The Fire Analog: A Comparison Between Fire Plumes and Energy Center Cooling Tower Plumes

M. M. Orgill

October 1977

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ABSTRACT

Thermal plumes or convection columns associated with large fires are compared to thermal plumes from cooling towers and proposed energy centers to evaluate the fire analog concept. Energy release rates of mass fires are generally larger than for single or small groups of cooling towers but are comparable to proposed large energy centers. However, significant physical differences exist between cooling tower plumes and fire plumes.

Cooling tower plumes are generally dominated by ambient wind, stability and turbulence conditions. Fire plumes, depending on burning rates and other factors, can transform into convective columns which may cause the fire behavior to become more violent. This transformation can cause strong inflow winds and updrafts, turbulence and concentrated vortices. Intense convective columns may interact with ambient winds to create significant downwind effects such as, wakes and Kármán vortex streets. These characteristics have not been observed with cooling tower plumes to date.

The differences in physical characteristics between cooling tower and fire plumes makes the fire analog concept very questionable even though the approximate energy requirements appear to be satisfied in case of large energy centers. Additional research is suggested in studying the upper-level plume characteristics of small experimental fires so this information can be correlated with similar data from cooling towers. Numerical simulation of fires and proposed multiple cooling tower systems could also provide comparative data.

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NOMENCLATURE

<u>Symbol</u>	<u>Definition</u>
A_c	Area around ground zero with radius R_c
C_p	Specific heat of air at constant pressure
D	Diameter of fire or cluster of cooling towers
g	Acceleration of gravity
I	Fire intensity
I_a	Rate of convective heat output per unit area of source
K_1	A constant
ℓ	Dissipation length (turbulence parameter)
N_c	Convection number
P_f	Rate at which the buoyant gases of the convection column do work at any height z as they ascend above the fire
P_w	Rate of flow of kinetic energy in the wind field at height z above the fire
Q	Energy release rate within area A_c
r	Forward rate of spread of the fire; radius vector and cylindrical coordinate
R	Radius of fire bed
R_c	Radius of convection plume annulus within fire bed
T_o	Free-air temperature at the elevation of fire
T_z	Temperature of central convection column at height z
Δt	Reference time interval
u	Root mean square velocity fluctuation (turbulence parameter)

<u>Symbol</u>	<u>Definition</u>
v	Reference wind speed
v_i	Indraft velocity to convection column (plume)
$v(z)$	Wind speed at height z
w	Central convection column (plume) vertical (or slant) updraft velocity
$\dot{w}$	Updraft acceleration at center of convection column or plume
z	Vertical height
β	Coefficient of volume expansion $\frac{1}{T}$
ψ	Angle representing change in direction of wind flow over convection column or plume
Π	3.14159...
Π_i	Symbol for dimensionless variable or group ($i = 1, 2, 3, \dots$)
ν	Kinematic viscosity
ρ	Density of atmosphere at height z
ρ_0	Reference atmospheric density

THE FIRE ANALOG: A COMPARISON BETWEEN
FIRE PLUMES AND ENERGY CENTER COOLING TOWER PLUMES

INTRODUCTION

Past studies on the waste heat from cooling towers and proposed energy parks suggest that the dissipation of this waste energy may result in significant meteorological effects. Preliminary calculations have shown that the rate of atmospheric dissipation of the waste energy from groupings of cooling towers is approximately equal to the atmospheric dissipation of energy by geophysical phenomena such as thunderstorms, volcanoes, and large fires. Cumulus clouds and convective vortices often result from these natural energy releases.

One of the geophysical analogs - the large fire - is evaluated in terms of how good a physical analog it is to cooling towers or groups of cooling towers. The literature on experimental and wild fires was reviewed in relation to how fire thermal plume characteristics may be typical of a thermal plume from cooling towers. Energy release rates and energy fluxes of fires are generally a little larger than those of cooling towers and energy centers but the range is so wide that a fire can possibly be matched with some cooling tower or group of cooling towers--energywise.

Although the waste energy from groups of cooling towers may be approximately the same as from large fires the physical differences between the cooling tower plume and fire plume shows that the fire analog concept can not be accepted unequivocally. In this report, the physical differences between cooling tower plumes and fire plumes are evaluated. Recommendations for further research are directed toward obtaining upper-level data on thermal plumes of small experimental fires so a better understanding of the physical characteristics of thermal plumes and

convection columns can be obtained. In addition, continuing numerical simulation work on cooling tower and fire plumes is also encouraged.

TYPES OF FIRES

Precise definition of types of fires has not been fully established but generally around nine types of fires have been recognized. These are

- Structural
- Urban
- Prescribed (field & forest slash)
- Experimental
- Ordinary Wild Fires (forest, etc.)
- Conflagrations
- Mass Fires
- Firestorms
- Moving Firestorms

An ordinary fire, whether structural, urban, or forest, is a fire with no particular violent fire behavior. If the fire reaches a certain size or intensity then the fire may reach a state in which its fire behavior becomes more violent. At this initial stage and beyond the fire may become a "mass fire", a conflagration or at the extreme limit--a firestorm.

Mass fires, conflagrations and firestorms are descriptive terms given to fires that exhibit the more violent fire behavior¹. General definitions are:

Conflagrations--a fire having a large burning area and a definite moving "front" or "fronts". Conflagrations are strongly affected by wind and topography and can move very rapidly. In forest fires, the crown fire is the major mechanism of propagation.

Mass fire--a fire area resulting from a mass of near simultaneous ignitions that generate high energy output. It can be a part of a conflagration. Tall convective columns, fire-induced winds and fire vortices are common features of mass fires.

Firestorm--the firestorm is a mass fire which results if high energy output is sustained over a relatively large area. High rotating inflow winds ($>30 \text{ ms}^{-1}$), widespread destruction in the fire area, and limited fire spread characterize the firestorm.

Moving firestorm--not well recognized but potentially the most dangerous and destructive because it has the characteristics of a firestorm yet moves rapidly into unburned areas.

In the past years, fire phenomena have been extensively studied in the laboratory on a small scale, but there has been some doubt to the validity of extrapolating results from these laboratory experiments to very large fires. The scientific study of adventitious large fires has proved difficult for several reasons. Therefore, the concept of experimental or controlled burns has been utilized as an aid in the study of fire and fire behavior.

There have only been a few major exploratory large-scale fire tests due to the expense and significant organizational effort needed for such experiments. These experimental fires have been:

- French Meteotron (1961, 1971-1973)
- Project Flambeau (1964-1967)
- Tumut Exploratory Mass Fire Experiment (1968)
- Operation Euroka (1969)

In addition to these experimental fires there have been a number of prescribed forest slash or brush fires in the United States, Australia, and other countries where fire behavior has

been observed and meteorological and other measurements were obtained over or near the fires.

The initial French Meteotron experiments used oil burners for the purpose of producing a strong ascending column and cumulus cloud. Vortices resembling tornadoes were also produced in these experiments²⁻⁵. The later experiments, using the same apparatus, provided data to be used for the theoretical study of artificial convection⁶.

Project Flambeau was a series of thirty burns of discretely distributed fuel piles ranging in size from 5 to 50 acres at isolated test sites in Nevada and California. The objectives of Project Flambeau were to investigate threshold conditions that distinguish mass fires from lesser ones, explore the problems of measuring large and intense fires; and developing instruments capable of getting the needed measurements^{1,7,8}.

Tumut Exploratory Mass Fire Experiment was a preliminary burn in Australia prior to Project Euroka. The burn was approximately 33 acres of eucalypt timber. The primary objective was to test an electrical firing system designed to achieve simultaneous ignition of a large area of forest fuel. Other objectives were to field test instrumentation and study fire behavior⁹⁻¹¹.

Operation Euroka was a mass fire experiment of 52 acres of brigalow timber in Langley, Queensland, Australia. The objectives were similar to Project Flambeau and extensive instrumentation was employed to measure fire parameters - wind inflow, radiant heat, air temperatures, etc.^{12,13}.

A number of wild fires have been documented on fire behavior such as the Sundance Fire^{14,15} and the Air Force Bomb Range Fire¹⁶ as well as a number of control forest slash and bush fires¹⁷⁻²².

The proceeding summary on fire types indicate that fires occur over a wide spectrum of sizes and intensities. In order to better understand the behavior of fires and how they may compare to cooling tower and energy park waste heat plumes the available fire literature will be briefly summarized. At this juncture the most relevant fire literature appears to be that dealing with the French Meteotron and mass fire experiments.

FRENCH METEOTRON EXPERIMENTS

The objective of this experimental project was designed to provide data to study artificial convective plumes and clouds. The heat source consisted of 97 oil burners releasing a total power of 600 MW. The heat source covered an area of about 4000 m^2 (radius 36 m). The average flame temperature was 1200°C . The working time of the system was generally 5 to 10 min.

The first experiments conducted around 1960 only used photogrammetry for the purpose of showing the interaction of the artificial convective plume with height-varying horizontal wind. When the Meteotron is working thick black smoke is emitted because of incomplete combustion of the fuel. This allows visual and photographic observations of the evolution of the ascending smoke column. During these first experiments "tornado" like vortices were observed to extend from the bent-over smoke plume and near the burners. The relatively strong ascending currents ($\sim 10 \text{ ms}^{-1}$) associated with the warm convective plume, fairly strong horizontal wind, and the instability of the air layers near the ground were suggested as possible mechanisms for the formation of the vortices⁴.

Eleven experiments were made from 1971 to 1973. The values of the plume radius, the temperature difference inside and outside of the plume, and the vertical velocity were measured at different heights. These data were measured with

a radiosonde-radiowind system, kite balloons, photogrammetry from four stations, a ground network of temperature and velocity sensors, smoke generators, and some aircraft measurements⁶.

Average data at 10 m above the ground showed a temperature excess of 50°C between the inside and the outside of the plume, and a vertical component of the plume velocity of 3 ms⁻¹. However, instantaneous variations were significant; the thermal maxima exceeded 100°C, and the vertical velocity maxima ranged from 7 to 8 ms⁻¹.

Figure 1 shows the results from a typical experiment. The plume rise was divided into two phases: 1) a vertical phase where the vertical component of plume velocity is higher or of the same order than the horizontal wind speed, and 2) a horizontal phase where the horizontal wind speed predominates. Near the ground, there was a contraction of the smoke column at about 30 m which was visible only under low wind speeds. The contraction indicated that the convergence from the surrounding air into the plume is important at this level (Figure 1b).

The variation of the mean plume radius, vertical velocity, and horizontal inflow velocities with height is shown in Figure 2. In the upper levels (100 to 300 m) the temperature and vertical velocity data showed that the effect of the plume on the surrounding atmosphere was weak: the temperature increased 0.5°C per 100 m of elevation at a distance of 30 m from the plume edge.

Eight of the eleven experiments were carried out when a temperature inversion was present. Beneath the inversion altitude, the atmosphere was generally neutral and the winds were always less than 5 ms⁻¹. When a temperature inversion was present, the plume penetrated the inversion if it occurred below 1000 m and had a thickness of no more than 150 m; in all other inversion cases, the plume only reaches the inversion layer, or occasionally raised it. In all the experimental

FIGURE 1. Plume Characteristics of 4 Aug. 1972 "Meteotron" Fire and Model of Dynamic Field in and Around the Plume. Horizontal and Vertical Vectors Have the Same Scale (After B. Benech)

FIGURE 2. Mean Plume Radius at Different Heights and Velocities in the Plume at Different Heights: +, Mean Vertical Velocities in the Plume; Δ Horizontal Inflow Velocities Along the Plume Borders (After B. Benech)

cases, the heat source was sufficient to cause the plume to rise to an altitude greater than 500 m above the source.

STATIONARY MASS FIRE

Before the characteristics of mass fires are discussed it is important to differentiate between moving fires and stationary fires because the vertical-wind profile requirements are not the same. A moving fire is defined as one which uses up its fuel supply in order to maintain its energy output. Almost all forest or wild land fires are moving fires. According to Byram²³ a stationary fire may be defined as one which meets the following requirements:

- There is a sufficiently large amount of fuel concentration in a limited area to maintain a high-intensity heat source for a fairly long time (20 min. or more).
- High-intensity burning does not require surface wind. Wind might or might not be present, but it is not an essential requirement. Oxygen is supplied by strong fire-induced indrafts.

Examples of stationary fires are 1) a group of burning buildings which were initially ignited in several places, 2) a burning oil-tank farm, and 3) a slash-disposal burn in which a large amount of fuel is concentrated in one location and ignited at numerous points over the area or around the perimeter of the area of concentrated fuel. Another possible situation would be an experimental fire burning a relatively uniform fuel supply (e.g., stubble) over level ground under relatively light and uniform wind conditions. In this case the fire progresses but the energy release rate may be sufficient to maintain a convective column. On a larger scale, a moving fire such as a conflagration may develop mass fire characteristics (i.e., the dynamic convection column) over part of its fire area.

Stationary Mass Fire Model

According to Countryman¹, observations of large and intensely burning fires suggest that a large fire system may have six different zones (Figure 3). These zones as defined by Countryman are:

- 1) Fuel Bed Zone: extends from the ground to the top of the fuel bed. The vertical dimensions may vary from less than 2 cm to many meters, depending upon kinds of fuel involved.
- 2) Combustion Zone: the actively flaming area in and above the fuel zone. Vertical height varies but is usually less than 30 meters above the fuel bed.
- 3) Transition (turbulence) Zone: lies between the combustion zone and the more organized flow of the main convection column. Both upper and lower boundaries are indefinite. In most fires, this zone probably does not extend more than 30 to 60 meters above the combustion zone.
- 4) Fire (thermal) Convection Zone: the area between the top of the transition zone and the base of the convection column cap. Energy for the convection in this zone comes chiefly from the fire, although some condensation of water vapor is also likely. Vertical height of this zone may vary from less than 300 meters in some fires to more than 4600 meters in others.
- 5) Smoke Fallout Zone: a relatively thin zone at the base of the convection cap. This thin layer of smoke spreading out from the convection column is characteristic of towering convection columns.
- 6) Condensation Convection Zone: the area from the smoke fallout zone to the top of the convection column. The column usually widens abruptly to form a "lap". It

FIGURE 3. The Countryman Model of a Fire System
Showing the Six Zones of a Mass Fire

is usually light in color as a result of the condensed water vapor or ice crystals. Heat from condensation is likely the chief source of energy for convection in this zone. This zone is not found in all fires. Its formation depends upon air mass characteristics as well as in size and energy output of the fire. The vertical length is variable but may approach the length of the fire convection zone.

Threshold Limits For Mass Fires

Just where on the scale of fire behavior a fire becomes a mass fire is uncertain. According to Countryman¹, fires large in area are not necessarily mass fires, since low energy release rates do not usually generate violent fire behavior. On the other hand, very small fires burning with a high rate of energy release seldom exhibit violent fire characteristics. The term "mass fire" then carries the connotation of both large size and high rates of energy release.

Since energy release rates and fire area are both on continuous scales the problem of defining mass fire resolves into setting threshold values on these scales where a fire can be considered a mass fire. A general definition¹ of these values is: the minimum fire area and energy release rate at which a further increase in fire area or energy release rate will not significantly change the pattern of fire behavior.

Experimental fires such as in Project Flambeau have been used to define approximate threshold's for energy production rate, fire area, ambient wind speeds and other factors for mass fires. Countryman has suggested an energy production rate threshold of 5000 to 8000 Btu/ft²/min. The area of fire at which the minimum energy release rate will produce a mass fire has been more difficult to delimit. Other factors than size are involved such as wind speed, fuel configuration and spacing,

coalescing of multiple fire convective columns and energy release rate. However, Countryman suggests that the minimum size fire to produce mass fire characteristics is on the order of 3 acres ($\sim 1.2 \times 10^4 \text{ m}^2$) or more. Therefore, the energy release rate of a minimum mass fire would be on the order of 1 to 2×10^{10} watts (1 to $2 \times 10^4 \text{ MW}$)*.

Countryman¹ lists some of the specifications of a mass fire as;

- Fire with massive turbulent flames, with multiple convective columns in the combustion and transition zones.
- Thermal energy output would exceed $5000 \text{ Btu/ft}^2/\text{min}$.
- Fire would dominate circulation patterns within the fire area.
- Fire area would be at least 3 acres.
- The ambient wind speed should be less than 3 ms^{-1} .

A more complete list of mass fire specifications has been given by Countryman¹.

CHARACTERISTICS OF MASS FIRES

Wildfires of various magnitude and experimental fires have provided important data and information on the various characteristics of mass fires. In the following discussion, these various characteristics will be briefly reviewed.

*Byram²³ and others classify wildfires by fire intensity or the energy release rate on a unit length of fire line. The majority of all forest fires seldom exceeds 1000 Btu/sec/ft of fire front but major conflagrations and high-intensity fires can reach intensities of $10,000$ to $30,000 \text{ Btu/sec/ft}$ of fire front.

Thermal Pulse

The thermal pulse is the rate of heat output per unit area per unit time. Its magnitude and shape are determined by the way in which fuel burns. Thus, all fuel and environmental factors affecting the rate and method of fuel combustion would affect the thermal pulse. Some of the fuel factors of importance are 1) fuel element geometry, 2) surface conditions, 3) chemical composition, 4) specific gravity, 5) thermal absorptivity, and 6) moisture content. The environmental factors are topography and air mass. Air mass includes wind, humidity, precipitation, temperature and air stability¹.

The thermal pulse, as represented by plottings of temperature or radiation against time, resemble "log normal distributions", i.e., a relatively rapid rise to a peak (period of most active flaming), a slower decline to some value much below peak and then a very long "tail" before reaching ambient values (residual burning). Superimposed on this ideal distribution will be many small variations representing fire pulsations²⁴.

Fuel moisture and wind appear to broaden the thermal pulse peak. With high fuel moisture the thermal peak during the surface burning stage is suppressed by the dilution and cooling of flammable gases by water vapor. The thermal energy output rate can be expected to be lower at all combustion stages when fuel moisture is high. On the other hand, higher wind speeds broaden the thermal peak by increasing the burning rate when fuel elements are in the second and third stage of combustion. The potential energy of the fuel will thus be released in shorter time¹.

Shape and magnitude of the thermal pulse characterizes fire behavior. Therefore, the characteristics of the fuel bed and element coupled with those of the environment are of primary importance in determining the type of fire. The relationships involved are complex because of the interaction

of fuel and environmental factors and the infinite combination of fuels and environmental conditions.

The total energy release of a fire consists of several components. A simple equation for the complete energy release is

$$E_t = E_r + E_c + E_{con} + E_L + E_m + E_o \quad (1)$$

where

- E_t = total energy
- E_r = radiant energy
- E_c = convective energy
- E_{con} = energy lost by conduction into ground
- E_L = energy lost by incomplete combustion
- E_m = energy lost due to vaporization of fuel moisture
- E_o = other energy losses.

These energy components were estimated in the Euroka experimental fire²⁵ and found to be E_r (19% of total energy available), E_c (37%), E_{con} (2%), E_m (7%), E_L (15%), and E_o (20%). The total energy available was 1.07×10^{14} joules.

Entrainment

The data on air entrainment into fires have been somewhat inconsistent. Both indrafts and outdrafts have been reported for the various types of fires. Usually, light indrafts have been observed for mass fires but occasionally outdrafts have been observed from stationary and moving fires. There is also some evidence that major air entrainment into the convection column may take place at a considerable distance above ground level¹.

In the experimental fires of Project Flambeau¹ it was observed that the fire actually blocked the ambient air movement. Air flow was similar to fluid flow around a solid object, with eddies and turbulence forming in the lee or wake of the fire. Above the fire in the transition and convection zone, the ambient air flow appeared to be absorbed into the fire system.

The wind flow at 2 m above ground level was modified by the fire to a marked degree in Project Euroka²⁵. This effect was observed as far as 140 m from the fire. The maximum wind speed generated by the fire was 28 m/sec and the inflow component at 2 m height, averaged around the fire perimeter, attained a maximum value of 4 m/sec. This was observed during the maximum intensity of the fire. The wind observations around the fire perimeter suggested the presence of an area of convergent streamlines, spiralling in a cyclonic sense, within the western quadrant of the fire.

In Tumut mass fire experiment⁹ the inflow winds were maintained around the entire perimeter of the fire and corresponded with development and collapse of the convection column and followed a trend very closely correlated with the total fire energy release.

Project Euroka has provided some interesting information on how the inflow winds may be created²⁵. The combustion area of the Euroka fire contained wandering columns of rising hot gas. These columns entrained air from slow moving cooler gas which channeled in from the sides of, and, on the upwind side, above the fire.

Near the ground these columns were as small as 5 to 10 meters in diameter, and about 100 to 1000 in number. The total area of contact between these hot columns and the cool air channeling into the fire was large, and rapid entrainment of the cool air occurred. As the columns rose they increased

in diameter both by entrainment of cool air and by coalescing with one another. Near the height of the pinch point they had coalesced into a single rising convection plume.

The pinching in of the overall convection plume was caused by the predominantly radial inflow winds near the ground. As the column ascended and the rate of entrainment decreased, the flow became predominantly axial. As the flow changed from radial to axial the overall convection plume slowed its rate of contraction and then began to expand (Figure 4).

Theoretical analysis by Lommasson, et.al.^{26,27}, shows that the induced inflow wind due to a large mass fire (e.g., firestorm) can be estimated by

$$V_{\text{inflow}} = \frac{K_1 Q^{1/3}}{A_c^{1/6}} \quad (2)$$

or when "pinch" effects are considered

$$V_{\text{inflow}} = \left\{ \frac{Q g \beta}{\pi \rho C_p R} \cdot \frac{R_c^2}{R^2} \left[1 - \frac{R_c^2}{R^2} \right] \right\}^{1/3} \quad (3)$$

Results from Project Euroka suggests that the cube root relationship between the velocity and fire convection energy release rate is adequate for the convection column but inadequate for the flow near the ground. It was suggested that the wind inflow near the ground could vary as the square root of the energy release rate rather than the cube root.

Further analysis indicated that for a given energy release rate a characteristic radius of the convection plume, such as its projection on the ground, R_c , may be a more important factor in determining the inflow velocity than the actual fire

FIGURE 4. Cross-Sectional Representation of a Fire-Induced Convection Column in a Calm Atmosphere (After Lomasson)

bed radius, R . For fires in which R_c/R is the same it was suggested that the inflow velocity is a weak negative function of the fire radius²⁵.

Convection Column

The most striking phenomenon of large mass fires is the significant convective activity and development of a convection column of hot gases, water vapor, and smoke that can extend several thousand meters into the atmosphere. Quite often, the extent of convective activity over a fire is a much better indicator of fire intensity than is the size or surface area of the fire.

The convection column from a fire differs from a convective cloud in that the former is anchored to a point on the ground, and some part of the entrainment with ambient air must be due to the prevailing wind. The convection column, because of its difference in temperature and density from the surrounding air may act as a semisolid barrier and generate mechanical turbulence (vortex pairs) in the wind field around the column²⁴.

Taylor, et.al.,²² has shown that there is a fairly good correlation between estimated fuel burning-rates (tons per hour) and the height of convection column. The higher burning rates corresponds to higher heights of the convection column.

Thermodynamic analysis can show that almost all the energy of a large mass fire comes from burning fuel; only a negligible part can come from the stability of the atmosphere. A part of this energy is converted into kinetic energy of motion as the hot gases expand and cool in traveling upwind. In this respect a large mass fire is analogous to a heat engine. An essential part of this fire heat engine is the convective column above the fire. The convection column has a relatively warm core which extends well into its upper heights. The temperature

of the core decreases rapidly upwards. Parcels of hot gas do not always travel directly up the core, but after traversing the core for a short distance they pass outward, downward, and into the core again. This process is repeated over and over. The convection column thus entrains and re-entrains its own gases. Meanwhile, the parcels of warm air are being diluted continuously by mixing with the environmental air. The top of the convection column may be rounded and a fairly continuous cap, which may be composed in part of condensed water vapor.

This type of a smoke column is an active convection column in that it should produce a low pressure area over the fire. To maintain its dynamic properties, this model convection column should maintain a nearly vertical position. To do this and at the same time keep moving over a continuous supply of new fuel, the convection column requires that wind speed decrease with height²³.

Byram^{23,28} has developed a theory for predicting the behavior of "blowup fires" on the basis of the ratio of the rate of conversion of thermal energy into kinetic energy in the smoke plume to the rate of flow of kinetic energy in the wind field. This ratio is called the convection number N_c ^{16,23} where

$$N_c = P_f / P_w \quad P_f = \frac{I}{C_p (T_o + 459)} \quad (4)$$

$$P_w = \rho \frac{(v(z) - r)^3}{2g}$$

When N_c is greater than unity for a considerable height above the fire, the rate of energy conversion in the convection column surpasses the energy flow in the wind field. The fire will change from a forced convection system to a free convection system and may exhibit violent, unpredictable behavior.

When the ratio falls well below unity, a smoke plume rather than a convection column exists and the energy flow in the wind field will dictate fire behavior. According to Byram, when N_c exceeds unity there are several different but equivalent ways to describe what happens:

1. The fire changes from an essentially two-dimensional to a three-dimensional phenomenon. It acquires vertical structure.
2. The fire changes from a forced-convection type to a free-convection type.
3. The fire acquires a chimney; or convection column, instead of maintaining a smoke plume.
4. The fire blows up.

Analysis of numerous case histories of wild fires has led Byram to the following observations:

- N_c is usually greater than unity for a vertical distance of at least 300 m before a "blow up" fire can occur.
- The condition most favorable to the sudden growth of the convection column occurs when N_c is greater than unity high above the fire. This condition is usually associated with a low-level wind speed maximum within 450 m of the surface.
- Erratic fire behavior may occur in the transition zone as N_c approaches unity.
- The vertical structure of the column is determined by the value of N_c rather than by the actual fire intensity and wind speed.

Several underlying assumptions have to be made when using the convection number concept. The atmosphere should be neutrally stable, long-distance spotting should not affect

rate of speed, and released fuel energy should flow into a single convection column.

The buoyancy force created by the heat of the fire causes both vertical motion and a vertical pressure gradient. In terms of air movement, the air flow above a large fire may be approximated by considering two zones, a zone close to the ground in which the air flow is predominantly horizontal and a zone well above the ground (the convection column) in which the flow is predominantly vertical.

The vertical motion in the convection column have been rarely measured in actual large fires for obvious reasons. Estimates can be made from mathematical models which relate the vertical velocity to the buoyancy of fire energy release rate²⁹. Generally, the models show a vertical distribution of vertical velocity decreasing with height.

Measurement of vertical velocities in the combustion and transition zones of experimental fires have shown that both downdrafts and updrafts may occur in and above the fire. Ring vortices appear to account for much of the variability in vertical motion in these zones. Speeds in excess of 30 to 50 m/s have been estimated within the smoke column above the fire³⁰.

Taylor, et.al.^{18,19,31} made measurements of the vertical motion of an aircraft over five prescribed or control fires in Australia. These measurements were made between 300 and 2500 meters. Although the vertical motion of the aircraft cannot be equated with that of air the two motions are related in the same sense. In general, it was found that slight downdrafts occurred before entering the smoke plume and that stormy updrafts were situated just inside the plume. The major turbulence effects also seemed to be located inside the column close to the boundary between smoke and clear air; however, within the major part of the smoke column itself there

was only spasmodic activity. The accelerations were within the range ± 0.55 g.

In the Darwin River control burn Taylor, et.al.²² describes the change in height of a convective column over part of a major bushfire. This short-lived tower rose from 3000 m to 5800 m in 15 min and occupied some 12% of the total fire area. Vertical motions were on the order of 3 ms^{-1} . Taylor reasons that this behavior can be explained by the tower acting effectively as a barrier to the wind, with consequent reduction of mixing, so that convection could proceed using only the released energy of the latent heat. A similar but lesser effect was noticed from an earlier fire.

Temperature

As mentioned earlier the air flow above a large fire is driven by the strong buoyancy forces which result from the high temperatures produced by combustion. In the lower regions, temperatures are several thousand degrees and heat transfer by radiation plays an essential role. High-temperature effects retain their importance for some distance above the level at which heat generation by combustion can be neglected, although cooling both by radiation and by entrainment of cold ambient air is vigorous, and the plume (or column) quickly attains a weak buoyant state.

Radiation is generally important only over heights of 2 to 3 source diameters and rapidly decreases with height. The temperature at the source is the largest single factor in determining the maximum height to which a plume will rise, although variations in opacity of the smoke plume can produce effects of about 5% to 10%³².

Temperature measurements of the combustion zone were made in Project Flambeau. Valid temperatures of 2500 °F or greater were recorded on nearly all fires. Temperatures in fire whirls

were considered greater based on the color of flames perhaps approaching 3500 °F. During most of the active fire the combustion zone was a mass of constantly moving, shifting flames. "Hot spots" would develop, burn briefly, and fade away only to reappear somewhere else. Therefore, there was considerable fluctuations in the temperature pattern^{1,33}.

The plume or convective column, to maintain its buoyant state, must have temperatures warmer than the ambient air. Taylor, et.al.^{18,19}, Vines³⁴ measured plume temperatures above Australian control burns from about 300 m to 1200 m and the results show a temperature difference between plume and clear air of about 2°C. However, in large fires the value of ΔT must vary considerably over the fire area depending on the intensity of the fire, the rate of entrainment of ambient air, and other factors.

Water Vapor and Clouds

The smoke plume from a fire consists of large amounts of water vapor that have come from the fuel, combustion of the fuel and entrainment of ambient air. The moisture content of fuel varies and the percentage of moisture has a major influence on ignition, combustion development and spread of fires.

Moisture in wood fuels reduces heat yield. This reduction may be in the order of 15 percent for a change in moisture from 0 to 100 percent when combustion is complete.

One of the important effects of fuel moisture is its smoothing action on the burning rate. Water vapor being distilled from wood dilutes the flammable gases. Evaporation of the water also cools both the fuel surface and the other gases being distilled. All of these effects tend to slow or inhibit combustion and to lower combustion zone temperature.

Observations of wildland fires and prescribed burns indicate that once a fire is established in a fuel bed, the fire will burn well over a wider range of moisture content when the fuel loading is deep than when it is sparse. This probably results from better conservation of available heat in the deep fuel bed, thereby offsetting the effect of water vapor¹.

Moisture in fuels consist of free moisture and chemically formed moisture. Free moisture may vary several percent depending on the dryness of the fuel. In natural burning processes moisture is chemically formed in the proportion, of 141 g of wood to 81 g of moisture²⁵. During a fire this moisture is vaporized and released to the atmosphere in latent form. As the water vapor rises in the convection column it may eventually condense out in cloud form--the height of cloud depending on ambient temperature and humidity conditions.

Many large fires have been observed with clouds capping the convective column. In fact, from a distance, it may be difficult to distinguish between clouds due to a fire's convective column and natural well-developed cumulus clouds²⁴.

Measurements of water vapor or moisture content within experimental fire convective columns have not been measured according to the literature. This oversight should be corrected in future studies.

Particulates and Gases

Smoke plumes from fires contain a number of different gases as well as particulates. Some of the gases are carbon monoxide, carbon dioxide, oxygen, oxides of nitrogen and hydrocarbons. Results from Project Flambeau showed that gases have a concentration time pattern quite similar to the thermal pulse pattern. For noxious gases, peak concentration occurred early in the fire at about the same time as peak flaming and mass

loss. Then came a long period of low but sometimes significant concentration of hazardous gases.

The oxygen concentrations followed the inverse of this pattern--minimum concentration occurred early in the fire and little oxygen deficiency was apparent in the later stages. Thus, peak concentration of noxious gases, maximum water vapor concentration, maximum oxygen and maximum heat all occurred at about the same time¹.

Large fires produce large quantities of particulates. In a burn conducted to dispose of logging slash in the Pacific Northwest maximum concentrations of particulates were estimated to be $1,980 \mu\text{g m}^{-3}$. In the Air Force Bomb Range Fire in eastern North Carolina it was calculated that the fire produced $1,380 \text{ lb of particulates sec}^{-1}$ (515 Kg sec^{-1}). Average concentrations of the plume was around $4,000 \mu\text{g m}^{-3}$, with visibility in the plume considerably less than 300 m ¹⁶. Course, larger particulates in the form of limbs, pine cones, leaves, needles, etc. eventually fall to the earth if not consumed.

Vortex Motions

Observations from experimental burns, wildland fires and the more violent forest fires and urban fires (mass fires), show that concentrated vortices are rather common fire behavior phenomena. These vortices appear to be associated with three aspects of fires 1) the combustion zone environment, 2) a tilted or leaning smoke plume or convection column, and 3) interaction of a strong convection column with the ambient winds.

Fire vortices (whirls) associated with the immediate fire environment vary greatly in size, strength, and duration. Most fire vortices are small, but occasionally a vortex may reach tornadic proportions causing considerable damage³⁵. Some conditions conducive to fire vortex development appear to be:

- Unstable atmospheric stability conditions
- Large heat source
- Distribution and arrangement of fuel
- Preexisting ambient vorticity
- Multiplicity of convective columns in fire
- Topography (lee side of ridges)

Vortices seem to occur more often under a strongly tilting convective column than a more vertical one. With tilting columns the vortices appear as fire whirls in the fire area, as vortices downwind from the fire and as vortex pendants extending down from the smoke column⁴. The more frequent occurrence of vortices under these conditions may be due to a combination of factors such as, the unstable conditions created by cool ambient air over the warm smoke column, air circulation patterns set up by the column itself, and wake eddies due to the interaction of the fire and smoke column with ambient winds.

Vortex activity may also be produced by the interaction of relatively strong ambient winds with a well-developed convection column. During the Sundance fire in northern Idaho in the early fall of 1967 the principal burning area concentrated in a relatively large deep valley (Pack River Valley) protected by high ridges on both sides. The burning was spontaneous and very intense. The main convection column was protected for several thousand meters and was able to accelerate to a high enough vertical velocity to resist being swept away by 13 to 20 ms⁻¹ prevailing winds at the top of the ridge. The convective column ascended to over 10,700 meters, tipping only slightly and forming a large cumulus congestus cloud. The severe conditions resulted in the fire being called a "moving firestorm"^{14,36}.

Observations of tree blowdown, firebrand activity and strong rotating winds suggested that the rapid spread of the fire was due to moving firebrand-carrying vortex columns which made up Kármán-type vortex streets downwind from the main convection column as shown in Figure 5.

In one of the experimental fires of Project Flambeau fuel arrangement and ignition pattern was designed to explore the relative importance of vorticity in fires³⁰. To minimize the effects of convergence i.e., the intensification of rotation due to the existence of absolute vorticity in the atmosphere, fire patterns were laid out so as to induce rotation opposite in sense to that of cyclonic convergence in the northern hemisphere. The principal results of the experiment were:

- The air flow into the fire was not symmetrical i.e., majority of inflow came from one direction.
- Significant amounts of vorticity were generated by the fire and its burning patterns. The whole fire plot became engulfed by a large fire whirl two hours after ignition.
- Solenoidal term in the vorticity equation is an important contribution to vorticity in fires.
- Most of the air for combustion in this fire came from higher elevations.

ENERGY DISSIPATION FROM COOLING TOWERS AND POWER PARKS

Cooling Tower Plumes

Cooling towers may be classified as wet types where water and air come in direct contact with heat exchangers or dry types where cooling is through indirect contact with heat exchangers. The movement of air for both types may be created either by mechanical draft with fans or by natural draft through a chimney. Since the majority of cooling towers in

FIGURE 5. Illustration of the Pack River Valley Firestorm and the Hypothesized Downwind Kármán Vortex Street Columns (After S. L. Lee)

operation are of the wet type the discussion will be directed toward this type of tower.

Details of the operation of wet cooling towers is reviewed by Woodson³⁷. If wet or evaporative cooling towers are used to dissipate excess heat then about 70-80% of the dissipated heat will be in the form of latent heat, which would be released to the atmosphere only when the water vapor condenses. The other 20%-30% of the dissipated heat is sensible or convective heat, which is immediately available to the environment.

Wet cooling towers emit visible (i.e., condensed or "wet") plumes over a wide range of atmospheric conditions. Past work has shown that plume behavior in general is well-described by a one-dimensional (or "top-hat") theory based on conservation of mass, momentum and energy and employing an entrainment hypothesis to allow for mixing with the environment. The equations governing the behavior of moist plumes in a calm environment were set down by Morton^{29,38} and extended to windy bent-over plume conditions by Csanady³⁹, Wigley and Slawson⁴⁰⁻⁴², EG&G, Inc.⁴³, Hanna⁴⁴, Richards⁴⁵, Weil⁴⁶, Wigley^{47,48}, Taft⁴⁹ and Moore⁵⁰.

The phenomena controlling the vertical growth of wet plumes from cooling towers are different from those controlling the movement of dry plumes, due to the energies involved in evaporation and condensation in the wet plume and the buoyancy accelerations. In wet plumes, the buoyancy forces are produced locally rather than being a function of the initial temperature of the effluent alone. Thus, the dynamics of the wet plume is closely related to that of an isolated cumulus cloud, where condensation warms the core of the plume while evaporation and cooling occur near the edges.

The penetration height of wet tower plumes depend directly on the radius of the tower, the saturation temperature, and the stack velocity. For a given set of tower parameters,

stability influences the penetration height as does the bending over effect of wind and wind shear. A most significant effect in determining the vertical plume dynamics is the entrainment, which is determined by the stack radius and the angular spread of the plume. Environmental relative humidity is important in controlling the evaporative cooling at the plumes edges and hence the rate of depletion of thermal buoyancy. For most cases of light winds ($<3 \text{ m sec}^{-1}$), penetration heights of 300-1400 meters can be obtained but for stable conditions with strong wind, the penetration heights are reduced to a few hundred meters.

In general, the combined plume from mechanical draft towers will have less vertical penetration than would a plume from a single hyperbolic tower having equal volume. The discrete small plumes may merge, but they do so with a large initial increase in entrainment, because of the dry environmental air between individual towers.

Hanna⁴⁴ suggests that for moist plumes in calm or windy conditions that the plume rise can be estimated from Brigg's formulae for dry plumes provided that the possibility of latent heat release is included in the definition of initial buoyancy flux. If condensation does not occur, then the initial buoyancy flux equals the flux due to virtual temperature. If all the initial vapor is expected to condense then the additional latent heat flux should be added to the flux due to temperature differences. This heat may cause the plume to rise during stable conditions from 20 to 100% higher than it would have due to the initial sensible heat flux, for typical cooling tower plumes. If only part of the initial water vapor condenses then it is possible that under certain conditions the moist plume may become convectively unstable even in a stable environment.

Calculations^{42,44} show that the longest visible cooling tower plumes occur in cold, humid, relatively unstable atmospheric conditions or possibly in a warm, humid environment. Small changes in atmospheric temperature and/or relative humidity can cause quite pronounced changes in visible plume length, particularly at low ambient temperatures and high relative humidities. An increase in atmospheric stability or a decrease in moisture with height can lead to much shorter plumes than would be predicted for a constant relative humidity, neutral atmosphere.

Energy Centers

The energy center concept generally involves grouping 10 to 40 power plants and associated cooling towers on a common site. On a smaller scale, a single cluster of 3 to 4 power facilities may be operational in less than 5 years. The waste energy released by power plants may take several forms in the atmosphere; increased temperature of the air (sensible heat), increased moisture content (latent heat), and increased atmospheric kinetic energy (wind). The dissipation of the waste energy from the large energy centers (10^4 to 5×10^4 MW) could result in significant meteorological effects⁵¹⁻⁵⁵.

The intensity of the heat and moisture plume from an energy center will depend on 1) number of cooling towers, 2) heat and moisture ejection rates, 3) the radii of the towers, 4) separation of tower groups, 5) rate of entrainment, and 6) the resultant plume rise. Obviously, as the number of towers increase more heat and moisture is released to the atmosphere. If the towers are very close to each other, the plumes will combine, and if they are far apart, the plumes will rise independently for a longer distance and height.

Hanna and Gifford⁵⁶ suggest that the possibility of cloud formation can be reduced by spacing the cooling towers as far

apart as possible so that their plumes do not merge until they are several kilometers from the site, and have passed beyond the most active stage of buoyant rise. If the sources are spaced at a distance greater than the expected plume rise from one source, merging of plumes during the stage of active plume rise may be avoided.

Briggs⁵⁷ indicates that the resultant rise of a merged thermal plume is a single-source rise times some function of the number of sources and the ratio of spacing between the sources to the single-source rise (this assumes sources of approximately equal magnitude). Briggs has defined an "enhancement factor" as the result of multiple sources which is,

$$E_N = \left(\frac{N+S}{1+S} \right)^{1/3} \quad (5)$$

and

$$S = 6 \left[\frac{(N-1)S}{N^{1/3} \Delta h_1} \right]^{3/2} \quad (6)$$

where N is number of sources, S is the spacing between adjacent sources and Δh_1 is the plume rise from a single source. Briggs suggests that Equation 4 could be conservatively applied to clusters of sources by replacing (N-1)S with the maximum diameter of the cluster. Plume merger would occur at a height

$$z_m \sim 4D/(N)^{1/2} \quad (7)$$

where D is the diameter of a cluster of sources.

FIRE ANALOG HYPOTHESIS

The previous discussion of fires, cooling tower, and energy parks have briefly presented the principal physical characteristics of each system. It is apparent that there are important differences as well as some similarities between the fire system and the cooling tower-energy center system.

If the fire system is to simulate the cooling tower system then modeling theory requires that the two energy systems have geometric, dynamic, thermal (energy) and kinematic similarity. Also, the two energy system's plumes should be affected in the same manner by similar boundary conditions. Figure 6 indicates how the two different energy system's plumes may resemble each other in a qualitative sense during relatively calm wind and windy conditions.

Byram⁵⁸ by use of dimensional analysis has derived a number of important dimensionless groups which for complete similarity should be the same for model (fire) and the full-scale prototype (cooling tower system). These dimensionless groups according to general type of similarity are:

Geometric Similarity

$$\Pi_4 = Z/D \quad \Pi_9 = r/D \quad \Pi_{11} = d/D \quad (8)$$

Dynamic Similarity

$$\begin{aligned} \Pi_1 &= V/(gD)^{1/2} & \Pi_3 &= \Delta t (g/D)^{1/2} & \Pi_5 &= V_i/(gD)^{1/2} \\ \Pi_6 &= u/(gD)^{1/2} & \Pi_7 &= W/(gD)^{1/2} & \Pi_{13} &= v/(gD^3)^{1/2} \end{aligned} \quad (9)$$

FIGURE 6. Qualitative Comparison Between Cooling Tower Plume and Stationary Mass Fire Plume or Convection Column

Thermal and Energy Similarity

$$\Pi_{12} = T_z/T_o \quad \Pi_2 = \frac{I_a}{(gD)^{1/2} \rho_o c_p T_o} \quad (10)$$

Kinematic Similarity

$$\Pi_8 = \dot{w}/g \quad \Pi_{15} = \psi \quad \Pi_{10} = \ell/D \quad (11)$$

Boundary Conditions

Vertical wind profile $V(z)$

Topography $h(x,y,z)$

Atmospheric stability γ

Upper-level boundary H

Other dimensionless variables could be derived from the above set such as the Reynolds number $\Pi'_{13} = \Pi_7/\Pi_{13} = WD/\nu$ based on the central convection column updraft velocity.

Data are insufficient, for both energy systems, to make a complete similarity analysis using the above dimensionless groups but they will be useful in discussing the various qualitative similarities and differences between the fire and cooling tower plumes.

Geometric Similarity

The principal requirement for geometric similarity is that certain length dimensions for both plume systems should be scaled similar. Hence, $\Pi_{11} = d/D$ requires that this ratio for both plume systems should be approximately the same. If the source diameter (D) is the same for both systems then the diameter of the plume (d) should vary with height in the same manner for both plume systems. Since the thermal plumes of both energy systems generally increase in diameter with height this type

of similarity could be satisfied if the ratios Π_4 , Π_9 and Π_{11} are matched for the two energy systems.

Dynamic Similarity

This type of similarity requires that the ratios Π_1 to Π_{13} or Π'_{13} be equal for the two systems. If the source diameter (D) is the same for both systems then this would require the plume inflow and updrafts to be similar for both energy systems. Generally, this is not true. In large mass fires inflow velocities are very unsteady in time varying from 4 ms^{-1} to 30 ms^{-1} . Updrafts in the lower levels of the fire may reach 50 ms^{-1} and higher levels maintain a speed of 3 ms^{-1} or more in rising columns of heated air.

In a cooling tower system the induced near-surface airflow (no wind) may have inflow velocities of about 2 ms^{-1} at a distance of 21 m from the towers⁵⁹. Air movement may not be detected at ground level for distances greater than 150 m from the towers. Updrafts a few hundred meters above the towers may reach 12 ms^{-1} or more but fall off rapidly with height; the decrease depending on stability conditions.

Thermal and Energy Similarity

The dimensionless number $\Pi_{12} = T_z/T_o$ implies that the plume or convection column temperatures should be equal at various heights for both systems. In the lower levels this is obviously not true because a fire is a very intense heat source and does not compare at all to a cooling tower system. Temperatures in a fire's plume decrease rapidly with height and, in the upper-levels, temperature differences (ΔT) between plume and clear air have been measured at about 2°C . However, in large fires the value of ΔT must vary considerably depending on intensity of fire, rate of entrainment, and the presence of heated particulate matter.

A major difference between cooling tower and fire plumes is the presence of heated particulates and noxious gases in the fire plume. One of the significant effects of this difference is that warm particulates may be transported through the fire plume enhancing the buoyancy of the plume. Also, particulates and smoke affect the opacity of the smoke column which can influence the maximum height a plume will rise.

Plumes from both energy systems also contain significant amounts of water vapor (no dimensionless number was derived for this variable). Generally, mixing ratios for both plumes are greater than the surrounding environment. Water vapor associated with both types of plumes can condense to form clouds and intense fires often have cumulus clouds capping a convection column. Clouds may also form over cooling tower plumes.

Some limited field measurements of temperature and moisture distributions associated with a forest-slash burn plume in Idaho and cooling tower's plume in California are shown in Figure 7. The aircraft measurements show that plume temperatures and mixing ratios for both systems are generally higher than ambient readings. Limited sampling of both plumes in the upper-level portions may explain in part why plume temperatures were cooler than the ambient levels.

The dissipated energy from fires consist primarily of sensible ($\sim 37\%$), radiant ($\sim 20\%$), and latent ($\sim 10-40\%$) while the energy from the cooling tower system is divided between sensible (20-30%) and latent (70-80%). One of the quoted similarities between large fires and cooling tower systems is that the rate of atmospheric dissipation of the waste energy is approximately the same⁵⁶. This implies that Π_2 or some equivalent energy dimensionless number should be equal for both systems.

FIGURE 7. Qualitative Comparison of Upper-Level Plume and Ambient Temperatures and Mixing Ratios for Cooling Tower Plume and Forest-Slash Burn Plume/Convection Column

To put energy releases from fires, cooling towers and proposed energy parks in perspective a number of known fire energy release rates and areas were plotted in respect to energy release rates from cooling towers, proposed energy centers and other geophysical phenomena in Figure 8^{55,60}. Figure 8 shows a number of interesting points. First, that the fire energy release rates and areas vary over a wide spectrum of values. Second, that "mass fires" have energy releases larger than single or double cooling towers. This may help explain why single or even small groups of cooling towers only perturb the atmosphere to a small extent. The French Meteotron experiment appears to be near the same energy and area range as single or double cooling towers. The fact that the Meteotron experiment generated concentrated vortices and cooling towers do not must be related to the physical difference between a fire and cooling tower and how the fire plume interacts with ambient winds. Third, the energy release rate of proposed energy centers approximate that of some mass fires but the energy flux (energy per unit area) appears to be somewhat less than these fires.

On the basis of Figure 8 one can generally conclude that the atmospheric dissipation of energy from "mass" fires is usually larger than dissipation of energy from single or small groups of cooling towers but about the same for energy parks. However, the energy per unit area for mass fires is generally larger than for proposed energy parks.

Kinematic Similarity

This type of similarity requires that the mean and turbulent flow fields of the two energy systems should resemble each other. Airflow accelerations in the vertical (w), streamline patterns (ψ), and scales of turbulence (ℓ) should be similar. Adequate quantitative data are lacking to make

- FM - FRENCH 'METEOTRON'
- MF - MINIMUM CRITERIA FOR MASS FIRE
- TF - TUMUT EXPLORATORY MASS FIRE
- PE - PROJECT EUROKA
- PF - PROJECT FLAMBEAU (FIRE 460-7)
- PR - PACK RIVER FIRE STORM (SUNDANCE FIRE)
- SF - SUNDANCE FIRE (TOTAL AREA)
- BF - BUCKHEAD FIRE
- HF - HAMBURG FIRESTORM
- EC - 40,000 MWe POWER PARK ON 1 KM² AREA

FIGURE 8. A Qualitative Representation of Power Dissipated by Various Fire Systems and Natural and Anthropogenic Activities as a Function of Their Scale Size

such comparisons. However, it is known that some turbulent features of fires have not been duplicated by cooling tower systems to date.

One of these phenomena is the nature of the fire environment to generate concentrated vortices. These vortices are associated with the immediate fire area as well as with bent-over plumes or columns. The available literature on environmental effects of cooling tower systems do not record any case where concentrated vortices have been associated with cooling tower plumes even though some 50 years or more of operational experience with cooling towers have taken place throughout the world.

It has been speculated that a plume from an energy center could lead to the development of vortices. This is postulated to happen by two mechanisms. First, by multiple cooling tower plumes merging rapidly into a large concentrated plume and interacting with ambient winds to cause wake vortices. Second, by the ascending cooling tower plume condensing into cumulus clouds, developing to cumulonimbus stage and possibly generating vortices, such as, tornadoes.

Boundary Conditions

The ambient vertical-wind profile can have a significant influence on the type and intensity of fire²³. Although strong convection over a fire is favored by low wind speeds both at the surface and aloft, the energy criterion (Equation 4) shows that the rate of heat output, or fire intensity, is equally important. For a stationary fire to develop a convection column, the only restriction on the wind profile is determined by the condition that P_f must exceed P_w for some 1000 meters above the fire.

Ordinarily, the wind speed increases with height so that P_w increases very rapidly with height. For fires spreading before a strong wind P_w will exceed P_f and may tend to limit the ultimate intensity. These fires are dominated by the energy of the wind and form smoke plumes rather than dynamic convection columns.

A moving fire, in order to survive, must continuously travel into new fuel to maintain its energy output. For a moving fire to build up a high intensity (mass fire) and establish a vertical structure then P_f must exceed P_w at the higher levels. The vertical wind profiles that meets these requirements are shown in Figure 9. Generally, a wind speed maximum is located at or slightly above the elevation of the fire with a zone of decreasing wind speed just above the maximum speed. This type of vertical wind profile permits a low-intensity forced-convection fire to overcome the wind-field barrier and convert to a free-convection fire of much higher intensity.

Plumes from cooling tower systems are generally dominated by the ambient wind and turbulence. Possibly, P_f will normally exceed P_w during light wind conditions. Strong winds and turbulence have a tendency to entrain ambient air into plumes causing the plume to dissipate especially if the air is not humid. Thus, cooling tower plumes are usually wind dominated while in the case of fires the wind profile may actually assist in transforming a fire plume into a strong convection column.

Large fires often occur in mountainous terrain where topography can have a direct and indirect effect on fire behavior. Fires spread more rapidly upslope than on level ground because fuels upslope from the fire are exposed to greater heating from radiation and convection and because upslope winds are generated by the fire of natural heating³³.

FIGURE 9. Six Types of Wind Profiles That Have Potential for Causing Fires to Transform From Forced-Convective Systems to Free-Convection Systems (Byram 1954)

Topography affects fire behavior directly through its effects on local weather and microclimate. Channeling of wind-flow by topography is an important indirect effect of topography on fire behavior. In addition, topography may effect the generation of fire vortices in and near the fire environment³³. As the result of these topographic effects and others it is unlikely that a large fire in rugged terrain would serve as an adequate model for a cooling tower system.

Atmospheric stability affects fire plumes in a like manner to cooling tower plumes. Under unstable lapse rates, vertical motions will be accelerated in both plumes. Stable lapse rates will suppress the vertical development of the plumes and elevated stable layers will limit the vertical growth of both plumes.

CONCLUSIONS

Fires with their associated smoke plumes or convective columns exist on a wide range of intensities depending on burning rate of fuel, size of fire, meteorological conditions and other factors. The energy release or power of larger fires varies from 10^2 MW to 10^7 MW with a energy flux between 10^{-3} and 1 MW m^{-2} . The power from single to groups of cooling towers varies from 10^3 MW to 5×10^4 MW with a energy flux between 5×10^{-4} and 1 MW/m^2 . Since fires have such a wide spectrum of energy releases and areas it's possible that a fire could be matched up to some cooling tower grouping--energy wise. However, energy release does not always delineate the physical differences between the energy release systems. This is the weakest aspect of a fire analog concept.

There are important physical differences between cooling tower waste heat plumes and the larger fire plumes. Fires, depending on burning rates and other conditions, are a transient phenomena that can go through a transformation in fire behavior

from non-violent to violent. This transformation generates strong inflow winds and updrafts; turbulence, concentrated vortices, convective columns and large quantities of smoke and particulates. These characteristics are not observed with cooling towers or groups of cooling towers--at least to date.

Cooling tower plumes are generally dominated by the ambient conditions of wind, turbulence and stability. Fires--mass fires--can generate intense convective columns which may or may not be dominated by ambient conditions. For intense convective columns, interactions with ambient wind conditions may create significant downwind effects such as, wakes and concentrated vortices.

Some initial estimates on large energy releases from proposed energy centers indicates that the addition of the energy to the atmosphere could result in increased cloudiness and fog, changed precipitation patterns, decreased daytime and increased nighttime temperatures, early initiations of convective clouds, and increased frequency of hail, lightning and convective vortices. Much of this impact is due to the anticipated large releases of water vapor to the atmosphere⁵⁵.

Whether a energy center thermal plume could become so concentrated as to resemble a fire's convective column depends on several factors. It's been speculated that this might happen if an energy center was located on a small area around 10^6 meters. According to Figure 8, this may be possible if only the energy flux (MWm^{-2}) is considered since for a energy center with a energy flux of about 10^{-2} MWm^{-2} would place it more in the range of mass fires. However, it is still questionable whether an energy center plume would be as concentrated as a convective column from a mass fire. Further research is needed on this aspect.

The French Meteotron fire experiments and some of the small controlled mass fire burns appear to exhibit similar general thermal and dynamic characteristics as compared to single or small groups of cooling towers. Since obtaining data from large mass fires is expensive and dangerous, a research project on collecting data from smaller control fires may still provide important information on thermal plumes. Upper-level data on temperature, humidity, turbulence and vertical motion appear to be lacking from past projects and this type of data is what is needed to understand the nature of thermal plumes better. Recommendations for a research program is briefly outlined in the next section.

RECOMMENDATIONS

The survey of fire literature as well as the information on cooling towers show that upper-level data for fire and cooling tower plumes are difficult to obtain and the present data are not adequate for making valid comparisons or correlations between the two physical systems.

Upper-level data for adventitious fire plumes or convection columns are quite difficult to obtain and can be dangerous. Damage to the aircraft, equipment and occupants is possible in traversing a strong convection column. In addition, many large fires occur in hilly or mountainous terrain which limits the capability of the aircraft.

Some possible experiments which could achieve some of the objectives of obtaining upper-level data for fire plumes could be the following:

- 1) A large stubble field is burned during light but steady wind conditions so that the energy release rate is sufficient to develop a plume of considerable height. Aircraft penetrations of the plume should be possible and data on temperature, water vapor, turbulence and

other wind parameters could be obtained from high response instruments. Several levels of the smoke plume could be penetrated so a composite of the upper-conditions within and outside the plume could be obtained. At least five good flights should provide sufficient data for valid comparisons with similar data taken from cooling towers.

- 2) Another possible experimental situation would be a small controlled burn using forest slash as fuel or a simulated French "Meteotron" experiment in which fuel oil is burned to create a convective plume. However, these last two experimental set-ups would require extensive planning and expenses.

In addition to the field experiments additional numerical work on cooling tower and fire plumes could provide important data for further comparisons.

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