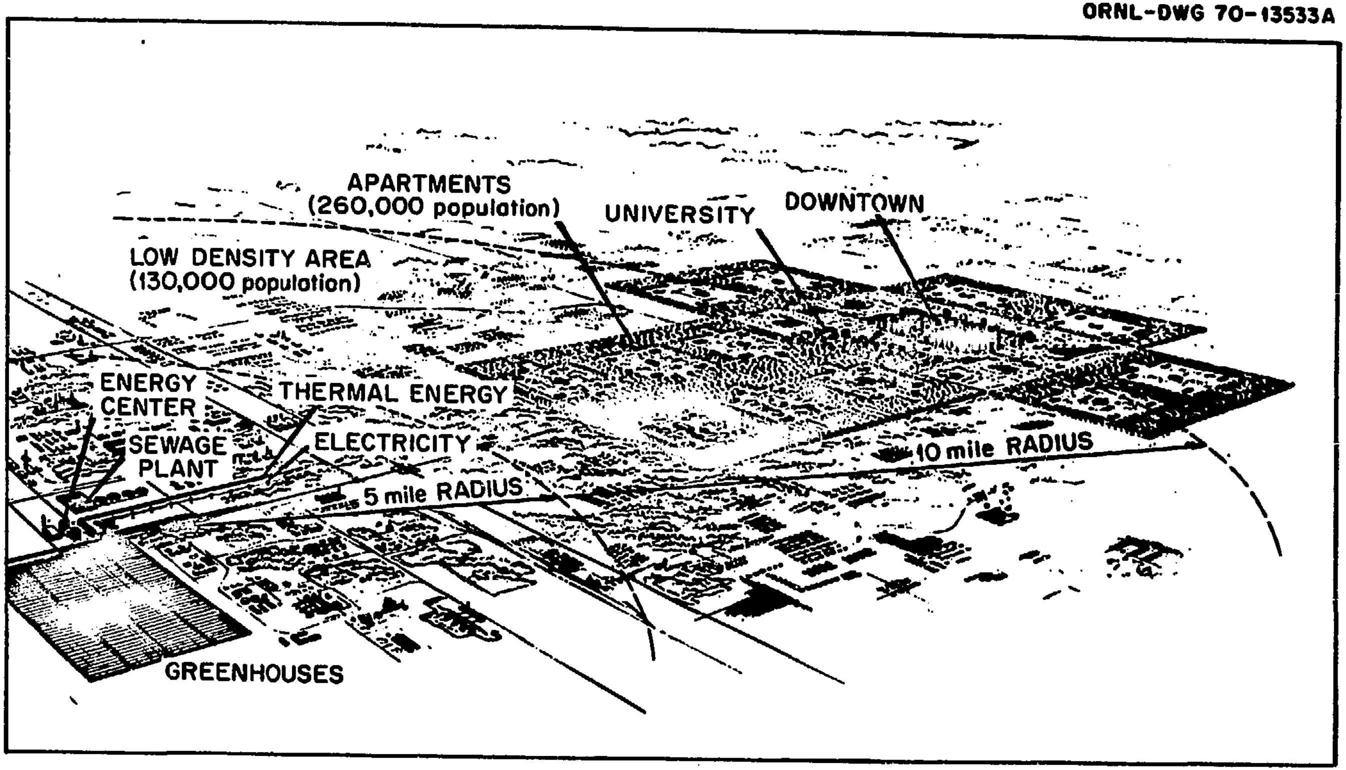
ORNL-DWG 70-14680
CONDENSER
CONDENSATE RETURN
WARM WATER
FOR GREENHOUSES
ELECTRIC
POWER
HP
BP
BP
LP
G
STEAM
GENERATORS
PRIME
STEAM
STEAM
FOR SEWAGE
DISTILLATION
INDUSTRIAL STEAM
HEAT EXCHANGERS
HX-1
HX-2
HOT WATER FOR
DISTRICT HEAT

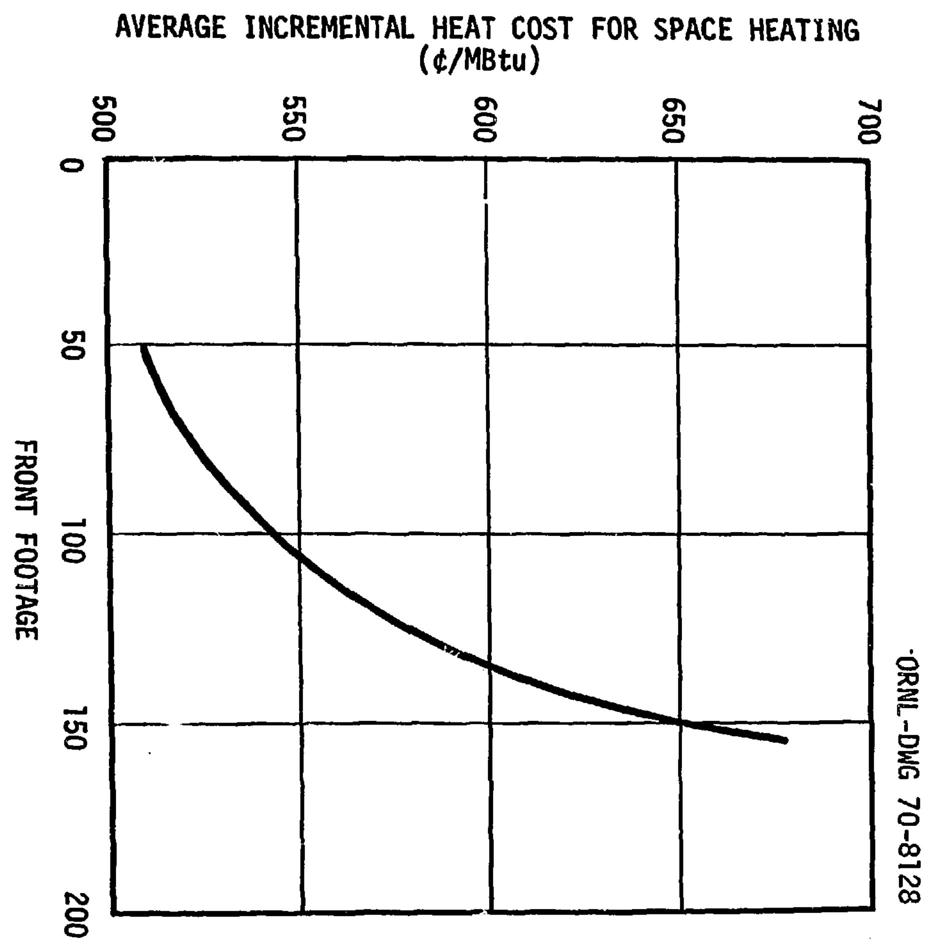

PLANT
THROTTLE CONDITIONS
FOSSIL-FIRED AND ADVANCED REACTORS (FFP AND AR)
~3515 psia AND ~1000°F
LIGHT-WATER REACTORS (LWR)
~965 psia AND ~540°F
FFP AND AR
LWR
GROSS CYCLE EFFICIENCY (%)
60
55
50
45
40
35
30
25
20
15
10
5
0
100
200
300
400
500
600
700
800
900
SATURATION TEMPERATURE OF WITHDRAWN STEAM (°F)
RATIO OF PROCESS HEAT TO ELECTRICITY
1:1
1.5:1
2:1
3:1
4:1
9:1


ORNL-DWG 70-14679
REDUCTION IN THERMAL REJECTION (%)
SATURATION TEMPERATURE OF WITHDRAWN STEAM (°F)
1.0
2.0
0.75
0.5
0.25
RATIO OF STEAM ALLOCATED FOR EXTRACTION TO STEAM INPUT OF SINGLE PURPOSE PLANT
FFP AND AR
LWR
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500


ORNL-DWG 70-4351R2
INCREASED ENERGY REQUIREMENTS (Btu/ton-hr)
12,000
11,000
10,000
9000
8000
7000
6000
5000
4000
30
35
40
45
50
55
GROSS CYCLE EFFICIENCY (%)
380/210 WATER SUPPLY/RETURN TEMPERATURE (°F)
ABSORPTION REFRIGERATION
300/210
COMPRESSIVE REFRIGERATION
250/210
ELECTRIC MOTOR DRIVEN
TURBINE DRIVEN
LWR
FFP AND AR

ORNL-DWG 70-13533A




AVERAGE INCREMENTAL HEAT COST FOR SPACE HEATING
(¢/MBtu)
500
550
600
650
700
0
50
100
150
200
FRONT FOOTAGE
ORNL-DWG 70-8128