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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Waste Heat Disposal From Nuclear Power Plants

RALPH M. ROTTY

Air Resources Laboratory
SILVER SPRING, MARYLAND
September 1974

ENVIRONMENTAL RESEARCH LABORATORIES

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UNITED STATES
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Robert M. White, Administrator

Environmental Research
Laboratories
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Ralph M. Rotty[1]

For more than a century, the global consumption of energy has been growing exponentially at a rate of 5.4 percent per year. In accord with the second law of thermodynamics all electrical power generation cycles must reject heat, and as larger and larger amounts of electricity are needed larger amounts of heat must be rejected. The quantity of reject heat is rapidly approaching a level at which its impact on the atmosphere cannot be neglected. Possible intensification of convective activity and associated concentration of vorticity may be caused by concentrating large amounts of heat rejection in small areas.

The type of cooling employed at a given power generation site has a major effect on the heat flux per unit of area. The use of once-through cooling spreads the heat added to the atmosphere over a wide surface area. The use of artificial ponds, lakes, or canals is next most effective in spreading the heat addition over largest possible areas; evaporative cooling towers, wet/dry, and dry cooling towers concentrate the heat added in comparatively small surface areas.

Once-through cooling is recommended for use whereever possible for the cooling of power plants. Smaller units and single-unit sites should be considered so that better advantage can be taken of the once-through capacity that may be available. Cooling systems having once-through cooling in combination with cooling towers are possibilities deserving careful investigation.

1. GLOBAL ENERGY PATTERNS

Nearly all energy released or used by mankind must find its way into the atmosphere before eventual radiation into outer space. This is true of energy as waste heat (e.g., from an electrical generating station or the radiator of an automobile), and that used for a desired purpose, such as illuminating a light bulb or propelling a vehicle. Most energy released by man is the stored variety it has been stored in its present form for thousands or millions of years. Nuclear fuels as well as fossil fuels are stored energy. Of those considered today as suitable energy sources only solar and hydro power have not been stored; thus, they are classed as *renewable*.

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For the climate of the earth to remain in a state of near equilibrium, the total energy radiated from the global environment must equal that entering the environment (from the sun) plus energy released by man from long-term storage. Until recently, this stored energy has been a very small amount in comparison with the solar energy absorbed by the earth and its atmosphere; however, the continuing industrial growth and the consequent rapid growth in the use of stored fuels require that the release of stored energy must be considered in future analyses of the global radiation balance.

Figure 1 shows the world's energy use for 1860 to 1970 (World Energy Requirements in 1975 and 2000, 1955; World Energy Supplies, 1972). Except for the periods 1913-1918 and 1941-1944 corresponding roughly to the two world wars, and 1929-1933 during the Great Depression, worldwide energy use has been increasing at a constant rate of 5.4 percent per year. Such growth for 75 more years would, if continued, give a global energy use of 10^{19} Btu per year (Wilcox, 1973)--a level significant in relation to the global solar flux of 5×10^{21} Btu per year, a third of which is reflected. Increasing the energy that must be radiated to space by 1 percent will undoubtedly cause significant changes in atmospheric temperature and thus influence the climate.

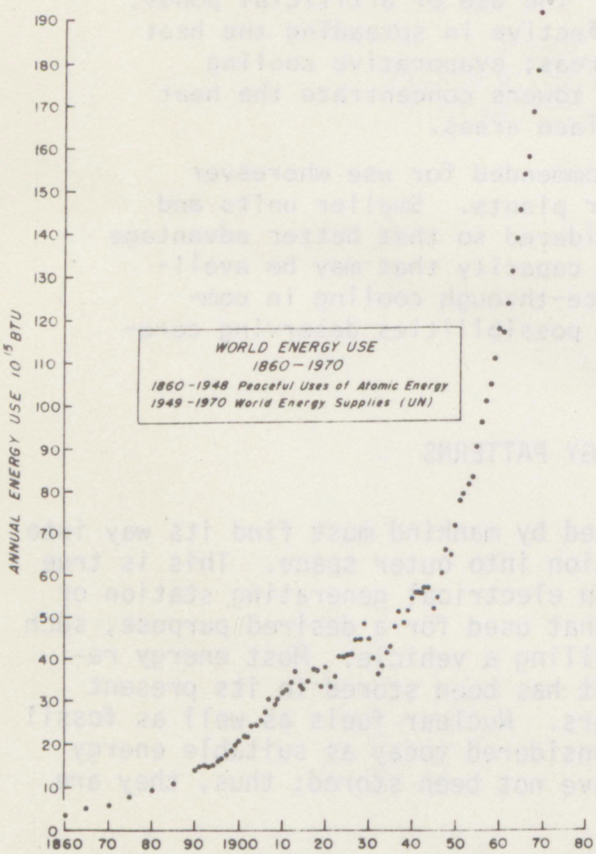


Figure 1. World energy use 1860-1970.

2. NUCLEAR ENERGY GROWTH

Nuclear electrical power generation plants planned and contracted for in the United States show the same general growth trend as the total energy used in the world. In figure 2, the cumulative nuclear generating capacity scheduled to become operational each year is plotted from data supplied by the electric utilities in connection with their license applications. The projected growth rate is greater during the earlier 1970's and lessens by 1980 and thereafter. In figure 2, a curve representing a 30 percent annual growth rate is shown only for comparison. Even a growth as large as 30 percent a year is to be exceeded during the next few years (to 1976) before it slows to 18 percent by 1980. Also shown is the projected growth of *all* post-1970 electrical generation capacity in the U.S.; this is based on a 6.2 percent per year growth as predicted by the Cornell-NSF Workshop (Cornell Workshop on Energy and the Environment, 1972). The long-range projections made by the Cornell-NSF Workshop and other groups have been questioned (Chapman et al., 1972). Considerations of price elasticity, population growth, and other possible changes make projections based on extrapolation of past growth rates subject to major errors if the time span becomes more than a few years. In the short range

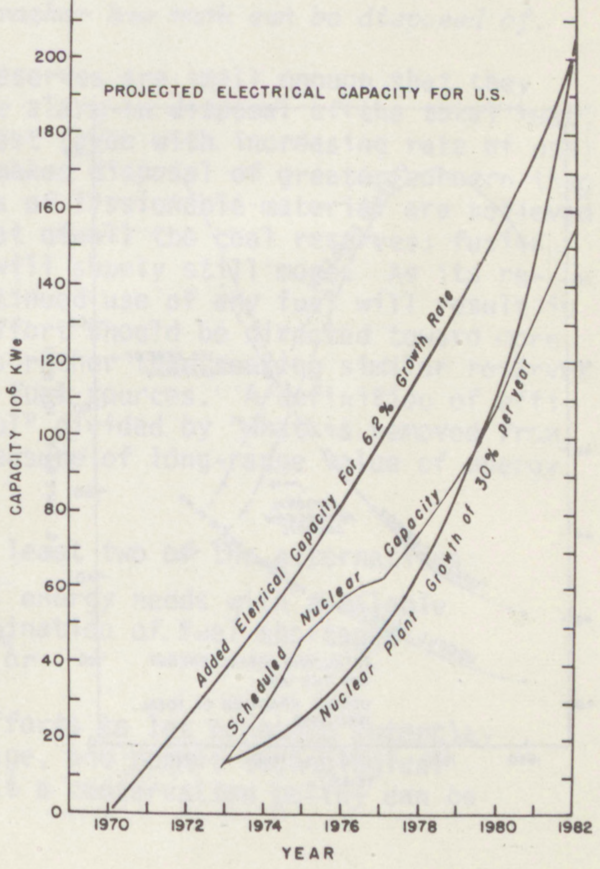


Figure 2. Projected electrical capacity for U.S.

all of these projections lie close together (Chapman et al., 1972), and using a growth rate value of 6.2 percent for 1974 to 1982 gives a reasonable estimate for the near future.

Growth of this kind can quickly (in a few decades) reach magnitudes that are important on a global scale. In the meantime, smaller scale changes of both local and regional importance, such as increased fog and rainfall and higher temperatures, should be expected. The large amounts of waste heat (roughly twice the electrical capacity) disposed of over a relatively small area will have a greater climatic impact than the smaller electrical energy distributed over a broad (consumer) area.

3. REJECTED FRACTION OF TOTAL ENERGY

On an even more alarming note, the trend of the fraction of energy *used* compared with the total *released* from long-term storage is projected to decrease, at least in the United States. Figure 3, based on data from U.S. Energy Flow Charts (1973) shows projections made by the U.S. Department of the Interior and by the National Petroleum Council. The energy converted by man for his use is projected to continue to increase through 1990 and is strongly related to continued economic growth and

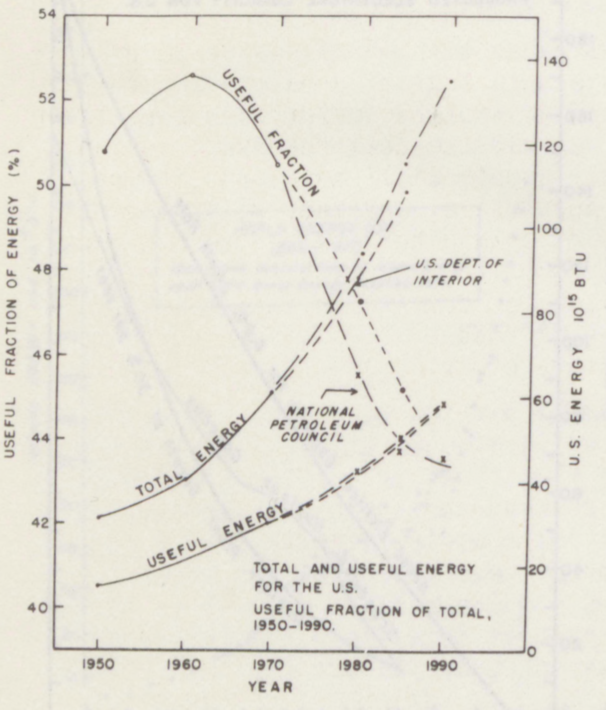


Figure 3. Total and useful energy for the U.S.

standard of living. The curve showing total energy withdrawn from long-term storage rises more rapidly, indicating a decreasing "efficiency" in our use of energy. The difference between the curve for useful energy and that for energy withdrawn from storage largely results from two major sources of heat rejection:

1. The reject heat from the steam-electric power-generation cycle that is discharged to rivers, lakes, or the atmosphere.

2. The reject heat from the propulsive cycles of transportation vehicles, which also discharge large quantities into the atmosphere.

The thermal efficiency of electric-power generation cycles lies between 30 and 40 percent (Peterson, 1973a), while most of the cycles presently used in transportation systems have a thermal efficiency of 25 percent or less. As greater fractions of the total national energy consumption are used for electrical generation and transportation, the curves of figure 3 will continue to diverge and the curve for fraction of energy used will continue downward.

It will soon become very important to obtain a maximum of useful effect for each amount of energy released from storage. *The limit is not so much what is available, but rather how much can be disposed of.*

Although oil and natural gas reserves are small enough that they cannot supply enough energy to cause alarm in disposal of the total heat, coal reserves are large enough to last (even with increasing rate of use) until the total energy consumption makes disposal of greater concern than the supply (Cheney, 1974). Reserves of fissionable material are believed adequate to supply energy beyond that of all the coal reserves; fusion, if current research is successful, will supply still more. As its reserves become more limited, the continued use of any fuel will result in an appreciable economic penalty. Effort should be directed toward more efficient use of our energy reserves rather than seeking similar reserves that will result in less economical fuel sources. A definition of efficiency of energy use, "what is useful" divided by "what is removed from storage," suggests an alternative measure of long-range value of energy research and development.

Jaske (1974) has documented at least two of the alternatives:

1. "We can strive to meet all energy needs with available technology and risk a combination of fuel shortages and climatic involvement, or

2. "We can make determined efforts to let economic interplay justify reduced energy usage, and permit technological advances to operate so that a conservation policy can be implemented."

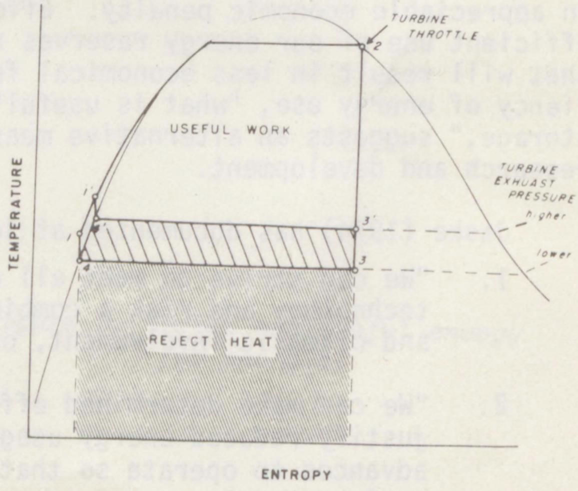
4. GENERATING CYCLE EFFICIENCY

Both boiling water and pressurized water reactor nuclear generating plants have a lower thermal efficiency than a corresponding fossil-fueled plant (Cheney, 1974; Jaske, 1974). Safety limits imposed on the temperatures (and pressures) within a light water reactor put these plants at a disadvantage with respect to plants where the limiting temperature is determined by turbine blade metallurgy. High temperature gas-cooled reactors (HTGR) are not as limited in this regard, and with advancing technology HTGRs are becoming more popular.

Elementary thermodynamics shows that thermal efficiency of power cycles is increased when the highest temperature in the cycle is raised. (See figure 4.) The area inside the locus of state points of the steam represents the useful energy produced (work).

Figure 4 shows that the useful energy produced is increased by lowering the temperature at which the heat is rejected. The lower the consenser temperature, the higher the thermal efficiency of the cycle. Obviously, the temperature at which the condenser operates is determined both by the temperature of the large volume of (relatively) cold fluid available to receive the heat and by the cooling method selected.

Figure 5 shows that for typical steam conditions in a light water reactor the theoretical turbine output is reduced 11 percent if the temperature of the condensing steam is increased from an 80°F level to 120°F. The curve in figure 5 is based on an ideal Rankine cycle and does not include cycle modifications to avoid excess moisture in the later stages of the turbine, the possibilities of reheat, or turbine inefficiency. While each system must be analyzed individually to determine the loss in output from increased condenser temperature, the values given for the theoretical cycle indicate the effects of condensing temperature.



STEAM CYCLE SHOWING EFFECT OF TURBINE EXHAUST PRESSURE

Figure 4. Steam cycle showing effect of turbine exhaust pressure.

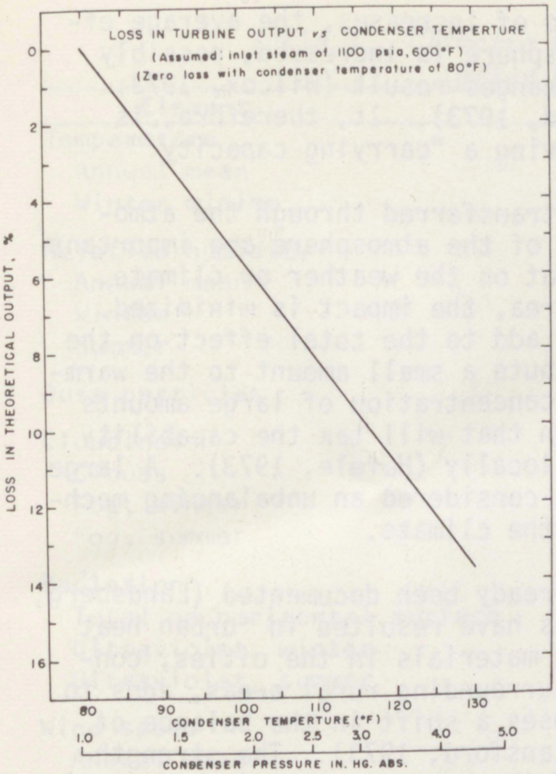


Figure 5. Loss in turbine output vs condenser temperature. (Assumed: inlet steam of 1100 psia, 600°F) (zero loss with condensor temperature of 80°F).

In evaluating the impact of a power plant cooling system, we must consider the total energy used (removed from storage) to produce a unit of useful energy (electricity). A 10 percent loss in output for the amount of energy used can be equated to the need to use 11.1 percent more energy to produce the initial (needed) output.

Thus the shift to nuclear electric generating stations adds to the inefficiency of the use of stored energy because of (1) the necessity to limit the maximum temperature in the steam power cycle, (2) movement to increasingly larger stations; whether nuclear or fossil (resulting in insufficient availability of cooling water and the consequent use of cooling towers) giving higher condenser temperatures.

5. IMPACT OF WASTE HEAT ON THE ATMOSPHERE

The availability of a suitable sink to accept the "waste heat" from a proposed nuclear electric generating station is one of the largest problems associated with the selection of a site. Whether the heat is rejected initially into a river, lake, or ocean as in once-through cooling, or into cooling ponds and canals, or through cooling towers, the energy eventually is transferred to the atmosphere for final radiation into outer space. As the total amount to be disposed of increases, the average effective radiating temperature of the atmosphere is increased, possibly to the extent that undesirable climatic changes result (Wilcox, 1973; Hafele, 1973; Vermont Public Service Board, 1973). It, therefore, is possible to think of the atmosphere as having a "carrying capacity."

The surface area over which heat is transferred through the atmosphere and the dispersion characteristics of the atmosphere are important in estimating the impact of the reject heat on the weather or climate. When the heat is dispersed over a large area, the impact is minimized. Other plants in the same broad region may add to the total effect on the regional atmosphere, and each will contribute a small amount to the warming of the global atmosphere. It is the concentration of large amounts of waste heat in a relatively small region that will tax the capability of the atmosphere to assimilate the heat locally (Hafele, 1973). A large heat release from a "point source" can be considered an unbalancing mechanism and may cause changes or shifts in the climate.

Some similar climate changes have already been documented (Landsberg, 1970). Energy releases in populated areas have resulted in "urban heat islands." The use of paving and building materials in the cities, contrasting with the natural vegetation of surrounding rural areas, adds to the effects of greater energy use and causes a shift in the balance of radiative equilibrium (Peterson, 1973a; Lansford, 1973). The strength of the urban heat island is a function of the concentration (or density) of energy consumption and the size of the area.

The standard review of urban climate that is now accepted by most others (e.g., Peterson 1969; Jaske, 1973) was initially presented over 10 years ago by Landsberg (1958; 1962). Research has since confirmed the values that he tabulated in his papers. Table 1, which describes the climate changes produced by cities, is taken from Landsberg's work.

Peterson (1973) has concluded that urban heat emissions decrease the likelihood of surface-based air temperature inversions. Other features of urban climate, not included in table 1, that are related to heat emissions are: (1) a longer frost-free growing season (e.g., in Washington, D.C., the growing season is more than a month longer than in nearby rural areas); (2) less snowfall because it melts before falling through the warmer urban atmosphere.

Oke (1973) recently has confirmed that the magnitude of the heat island is a function of city size. The larger the city, the more heat released by the population, and the greater the temperature difference between the urban values and the rural values; however Oke has established that this is not a simple linear relation.

In 1970, the United States' rate of per capita energy consumption was 303.8 million Btu per person per year (World Energy Supplies, 1972). Should this consumption be typical of urban dwellers, then a city whose population density is equal to that of Washington, D.C., would have an

Table 1. Climatic Changes Produced by Cities
(after Landsberg, 1962)

Element	Compared with rural environs
Temperature	
Annual mean	1.0 to 1.5°F higher
Winter minima	2.0 to 3.0°F higher
Relative humidity	
Annual mean	6 percent lower
Winter	2 percent lower
Summer	8 percent lower
Dust particles	10 times more
Cloudiness	
Clouds	5 to 10 percent more
Fog, winter	100 percent more
Fog, summer	30 percent more
Radiation	
Total on horizontal surface	15 to 20 percent less
Ultraviolet, winter	30 percent less
Ultraviolet, summer	5 percent less
Wind speed	
Annual mean	20 to 30 percent less
Extreme gusts	10 to 20 percent less
Calms	5 to 20 percent more
Precipitation	
Amounts	5 to 10 percent more
Days with > 0.2 inch	10 percent more

energy flux rate of 14 Btu/hr ft^2. This value depends upon population density rather than the city's size. Oke's data indicate the effect of the energy release, as measured in temperature increases, does depend on city size; he has measured up to a 12°C (21.6°F) difference between the Montreal urban temperature and the surrounding rural areas. Although Montreal, with a population of 2 million, apparently experiences a "heat island" effect of this degree only on relatively clear nights when the wind speeds are extremely low, even with winds about 9 or 10 mph (5 m/sec) the "heat island" effect raised the temperature 5 to 7°C (9-12°F).

The relative magnitudes of "artificial" urban heat and natural radiation heat for Sheffield, England, have been analyzed (Garnet and Bach, 1965; Torrance, 1972). The difference between the radiant energy received at the surface and that radiated by the surface was 17.8 Btu/hr ft^2. This amount must be transferred from the surface to the atmosphere either as sensible heat or as latent heat. An additional 6.13 Btu/hr ft^2 is added to the atmosphere by "artificial" urban heat; this is a significant addition to the "natural" heat and will cause changes in the convective processes.

Lees (1970) has drawn attention to the thermal problem in urban areas, particularly around Los Angeles. Jaske et al. (1970) have expanded on Lees' method and have predicted a 5°F thermal elevation for the Boston-Washington corridor by 2000 A.D. Applying the same procedures to the smaller area of New York-Philadelphia, Jaske et al. (1970) indicate a mean annual temperature increase approaching 15°F.

As electrical generating units (nuclear or fossil) become clustered within relatively small geographical areas, their "reject heat" can have climatic effects that approach those of the *city* heat island. For example, the reject heat flux density from all units of the Dresden, LaSalle, and Braidwood nuclear stations, when fully operating, will be 6.2 Btu/hr ft^2. This flux density is based on an area of 245 square miles (a semicircle of about 25 mile diameter can include all three sites). This is the equivalent of using the entire area as a giant cooling pond to distribute the heat in a manner that would approximate that of cities. If only two of the three stations (Dresden and Braidwood) are considered, the "effective pond area" can be reduced to an area equal to that of a city of one million people and with a corresponding heat flux density of 11.2 Btu/hr ft^2.

An area 12 miles long by 5 miles wide (60 square miles) can be selected that includes the Summit, Salem, and Hope Creek sites. The reject heat from all proposed units at these stations will have a flux density of 23.4 Btu/hr ft^2. Enlarging the area to 500 square miles to include the Peach Bottom and Fulton plants results in a flux density of 4.8 Btu/hr ft^2 (not including non-nuclear power plants, proposed power plant sites in Maryland falling within this area, and heat from other sources).

Table 2 summarizes the heat flux density for various sources. The larger the area over which the heat is dissipated, the smaller the heat flux density; this is true for heat both from cities and power plants.

Meteorologists have known that there are certain "preferred" storm tracks and areas for storm genesis. These favored paths and sources are the result of topography, land-water boundaries, and differential heating of the atmosphere by the earth's surface. As clusters of power plants continuously add energy to the atmosphere, the development of man-made areas of storm genesis also may occur (Peterson, 1973a). While there is no evidence that power plants have influenced storm tracks, growing energy needs indicate that some attention should be paid to this. The continuing concentration of large nuclear plants in the eastern U.S. (where the need for power is the greatest) is an example. States east of the Mississippi River, with only 28.8 percent of the area of the contiguous U.S., contain 78.5 percent of the nuclear power units announced, ordered, under construction, or operating as of March 1, 1974. Since these units will also provide 78.5 percent of the total nuclear generating capacity in the U.S., the average size of a unit is not a function of eastern or western U.S. siting.

Table 2. Heat Flux Density for Various Sources (large areas)

	Area (mi^2)	Heat Flux Density (Btu/hr ft^2)
Solar Constant	·	429
24-hr average solar radiation at the ground at 40°N in June or July (Langhaar, 1953)		130
Anthropogenic Heat from Cities		
Manhattan, New York City (Inadvertent Climate Modification, 1971)	22.8	200
Moscow (Inadvertent Climate Modification, 1971)	340	40.3
Washington, D.C.	67	14
Los Angeles Basin (Inadvertent Climate Modification, 1971)	3,861	2.4
Boston-Washington Metropolitan Area Projection for 2000 A.D. (Jaske, 1973)	12,057	11.4
Sheffield, England (Garnett and Bach, 1965)	18.5	6.1
Power Plant Waste Heat		
From Dresden and Braidwood plants (over area equivilant to city of 1 million people)	89	11.2
From nuclear plants only in area including Dresden, LaSalle, Braidwood	245	6.2
From nuclear plants only in area including Summit, Salem, Hope Creek (12 mi x 5 mi)	60	23.4
From nuclear plants only in area including Peach Bottom, Fulton Summit, Salem, Hope Creek (50 mi x 10 mi)	500	4.8
From nuclear plants only for all U.S. east of Mississippi River	854,600	0.023

While heat flux density (as shown in table 2) provides an indication of the impact of a power plant as a "heat island," the heat released in most cases (especially those plants with cooling towers) is actually much more concentrated than that from cities and can be responsible for far greater impacts (and is more difficult to understand thoroughly). As suggested by Hanna and Gifford (1974), large heat releases from very large power generating stations may, under some conditions, produce convective effects that have the potential to generate thunderstorms and possibly associated squalls.

Dessens (1964) reported on the French meteotron which has produced "artificial thunderstorms and even tornadoes." This meteotron consists of an array of 100 oil burners that can release 700,000 kW of heat (2.4 x 10^9 Btu/hr). These heaters covered 3200 m^2 (34,445 ft^2). The heat flux density from the French meteotron is 69,000 Btu/hr ft^2. The weather modifications reported by Dessens are large including vertical currents of 32 ft/sec. While the products of combustion from the oil burners contribute to the meteorological effects, the heat provides the initial stimulus for convection. A typical hyperbolic natural-draft cooling tower, dissipating the heat from a 1130 MW(e) generating unit, must discharge into the atmosphere 7680 x 10^6 Btu/hr. Such a tower may have a discharge diameter of 250 ft, and thus a heat flux density of 153,600 Btu/hr ft^2--over twice the amount of the French meteotron.

Table 3 summarizes the heat-flux densities from several known large sources of heat addition to the atmosphere and a brief summary of the meteorological effect of each where possible.

The precise impact of the quantities of heat released to the atmosphere over small areas cannot now be specified. It is evident, however, that the impact will be observable and will be greater with power plants using cooling towers than with cooling systems that spread the heat to the atmosphere over larger areas. Although much more study is required before quantitative estimates can be made, the heat rejected is now of a magnitude that requires careful consideration of atmospheric effects. The large amounts of heat being rejected from large nuclear power plants *are* comparable with amounts from the other phenomena that have caused atmospheric pertubations and/or climate changes. For the changes to be as small as possible, the heat should be transferred to the atmosphere over as wide a geographical area as possible.

6. TYPES OF POWER PLANT COOLING AVAILABLE

6.1 Once-Through Cooling

Until relatively recently, most steam electric power plants both in the U.S. and throughout the world used water from rivers or lakes to provide the necessary cooling in the condensers. As progressively larger generating units were built, the amount of water needed for once-through cooling became increasingly difficult to find.

In terms of impact on the atmosphere, once-through cooling has a major advantage over the others. The heat, which must eventually pass through the atmosphere for radiation to space, is spread over a large surface area (Hauser and Oleson, 1970). If the discharge system is well designed and located so that the discharge water mixes well with ambient water, the temperature rise of the water body may be small. Then the driving potential for transferring the heat to the atmosphere is small and the area over which the heat is transferred is quite large. Although no estimates of effective areas of heat transfer to the atmosphere from once-through cooling have been found in the literature, under good mixing conditions it could be tens or even hundreds of square miles. Where the warm water from the condenser is discharged at or near the surface with little mixing, the bulk of the heat may be transferred in areas of 2 or 3, up to 10 square miles.

The heat transfer from a natural water body to the atmosphere and/or outer space can be a very complex combination of several modes of heat transfer, each dependent on many variables. The evaporation of water from the surface and the convection of heated air and moisture are most important quantitatively--both evaporation and convection depend upon wind speed.

While once-through cooling has advantages because of its minimal impact on the atmosphere, this system has very serious drawbacks because of its possible impact on the ecosystem of the water body used. Unless intakes are very carefully designed and located, the possibility that large amounts of fish and other aquatic life may be trapped or killed can create a serious problem. Small, even microscopic, forms of life may be entrained in the flow into the condenser where they are subjected to sharply increased temperature. Should such life be critical to the total health of the water body, the use of once-through cooling must be evaluated in terms of these ecological considerations. The most serious problem in once-through cooling is the discharge of heated water back into the main water body. In some cases, very serious consequences of "thermal pollution" have resulted and have become an excuse in others to completely avoid heated discharges. Attempts to discharge very large amounts of heat into water bodies of quite limited size have caused the temperature of the water body to rise substantially over a significant area, thus altering the aquatic life of that water body.

Another very important consideration in connection with once-through cooling is the "cold shock" effect. When the ecosystem of the water body has adjusted and become accustomed to the warmer temperatures resulting from a power plant operation, a forced or scheduled shutdown can cause a sudden cooling of the water and result in a shock to the aquatic life.

Cairns (1974) states that most freshwater and marine environments can assimilate some heated water without being seriously degraded. Fixed national standards must be based on the worst conditions and therefore do not permit the full use of a particular water body's assimilative capacity. As nuclear and large fossil-fueled power plants planned and being built grow in number and size, the number of sites with enough water flow to provide for once-through cooling for the total plant capacity without serious thermal pollution is becoming very limited. The idea of using that assimilative capacity that is available, even though this may be less than the total cooling capacity required by the power plant, has not been given the full consideration it deserves.

Table 3. Effects of Large Heat Additions to the Atmosphere.

Total Energy Rate (Btu/hr)	Area (ft^2)	Energy Flux Density (Btu/hr ft^2)	Meteorological Consequences
Phenomenon/Reporter: Solar Radiation 40°N (average over 24 hrs)/Langhaar (1963)			
---	---	130	Normal weather, clear hot summer day.
Phenomenon/Reporter: Large brush fire/Taylor et al. (1973)			
$341,000 \times 10^6$	538×10^6	634	(Relatively small energy flux density, very large area) Cumulus cloud reaching to a height of 6 km formed over 1/10 area of fire. Convergence of winds into the fire area.
Phenomenon/Reporter: Forest Fire Whirlwind/Graham (1955)			
N/R	N/R	---	Typical whirlwind: Central tube visible by whirling smoke and debris. Diameters few feet to several hundred feet. Heights few feet to 4000 ft. Debris picked up — up to logs 30 inches in diameter, 30 ft long.
Phenomenon/Reporter: WW II Fire Storms/Landsberg (1947)			
N/R	N/R	125×10^6	Turbulent column of heated air 2½ miles high 1½ miles in diameter. Fed at base by inrush of surface air. One and a half miles from fire, wind speeds increased from 11 to 33 mph. Trees 3 ft in diameter were uprooted.
Phenomenon/Reporter: Fire at Hiroshima/Hersey (1946)			
N/R	---	---	(10-12 hrs after A-bomb). "The wind grew stronger, and suddenly — probably because of the tremendous convection set up by the blazing city — a whirlwind ripped through the park. Huge trees crashed down: small ones were uprooted and flew into the air. Higher a wild array of flat things revolved in the twisting funnel...the vortex moved out onto the river, where it sucked up a waterspout and eventually spent itself.

Phenomenon/Reporter:	Surtsey Volcano/Bourne (1964)		
$341,000 \times 10^6$	$< 10.8 \times 10^6$	31,700	Permanent cloud extending to heights of 5 to 9 km. Continuous sharp thunder and lightening, visible 115 km away. (Phenomenon probably peculiar to volcano cloud with many small ash particles.) Waterspouts resulting from indraft at cloud base, caused by rising, buoyant cloud.
Phenomenon/Reporter:	Surtsey Volcano/Thorarinsson Vonnegut (1964)		
$650,000 \times 10^6$	10.8×10^6	62,960	Whirlwinds (waterspouts and tornadoes) are the rule rather than the exception. More often than not there is at least one vortex downwind. Short inverted cones, or long, sineous horizontal vortices that curve back up into the cloud, and intense vortices that extend to the ocean surface.
Phenomenon/Reporter:	French Meteotron/Dessens (1964)		
$2,400 \times 10^6$	34.5×10^3	69,400	"artificial thunderstorms, even tornadoes," many cumulus clouds ... substantial downpour. Dust devils.
Phenomenon/Reporter:	French Meteotron/Dessens (1962)		
$1,200 \times 10^6$	168×10^3	7,135	15 minutes after starting the burners, observers saw a whirl 40 m in diameter ... whirlwind so strong burner flames were inclined at 45°.
Phenomenon/Reporter:	Saturn V — S-1C Static Firing/Morris (1968)		
$432,000 \times 10^6$	7.9×10^3 (100 ft dia.)	55×10^6	(Maximum firing time 2.5 minutes) Explosive cumulus growth for first 90 sec — reached maximum height in 5 minutes.
Phenomenon:	Single large cooling tower		
$7,680 \times 10^6$	50×10^3	153,600	Unknown.
Phenomenon:	Array of large cooling towers (Nucl. Park) (Data based on preliminary plans for nuclear center at River Bend, La.		
$245,700 \times 10^6$	43×10^6	5,715	Unknown

Public Law 92-500 prohibits thermal discharges (to water bodies) except under certain special circumstances (Sec. 316). As the "Federal Water Pollution Control Act" (PL 92-500) did not consider atmospheric interactions, it may not provide for minimal *total* environmental impact. Eventual revision of the law to allow for assimilation of the heat that will not cause serious degradation to the water body will offer some protection to the atmosphere through reducing heat added from a source of small area.

6.2 Cooling Ponds, Lakes, and Canals

To avoid thermal discharges to public water bodies, some power plant operations have built ponds, lakes, and/or canals that provide a "closed cooling system" to cool the water before it is returned to the public water body. As a rule of thumb, the areas of artificial cooling ponds or lakes fall in the range of 1 to 2 acres/MW of electrical capacity (Hauser and Oleson, 1970). A modern, 1000 MW(e) nuclear power plant thus requires a cooling lake area of 1.5 to 3 square miles. The actual area required for sufficient cooling depends on location, the average and the variability of wind speed, air temperature, and humidity. More cooling capacity per unit area is obtained by using water sprays; these increase evaporation and thus enhance heat transfer to the atmosphere.

Obviously, as the cooling lakes become larger this method of cooling will have a smaller impact on the atmosphere. Economics generally dictate that as little land as possible be devoted to artificial cooling lakes which puts a greater burden on the local atmosphere.

Among the various operating nuclear generating plants, only Dresden, Oconee, and Robinson use an artificial lake or pond for cooling. To comply with Public Law 92-500 without extended hearings of a doubtful outcome, the cooling lake must be totally private and not associated with a public water body. Cooling ponds or lakes have sometimes provided the basis for a possible compromise between once-through cooling and cooling towers, but problems of fogging, icing, and drift (if sprays are used) can occur and make up water for that evaporated must be available.

6.3 Evaporative Cooling Towers

Since many new power plant sites have water supplies inadequate for once-through cooling, electric utilities are turning to cooling towers. Between 1962 and 1970, 22 percent of the cooling for new electric power generation was through cooling towers. Mechanical draft towers were favored over natural draft towers by more than 3 to 1 (Kolflat, 1974). Forty percent of new plants between 1972 and 1976 will use cooling towers, and this fraction is expected to rise to 50 percent for the 1976-1980 period.

Cooling towers have the disadvantage (with respect to impact on the atmosphere) that they reject heat over a very limited area. As pointed out in this report, it is the large quantities of heat per unit area that can have the greatest atmospheric impact. A large cooling tower whose capacity is sufficient for a 1000 MW(e) unit typically has a discharge area of about 1 acre for natural draft towers and up to 20 to 30 acres for mechanical draft towers. This compares with areas of 1000 to 2000 acres for cooling ponds or lakes that have the same cooling capacity.

6.3.1 Mechanical Draft Cooling Towers

The most prevalent type of cooling tower is the mechanical induced-draft evaporative crossflow tower (Kolflat, 1974). In evaporative towers, about three-fourths of the heat transfer occurs by evaporation; the other one-fourth is transferred by conduction/convection. The water and air are in intimate contact; the water falls vertically through the air that is drawn through the tower by the fans (induced-draft). Power must be supplied for operating the tower, both to pump the water to the supply manifold, and to drive the fan. For mechanical draft towers, this power requirement is about 2 percent of the net annual output of the plant and is higher in summer than in winter.

Because evaporation provides most of the cooling, the ambient wet-bulb temperature limits how much the water may be cooled. The approach, the difference between the temperature of the cooled water and the ambient wet-bulb temperature, may typically average 15°F. Thus, an evaporative cooling tower can provide water to the condensers at 15°F above the ambient wet-bulb temperature, while in once-through cooling the water enters the condenser at the ambient temperature of the supply water body.

Mechanical draft cooling towers are less expensive than natural draft towers by a factor of 1/3. In both cases, the cost decreases as the design wet-bulb temperature is reduced. A mechanical draft tower may conservatively cost $2.50/kW of electrical capacity ($2,500,000 for a 1000 MW unit); this cost is about 80 percent for the material and 20 percent for construction labor.

Mechanical draft cooling towers discharge a large volume of warm moist air into the atmosphere at low levels (generally within 50 ft (17 m) of the ground). This results in impacts on the atmosphere that are very evident to the local population. Fogging and icing, for example, may occur in winter when the warm very moist air from the tower mixes with the cold ambient air near the ground. The effective addition of heat and moisture near the ground make the atmosphere in the area more unstable and add to the tendency of a cloud layer to form at higher levels.

Vapor plumes from cooling towers can cause problems. Plumes behave as any other cloud system; they reduce the sunshine incident on the surrounding land.

Near the seacoast, plumes from cooling towers using salt or brackish water in the cooling system contain salt particles that are carried aloft in the bouyant plume. This salt may cause damage to agriculture or other industry where it settles out. The recently proposed use of sewerage as a coolant in cooling towers also may be expected to present problems. Lewis (1974) calls attention to the spread of bacteria through cooling tower effluents.

6.3.2 *Natural-Draft Cooling Towers*

Although used less frequently in the past than mechanical draft towers, natural draft towers require no fan (and no fan power) to move the air over (or through) the water being evaporated. By early 1973, there were only 35 natural draft cooling towers in operation, under construction, or planned for major electrical generating stations in the U.S. (Kolflat, 1974). Most of these are in the Appalachian region; only three are west of the Mississippi River.

As for mechanical draft towers, the ambient wet-bulb temperature is the factor having the greatest influence on natural draft tower performance. These towers are also dependent on buoyancy and chimney effect; operation improves as wet-bulb temperature is reduced. Probably the most important factors in deciding to use a natural draft tower rather than a mechanical draft one are the elevated discharge from the natural draft tower and reduced long-term maintainance.

Natural draft cooling towers for major electrical generating units are 300 to 500 feet tall. The discharge of warm moist air at this height makes fogging or icing at ground level much less likely. The appearance of natural draft towers sometimes is objectionable because of their height. In addition, they must be designed for appropriate wind loading.

A natural draft tower takes longer to build than a mechanical draft tower; much more of it must be erected in the field, rather than built in the shop. A natural draft tower is three times more expensive and may cost between \$20 million and \$50 million for a 1000+ MW(e) nuclear unit, which is divided about 50 percent for materials and 50 percent for labor.

The "energy penalty" for use of a counter-flow natural draft tower is about the same as for a mechanical draft tower; the added pumping power required for the greater height is nearly an equal trade-off for the fan power required for mechanical draft. A cross-flow natural draft tower requires less pumping and thus reflects an energy savings. A natural draft tower may use less water per unit of electrical output than does a mechanical draft tower but does not cool the condenser water to as low a temperature unless the wet-bulb temperature is less than 70°F. The condensing temperature for generating cycles that use natural draft towers is 5 to 7°F higher than are the temperatures for mechanical draft towers. The penalty in cycle efficiency associated with this higher condensing temperature can be thought of as part of the cost imposed to avoid problems of local fogging and icing.

6.4 Wet/Dry and Dry Cooling Towers

Many environmental problems associated with evaporative cooling towers can be avoided by employing dry cooling, either for a part or all of the cooling capacity. When dry cooling is employed, all of the heat is transferred by conduction/convection, and this has the advantage of reducing water losses through evaporation. With dry cooling, the total heat transfer depends on dry-bulb temperature rather than wet bulb temperature (McFeron and Emery, 1973); therefore, the driving potential for heat transfer, the temperature difference, is reduced. Because of the lower heat transfer coefficient for air in dry cooling towers, a larger temperature difference between the water and the air is necessary than for wet cooling towers (McFeron and Emery, 1973). The turbine cycle efficiency also is reduced because of the higher condensing temperature that results.

The problem of visible plumes can be almost completely eliminated. The amount of cooling accomplished in each portion of a wet/dry tower can be adjusted to control the relative humidity of the effluent plume. Figure 6 shows this on a psychrometric chart.

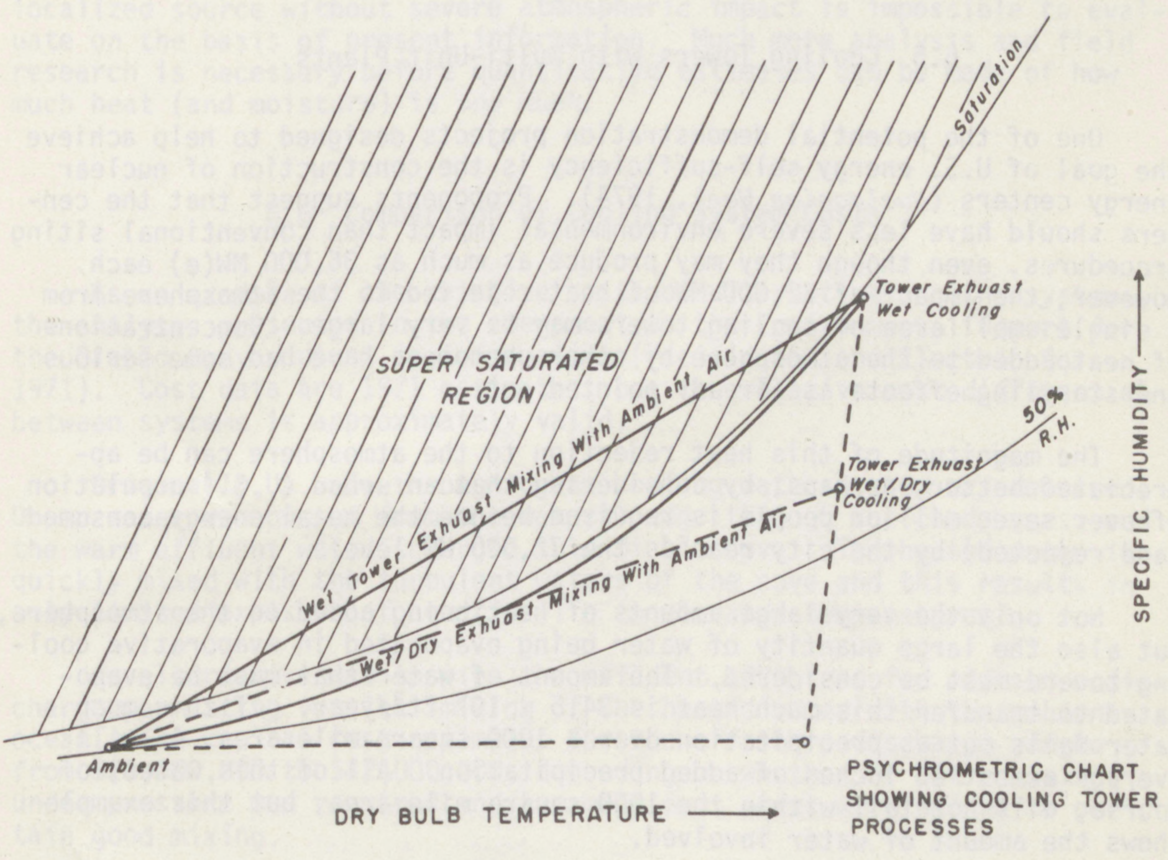


Figure 6. Psychrometric chart showing cooling tower processes.

With wet/dry or dry towers, fogging and icing are eliminated. Wet/dry towers can be designed either to conserve water or to control or eliminate visible plumes. A wet/dry system designed for water conservation can accommodate those cases where water supply is critical. As little as 15 to 20 percent of the water used in evaporative towers may be required for a wet/dry system (Westinghouse Wet/Dry Cooling Tower System, 1974).

Dry cooling towers can be operated to solve the problems of both visible plume abatement and water conservation.

Dry towers are much larger and, therefore, more costly than evaporative ones (McFeron and Emery, 1973) and require much more land. The performance penalty, in addition to high capital costs, makes electrical generation with dry cooling about 15 percent more costly than with evaporative systems (Westinghouse Wet/Dry Cooling Tower System, 1974). Under most atmospheric conditions, plumes from dry cooling towers are not likely to produce large clouds or significant amounts of precipitation near the plant (Kearney and Boyack, 1973). Much more work must be done before the effect of dry tower plumes (especially from multi-unit sites) on the mesoscale atmosphere can be determined.

6.5 Cooling Towers with Multi-Unit Plants

One of the potential demonstration projects designed to help achieve the goal of U.S. energy self-sufficiency is the construction of nuclear energy centers (*Nucleonics Week*, 1974). Proponents suggest that the centers should have less severe environmental impact than conventional siting procedures, even though they may produce as much as 36,000 MW(e) each. However, the impact of 72,000 MW of heat rejected to the atmosphere from a single small area of cooling towers may be very large. Concentrations of heat added to the atmosphere by other phenomena have had some serious and startling effects as already pointed out.

The magnitude of this heat rejection to the atmosphere can be appreciated better, perhaps, by considering that an urban (U.S.) population of over seven million people is required before the total energy consumed (and rejected) by the city reaches the 72,000 MW level.

Not only the very large amounts of heat being added to the atmosphere, but also the large quantity of water being evaporated in evaporative cooling towers must be considered. The amount of water that must be evaporated to transfer this much heat is 34.5×10^9 ft^3/year. If this much water falls out as precipitation over a 1000 square mile area, it will average almost 15 inches of added precipitation. All of this water, of course, will not fall within the 1000 square mile area, but this example shows the amount of water involved.

This much water added to the atmosphere in combination with 72,000 MW of heat must result in increased cloudiness. In locations where the humidity is naturally high a large portion of the time, the plume from cooling towers at a nuclear energy center may be expected to cause a nearly permanent cloud to form over the area.

Hanna and Gifford (1974) and Briggs (1974) have suggested that a heat release of the magnitude suggested here has the potential for generating a thunderstorm at times and will "trigger" thunderstorms in areas where natural occurrence is already frequent. The vortex activity observed in other cases of large heat additions is a possibility. The indraft at the base caused by a rising, buoyant cloud can act to concentrate vorticity. Such effects from large concentrations of cooling towers cannot be ruled out.

Although there is no conclusive evidence of dire impacts from heat released on this scale, there is a sufficient possibility to sound an alarm. A single isolated cooling tower for a 1000 MW unit could probably be operated without much impact most of the time; towers for two units will be noticed more often and at a greater distance, but usually should not cause a great deal of concern. Towers for many units at the same site will present problems. How much heat can be rejected from one localized source without severe atmospheric impact is impossible to evaluate on the basis of present information. Much more analysis and field research is necessary before quantitative estimates can be made of how much heat (and moisture) is *too much*.

6.6 Comparison of Cooling System Costs

As an example of the relative costs of alternative cooling systems, the analysis presented in the amendment to the Environmental Report for the Diablo Canyon plant is informative (Pacific Gas and Electric Co., 1971). Cost data are 1971 estimates, but the relative cost differential between systems is approximately valid.

Originally, a once-through ocean cooling water system was selected. Ocean water was pumped from the waters' edge through the condensers, and the warm effluent was discharged into Diablo Cove. The heated water is quickly mixed with the turbulent waters of the cove and this results in only limited exposure of aquatic life to elevated temperatures.

An alternative was to pipe the effluent 1700 feet for off-shore discharge permitting vertical mixing of the heated water with the ambient ocean. The capital cost estimates for the off-shore discharge ranged from $28,000,000 to $42,000,000, depending on whether or not tunneling under pressure was required and how many exit ports were needed to obtain good mixing.

The capital cost of mechanical draft evaporative towers (two units) was estimated to be $38,000,000 with added maintainance costs of $350,000 per year. In warm periods, the cycle's reduced efficiency would cause an output loss up to 85 MW(e) in addition to the 15 MW(e) cooling tower fan requirements.

Natural draft evaporative towers were estimated to have a capital cost of $37,000,000 and a maintainance cost of $300,000 annually. Reduced cycle efficiency causes a loss in capacity of up to 160 MW(e).

The capital cost of dry cooling towers was estimated at 3½ times the cost of evaporative natural draft towers. Because of higher condenser inlet temperatures, the capacity loss with dry cooling towers was estimated to be 12 percent or 275 MW(e).

It was estimated (Pacific Gas and Electric Co., 1971) that the inlet cooling water to the condenser would have the following temperatures for each cooling system:

Once-through cooling	69°F
Evaporative cooling towers	78°F
Dry cooling towers	108-113°F

7. SUMMARY AND RECOMMENDATIONS

The foregoing remarks indicate that continuing the present trends can invite additional problems for the energy industry. The question of whether or not a specific new energy facility of a given size should be developed must be posed in each case with the understanding that the answer may frequently be "no." Growth rates in energy use during the past several decades have been great enough to cause concern. Should such rates continue, the global carrying capacity may be approached too rapidly, and with the possibility of overshooting. Future growth in total energy use must be considered very carefully--both in the United States and the world as a whole.

It should be possible to control the energy growth rate, while maintaining the present high living standards in developed countries and concurrently improving those in less well-developed areas. A step in this direction would be to reverse the downward trend in the fraction of energy which is "useful" (fig. 3). Use of "waste heat" to handle requirements for which additional fuel would otherwise be used should be explored, even when it is "cheaper" to use another heat source rather than to accept the cost of distributing the "waste heat."

To mitigate the impact of the waste heat from nuclear power plants, plants should be located where: (1) the waste heat can be minimal, i.e., the useful fraction is increased, (2) the waste heat that cannot be used is rejected to the atmosphere over as wide a surface area as possible. The automatic assumption that "a cooling tower or towers is the way to reject heat which gives least environmental impact" is unproved. Siting (and sizing) plants so that a portion of the waste heat can be used beneficially, and so that a natural water body can be used to dissipate the heat into the atmosphere over as large an area as possible will reduce the growth rate of total energy expenditure without affecting living standards, because the useful fraction is higher.

The arguments presented above suggest that there are *potential* problems in the clustering of several large generating units at the same site. It is impossible, at this time, to establish how the number of units relates to the average or possible atmospheric conditions at the site.

The continued use of once-through cooling where possible, e.g., oceans, great lakes, and other large water bodies, will give the best heat dispersion and, hence, impose the least impact on the atmosphere. The Cornell Workshop (1972) states, "We may very well have future regrets if stringent uniform standards require that once-through cooling be abandoned hastily."

Artificial lakes, ponds, and canals are the next most desirable for dispersing heat over a large area, but these systems consume more water through evaporation than once-through systems.

It is recommended that:

1. Once-through cooling be used where and whenever possible.

2. Smaller units be considered as well as single-unit sites in order to take advantage of cooling capacity of smaller water bodies. The resulting improvement in cycle efficiency can at least partially compensate for the economic penalty of operating smaller units and single-unit sites.

3. "Combination" cooling systems be considered. When once-through cooling will not meet the requirements of the whole plant because of inadequate water supply, a portion of the total cooling requirement might be accomplished by once-through and the remainder by other cooling procedures. Actually, a division among the many possibilities for heat rejection should be beneficial both in the efforts to cause as small an impact as possible on the atmosphere and in the efforts to have cycle efficiency as high as possible. The opportunity to vary the portion of cooling by each method with the season and with atmospheric conditions can result in a more efficient operation, and one with less impact on the atmosphere.

4. Major research efforts be undertaken to understand the impact of large heat and/or moisture additions to the atmosphere. Such research should include:

   a. Extensive field measurements of atmospheric variables before and after the start of operation at a given site (Peterson, 1973). The development of appropriate baseline data for at least a few years for most meteorological variables is essential to the understanding of changes resulting from large amounts of heat rejection.

   b. Measurements on and near a site that is scheduled to have several large cooling towers. The interaction of several plumes and interference between tower intakes should be noted. Comparison of data as an additional tower is brought on line can help determine possible impact of multiple tower installations.

Among the major atmospheric impacts that can be quantified and be better understood with the aid of good field research are:

1. The establishment of a "heat island," comparable with those of major cities of the world.

2. The determination of possibilities of storm genesis or other changes in basic circulation patterns.

3. The determination of the atmospheric conditions under which various heat additions make possible vorticity concentrations to serious levels.

Mathematical models of the atmosphere have been used and will continue to be proposed as ways to answer the questions suggested above. The need for some reliable field data is great--because the computer models rely on a *number of assumed constants*. More accurate estimates of these constants require carefully measured data.

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