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THERMAL DISCHARGES INTO THE COASTAL WATERS OF SOUTHERN CALIFORNIA

by

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SCCWRP

SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT

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FOREWORD

The Southern California Coastal Water Research Project (SCCWRP) is a part of today's evaluation of human activities as they affect the relationship between man and his environment. The Project aims at encouraging the conservation and enhancement of resources along the southern California coast by providing a better understanding of the ecological systems of the coastal waters in this area.

The Project was conceived by the five agencies of local government* that are responsible for most of the discharge of treated wastewater into the coastal waters of the region. Believing that their established applied research programs could benefit from the addition of a project with a region-wide geographical focus, they entered into a joint powers agreement to sponsor SCCWRP. The agreement established a commission, the SCCWRP Authority, to assume control of the Project and to be responsible to the public. This arrangement has provided the Project with complete freedom from control by any other agency, including the sponsors.

To ensure an adequate scientific basis for the Project, the joint powers agreement specified that a Consulting Board of internationally recognized experts be appointed to play a major role in the Project's supervision. The combination of experienced consultants and a relatively young but highly trained staff has created a unique interdisciplinary force directed at some of the most challenging technical problems of our time.

The general goals and objectives of SCCWRP are:

1. To attain a substantial understanding of the ecology of southern California coastal waters in present and recent times.
2. To gain insight into man's past, present, and predicted effects on the ecology, principally through wastewater discharge.
3. To outline methods for limiting or reversing the harmful effects of the various wastewater discharges in the future, and to recommend monitoring procedures.

In the initial review phase of the Project, an intensive information search has been conducted in 17 task areas of physical and chemical oceanography, marine biology, public health, and environmental engineering. Over 1,500 references and a large amount of the available raw data have been reviewed, and discussions with many individuals having relevant but unpublished information have been held. This document covers a few of the topics in the various task areas; the report therefore summarizes only a part of SCCWRP's initial assessment.

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*Ventura County, the Cities of San Diego and Los Angeles, and the County Sanitation Districts in Orange County and Los Angeles County.

The active research phase of the SCCWRP program is being developed from information collected and evaluated during the review. The last stage of the Project effort will be devoted to the analysis of all data and preparation of a final report. The report is expected to recommend criteria for wastewater discharge, to suggest alternate solutions for the problems of total environmental usage, and to outline further research needed to ensure protection and enhancement of the environment.

GEORGE E. HLAVKA
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CONTENTS

I INTRODUCTION 1

II METHODOLOGY 3

III THERMAL DISCHARGES OF POWER-GENERATING STATIONS 5
- Present Thermal Power Plants in the Coastal Area of Southern California 5
- Thermal Efficiency and Heat Wastage 5
- Waste Heat Discharge and Cooling Water Flow 6

IV SENSIBLE HEAT DISCHARGE OF WASTEWATERS 9
- Temperature Differential 9
- Sensible Waste Heat Discharge 11

V ENERGY INPUT THROUGH OXIDIZABLE ORGANIC MATTER 13
- Decomposition of Organic Matter 13
- Measurement of Organic Concentration and Energy Input 13

VI ENERGY TRANSFER ACROSS THE AIR-WATER INTERFACE 15
- Mechanisms of Energy Transfer 15
- Net Solar Radiation 15
- Net Atmospheric Radiation 16
- Absorbed Radiation 17
- Energy Loss Terms 17
- Net Heat-Transfer Rate 18

VII IMPACT OF THERMAL DISCHARGE ON WATER TEMPERATURE 19
Comparison of Natural and Man-Induced Energy Inputs 19
Man-Induced Water Temperature Elevation 19
Immediate Dissipation of Waste Heat Discharges 21
Comparison of Analytical and Empirical Methods of Predicting Water Surface Temperature Elevation 22

VIII SUMMARY 25

IX CONCLUSIONS AND RECOMMENDATIONS 27

REFERENCES 29

ILLUSTRATIONS

1 Location of Thermal Power Plants and Major Sewage Outfalls in Southern California 6

2 Schematic Diagram of a Steam Power-Plant Cooling Water System 7

3 Sewage Treatment Plant Effluent and Ocean Water Temperature 10

4 Average Monthly Solar Radiation Received on the Horizontal Surface 16

5 Brunt Coefficient, C, from Air Temperature, T_a, and the Ratio of Measured Solar Radiation to Clear Sky Radiation 17

6 Horizontal Distribution of Excess Temperature 22

TABLES

1 Estimated Waste Heat Discharge and Cooling Water Flow From Thermal Power Stations in the Southern California Coastal Area 7

2 Monthly Temperature Differentials for Hyperion, Orange County and San Diego Outfalls 10

3 Estimated Wastewater Sensible Heat Discharge for Municipal and Non-Power Industrial Discharges, 1970 11

4 Examples of Thermochemical Reactions of Aerobiosis and Oxidative Assimilation 14

5 Heat of Reaction of Complete Aerobiosis and Oxidative Assimilation 14

6 Estimated Energy Input of Oxidizable Organic Matter in Wastewaters 14

7 Estimated Average Monthly Values for the Rates of Heat Transfer Across the Air-Water Interface in the Southern California Coastal Area 16

8 Comparison of Natural (Absorbed Radiation) and Man-Induced Energy Inputs 20

9 The Area Contained within Specified Isotherms of Excess Temperature in a Thermal Plume . . . 22

INTRODUCTION

I

The coastal waters of southern California are the immediate receiving environment for a portion of the waste heat generated by man's activities in the coastal region. The concern about the potential impact of excess heat discharge experienced in other receiving waters has prompted SCCWRP to initiate an inventory of the present artificial thermal inputs into the coastal waters. The biological effects of thermal variations are not discussed here; however, this report will hopefully be of value to various agencies in assessing the relative significance of thermal waste as compared to the other effects of man on the marine environment.

The specific objectives of this report are (1) to evaluate, from the standpoint of energy flux, the inputs of cooling water, municipal wastewaters, and industrial wastewaters into the southern California coastal waters; (2) to estimate the energy transfer across the air-water interface; (3) to compare and place in perspective the man-induced energy inputs with the natural inputs; and (4) to examine the impact of thermal discharges on the surface temperature of the coastal waters.

METHODOLOGY

II

There are different kinds or states of energy. Discussions of the biotic and abiotic implications of each type of energy in the environment, or of the transformation of energy from one type to another, are beyond the scope of this report. Therefore, no distinction has been made between the terms "energy" and "heat," and they are used interchangeably in the text.

The energy balance method has been used by many researchers to conduct water-related studies in lakes and reservoirs and in the open sea (Krenkel and Parker, 1968). In the absence of any artificial (or man-induced) heat input, the energy budget for a segment of the coastal water environment may be written as follows:

$$dH/dt = A(q_s + q_a - q_b - q_c - q_e) + Q_V + Q_D \quad (1)$$

where

H = the heat content of the water body

dH/dt = the rate of change of heat content of the water body

A = the water surface area

q_s = the net solar radiation absorbed at the water surface

q_a = the net atmospheric radiation absorbed at the water surface

q_b = the back-radiation from the water surface

q_c = the rate of sensible heat exchange between the air and water due to conduction

q_e = the rate of evaporation loss (or condensation gain) of latent heat by the water surface

Q_V = the net energy gain to (or loss from) the water body in inflow (or outflow), including precipitation.

Q_D = the net diffusive heat exchange at a boundary other than the water surface.

Because of the lack of pertinent data, some terms in the natural energy budget could not be examined in detail in this report.

Superimposed upon the natural energy budget to the segment of coastal water are the man-induced energy inputs, Q_M. This factor includes cooling waters from thermal power plants, raised-temperature wastewaters of municipal and industrial origin, and oxidizable organic matter in waste discharges. The rate of heat input from each man-induced source has been computed for the year 1970 on the basis of available data. The calculated annual man-induced energy inputs have then been compared with the natural energy input of absorbed radiation at the air-water interface.

The impact of power-plant thermal discharge on the surface water temperature of southern California coastal water has been examined for both the broad and local scales. The influence area of waste-heat-induced temperature changes has been calculated by the analytical method of Pritchard (1970, 1971) and the empirical method of North and Adams (1969). A comparison has been made of the results predicted by each method.

THERMAL DISCHARGES OF POWER-GENERATING STATIONS

III

PRESENT THERMAL POWER PLANTS IN THE COASTAL AREA OF SOUTHERN CALIFORNIA

As shown in Figure 1, fourteen major thermal power-generating stations, with a total capacity of 10,275 megawatts (mw), are located near and discharge cooling water into the southern California coastal waters, bays, and estuaries. Of these, only San Onofre is a nuclear power-generating station. The remainder are conventional thermal power plants that use fossil fuels such as gas and oil.

Operating data for 1970 have been obtained from the various power companies and are shown in Table 1. The total annual thermal power generation for the 14 power stations is estimated to be 50.5 x 10^9 kilowatt-hours (kwh). This represents about 70 percent of the total energy requirements for 1970 in southern California (State of California Resources Agency, 1970).

The annual average load factor for the 13 fossil fuel stations has been calculated to be about 55 percent for the year 1970. This value is much lower than the annual average load factor for all power plants in the United States, which has been estimated at 64 percent by the Edison Electric Institute. A load factor of 80 percent for 1970 has been reported for the San Onofre nuclear power plant.

THERMAL EFFICIENCY AND HEAT WASTAGE

In a steam thermal power plant, whether fossil fuel or nuclear, the steam cycle converts part of the heat from a hot source (the furnace or the reactor) into electrical power, and the remaining heat is discharged to the environment as waste. Figure 2 is a schematic diagram of a steam power-plant cooling water system. Here, the water temperature is raised as it flows through a condenser, where the steam that drives the turbine is cooled.

The amount of waste heat discharged from a thermal power station into receiving water can be calculated by the estimate of heat wastage (heat wasted per kilowatt hour of power generated). The heat wastage of a thermal power plant depends on the efficiency or operating condition of the system. Hence, if

$E =$ the overall efficiency or the fraction of the input energy that is converted to electricity

$1 - E =$ the fraction of input energy lost to the environment

Q = the heat waste per unit of electricity produced,

then,

$$Q = \frac{1 - E}{E}. \tag{2}$$

A conventional thermal power plant operating at a temperature and pressure higher than 1,000°F and 3,500 psi, respectively, has an overall efficiency of about 35 to 40 percent. Nuclear power plants operating at a temperature of 500 to 600°F and a pressure up to 1,000 psi are less efficient, which results in higher heat wastages. Typical heat wastages of new plants are as follows:

Type	Overall Efficiency	Heat Wastage
Conventional (fossil fuel)	35 to 40%	1.8 to 1.5
Nuclear	30 to 35%	2.3 to 1.8

The actual thermal efficiencies of southern California power plants are from 25 to 36 percent for the conventional fossil-fuel type and 32 percent for the San Onofre nuclear power plant.

WASTE HEAT DISCHARGE AND COOLING WATER FLOW

The waste heat discharge from each power station in the southern California coastal area has been calculated for the year 1970 and is shown in Table 1. When capacity-weighted mean is considered, the conventional thermal power plants in this area have been found to have an overall efficiency of about 34 percent. Thus, the average fuel requirement is 10,033 Btu/kwh (since 1 kwh = 3,413 Btu) power generated, of which 6,620 Btu are being wasted. Part of the waste heat is dissipated into the atmosphere through the stacks. If 15 percent is assumed to be lost through the stacks, approximately 5,630 Btu of the heat will be removed by cooling water and discharged into the receiving

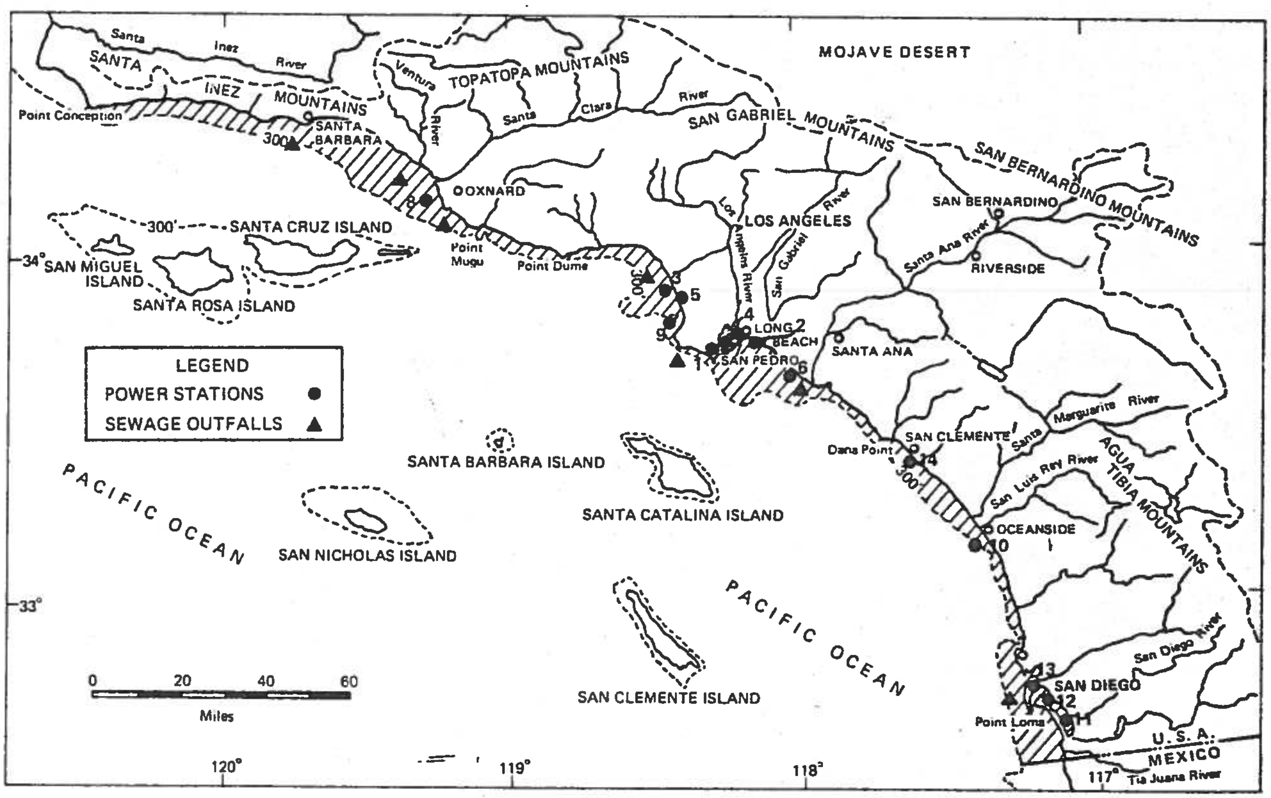


Figure 1. Location of thermal power plants and major sewage outfalls in southern California.

Table 1. Estimated waste heat discharge and cooling water flow from thermal power stations in the southern California coastal area.

(As of 1970)[a]

Fuel Type – STATION – Location	Plant Operation: 1 MW$_e$ Capacity (mw)	Plant Operation: 2 F Load Factor (%)	Plant Operation: 3 E Overall Efficiency (%)	Estimated Waste Heat to Cooling Water (d): 4 Q Waste Heat per unit of Electrical Output	5 Q_w Waste Heat to Cooling Water per Unit Output	6 H Plant Waste Heat 10^{10} Btu/day: 6A H_{max} Maximum Instantaneous	6B H_{ave} Annual Average	Estimated Cooling Water Flow (d): 7 T Normal Average Temperature Rise (°F)	8 R Cooling Water Flow Rate (mgd): 8A R_{max} Maximum Instantaneous	8B R_{ave} Annual Average
I. Fossil-Fuel Type										
L.A. Dept. of Water & Power										
1. Harbor, Wilmington	445	14	25	3.00	2.55	9.3	1.3	20	557	78
2. Haynes, Seal Beach	1,625	60	36	1.78	1.51	20.1	12.1	19	1,270	762
3. Scattergood, Playa del Rey	350	59	34	1.94	1.65	4.7	2.8	18	313	185
(Subtotal)	2,420					34.1	16.2		2,140	1,025
Southern California Edison Co.										
4. Alamitos, Seal Beach	1,950	58	36	1.78	1.51	24.1	14.0	20	1,450	841
5. El Segundo, El Segundo	1,020	50	35	1.86	1.58	13.2	6.6	22	720	360
6. Huntington, Huntington Beach	990	65	35	1.86	1.58	12.8	8.3	21	732	475
7. Long Beach, Long Beach (b)	210	20	25	3.00	2.55	4.4	0.9	19	278	56
8. Mandalay, Oxnard	430	73	36	1.78	1.51	5.3	3.9	20	318	232
9. Redondo, Redondo Beach	1,600	52	33	2.03	1.72	22.6	11.7	20	1,360	708
(Subtotal)	6,200					82.4	45.4		4,858	2,672
San Diego Gas and Electric Co.										
10. Encino, Carlsbad (b)	345	55	34	1.94	1.65	4.7	2.6	19	296	162
11. Silver Gate, San Diego Bay (b)	235	55	34	1.94	1.65	3.2	1.7	13	296	162
12. South Bay, San Diego Bay (b)	530	55	34	1.94	1.65	7.2	4.0	13	665	365
13. Station "B", San Diego Bay (b)	95	55	34	1.94	1.65	1.3	0.7	13	120	66
(Subtotal)	1,205					16.4	9.0		1,377	755
Total, Fossil-Fuel Type	9,825					132.9	70.6		8,375	4,452
Weighted Mean (c)		55	34	1.94	1.65			19.1		
II. Nuclear										
14. San Onofre–San Clemente	450	80	32	2.12	2.02	7.4	6.0	18	500	398
III. Grand Total	10,275					140.3	76.6		8,875	4,850

NOTE: (a) Station operating data provided by power companies, except as noted in (b).
(b) Estimated values for the year 1970.
(c) All mean values are weighted by plant capacity.
(d) Calculations:
(i) Column (4): $Q = (1 - E)/E$.
(ii) Column (5): Assume 15% of heat wastage lost through stack for fossil-fuel-type plant; 5% for nuclear power plant.
(iii) Column (6A): $H_{max} = 24 \times 3413 \times 10^3 \times (MW_e) \times (Q_w) = 8.19 \times 10^7 \times (MW_e) \times (Q_w)$.
(iv) Column (6B): $H_{ave} = (H_{max}) \times F$.
(v) Column (8A): $R_{max} = (H_{max})/(8.34 \times 10^6 \times T)$.
(vi) Column (8B): $R_{ave} = (H_{ave})/(8.34 \times 10^6 \times T)$.

water. Data from San Onofre show a total heat loss of 7,236 Btu/kwh power production, of which 6,775 Btu are carried away by cooling water. Based on estimates of the heat wastage, the total maximum instantaneous waste heat discharge is calculated to be 140.3 x 10^{10} Btu/day for all southern California power plants. Using the load factors reported for each station, the annual average waste heat can be estimated to be 76.6 x 10^{10} Btu/day for the year 1970.

The amount of cooling water required for a thermal power plant to remove a certain amount of waste heat is dependent upon the temperature rise. The normal temperature increase for the cooling

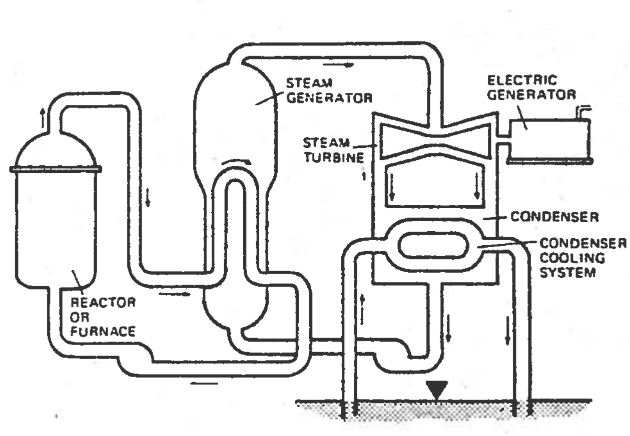


Figure 2. Schematic diagram of a steam power-plant cooling water system.

water flow in southern California power plants has been reported to be about 13°F in the San Diego Bay area and from about 18 to 22°F in the other coastal areas. On an annual average basis, approximately 4,850 mgd of saline water is being used for power-plant cooling purposes. The cooling water temperature is raised by 19°F, and it is subsequently returned to the coastal environment. The present maximum rate of instantaneous cooling water flow for the power stations in the southern California coastal area is about 8,875 mgd.

SENSIBLE HEAT DISCHARGE OF WASTEWATERS

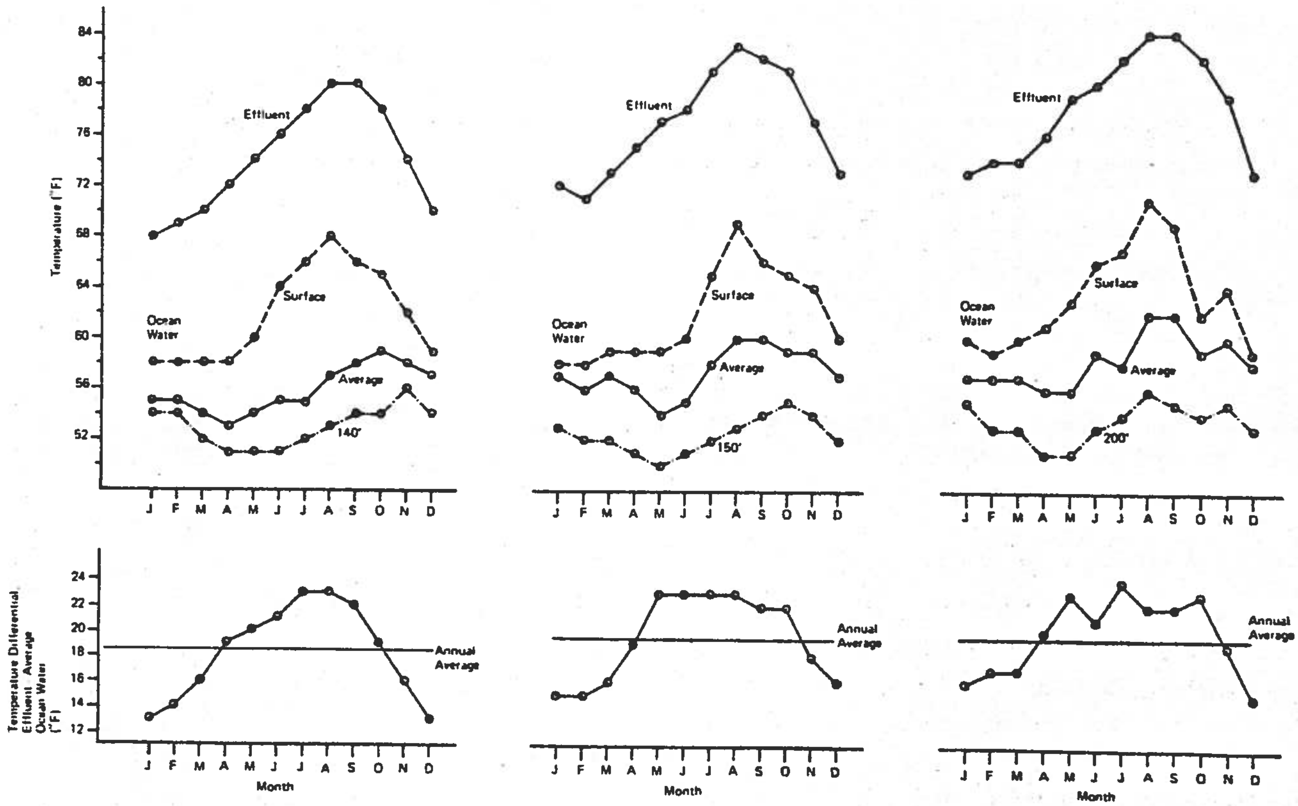
IV

TEMPERATURE DIFFERENTIAL

The rate of sensible heat discharged with municipal or industrial wastewater is proportional to the volumetric flow rate and the temperature difference between the waste stream and the receiving water. The wastewater temperature depends upon the source of water supply, the type of waste-generating activities and the geographical location of the service area. Figure 3 presents the effluent and seawater temperatures, as well as the calculated temperature differentials for three municipal sewage outfalls in the southern California coastal area. As shown on the figure, the monthly average sewage effluent temperature in the coastal region varies from 68°F in January at the Hyperion Sewage Treatment Plant to about 84°F in summer months at the Point Loma Treatment Plant. The Hyperion effluent temperatures are always 2 to 5°F lower than those of Orange County and City of San Diego for almost all months. This may be attributable to the lower ambient air temperature and the colder water supply.

Most of the major ocean outfalls in the southern California coastal area are discharging at deeper waters (approximately 200 ft. deep). Seasonal and latitudinal variations in vertical temperature distribution make it difficult to select any particular depth for obtaining the reference ambient receiving water temperature needed to calculate the temperature differential. A vertically integrated mean water temperature had therefore been calculated for each month at three major outfall locations. Computations were made from the measured water temperature data at several depths and were guided by the typical vertical temperature gradient (State of California, Water Quality Control Board, 1965) at each location. The average ocean water temperature, together with those of the surface and deeper waters, has been calculated for each month of the year and is shown in Figure 3.

The annual average temperature differentials for these municipal outfalls have been computed and are shown in Table 2. The monthly temperature differential at San Diego varies from 15 to 24°F, with an annual average of 19.9°F. Data from Orange County Sanitation Districts show a range of 15 to 23°F, with annual average of 19.6°F. At Hyperion, the 3- to 4°F-lower effluent temperature is offset by the relatively low water temperature in Santa Monica Bay. Hyperion therefore has been calculated to have an annual average temperature differential about 1.5°F lower than those of Orange County and San Diego. The monthly temperature differential at Hyperion varies from 13 to 23°F, with an annual average of 18.3°F. These values have been used as the bases to develop



a. City of Los Angeles, Hyperion Treatment Plant Effluent, Santa Monica Bay.

b. Orange County Sanitation District Plant Effluent, Santa Ana Region.

c. City of San Diego, Point Loma Treatment Plant Effluent, San Diego Region.

Figure 3. Sewage treatment plant effluent and ocean water temperature.

Table 2. Monthly temperature differentials for Hyperion, Orange County and San Diego outfalls.

Month	Hyperion Effluent Outfall			Orange County Outfall			San Diego Outfall		
	Effluent Temp. (°F)	Seawater Temp. (°F)	Temp. Diff. (°F)	Effluent Temp. (°F)	Seawater Temp. (°F)	Temp. Diff. (°F)	Effluent Temp. (°F)	Seawater Temp. (°F)	Temp Diff. (°F)
January	68	55	13	72	57	15	73	57	16
February	69	55	14	71	56	15	74	57	17
March	70	54	16	73	57	16	74	57	17
April	72	53	19	75	56	19	76	56	20
May	74	54	20	77	54	23	79	56	23
June	76	55	21	78	55	23	80	59	21
July	78	55	23	81	58	23	82	58	24
August	80	57	23	83	60	23	84	62	22
September	80	58	22	82	60	22	84	62	22
October	78	59	19	81	59	22	82	59	23
November	74	58	16	77	59	18	79	60	19
December	70	57	13	73	57	18	73	58	15
Average	74.1	55.8	18.3	76.9	57.3	19.6	78.3	58.4	19.9

the temperature differentials needed in estimating the sensible heat discharge from municipal and industrial wastewaters.

SENSIBLE WASTE HEAT DISCHARGE

Approximately 1,260 mgd of municipal and industrial wastewaters are produced in the southern California coastal area. Of this amount, 1,105 mgd (or 87 percent) are discharged directly into the coastal waters through waste treatment facilities between Point Conception and San Diego (Figure 1). In estimating the sensible heat discharge, the temperature differential used for the Santa Ana and San Diego regions was 20°F, and for the Santa Barbara and Ventura-Los Angeles regions, was 18°F. All were based on the annual average figures listed in Table 3. These temperature differentials were developed from data on municipal wastewaters (which include domestic and industrial wastes); however, in this analysis, they were used in estimating sensible heat discharge from discrete industrial wastewaters, as the latter constitute only about 10 percent of the total wastewater flow in the southern California coastal region. The total annual sensible waste heat discharge from wastewaters has been estimated to be 17.0 x 10^{10} Btu/day.

Table 3. Estimated wastewater sensible heat discharge for municipal and non-power industrial discharges, 1970.

Area Discharger	Wastewater Flow (mgd)	Temperature Differential (°F)	Annual Average Heat Discharge (10^{10} Btu/day)
Santa Barbara Area			
Total Wastewater	15	18	0.2
Ventura-Los Angeles Area			
Hyperion	335		
Whites Point	375		
Others	122		
	832	18	12.5
Santa Ana Area			
Orange County	130		
Others	20		
	150	20	2.5
San Diego Area			
Point Loma	83		
Others	25		
	108	20	1.8
TOTAL	1,105		17.0

ENERGY INPUT THROUGH OXIDIZABLE ORGANIC MATTER

V

DECOMPOSITION OF ORGANIC MATTER

The decomposition of organic matter in water depends on the presence of bacteria and other organisms. In an aquatic environment with ample dissolved oxygen, such as the ocean, most decomposition of dissolved organic matter is by complete aerobiosis and/or oxidative assimilation by heterotrophic organisms. In the process of complete aerobiosis of organic matter (an energy-yielding reaction), the end-products are normally very stable compounds such as carbon dioxide, nitrous oxide, and sulfate. The process of oxidative assimilation involves simultaneous reactions of oxidation (energy yield) and synthesis (assimilation) within an organism. The dominant net result is an increase in cellular mass and stable end-products.

In considering energy sources in wastewater, it appears logical to adopt an arbitrary energy scale by considering the energy level of stable products to be zero. By this energy scale, the energy input of oxidizable organic matter in wastewater can be estimated by means of thermochemical reactions of aerobiosis and/or oxidative assimilation and the mass rate of organic discharge. Table 4 shows some hypothetical reactions of complete aerobiosis as reported by Camp (1963) and some oxidative assimilation equations by Burkhead and McKinney (1969).

MEASUREMENT OF ORGANIC CONCENTRATION AND ENERGY INPUT

Municipal and industrial wastewaters contain a complex mixture of organic compounds; some are nitrogenous while others are merely carbonaceous. Data on total organic carbon and organic nitrogen content provide little quantitative information concerning energy sources, and such measurements are not routinely conducted on most waste discharges. As shown in Table 5, the heat of reaction per unit weight of substrate or per unit weight of carbon depends chiefly on the nature of the compound and varies widely. The variation is summarized as follows:

	Heat of Reaction	
	Kcal/gm Substrate	Kcal/gm C
Complete aerobiosis	3.3 to 9.2	8.3 to 12.0
Oxidative assimilation	0.7 to 1.6	1.8 to 3.1

In their study of the oxidative assimilation of sixteen organic substrates in activated sludge process, Burkhead and McKinney (1969) have reported a relationship between the heat of reaction (which is related to heat loss) and oxygen utilization. The heat of reaction ranged from 2.72 to 3.96 Kcal/gm of oxygen utilized. The average value reported by the authors was 3.30 Kcal/gm of oxygen utilized.

Data from Camp (1963) have shown a similar result, with a range from 3.13 to 3.43 Kcal/gm of oxygen utilized.

The biologically oxidizable organic matter in wastewater is generally measured by a conventional 5-day biochemical oxygen demand (BOD_5) test. The annual average organic waste discharged to the southern California coastal water from all municipal and industrial wastes is estimated to be 1.718 x 10^6 lb BOD_5/day (Table 6). The BOD_5 values have been converted to ultimate first-stage BOD values by assuming that the ultimate BOD is approximately 50 percent greater than the BOD_5 measurement (based upon a first-order reaction rate constant of 0.23/day). Using the average heat of reaction of 3.30 Kcal/gm of oxygen utilized (or 5.9 x 10^3 Btu/lb of ultimate BOD) derived above, the average energy input of oxidizable organic matter is about 1.51 x 10^{10} Btu/day.

Table 4. Examples of thermochemical reactions of aerobiosis and oxidative assimilation

a. Reactions of complete aerobiosis in water. After Camp (1963).	
1. Acetic acid	$C_2H_4O_2 + 2\,O_2 \rightarrow 2\,CO_2 + 2\,H_2O + 200$ Kcal
2. Stearic acid	$C_{18}H_{36}O_2 + 26\,O_2 \rightarrow 18\,CO_2 + 18\,H_2O + 2599$ Kcal
3. Glycerol	$C_3H_8O_3 + 3.5\,O_2 \rightarrow 3\,CO_2 + 4\,H_2O + 383$ Kcal
4. Glucose	$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + 650$ Kcal
5. Protein	$C_{4.41}H_7O_{1.44}N_{1.14}S_{0.03} + 4.63\,O_2 \rightarrow 3.27\,CO_2 + + 0.62\,H_2O + 1.14\,HCO_3 + 1.14\,NH_3 + 0.03\,H_2SO_4 + 509$ Kcal
6. Dry cell solids	$C_5H_7NO_2 + 5.75\,O_2 \rightarrow 5\,CO_2 + 3.5\,H_2O + 0.5\,N_2 + 565$ Kcal
b. Reactions of oxidative assimilation. After Burkhead and McKinney (1969).	
7. Acetic acid	$C_2H_4O_2 + 0.84\,O_2 + 0.21\,NH_3 \rightarrow 0.21\,C_5H_7O_2N + 0.95\,CO_2 + 1.58\,H_2O + 90$ Kcal
8. Butyric acid	$C_4H_8O_2 + 1.65\,O_2 + 0.67\,NH_3 \rightarrow 0.67\,C_5H_9O_3N + 0.65\,CO_2 + 1.99\,H_2O + 144$ Kcal
9. Glucose	$C_6H_{12}O_6 + 1.26\,O_2 + 0.96\,NH_3 \rightarrow 0.96\,C_5H_{11}O_4N + 1.20\,CO_2 + 2.16\,H_2O + 130$ Kcal
10. Sucrose	$C_{12}H_{22}O_{11} + 2.98\,O_2 + 1.72\,NH_3 \rightarrow 1.72\,C_5H_{11}O_4N + 3.40\,CO_2 + 4.15\,H_2O + + 380$ Kcal
11. Glutamic acid	$C_5H_9O_4N + 2.02\,O_2 \rightarrow 0.48\,C_5H_7O_2N + 2.60\,CO_2 + 2.04\,H_2O + 0.52\,NH_3 + 187$ Kcal
12. Composite substrate	$C_{4.64}H_{3.78}O_{4.15}N_{0.49} + 1.63\,O_2 + 0.05\,NH_3 \rightarrow 0.54\,C_5H_{11}O_4N + 1.94\,CO_2 + 1.50\,H_2O + 162$ Kcal

Table 5. Heat of reaction of complete aerobiosis and oxidative assimilation.

Reaction*	Heat of Reaction: Kcal/gm of Substrate	Kcal/gmC	Kcal/gm of O_2 Utilized
A Complete Aerobiosis, after Camp (1963)			
1 acetic acid	3.33	8.33	3.13
2 stearic acid	9.15	12.0	3.13
3 glycerol	4.17	10.6	3.42
4 glucose	3.60	9.04	3.39
5 protein	5.09	9.6	3.43
6 dry cell solids	5.0	9.4	3.10
B Oxidative Assimilation, after Burkhead and McKinney (1969)			
7 acetic acid	1.5	2.16	3.32
8 butyric acid	1.64	3.0	2.72
9 glucose	0.72	1.8	3.22
10 sucrose	1.11	2.64	3.96
11 glutamic acid	1.27	3.12	2.92
12 composite substrate	1.18	2.92	3.08

*Reactions of aerobosis and oxidative assimilation are as indicated in Table 4.

Table 6. Estimated energy input of oxidizable organic matter in wastewaters.

Area Discharger	BOD_5 (10^3 lb/day)	Ultimate BOD (10^3 lb/day)	Energy Input (10^{10} Btu/day)
Santa Barbara Area			
Wastewater	50		
Subtotal	50	75	0.04
Ventura-Los Angeles Area			
Hyperion	336		
Whites Point	795		
Other Wastewater	89		
Subtotal	1,220	1,830	1.08
Santa Ana Area			
Orange County	199		
Other Wastewater	38		
Subtotal	237	356	0.21
San Diego Area			
Point Loma	141		
Other Wastewater	67		
Subtotal	208	312	0.18
Total	1,718		1.51

ENERGY TRANSFER ACROSS THE AIR-WATER INTERFACE

VI

MECHANISMS OF ENERGY TRANSFER

The various mechanisms by which energy is exchanged between water and the atmosphere have been identified previously in the energy budget Equation (Equation 1). The net solar and atmospheric radiations, q_s and q_a, are independent of water temperature. The sum of these radiation terms is called absorbed radiation. The major mechanisms of heat loss from water surface, including q_b, q_c, and q_e, are surface phenomena, and the magnitudes of these terms are dependent on the water surface temperature. All of the mechanisms are discussed in more detail below.

With the possible exception of solar radiation, direct measurement of energy transfer terms across the air-water interface in the energy budget (Equation 1) is limited to laboratory and field experiments. Empirical methods, employing such measurements as sea-surface and air temperature, humidity, wind velocity, solar radiation, and evaporation rate, will have to suffice for the purpose of this report. A variety of empirical relationships are available for the computation of each energy budget term. Table 7 summarizes the estimated average monthly values of energy transfer rate for the southern California coastal area. The methods used to obtain these estimates are discussed in the following paragraphs.

NET SOLAR RADIATION, q_s (Btu/ft^2/day)

The short-wave radiation originating from the sun ranges in wavelength between 0.14 and 4.0 microns, with the maximum intensity at 0.5 microns. The amount of short-wave solar radiation reaching the sea surface varies with latitude, time of day, season, cloud cover, and other atmospheric conditions. The amount of solar radiation incident on the earth surface is usually measured with a pyrheliometer. The net solar radiation, q_s, absorbed by water can be calculated as the difference between the incident and reflected values, when a solar reflectivity of 0.06 is assumed.

Monthly mean values of solar radiation at Fresno, Riverside, and La Jolla are shown in Figure 4. These values are drawn from the published records measured by regular Weather Bureau pyrheliometers on a horizontal surface inside a spherical glass (Brooks, 1936). The arithmetic mean values of the solar radiation for these three locations are plotted as curve 5 in Figure 4, which has been used as the basis for estimating the monthly mean net solar radiation for the entire southern California coastal area. The estimated net solar radiation absorbed by water (Table 7) was calculated to be 94 percent of the incident values (curve 5, Figure 4). The other 6 percent of the incident values can be accounted for by the

Table 7. Estimated average monthly values for the rates of heat transfer across the air-water interface in the southern California coastal area.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean
A. Clear sky solar radiation (Btu/ft²/day) at 32 to 35° N.	1,300	1,620	2,070	2,500	2,800	[illegible]	2,850	2,600	2,250	1,800	1,400	1,250	2,116
B. Absorbed radiation (energy gain) (Btu/ft²/day)													
Net solar radiation, q_s	800	1,040	1,400	1,720	1,920	[illegible]	1,980	1,810	1,530	1,220	980	720	1,428
Net atmospheric radiation, q_a	2,580	2,590	2,660	2,700	2,750	[illegible]	2,900	3,020	2,950	2,850	2,770	2,650	2,770
Total Absorbed radiation, $q_s + q_a$	3,380	3,630	4,060	4,420	4,670	[illegible]	4,880	4,830	4,480	4,070	3,750	3,370	4,198
C. Energy loss terms (Btu/ft²/day)													
Back radiation, q_b	2,920	2,900	2,920	2,940	2,970	3,010	3,090	3,160	3,110	3,070	3,010	2,940	3,004
Evaporation loss, q_e	505	420	840	1,010	1,175	[illegible]	1,510	1,510	1,175	1,090	505	420	952
Convection, q_c	−43	14	68	92	114	114	108	144	162	76	76	0	77
Total heat loss, $q_b + q_e + q_c$	3,382	3,334	3,828	4,042	4,259	[illegible]	4,708	4,814	4,447	4,236	3,591	3,360	4,033
D. Estimated net heat transfer rate (Gain-loss) (Btu/ft²/day)	−2	296	232	378	411	456	172	16	33	−166	159	10	165
E. Meteorological conditions													
Average air temperature, T_a (°F)	57.5	58.5	61	62.5	64	66	69	73	71.5	67.5	65.5	60	
Average surface water temperature, T_s (°F)	59	58	59	60	61	63	66	69	67	65	63	60	
Average relative humidity, R_H (%)	65	65	75	75	75	80	80	80	70	70	70	65	
Average evaporation rate, E (in./mo)	3	2.5	5	6	7	7.5	9	9	7	6.5	3	2.5	
Average wind velocity, W (mile/hr)	5	5	8	9	10	10	9	9	9	6	6	6	

reflected losses from the water surface.

The southern California coastal area extends from 32° to 35° N. latitude. Along the coast, the clear sky solar radiation ranges from 1,400 Btu/ft²/day during the winter to as high as 2,900 Btu/ft²/day during the summer, with an annual average of 2,120 Btu/ft²/day (curve 1, Figure 4). The actual annual net solar radiation energy absorbed by the water is estimated as 1,430 Btu/ft²/day, which is about 68 percent of the clear sky radiation value. The clear sky radiation values are plotted in Figure 4 for reference.

NET ATMOSPHERIC RADIATION, q_a (Btu/ft²/day)

The long-wave radiation from the atmosphere ranges in wave-length between 4.0 and 120 microns and has a peak intensity at about 10 microns. The magnitude of long-wave radiation depends primarily on air temperature and humidity and increases as the air-moisture content increases. Normally, it is calculated by empirical formula, such as the

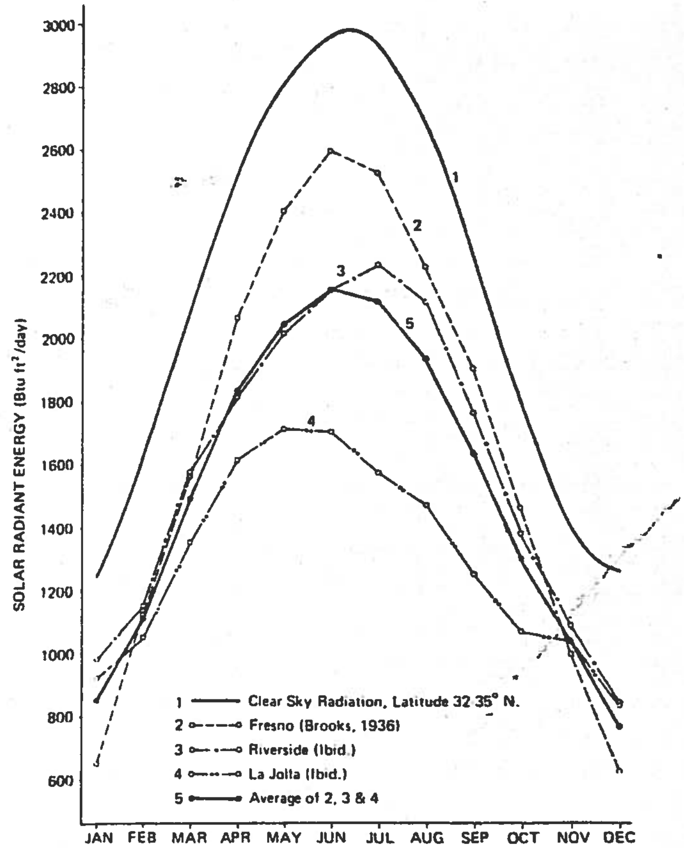


Figure 4. Average monthly solar radiation received on the horizontal surface.

Brunt formula (Edinger and Geyer, 1965):

$$q_A = 4.5 \times 10^{-8} (T_a + 460)^4 (C + 0.031\, e_a^{1/2}) \qquad (3)$$

where

T_a = the air temperature (°F) at 6 feet above the water

e_a = the air-vapor pressure (mm Hg) at 6 feet above the water

C = Brunt coefficient, dependent on meteorological conditions.

The net long-wave atmospheric radiation absorbed by water can be calculated as the difference between the incident and reflected values, or

$$q_a = q_A (1 - R_{ar}) \qquad (4)$$

where R_{ar} is the atmospheric reflectivity of the water surface. Studies have shown that the atmospheric reflectivity is relatively constant at about 0.03.

The net atmospheric radiation values listed in Table 7 were calculated by empirical Equations 3 and 4. Despite the nonlinearity of Equation 3, the calculation based on monthly average meteorological conditions is assumed adequate for this analysis. The Brunt coefficient, C, in Equation 3 is a function of air temperature and ratio of the measured solar radiation to the clear sky solar radiation. This relationship is shown in Figure 5. Each curve in Figure 5 represents a different value of the ratio of the measured solar radiation to the clear sky radiation given in Figure 4.

The estimated average monthly net atmospheric radiation absorbed by the sea surface in the southern California coastal area ranges from 2,580 to 3,020 Btu/ft² /day. The annual average value is estimated as 2,700 Btu/ft² /day, which is about 94 percent higher than that of the net solar radiation.

ABSORBED RADIATION

As mentioned previously, the sum of net solar and atmospheric radiation is called absorbed radiation and is the major natural energy input across the air-water interface. By rounding off the values listed in Table 7, an annual mean absorbed radiation of 4,200 Btu/ft² /day is obtained. The input varies from about 3,400 Btu/ft² /day during the winter months to about 4,900 Btu/ft² /day during the summer months.

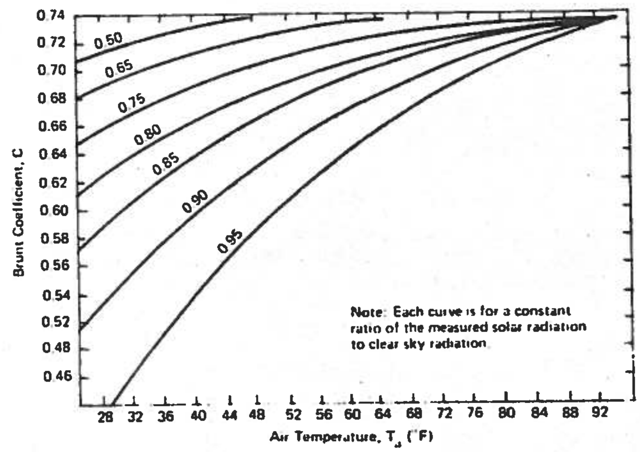


Figure 5. Brunt coefficient, C, from air temperature. T_a, and the ratio of measured solar radiation to clear sky radiation. After Koberg, 1960.

ENERGY LOSS TERMS

BACK RADIATION FROM WATER, q_b (Btu/ft² /day)

The back radiation from water is the energy in the form of long-wave radiation emitted from water acting as a perfect black body. Back radiation can be calculated by the Stefan-Boltzmann fourth-power law:

$$q_b = \gamma_w K (T_s + 460)^4 \qquad (5)$$

where

γ_w = the emissivity of water, which is nearly equal to 0.97

K = the Stephan-Boltzmann constant = 4.15×10^{-8} Btu/ft² /day/(°F)⁴

T_s = the water surface temperature (°F).

The variation in the monthly rate of back radiation throughout the year in the southern California coastal area is relatively small, having a range of about 9 percent of the annual average. Back radiation is the major heat loss mechanism; it is the cause of about 70 percent of the total energy loss from the water surface.

HEAT LOSS BY EVAPORATION,
q_e (Btu/ft² /day)

Each pound of water evaporated will carry a latent heat of vaporization of 970 Btu. If the evaporation rate has been determined, q_e can be calculated by the following equation:

$$q_e = 970 \rho E \tag{6}$$

where E is the evaporation rate in feet per day and ρ is the density of water in pounds per cubic foot.

When the evaporation rate is not available, the evaporation heat loss may be estimated on the basis of windspeed and air-vapor pressure. The most general form of such an equation is

$$q_e = (a + bW)(e_s - e_a) \tag{7}$$

where

- a,b = empirical coefficients
- W = windspeed (mi/hr)
- e_a = air-vapor pressure (mm Hg)
- e_s = saturation vapor pressure of water determined by the water surface temperature, T_s (mm Hg).

Evaporation heat loss for the southern California coastal waters has been estimated by evaporation rate measurement rather than by empirical method. Evaporation rate, temperature, and windspeed are constantly measured and recorded at several inland evaporation stations in the coastal region by the State Department of Water Resources. These data have been used as a basis in estimating evaporation rate for the coastal waters, with adjustments made for the differences in temperature, windspeed, and relative humidity. Both the average monthly evaporation rate and evaporation heat loss are listed in Table 7. The annual average evaporation heat loss at the air-sea interface in southern California is estimated to be about 950 Btu/ft² /day.

CONDUCTIVE HEAT LOSS OR GAIN,
q_c (Btu/ft² /day)

The rate of conductive heat transfer is equal to the product of the heat transfer coefficient and the air-water temperature differential. A direct measurement of this quantity is not available. However, Bowen has developed a Bowen ratio in the following form:

$$R_B = \frac{q_c}{q_e} = \frac{0.26\,P\,(T_s - T_a)}{760\,(e_s - e_a)} \tag{8}$$

where P is the atmospheric pressure (mm Hg). However, for a standard barometric pressure of P equal to 760 mm Hg, the expression for the rate of heat conduction can be written using the general evaporation equation (Equation 7):

$$q_c = 0.26\,(a + bW)\,(T_s - T_a)\,. \tag{9}$$

Conductive heat exchange at the water surface is relatively unimportant to the entire energy budget for the southern California coastal waters. Estimated average monthly values show that the rate of conductive heat exchange for the coastal region varies from a gain of 43 Btu/ft² /day by water to a loss of 162 Btu/ft² /day from water surface.

NET HEAT-TRANSFER RATE

The difference between the absorbed radiation and the total heat loss terms is the net heat-transfer rate across the air-water interface. The annual net heat-transfer rate for southern California coastal water has been calculated to be 165 Btu/ft² /day. This value was derived using approximate estimates of individual energy budget terms and may be in error. However, it does serve to illustrate that the amount of net heat transfer across the air-water interface is always smaller than those of the individual major heat-transfer mechanisms. All too often, this net energy-transfer rate has been considered a simple yardstick in evaluating the impact of man-induced heat input on a water body. As the temperature dependence of the heat loss (to the atmosphere) and other heat dissipation mechanisms have been disregarded, this kind of comparison is erroneous and misleading.

IMPACT OF THERMAL DISCHARGE ON WATER TEMPERATURE

VII

COMPARISON OF NATURAL AND MAN-INDUCED ENERGY INPUTS

The average yearly energy input from man-induced sources into the coastal waters of southern California has been estimated to be 95.1×10^{10} Btu/day (Table 8). Compared with the estimated rate of absorbed radiation across the air-water interface ($4{,}200$ Btu/ft^2/day), the man-induced energy input is equivalent to absorbed radiation on about 8 sq mi of the coastal water.

Table 8 indicates the relative significance of the man-induced energy sources as compared with natural energy sources of absorbed radiation in the southern California coastal area. In this analysis, an area including essentially the southern California mainland shelf (State of California, Water Quality Control Board, 1965)—the shaded area in Figure 1—was chosen for comparison. The length of this shelf from Point Conception to the Mexican border is about 270 miles. The area is 1,400 sq mi, ranging from less than a mile to 12 miles in width (average width: 4.5 miles) and terminating at a depth of 250 to 400 feet.

From the estimated rate of absorbed radiation of 4,200 Btu/ft^2/day, the total radiation energy absorbed by the water surface of the mainland shelf can be calculated to be from $13{,}200 \times 10^{10}$ Btu/day in winter to $19{,}200 \times 10^{10}$ Btu/day in summer. The man-induced energy input represents 0.7 and 0.5 percent, respectively, of the total natural energy absorbed by the water surface. If all power plants along the coast were operating at their maximum capacities simultaneously, the maximum instantaneous waste heat flux from cooling water would be 140×10^{10} Btu/day. This value is about 1 percent of the total natural energy absorbed by the water surface of the southern California mainland shelf during the winter months of low radiation. When the entire Southern California Bight (an area of more than 40,000 sq mi) is considered, the contribution of the man-induced energy sources to the total energy budget is less than 0.02 percent of the natural input terms.

MAN-INDUCED WATER TEMPERATURE ELEVATION: A BROAD-SCALE CONSIDERATION

Consider a segment of the coastal water environment of volume, V, and let the water surface be the upper boundary. Assume the thickness of the segment to be equal to or exceeding the depth of vertical mixing of any artificially introduced heat. The natural heat budget of the segment is

$$dH/dt = A\,(q_s + q_a - q_b - q_c - q_e) + Q_V + Q_D \qquad (1)$$

and

$$H = V\rho cT \qquad (10)$$

where ρ is the water density, c is the specific heat, and T is the mean water temperature.

Now consider the addition of a steady input from man-induced energy sources, Q_M. The result will be increase in water temperature and, consequently, the changes of all water temperature-dependent terms in the energy budget. The energy budget under this condition will become

$$dH'/dt = A\,(q_s + q_a - q_b' - q_c' - q_e') + Q_V' + Q_D' + Q_M \qquad (11)$$

and Equation 10 may be rewritten

$$H' = V\rho cT' \qquad (12)$$

where a prime superscript designates those terms influenced by man-induced energy input.

Table 8. Comparison of natural (absorbed radiation) and man-induced energy inputs.

	Heat Flux 10^{10} Btu/day	Comparison with Natural Energy (Absorbed Radiation) Input Across the Water Surface of Southern California Mainland Shelf*		
		In Terms of Minimum Monthly (%)	In Terms of Maximum Monthly (%)	In Terms of Average Yearly (%)
I. Man-induced energy input				
Cooling water				
Maximum instantaneous	(140.3)	(1.05)	(0.73)	(0.85)
Average yearly	76.6	0.58	0.40	0.47
Wastewater sensible heat	17.0	0.13	0.09	0.11
Oxidizable organic matter	1.5	0.01	0.01	0.01
Total average yearly input	95.1	0.72	0.50	0.59
II. Natural energy (absorbed radiation) input across water surface of southern California mainland shelf*				
Minimum monthly (3,400 Btu/ft²/day)	13,200	100	–	
Maximum monthly (4,900 Btu/ft²/day)	19,200	–	100	–
Average yearly (4,200 Btu/ft²/day)	16,400	–		100

*Total area of southern California mainland shelf is about 1,400 sq. mi.

Observational evidence indicates that with a steady addition of man-induced heat input, the temporal variation of water temperature with time will be superimposed by a finite increment above the natural variation and to a good approximation $dT/dt = dT'/dt$. Hence

$$dH/dt = dH'/dt\,, \qquad (13)$$

and subtracting Equation 1 from Equation 11 results in

$$Q_M = A(\Delta q_b + \Delta q_e + \Delta q_c) + \Delta Q_V + \Delta Q_D \qquad (14)$$

$$\Delta q_b = q_b' - q_b, \text{ etc.} \qquad (14a)$$

$$\Delta Q_V = \rho c F_V\,(T' - T) \qquad (14b)$$

$$\Delta Q_D = \rho c F_D\,(T' - T) \qquad (14c)$$

where

F_V = the net avective flow through the segment of the coastal water environment

F_D = the equivalent diffusive flow at the seaward boundary.

Note that the three terms in parentheses on the right-hand side of Equation 14 are the rate of excess heat dissipation at the surface. The last two terms in the equation are the rate of excess heat dissipation at other boundaries of the segment. Edinger and Geyer (1965) and Pritchard (1970 and 1971) have shown that the rate of excess heat dissipation to the atmosphere, ΔH_s, from water that is under influence of man-induced energy input can be expressed by

$$\Delta H_s = A(\Delta q_b + \Delta q_e + \Delta q_c) = A\mu(T' - T)\,. \qquad (15)$$

Thus the mean excess temperature, $\Theta = T' - T$, of the segment is determined by (1) the rate of the man-induced energy input, Q_M; (2) the surface area of the segment, A; (3) the surface cooling coefficient, μ, which in turn depends on windspeed and ambient temperature; and (4) the loss of excess heat across the seaward boundaries due to advection and diffusion. By means of Equations 14 through 15, the man-induced water temperature elevation on the southern California mainland shelf can be examined on a broad-scale basis.

SURFACE COOLING ALONE

Assuming there is no renewal of water in the segment of the coastal water above the mainland shelf, the dissipation of excess temperature will rely entirely upon the mechanism of surface cooling. Therefore,

$$Q_M = \Delta H_s = A\mu\Theta$$

or

$$\Theta = Q_M/\mu A\,. \qquad (16)$$

For an average natural condition of 8 knots windspeed and a water surface temperature of 60 to 70°F, μ can be estimated to be about 120 Btu/ft^2/day/°F for a water surface with less than 1°F excess temperature. With this value, μA can be calculated to be 470 x 10^{10} Btu/day/°F of excess temperature for the entire southern California mainland shelf. Hence, on a broad scale, the man-induced energy input of approximately 95 x 10^{10} Btu/day will increase the water temperature over the mainland shelf by an average of about 0.2°F above natural level.

SURFACE COOLING PLUS DILUTION AND DIFFUSION AT BOUNDARY

Assume a net advective flow of 10 cm/sec (0.33 ft/sec) in a direction parallel to the coastal line, and assume an equivalent diffusion velocity of 1 cm/sec (0.033 ft/sec) at the seaward boundaries of the southern California mainland shelf. Equation 14 becomes

$$Q_M = \mu A \Theta + (F_V + F_D)\,\rho c \Theta$$

or

$$\Theta = \frac{Q_M}{\mu A + (F_V + F_D)\,\rho c} \qquad (17)$$

Consider the upper 50 feet of the segment as the vertical mixing depth of the major man-induced heat input. The effective advective and equivalent diffusive flow can then be calculated as

$$F_V = 3.9 \times 10^{10} \text{ ft}^3/\text{day}$$

$$F_D = 21 \times 10^{10} \text{ ft}^3/\text{day}$$

$$\rho c\,(F_V + F_D) = 1{,}520 \times 10^{10} \text{ Btu/day/°F} .$$

The average water temperature elevation, Θ, can be determined to be equal to 0.05°F above natural level.

The broad-scale analysis indicates that the water temperature elevation due to man-induced heat discharge is about 0.05°F to 0.20°F, depending upon the rate of renewal of water above the southern California mainland shelf. The problem related to waste heat discharge is therefore a matter of local rather than broad-scale concern.

IMMEDIATE DISSIPATION OF WASTE HEAT DISCHARGES

Two processes contribute to the immediate dissipation of excess temperature in receiving water. The first process is the mechanism of surface cooling, which includes the loss of heat from the water surface by conduction, evaporation, and back radiation. The second process includes the mechanisms of dilution and dispersion of the heated waste stream with the receiving waters. The relative importance of each process in dissipating excess heat depends upon the physical characteristics of the receiving environment, as well as the discharge structures of the heated waste stream.

The dilution and dispersion processes play a dominant role in the dissipation of sewage-associated sensible heat if the effluent is discharged through a properly designed marine outfall. Most sewage outfalls are designed to discharge into deeper waters, and an initial dilution of 20:1 or higher (generally greater than 100:1) is readily obtainable by diffuser systems. If an incoming waste stream has a temperature differential of 20°F over the deep water, the excess temperature in the waste plume will be reduced to 1°F or lower due to initial dilution. The ambient temperature rises as the waste plume moves upward. Because the plume is usually trapped at the thermocline, this kind of heat discharge has no significant effect on the surface water temperature. When the thermocline is weak, however, the surfacing plume may actually reduce the surface temperature.

Waste heat discharges from power plants and the relative importance of several processes that control the temperature distribution in the thermal plume have been considered by other researchers. For example, Pritchard (1971) has developed an analytical model to predict the temperature gradient in the thermal plume resulting from a horizontal surface discharge (Figure 6). He has developed the following example computations, which may serve to compare the different temperature distributions resulting from heat discharges with different structural designs. It is assumed that a thermal power plant discharges 6.8 x 10^9 Btu/hr (16.3 x

10^{10} Btu/day) of waste heat through cooling water into the surface layer of the receiving water. The cooling water flow rate is 1,520 ft^3/sec (982 mgd), with a temperature rise of 20°F. (This waste heat corresponds to that of a 1,700-mw fossil fuel plant at the present level of efficiency.)

The discharge structural design varies from allowing no dilution of the heated waste stream (case I, Table 9) to allowing a rapid dilution (Case IV, Table 9). Table 9 gives the results of four such example computations. The results are shown in terms of the area contained within the specific isotherms of excess temperature. The analytical model also gives the length, width, and general shape of the isotherms. Figure 6 presents a schematic plane view of the excess surface temperature distribution in the form of contours adjacent to the point of heat discharge. According to Pritchard (1971), case IV represents criteria that can be resolved with reasonable engineering effort to promote rapid dilution of the waste heat plume by receiving waters. This principle has been applied to at least five power plants under construction or in the planning stage in the United States.

The salient feature of Pritchard's results is their indication that (1) the process of dilution can be made more effective than that of surface cooling for the immediate dissipation of excess temperature in the thermal plume and (2) it is not only technically possible but also economically feasible to minimize the excess temperature in the thermal plume by a properly designed discharge structure. It should be noted that, in the example computations (Table 9), it was assumed that all of the excess heat would be contained in a surface layer 10 feet thick. When the waste heat is discharging into a deeper open sea, it appears that it may be even easier to reduce the excess surface temperature.

COMPARISON OF ANALYTICAL AND EMPIRICAL METHODS OF PREDICTING WATER SURFACE TEMPERATURE ELEVATION

Many researchers have measured surface tempera-

Table 9. The area contained within specified isotherms of excess temperature in a thermal plume.*

	CASE I	CASE II	CASE III	CASE IV
Case Descriptions	A hypothetical case, no dilution. Heat dissipation by surface cooling only	A case producing the practical minimum of dilution	Typical of many existing cooling water discharge structures	A condition which can be achieved by reasonable engineering effort
Discharge Orifice (width x depth)	(Surface cooling only)	500′ x 10′	50′ x 10′	15′ x 10′
Discharge Velocity		0.3	3.0	10.1
	Area Contained within Specified Isotherms (Acres)			
14°F	378	166	1.9	0.2
10°F	771	542	7.1	0.6
5°F	1,660	2,570	111	10
3°F	2,360	3,190	465	44
2°F	2,940	3,260	1,000	99
1°F	3,900	3,290	3,470	391

*The plume results from a waste heat discharge of 6.8 x 10^9 Btu/hr (cooling water flow rate = 1,520 ft^3/sec at 20°F temperature rise) from a power plant, for four different discharge structure designs. (This rate of heat wastage corresponds to that of a 1,000-mw nuclear power plant or a 1,700-mw fossil fuel plant at present efficiency levels.)

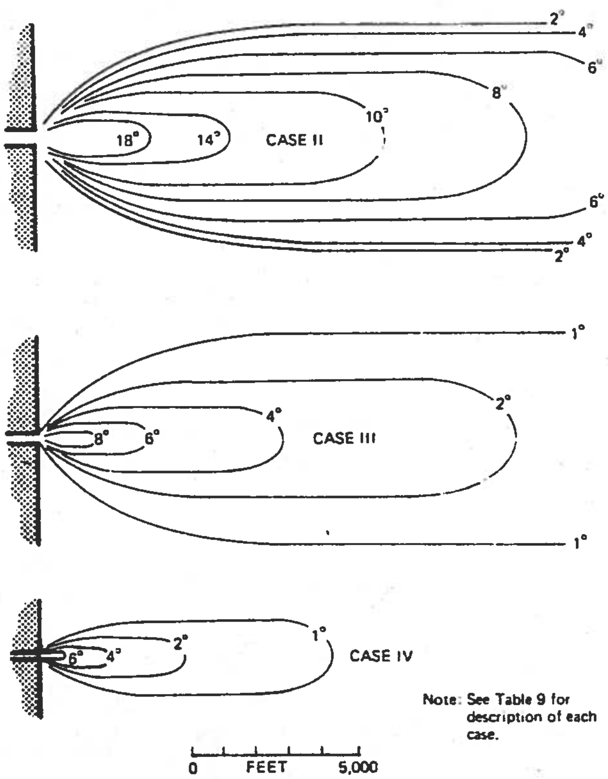


Figure 6. Horizontal distribution of excess temperature. After Pritchard, 1971.

ture rise and the corresponding influence area at thermal discharge sites on the Pacific Coast, either by infrared mapping techniques (Squire, 1967) or by direct marine monitoring (Adams, 1968; Reeves, 1970). From the observed results, North and Adams (1969) have used 35 measurements at 9 power stations to develop the following set of linear regression equations to calculate the influence area:

$$2^\circ F \text{ rise: Area (acres)} = 104 + 0.09 \text{ (MW)}$$

$$10^\circ F \text{ rise: Area (acres)} = 2.8 + 0.013 \text{ (MW)}$$

where MW is plant capacity and ranges from 50 to 1,000 mw.

In their calculations, North and Adams (1969) have not considered the differences between a fossil fuel and a nuclear power plant, or the differences in the various discharge structure designs. However, their method can be used for comparison with the results obtained by the analytical methods. With 14 power stations of 10,275-mw total capacity on the southern California coast, a total of 3.6 sq mi (2,380 acres) of surface water would be raised 2° F or higher above normal. An area of 0.26 sq mi (173 acres) would be raised 10° F or higher above normal.

From the North and Adams regression equations, the influence areas for a 1,700-mw power-plant waste heat discharge can be calculated as 257 acres for 2° F temperature rise and 25 acres for 10° F temperature rise. A comparison with Table 9 data indicates that, on the average, the waste heat discharge structures of all existing power plants in the southern California coastal area are similar to the conditions somewhere in the range between cases III and IV.

Assume that case III of Pritchard's analytical model is typical of all existing power plants in the southern California coastal area. A total of 7.5 sq mi and 35 acres of water surface would have increased 2° F and 10° F or higher above normal water temperature, respectively, for an average heat waste discharge of 76.6 x 10^{10} Btu/day. However, if all power plants were designed with a high-velocity cooling water discharge structure (case IV), and the same amount of waste heat were discharged, the area having a temperature equal to or greater than 2° F above ambient would be about 0.74 sq mi.

The local temperature gradient in the immediate vicinity of a thermal discharge cannot be defined by the empirical method (North and Adams). However, the predicted results do indicate that, at present, the man-induced waste energy has not significantly altered the surface temperature of the coastal waters. In the immediate vicinity of a power-plant waste heat discharge, some excess temperature rise does occur. The amount of the temperature increase depends on the design of the discharge structure, the mixing characteristics of the receiving water, and the magnitude of the waste heat load at peak operation. These local conditions can be studied by a continuous thermal monitoring of the receiving water or by use of the analytical model of Pritchard (1971) or similar techniques.

SUMMARY

VIII

1. The 14 thermal power stations in the coastal region of southern California have a total capacity of 10,275 mw. The maximum instantaneous waste heat discharge into the coastal water from this source has been estimated as 140 x 10^{10} Btu/day, with a cooling water flow rate of about 8,900 mgd. The annual average cooling water flow has been calculated to be approximately 4,900 mgd.

2. The annual average man-induced energy inputs into the southern California coastal waters have been estimated as follows (Table 8):

Power-plant cooling water	76.6 x 10^{10} Btu/day
Wastewater sensible heat	17.0 x 10^{10} Btu/day
Oxidizable organic matter	1.5 x 10^{10} Btu/day
Total	95.1 x 10^{10} Btu/day

3. The natural energy or radiation absorbed by the air-water interface on the southern California mainland shelf has been estimated to be about 4,200 Btu/ft^2/day or 16,400 x 10^{10} Btu/day for a total area of 1,400 sq mi. The total man-induced energy input of 95.1 x 10^{10} Btu/day amounts to about 0.6 percent of the natural radiation energy absorbed by the water surface.

4. On a broad-scale basis, and depending upon the water renewal rate, the man-induced water temperature elevation for the entire southern California mainland shelf is estimated to be less than 0.05 to 0.20°F above the natural temperature level.

5. The annual average heat discharge has been calculated to be 76.6 x 10^{10} Btu/day from power plants alone. Therefore, the total coastal water area having a surface temperature elevation of 2°F or higher above ambient may be estimated to be 3.6 sq mi by the North and Adams empirical method, and 7.5 sq mi by Pritchard's analytical model (assuming case III of the Pritchard model is typical of the existing discharge structures of power-plant cooling waters). However, if the discharge structures were designed with a high-velocity discharge, as in case IV of Pritchard's analytical model, this total area would be less than 1 sq mi.

6. According to Pritchard's analytical model, the area of the waste heat plume having excess temperatures exceeding, say, 1°F can be minimized by a properly designed cooling water discharge structure.

CONCLUSIONS AND RECOMMENDATIONS

IX

1. Present man-induced energy inputs constitute a small fraction of the natural source terms to the energy budget of the coastal waters of southern California.

2. Artificially added waste heat has produced no significant broad-scale effect on the surface temperature of the coastal waters up to the present time.

3. The intermittent operation of a thermal power plant results in an intermittent discharge of cooling waters. Therefore, a more detailed, non-steady-state analysis is needed to identify extreme temperature changes that may occur in the vicinity of power-plant waste heat discharges. Theoretically, the waste heat discharge will vary from nearly zero to its maximum rate, with an annual average rate of about 55 percent of maximum.

4. Continuous thermal monitoring of receiving water and waste heat stream is needed in the immediate vicinities of the power-plant heat discharge points. However, the influence of individual heat discharges does not appear to extend over a large area.

5. Fluctuating temperatures are but one aspect of a complex environmental problem. When cooling water and other types of wastes are discharged into the same receiving water, the influence areas may overlap. The combined effect becomes more complicated and cannot be predicted by integrating the effects of individual factors. A multivariate study of interactions between temperature and other environmental factors is warranted not only for avoiding the deleterious effects but also for making use of the possible beneficial effects of the wasted energy. Such a study should include both laboratory experimentation and field observations.

6. It is technically and economically feasible to reduce the excess temperature in a waste heat plume to an ecologically desirable level by a properly engineered discharge structure. It is also possible for a coastal power plant to use deep, cold ocean water for cooling purposes; hence, the discharge temperature can be near the ambient water surface temperature. These principles should be examined in detail and applied in the planning of future power-plant cooling systems in the southern California coastal area.

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