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AN EVALUATION OF ENERGY GROWTH
AND USE TRENDS AS A POTENTIAL
UPPER LIMIT IN METROPOLITAN
DEVELOPMENT

OCTOBER 8, 1971

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AN EVALUATION OF ENERGY GROWTH AND USE TRENDS AS A POTENTIAL
UPPER LIMIT IN METROPOLITAN DEVELOPMENT*

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INTRODUCTION

"An abundant supply of low-cost energy is the key ingredient in continuing to improve the quality of our total environment."

L. A. DuBridge from hearings before
the Joint Committee on Atomic Energy
October-November, 1969; Ref. (1)

As we enter the final thirty years of the 20th century, these words summarize better than most, the principal thrust of the energy policy of the United States as it has existed from its inception to the present. Yet as these very words were recorded, the forces at work within the technological economy have been giving prominent signals that a new policy may be thrust upon us. During the time since these hearings, which may have represented some apogees in the scope of present growth policies, there has been an awakening of interest in the consequences of man's activities on earth which can be compared to no other period in the nation's or the world's recorded history. This reflection in the course of our nation's development has not by any means been accepted by a majority of the technical leadership, and while a continued series of new legislative acts designed to create a more favorable turn of events continues to be promulgated, a number of older concepts continue to attract followers. Among these are the beliefs that the present ad hoc system of metropolitan expansion can be continued ad infinitum and that the atmosphere represents a limitless sink for all of the unpleasant

left-overs of our technological society. This belief extends to the continued concentration of energy and power dissipation in metropolitan areas, including actions which tend at times, to decrease the efficiency of power conversion apparatus and usage in the interests of protection of portions of the environment at the potential risk of endangering others. The promotion of the electric automobile is an outstanding example of such actions; there are many others. All involve a latent misunderstanding on the part of the public regarding the nature and end fate of expended energy.

It is time to begin to stress the fact that all energy produced and consumed is converted to thermal modification and potential pollution of the environment. This occurs irrespective of the efficiency of the conversion or the cascading of the uses of "waste heat" for a number of useful purposes. In fact, as stated succinctly by Brooks⁽²⁾ in a recent paper: "Heat as a pollutant has a unique characteristic. Because of the basic laws of thermodynamics there is no treatment as such; any efforts to concentrate it (by heat pumps) simply require more mechanical energy, which means more waste heat is generated at the power plants. Other types of environmental pollution can be alleviated by various processes, which usually consume power and ultimately produce waste heat. Thus, heat is an ultimate residual of society's activities."

It is the purpose of this paper to examine the growth in power and energy use trends on a national and regional scale and relate these to known facts concerning alteration of the urban environment. These facts suggest that a thermodynamic limit may exist above which the climate of the city would become intolerable. This is in addition to the

cultural forces which at present raise serious questions about the role of megalopolis and have led to the principal recommendation of the National Goals Research Staff report⁽³⁾ to seek the deconcentration of metropolitan areas.

A BASIS FOR CONCERN

A great deal of serious study has been devoted to the production of energy forecasts for the United States. No single technical issue is so important to our technological forecasting, nor is one so uncertain. On the one hand, the advocates of continued compound rate growths urge the planning of crash programs for the meeting of energy needs, while others urge restriction of growth on a number of bases which are far from acceptable or resolved. At best, the question of the energy needs of the nation remain a deep and unresolved issue. An indication of this is the recent passage of Senate Resolution 45 which charges the Senate Interior Committee with the task of defining a national energy policy for the coming decades - a policy which will suffice for societal needs while permitting management of the physical environment to satisfactorily high levels of quality.

In the absence of clairvoyance, resort must be made to the projections of the Federal Power Commission and a number of independent estimates which have been proposed. These have been summarized by Battelle Memorial Institute for the Office of Science and Technology in a widely publicized report⁽⁴⁾. The results of this projection have been further translated into a study of the total energy release as thermal energy to the six conterminous regions of the United States⁽⁵⁾. Since the purpose of this paper is not to examine the details of these projections, but to consider

what may result if they come true, we will spare the reader the time needed to justify the actual projections and accept them as the best available projections.

Figure 1, based on a total U.S. population of 300 million by 2,000 AD, places the expected overall energy usage per capita in perspective. Energy usage per capita is expected to increase by some 250% based on 1960 estimates and electrical energy (kilowatts at the busbar) is expected to increase by 1,350% in the same period. Thus electrical energy use at the busbar will be expected to increase over five times as fast as traditional sources if the projections prove correct.

Figure 2 summarizes the total energy use and release to the environment from another perspective, that of the total for all sources for the entire United States. The growth shown in Figure 2 will occur primarily in the use of electricity to replace traditional heat sources in the conversion industries and for lighting and space heating and air conditioning. Because the consumption of power in office buildings has become a large factor in peak load characteristics of municipal systems, better design is expected to reduce the per capita consumption largely by elimination of incandescent lighting, low efficiency fluorescent lighting, and employment of regenerative systems to reduce heating and cooling loads.

Despite increases in efficiency forced by higher expected rates, which have been forecasted to increase by over 4% per year for the foreseeable future⁽⁶⁾, total energy use by industry is expected to increase about twice as fast as factors related to population. However, since electrical energy requirements are shown to be the predominant growth

FIGURE 1. PER CAPITA ENERGY USE BY DECADES THROUGH 2000 AD

FIGURE 2. PROJECTED TOTAL ENERGY DEMAND IN THE UNITED STATES

factor in the next 30 years, rising from a present 21.5% of all energy requirements in 1965 to 52% of all requirements by the year 2,000, the primary emphasis on the analysis of the effects of future energy uses is largely determined by the electrical portion of the growth function.

Careful observation of Figure 2 reveals a number of important considerations. Chief among these is the fact that Rankine cycle thermal plants, if used to meet all of the projected electrical needs through 2,000 AD will reject 50% more heat to the environment than the total consumption of all energy in the United States in 1955, some 50,000 trillion BTU per year. Another serious implication of present trends in plant construction is the use of cooling tower systems. These penalize plant efficiency by an average of 6%. If all of the forecasted plants constructed from now on were subjected to this penalty, the total thermal increment attributable to cooling towers might reach 3,000 trillion BTU per year, a value not far different than the total use of energy for electrical production in 1955.

If these forecasted energy releases are distributed evenly over the entire surface of the United States they amount to an insignificant fraction of the total sun's energy, approximately equal to a standard deviation of the net energy absorption during a year. However, Figure 3 illustrates that the projected growths are not expected to be so distributed. A majority of the energy use is concentrated in the Northeastern and Mid Central United States. In other areas such as the Los Angeles area, because of the local terrain the concentration is even higher. Lees⁽¹⁰⁾ has reported that presently, Los Angeles releases 5% of the sun's energy and this is expected to grow to a value of 13% or greater if the

FIGURE 3. PROJECTED ELECTRICAL CONSUMPTION BY REGIONS THROUGH 2000 AD

projection holds true. Since a standard deviation of net solar radiation received at a point on the ground is on the order of 1 to 2%, the projected releases suggest that a more careful examination of the presently known effects of such energy concentrations is needed. Table 1 presents another examination of the net results of the projections for the Boston-Washington metropolitan area. The data indicate that man made releases in that area will range from 15% in the summer and 50% in the winter of the net solar radiation over the entire 12,000 square mile area. Intuitively, one is forced to come to the conclusion that a second more detailed examination is justified.

THE CLIMATE OF METROPOLITAN AREAS

For years a limited number of investigators have begun to point out the development of unique micro-climates in the large metropolitan centers of the world. However, the development of a clear, precise descriptive model of the urban climate has been delayed because the theoretical considerations have been divided into thermal considerations as climatology and winds and turbulence as micro-meteorology. Recently investigators such as J. Murray Mitchell and H. E. Landsberg have begun to integrate the components of the urban climate into a coherent science, and as a result new attention is being focussed on the implications of mans relation to the urban atmosphere. Landsberg's historic summary⁽⁷⁾ provides dramatic insight into effects of growing urbanization. There is a growing realization that the climate of cities is caused by the cities themselves. If this is the case, then it must follow that the ingredients of the urban atmosphere may have a unique relationship to the city itself, and that these may provide a basis for a limitation on the emission

TABLE 1

	<u>Average Daily Total Solar Radiation for New York City</u>		<u>Heat Rejection from Energy Use as Fraction of Solar Heat in 2000 AD</u>
	cal/cm ² (a)	Btu/ft ²	
January	130	480	0.50-0.57
April	369	1360	0.175-0.201
July	459	1690	0.141-0.162
October	242	893	0.267-0.307

(a) Solar heating data from Oxford Regional Economics Atlas,
United States and Canada, Clarendon Press, Oxford, 1967.

(b) Based on estimated heat rejection rates of 238-274 Btu/ft²
per day in Atlantic Metropolitan Area.

Atlantic Metropolitan Area: Boston-to-Washington

Area in year 2000: 12,057 mi²
Population in year 2000: 56,248,000
Population Density: 4670 per square mile

Energy use based on per capita usage of 6.92×10^4 Btu/hr
(national per capita average in year 2000)

Assumes: Metropolitan area of 12,000 + mi² includes
proportionate share of industrial areas

Energy use per square mile:

$$\left(4670 \frac{\text{person}}{\text{mi}^2}\right) \left(6.92 \times 10^4 \text{ Btu}\right) = 3.23 \times 10^8 \text{ Btu/hr-mi}^2$$

This equals: 11.4 Btu/hr-ft² Average or 274 Btu/ft² per day.

Energy use based on electrical demand forecast:

Demand forecast of major load centers in metropolitan region:

168.5 GW or 5.75×10^{11} Btu/yr

Equivalent to 4.77×10^7 Btu/hr-mi² or 1.71 Btu/hr-ft² heat from
electrical consumption.

Northeast Region average ration of total energy use to electrical consumption is 5.9

Applying this ratio, assuming it to apply within the metropolitan area:

Total heat rejection from energy use = $10.1 \text{ Btu/ft}^2\text{-hr}$
or 242 Btu/ft^2 per day.

spectra of the whole range of urban detritus released in a large urban center including heat.

Perhaps it would be useful to detail to a limited extent the reasons for the formation of urban microclimates as a basis for quantifying conclusions which may be drawn from this presentation. Two major factors are involved in the analysis, the heat and water balance and the changes in the turbulence conditions. We will cover the turbulence first.

The development of urban areas is accompanied by gross changes in the surface roughness. As the size of urban structures begins to exceed the scale of turbulence, a change in the wind field occurs and as a result the vertical wind profile is modified so that wind speeds near the surface of the ground are greatly reduced. In addition the structural features of cities increase the number of small-scale eddies and modifies the turbulence spectrum. Hanna⁽⁸⁾ states it this way: "The distribution of wind in the boundary layer during steady state, adiabatic conditions is completely determined by the following parameters: the geostrophic or free stream wind speed G , the Coriolis parameter (f), and the roughness length z_0 . If the roughness elements occupy a sufficient volume, the displacement length must be added to this list. We can use the results of Kutzbach's (1961) study of the reaction of the wind profile to bushel baskets placed on the ice to derive laws relating the roughness length and the displacement length to building size and placement. If A is the ratio of the total area of a given region to the area of the buildings in that region, and h is the average height of the structures, then Kutzbach suggests the laws:

$$(1) \quad d/h \approx A^{-0.3} \quad \text{and} \quad (2) \quad z_o/h \approx A^{-1.1}$$

The parameter A for German cities (Kratzer, 1956) varies from 2 to 10. This range of values is valid for most other cities, too, as can be seen in aerial photographs. Consequently, if (h) is about 10 meters, the roughness length z_o is between 0.5 and 2 meters and the displacement length (d) is between 6 meters and 9 meters. In past studies the displacement length was often neglected when urban roughness was modeled. Ariel, et al (1960) measured the wind speeds at heights of 24 and 48 meters at Kiev and estimated the roughness length to be 4.5 meters. However, they neglected the displacement length. If we use $d = 10$ meters, we obtain z_o about 1.5 meters. It is clear the both z_o and d must be accounted for over a city, and that equations by Kutzbach provide a simple method of approximating these parameters." Other investigators have used the same methods to estimate the roughness of rural areas and have obtained values on the order of 0.15 meters, a value consistent with the expected differences between the urban and rural topography.

The effects of the change in heat flux are considerably more pronounced. As poorly conducting and evaporating vegetable surfaces are replaced by well conducting, essentially dry, surfaces of high heat capacity and low albedo, the result favors a higher thermal balance in urban areas relative to rural areas. As thermal releases increase from energy decay, human sources including metabolic sources, industrial and transportation activity are concentrated, and the surface roughness of the urban landscape increases, a relatively stable low pressure area develops which prevents normal nocturnal circulation to the free wind field and confines the local circulation to a toroidal urban circulation

pattern which concentrates the effluents of the urban aggregation.

The energy budget of the metropolitan area has been greatly affected by the prodigious production of pollutants. Ultra-violet radiation is much reduced, and net involving radiation is concentrated in upper air masses instead of being distributed. These redistributed fractions of the energy spectrum then react with the trapped chemical ejecta of our man made volcano to produce a fantastic array of photo-chemical products known to be injurious to all higher plants and animals.

While the major substantive changes affecting large regional segments of the atmosphere can be traced to the release of chemical pollutants and particulates associated with various combustion processes, the role of the urban heat island in stabilizing and concentrating these releases is becoming more and more apparent. Czapski⁽⁹⁾ has suggested that the climatic effects "observed" near cities may in fact be more due to the effect of the added heat than the condensation and freezing nuclei to which they are usually attributed. Czapski predicts severe consequences of large latent and sensible heat emissions:

- (1) rainfall will be increased downwind for a considerable distance
- (2) cumulus clouds will prevail most of the time downwind from a large power plant or aggregation of power plants
- (3) severe thunderstorms and even tornadoes can be caused in very unstable weather by dry and clear heat.

The following table adapted from Landsberg's publications summarizes the known effects of urban heat islands and the associated climatic effects:

TABLE 2

CLIMATIC CHANGES PRODUCED BY CITIES

<u>Element</u>	<u>Comparison with Rural Environs</u>
<u>Radiation</u>	
Total on horizontal	15 to 20% less
Ultraviolet, Winter	30% less
Ultraviolet, Summer	5% less
<u>Cloudiness</u>	
General cloud cover	5 to 15% more
Fog, Winter	100% more
Fog, Summer	30% more
<u>Precipitation</u>	
Total amounts	5 to 10% more
Heavy rains over 0.2 in/day	10% more
<u>Temperature</u>	
Annual mean	1 to 1.5°F more
Winter minimum	2 to 3 °F more
<u>Relative Humidity</u>	
Annual Mean	4 to 6% less
Winter	2% less
Summer	8% less
<u>Wind Speed</u>	
Annual mean	20 to 30% less
Extreme gusts	12 to 20% less
Calms	5 to 20% less
<u>Contaminants</u>	
Dust and particulate	10 times more
Sulfur Dioxide	5 or more times
Carbon Dioxide	10 times more
Carbon Monoxide	25 times more

FIGURE 3. REGIONAL THERMAL ELEVATIONS COMPUTED FROM ENERGY FORECASTS

Having demonstrated the size of the energy release potential in the United States and the documented effects of past releases on the urban climate, it is instructive to do some forecasting of what may occur in the event the actual releases are as large as estimated. Lees⁽¹⁰⁾ has computed these effects for the Los Angeles Basin and has used these computations to draw attention to the seriousness of the thermal problem in urban areas in general and to the particularly acute problem in the Los Angeles Basin. The method used by Lees (see Appendix), while subject to additional refinement is based on sound concepts and appears to be worthy of additional development. The author has taken known data from the Boston-Washington area and developed a thermal projection using Lees method. Since the "ventilation box" concept cannot be applied directly, in the author's comparison, the stable heat island itself is considered as the boundary condition. Using the present thermal elevation of about 1.5 degrees F for the region, the critical size was calculated using Lees expression. This worked out to 150 miles, roughly correct as the short side of an ellipse 150 x 300 miles in size. This size was then used to project a thermal elevation for the region using the thermal loading for the area developed by Jaske et al⁽⁵⁾ of 34×10^{15} BTU/year for the year 2000 AD. Application of the method to smaller areas where the mean concentration would produce very high thermal elevations suggests that the New York-Philadelphia area as a sub-region could approach the 15°F mean annual increase of the Los Angeles Basin forecasted by Lees.

The problem is not unique to the United States alone. Energy concentrations in Europe have been under study for a number of years.

Paris has had an identifiable thermal island of some 3°F as reported by Dettwiller as early as 1961. The region is especially significant in that it is essentially flat and devoid of orographic complexity. London has been similarly charted, and a thermal island on the order of 1.5°F identified. All in all, the climatological records and the thermal forecast of the future loadings signal the need for consideration of thermodynamic pollution as a potential limit to the size of urban areas.

WHY LIMIT THE SIZE OF URBAN AREAS?

The nation stands at the verge of a series of decisions which could remake the face of the country. A number of pressing considerations are involved, not the least of which is the ability of the technological system to relate to the needs of the public through a viable system of national and regional goals. The computations cited above raise a controversial and deep question. For if we spend 100 billion dollars in the next 20 years to clean up the environment as suggested by the President and a number of reliable sources, only to face a new crises - that of energy pollution, we will have accomplished very little indeed. A guide to the resolution of the dilemma lies in the use of the great technological strength of the country to re-examine and re-develop the land. The following quotes from the President's National Goals Research Staff report⁽³⁾ issued July 4, 1970 are germane to the technical discussion which has preceded them.

"Man is re-defining his relationship to his environment. He has progressed from fearing, to understanding, to using, to abusing, and now to worrying about the physical and biological world about him. Throughout all but the very recent history of the United States, our relationship

to the environment has been one of exploitation. We have seen our natural endowment as a source of riches to be extracted and used, or, later, to be extracted and processed. Concern for the environment was generally limited to whether or not we were exhausting our inheritance of sources of food, energy, and materials."

"The current interest in the environment has two distinctively novel emphases. The first is that the limitations that the environment places on our activities may not be on the input side (sources of food, energy, and materials), but on the output side (a place to dispose of our wastes). The second, which is closely related to the first, is that the environment, in addition to having a limited capacity to absorb wastes, is a complex ecological system in which intervention of an apparently minor sort can, and often does, have far reaching consequences through a chain of unsuspected reactions."

"Both of these aspects of thinking about the environment have important consequences on the way we think about other things. They raise the question of whether or not there may be an upper limit on our economic growth as a consequence of the limitations on how much waste can be absorbed. And, the model of complex ecological systems affects our whole way of thinking about the consequences of our action not only in the environmental sphere, but also in the social sphere where we are coming to realize that causation is just as complex."

"Some scientists and other anxious citizens assume a doomsday model of the future in which increased economic production will drive us to our destruction. In response, others propose what is called a paradise-regained model which would return us almost to a state of nature.

Fortunately, the doomsday model does not forecast that which is inevitable, and the latter, which would probably be unattainable if tolerable, need not be entertained."

"A mixed strategy of response to our environmental problems is proposed. We need to expand our inadequate knowledge of ecological systems. But while expanding this knowledge, we must take those measures which we know are called for. We need to consider our current technological and economic alternatives in the light of long-range ecological balance. Additionally, we need to resolve conflicts between our demands for products and services, and the depletion and pollution generated by them."

"Our environmental problems are a result of our technological and economic successes and of our philosophical view of nature. Now we must learn to use our technology and our economic output better to bring us in harmonious relationship to that environment. As will be found in other sections of this report, it is becoming apparent that the relatively narrow criteria by which we have, in the past, judged technical and economic progress must be expanded to consider a wider range of consequences."

"We have before us a set of decisions. One which appears not to be urgent is that of overall-size of the population--even after the effects of a considerable amount of immigration are taken into account. Apropos of population distribution, we need to decide on whether or not we will adopt a deliberate strategy to encourage internal migration to negate the forecasts of ever-growing urban congestion in a few megalopoli. A viable option for such an alternate strategy is a policy

of encouraging growth in alternate growth centers away from the large urban masses, coupled with a complementary effort of the use of new towns."

That such a strategy is not only feasible, but perhaps indispensable has been suggested by the technical facts detailed in this paper. The implementation of such a policy has been suggested previously by a number of authors in terms of the development of linear cities paralleling high speed transportation systems. Even the question of water supply has been previously outlined in the canal-lake inter-basin diversion scheme outlined by Jaske, Karr and Touhill⁽¹¹⁾. Figure 5 illustrates the concept in schematic form. The system provides the basis for a resolution of the question of how to proceed in the face of the necessity to realize we have little or no choice.

CONCLUSIONS

The case of energy use and distribution as forecast from a composite of authoritative United States sources has illustrated that the extent of energy concentration in large metropolitan areas is expected to reach significant fractions of the solar input to the earth's surface. Related trends in prime mover development which have tended to decrease overall thermal efficiency relative to economic forces tend to exacerbate the problem of energy release concentrations. Although incremental costs of environmental control appear reasonable, the related increases in energy release projected on the same geometric basis as power demands appears to involve extremely serious climatic consequences.

Examinations of total energy release suggest direct relationship in weather modification of metropolitan areas such that mean temperatures

FIGURE 5. SCHEMATIC OF NUCLEAR-PUMPED STORAGE - CANAL LAKE SYSTEM

are increasing, cloudiness is increased and total precipitation markedly increased. Thermal energy releases appear as a stabilizing element in decreasing the ventilation of pollutants from large cities. Forecasts of total energy release in metropolitan areas as large as the Boston-Washington megalopolis and greater Los Angeles indicate heat fluxes of 30 to 40% of the incident solar energy by the year 2000 AD. Such releases have been shown to cause temperature increases on the order of 5 to 15°F in the mean annual temperature which in turn can be expected to effect stream temperatures and the power demands for air conditioning.

The situation suggests a close examination of the trends in the mix of fossil and nuclear facilities, the general use of energy in metropolitan areas and related practices in prime mover design and development. The relationship of power economics, building codes, public taste and resources distribution appear so intricately related as to indicate serious difficulty in the development of a national and international policy.

A tentative solution appears to include emphasis on metropolitan de-concentration of energy, people and general industrial activity. The concept of the linear or distributed city, paralleling canal lake diversion of water-courses and high speed transportation systems offers a way to satisfy the needs of society by utilizing the assimilative capacity of the land surface in a way which is in keeping with maintenance of ecological balance. A number of other alternatives such as higher rates, improved efficiency of generation and usage and financial means of regulating supply, demand and effects could also be suggested. Indispensable to all of these must be the development of a national land

use policy. It appears that a new and decisive element in the formation of such a policy will be the need to consider a limit on the energy releases in existing urban areas and the design of new urban areas around the concept of limited thermal energy releases.

APPENDIX (From Lees, Ref.10)

Relation Between Thermal Power Generation in L. A. Basin and
Increase in Average Ground Temperature

Referring to Figure A1 the dry adiabatic temperature distribution with height in the mixing layer is given by

$$T_{ad} = T_G - (5.5 \times 10^{-3})Z, \quad (A-1)$$

and the initial temperature distribution below the top of the inversion layer in the marine air as it crosses the coastline is represented by

$$T_{INV} = T_1 + \left(\frac{T_2 - T_1}{Z_I} \right) Z = T_1 + \alpha Z \quad (A-2)$$

where $\alpha = \frac{T_2 - T_1}{Z_I}$. Thus the height of the mixing layer where $T_{ad} = T_{INV}$ is given by

$$T_G - T_1 = (5.5 \times 10^{-3} + \alpha)Z_M \quad (A-3)$$

Similarly

$$T_{oG} - T_1 = (5.5 \times 10^{-3} + \alpha)Z_{M_o} \quad (A-4)$$

Now the increase in the rate at which heat energy is convected away compared with "normal" conditions many years ago is proportional to the difference in the areas of the triangles (T_1, Z_M, T_G) and (T_1, Z_{M_o}, T_{oG}) in Figure A1. By using equations (A-3) and (A-4) the difference in these areas is evaluated as follows:

$$\begin{aligned}\Delta (\text{area}) &= \frac{1}{2} \left[(T_G - T_1) Z_M - (T_{oG} - T_1) Z_{M_o} \right] \\ &= \frac{1}{2} (5.5 \times 10^{-3} + \alpha) (Z_M^2 - Z_{M_o}^2)\end{aligned}\quad (\text{A-5})$$

But using equations (A-3) and (A-4) again we find that

$$Z_M = Z_{M_o} + (5.5 \times 10^{-3} + \alpha)^{-1} \Delta T_G \quad (\text{A-6})$$

where $\Delta T_G = T_G - T_{oG}$,

and by inserting this last result into equation (A-5) one obtains

$$\Delta (\text{area}) = Z_{M_o} \Delta T_G + \beta (\Delta T_G)^2 \quad (\text{A-7})$$

Under the conditions existing many years ago the incoming solar radiation was balanced by the outgoing infrared radiation corresponding to T_{oG} plus the rate at which heat energy was convected away by the marine air in the mixing layer of height Z_{M_o} . In "modern" times the incoming solar radiation plus the thermal power generation is balanced by the infrared radiation at temperature T_G , plus the rate at which heat energy is convected away in the mixing layer of height Z_M (Figure 3).

By subtraction,

$$\text{Thermal Power (MW)} \approx (\sigma T_{oG}^4 A) \left(\frac{4 \Delta T_G}{T_{oG}} \right) + \rho C_P V_{MPH} L_{MI} \Delta(\text{area}), \quad (\text{A-8})$$

where ρ = air density, C_P = specific heat, A = area of the L. A. Basin $\approx 1500 \text{ mi.}^2$, $T_{oG} = 530^\circ\text{F}$, $\sigma T_{oG}^4 \approx 500 \text{ MW/mi.}^2$, and $\Delta(\text{area})$ is given by equation (A-7). Finally,

$$\text{Thermal Power (MW)} = (5.65 \times 10^3) \Delta T_G + 0.137 V_{\text{MPH}} L_{\text{MI}} \left[Z_{\text{M}_o} \Delta T_G + \beta (\Delta T_G)^2 \right]$$

(A-9)

FIGURE A1. SCHEMATIC EFFECT OF THERMAL POWER GENERATION IN L.A. BASIN ON MIXING LAYER TEMPERATURES AND HEIGHT

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