A QUALITATIVE STUDY OF RECIRCULATION IN COOLING TOWERS

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1958

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Date thesis is presented May 3, 1958

Typed by Jane J. Bower

ACKNOWLEDGMENT

The author wishes to express his particular appreciation for the advice and patient assistance received from Associate Professor Wesley W. Smith of the Department of Mechanical Engineering. He also wishes to thank the other members of the mechanical engineering department for their support, the Fluor Products Company for their generous contribution, and Stuart A. Krieg for his continuous aid.

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INTRODUCTION

Cooling towers are a common sight in many parts of the world where the reuse of water for commercial processes is an economic necessity. Basically, a cooling tower is a device for the cooling of water by direct contact with the atmosphere. Obviously one would expect a reduction in the cooling potential of the air after it passes through the tower. The factors that influence the recirculation of this air is the subject to be investigated in this study.

In general, water shortage has nothing to do with drought but can be attributed to overpopulation in cities and increased industrial and agricultural requirements. The requirements of the United States are 100 billion gallons (15, vol.73, p.1031) per day for everything from drinking and irrigation to making steel and watering the lawn; that is 700 gallons per day per person. This sum is more than double what it was a decade ago and may be anticipated to increase at an even greater rate in the future.

The manufacturing industries are huge consumers of water. Some industries require up to 2500 pounds of water per pound of finished product. One of the most effective conservation measures available to these industries is the reuse of cooling water. Therefore, the most effective and hence economical water cooling method becomes more important as power demands increase and industries expand their water usage.

During the past forty years the progressive improvement of methods for cooling and subsequent reuse of water have been utilized in the following sequence: (1) Rivers, lakes, wells and cooling ponds; (2) spray ponds; (3) evaporative condensers; (4) natural-draft cooling towers; (5) forced-draft cooling towers; and (6) induced-draft cooling towers.

Prior to 1920, large water-cooling systems were used only with steam-electric generating stations, usually located on the banks of rivers, lakes, or artificial cooling ponds. In some installations it was expedient to use spray ponds. Refrigeration and ice making constituted the second largest usage, with roof-located natural draft towers and spray ponds.

Since the year 1920, numerous new applications have arisen, others grown; and, with this shift, requirements have become increasingly varied and exacting, necessitating refinements and specialized adaptations of water-cooling equipment. The principal demand for large water-cooling systems in recent years has been from the petroleum industries, steam power plants, process industries, and chemical plants. Refrigeration, air conditioning, and engine-jacket cooling employ a large percentage of the medium-sized and small cooling units installed today.

Progress in the cooling-equipment industry is apparent when it is realized that for a definite need, a modern cooling tower requires only one square foot of ground area as compared to fifty square feet for the spray pond and about one thousand square feet for a natural cooling lake or pond. The modern cooling tower is the result of a continuous search for a more compact design, better construction, lower cost, larger capacity, greater flexibility of operation, independence from atmospheric uncertainties, and improved all-around performance.

The development of cooling towers has evolved from the first crude designs to the currently favored, induced-draft towers. Natural draft towers, though still in use, are unattractive because of their high capital cost, dependency on atmospheric conditions, and because industrial plant economics often demand a close approach to the atmospheric wet-bulb temperature. The early mechanical draft towers were of the forced air variety. Perhaps the principal disadvantages of forced draft arrangement of blowing air in at the base of the tower were the uneven air distribution through the packing and the tendency of recirculation of the warm exit air back into the down-wind fans.

A "conventional" induced-draft cooling tower is an enclosed structure for the evaporative cooling of water by contact with the air, consisting of one or more individual adjacent cells, each with its own induced-air-circulation fan, gear and motor drive mounted on top of the tower structure. Generally, wood filling is used to provide wetted cooling surface and water break-up. In many cases, a combination of the spray-filled and wood-filled design is used.

Water, when cooled by the evaporative effect in a cooling tower, transfers to the air about 1000 Btu per pound of water evaporated. In other words, 100 pounds of water can be cooled ten degrees Fahrenheit by the evaporation of one pound of water. Air, absorbing heat from water in this manner, is capable of cooling water below the atmospheric (dry-bulb) temperature.

Theoretically, water may be cooled by the evaporative method until its temperature is lowered to the air's wet-bulb temperature (1, p.793). In practice, however, water is cooled to a temperature approaching the wet-bulb; the closer this "approach" the larger the size of the cooling equipment required for a given duty. Generally, the wet-bulb temperatures used for design are seventy to eighty degrees Fahrenheit, depending upon the service and geographical location of the unit.

"Cooling range" is the number of degrees Fahrenheit that the water is cooled with water cooling equipment. It is the difference between the temperature of the hot water coming to the cooling tower and the temperature of the cold water leaving the tower. It is the cold water temperature supplied by the cooling tower to the plant which determines plant efficiency and plant economy. And this cold water temperature is established by the selected approach to the wet-bulb temperature. It is, therefore, necessary to examine closely this wet-bulb temperature.

It should be apparent that the heat rejected by the water must equal the heat absorbed by the air passing through the tower. The rate of heat transfer to the air depends primarily upon the enthalpy of the air, the latter being essentially dependent on the wet-bulb temperature of the air. This explains the common observation that cooling tower performance is independent of inlet dry-bulb temperature, and that adiabatic conditions exist.

Selection of the most applicable wet-bulb temperature to use in the tower design is about the most difficult decision to make (10,p.5-7).

The temperature level at which heat from a process can be rejected into the atmosphere depends on the prevailing wet-bulb temperature, and the wet-bulb temperature is seldom constant. It is in almost continuous fluctuation during the day and during every day of the year. As soon as a plant is built which requires various discharges of heat or steam into the atmosphere or when the buildings hinder the natural flow of air, even the normal fluctuations are altered. And to further complicate the correct wet-bulb choice is the phenomenon known as recirculation.

Recirculation can be defined as an adulteration of the atmosphere entering the tower by a portion of the atmosphere leaving the tower, thereby increasing the enthalpy of the entering mixture. It follows that the recirculated portion can contribute little or nothing to the cooling process. The heat exchange is then entirely restricted to the ambient atmosphere flowing through the equipment and the performance can be seriously curtailed (9, vol.73, p.1037-1039). To illustrate how serious recirculation can be, consider a cooling tower designed to cool water from 100 degrees Fahrenheit to 80 degrees Fahrenheit with a design wet-bulb temperature of 78 degrees. Only 10.5 per cent recirculation would make it impossible to meet the design water cooling specifications because a tower of infinite size would be required.

Recirculation is caused by air currents existing around the equipment, so that portions of the exhaust atmosphere tend to flow toward points of low pressure, represented by the air entrances of the equipment located in the opposite direction to the prevailing wind.

Only if the mass of atmosphere surrounding the equipment were immobile would a cooling tower discharge the exhaust atmosphere of lower density straight upward where its heat would be dissipated into the ambient atmosphere. However, more or less strong winds are always present.

In addition to the discharge by the tower causing disturbances and air currents, the horizontal movement of air due to prevailing winds may tend to cause the exhaust portions to reenter the tower. Whether recirculation occurs, and to what degree, will depend upon the design and size of the equipment and its location in relation to its surroundings. The effect of the latter factor is determined by the prevailing winds, nearby structures that can reflect the exhaust atmosphere back into the tower, and to other less definable influences. The consideration of the prevailing winds in relation to the tower and its surroundings will be investigated in this thesis.

According to experts in the cooling tower field such as Joseph Lichtenstein and W. M. Larinoff, there has been a lot of comment among users and manufacturers about recirculation, but very little information has been published. Most of the information that has been published concerns investigations that have been undertaken in the field for specific types of towers or geographical locations. Mr. L. G. Smith and G. J. Williamson recently combined field and wind tunnel tests to discover patentable design changes for new towers which incorporate baffles underneath the packing that allow controlled air flow through the tower to the downwind side to decrease the likelihood of recirculation (17, vol.170, p.1209-1210).

It is the purpose of this study to investigate the geometric considerations in relation to variable prevailing winds that influence the tendency towards recirculation.

EXPERIMENTAL LOW VELOCITY WIND TUNNEL

Theoretical Considerations

Two techniques have been employed in the last few years to study dispersion patterns and air currents around buildings. One method is to use smoke grenades or smoke generators in conjunction with the full-scale building. The main advantages of the full-scale approach is that observations can be made under many types of actual weather and turbulence conditions which cannot be reproduced in the wind tunnel. The main disadvantages are that the buildings of the type in question must be accessible, that the results will be accurate for the local conditions only, that in most field studies of this type the smoke source is a point in space, hence the plume has no initial velocity, and finally, and likely the biggest deterrent, is that a great deal of time might elapse before the desired wind conditions can be observed (4, vol.2, p.109).

To overcome or at least reduce the obstacles of full-scale building testing, low speed wind tunnels and models have been used. The plume path of smoke about small models may be observed or photographed as it is affected by numerous variables such as the wind direction or the turbulent eddies caused by the geometry of adjacent buildings or other structures. In some instances the tunnel is designed to simulate certain specific conditions, but the more common practice is to design the tunnel to be as flexible as possible. By means of static screens, temporary obstructions or heated surfaces, most geographical or geometrical situations can be closely approximated.

For this study of cooling towers, a flexible, low velocity wind tunnel was required. The preliminary design conditions were investigated in literature and by correspondence with institutions using similar tunnels and experimental techniques. The provisions most appropriate in view of the anticipated use of this tunnel were incorporated in its design. The prime considerations were controlled air flow of acceptable velocity and gradient, and adequate size to facilitate model manipulation and photography.

In expressing the design criteria it is impossible to divorce one consideration from another because of the inter-related effects. If the size is first considered, the influencing factors, besides the physical limitation of available space for construction or desired uses, were the velocity gradient and constriction of the air stream. The latter factor dictated that the cross-section of the tunnel be large in comparison to the models used. By using relatively small models, the effects of the constriction upon the velocity would be negligible.

Simulation of any desired velocity distribution in the flow approaching a model can be attained by the use of successive upstream screens of the proper height and mesh (5, vol.74, p.221-228). However, the natural winds to be expected under actual operation are by no means steady. The mean flow is accompanied by gusts of a magnitude which is predictable only statistically and even then for a limited geographical area alone. Wind tunnel tests, therefore, are usually conducted in an air stream of constant velocity corresponding to the nominal meteorological value.

Since the basic problem involved in this study is the behavior of air patterns as the air passes over and around a structural form--in this case a model cooling tower, it must be determined that these patterns are of the same type that are found around full-size cooling towers. These patterns are formed by the pressure and velocity distribution about test forms in accordance with the elementary pressure-velocity relationship,

$$p - p_o = \frac{\rho V_o^2}{2} - \frac{\rho V^2}{2}$$

Evidently, as the velocity V increases above its initial value V_o, the pressure p decreases, and vice versa in proportion to the density ρ and the square of the velocity.

Just as the velocity variation depends on the pressure distribution which the body produces, the velocity variation in turn is related to the pattern of the surrounding flow. Thus according to the continuity principle, the velocity will decrease where the stream lines are caused to diverge and increase where the stream lines are caused to converge. This flow pattern, finally is controlled by three independent groups of factors: the geometric dimensions of the body, the kinematic characteristics of the undisturbed flow, and dynamic properties of the fluid (3, p.2-3). Thus, the body and its orientation can be fully described by a series of linear dimensions and one or more angles, the oncoming flow by the distribution of velocity, and the fluid by its density ρ and viscosity μ. These factors may be grouped together dimensionalessly for purposes of generalization. The relative proportions of the body may be represented by a series of geometric ratios (such as length to height L/H, width to height W/H). The ratio of the accelerative characteristics to the viscous characteristics of the flow takes the form of the Reynolds number where $R = \rho V_0 H/\mu$.

Construction of a model to any given scale to attain geometrical similarity involves little difficulty, particularly if it is the effect of the overall proportions which is to be studied rather than that of the small details. Complete dynamic similarity between model and prototype is considerably more difficult to attain, because--if the same fluid is used at the same condition as it affects the prototype--constancy of the Reynolds number requires a change in velocity which is inversely proportional to the change in linear scale. In studying industrial sized cooling towers the model would have to be reduced in scale at least sixty-fold to be accommodated in a reasonably sized wind tunnel without constriction effects, and since winds of at least twenty miles per hour would have to be examined, this would require a model air speed of at least twelve hundred miles per hour. Not only is such a value greater than Mach number 1.0 at test conditions, but rough computation will show that a mean air speed even as low as two hundred and fifty miles per hour can result in appreciable effects of compressibility. The possibility of conducting tests in a water channel would have the advantage of a tenfold decrease in velocity as compared with tests in air, but such water speeds (with comparable cross sectional dimensions) are practically out of the question.

To compensate for this apparent dilemma is the fortunate circumstance that duplication of the prototype Reynolds number is not directly necessary unless the body under study is well streamlined, since only then (for the velocity range in question) do viscous influences generally govern the flow pattern (3, p.3-4). The extent to which the Reynolds criterion of similarity can be disregarded thus depends largely upon the extent to which the body to be tested departs from the streamlined ideal. A cooling tower could hardly be less streamlined.

A review of pertinent literature on this subject generally concedes that this type of test is one the most completely free of Reynolds number effects. Initial testing under this presumption in the case of the Empire State Building and the Rock of Gibraltar were subsequently verified by actual measurements (12, p.557-558). Most buildings are so angular that the flow patterns around them are quite independent of viscous influence (assuming the velocity distribution of the approaching flow to be the same) and it was found that dynamic similarity between model and prototype will be attained at velocities even well below that which is being simulated.

Since the dynamic similarity is established by the inherent shape of the structure to be tested and the geometric similarity is an arbitrary scale ratio based on the prototype and tunnel size, the essentially uniform distribution of the approaching flow must be assured in the tunnel construction. The air was introduced directly to the tunnel through an entrance bell in this case because the entire assembly was in a closed room of negligible wind currents. If outside air were used a stilling chamber would be required to diminish external currents. It has been proven that the shape of the entrance bell is not critical. In general, the entrance bell should be approximately a large throat dimension long and flared very gradually at the downstream end so that the flow has time to even out (13, p.60-61). The upstream end of the bell may contract abruptly, but pressure rises rapid enough to cause separation should be avoided. For the best tunnel the recommended value of a bell radius equal to 1.54 times the vertical dimension of the tunnel was used. This experimental value was used to make the smoothest entrance along the base since the testing would be near the floor of the tunnel and placed well away from the sides. To further reduce turbulence of the incoming air, a honeycomb was placed at the small end of the bell at the immediate start of the rectangular section of the tunnel. Honeycombs have been proved to reduce turbulence to a remarkable degree. They are most effective when the subdivisions are five to ten times as long as they are wide (14, p.5) (13, p.60). The plastic grids used in the test tunnel conformed to this specification.

Tunnel Description

Before construction of the full size tunnel was attempted, a cardboard model was built on a scale of five to one. One entire side was made transparent to allow unrestricted observation. The power was provided by an eight inch electric fan and cigarette smoke was used for air flow indication.

The points of interest to be investigated were the effect of the entrance bell on the air flow, the use of a honeycomb air straightener, and the type of shutters necessary for quantity control of the flow. From this preliminary study the following conclusions were indicated:

1. The air flow was less turbulent when the entrance bell was used.
2. The turbulence was further decreased by the addition of a honeycomb air straightener.
3. The smoothest air flow occurred near the upstream end of the tunnel. This indicated the probable location of the test section in the first one-third of the tunnel length.
4. Both the blade action of the fan and the obstruction caused by the shutters tended to increase the turbulence in the downstream end of the tunnel. This turbulence appeared to increase gradually in the downstream end of the tunnel. Changing the types of shutters failed to indicate a change of air flow patterns.

Using the information provided by the model tunnel, components and dimensions were determined. Available equipment and material dictated a rectangular cross section as deemed feasible in the model. A relatively large cross sectional area of four feet by eight feet was selected to allow the test models to be of good size. Results of similar testing at the Texas Engineering Experiment Station and the Iowa Institute of Hydraulic Research indicated the frontal area of the models should not exceed five per cent of the cross sectional area to avoid constriction effects. Although the anticipated size of the models for this project would not be over one per cent of the cross sectional area, it was deemed advisable to make it large enough to accommodate any reasonably sized experiments that might be carried on in the future.

The entrance bell was constructed first. Supporting ribs were cut from three-quarter inch plywood with a seventy-four inch radius. Points were projected onto four by eight foot sheets of one-quarter inch plywood to conform with the correct curve. The plywood sections were then nailed to the ribs. Each side of the bell was built separately and joined with nails and glue as shown in figure 1.

It was necessary to put the floor of the tunnel thirty inches from the room's floor to allow the bell to extend an adequate length. A three inch space between the lip of the bell and the room's floor was left to provide air entrance around its entire periphery.

Framing for the rectangular section of the tunnel was built of two by four inch lumber. Four by eight foot plywood sheets, butted closely, were nailed to the framing to conform with the design cross sectional area. From the cardboard model tunnel it was anticipated the test section would be in the first twelve feet of the rectangular section so the flooring in this length was reinforced enough to be walked upon. An enclosed control room of four by eight foot dimensions was attached to the tunnel four feet from the small end of the bell. To allow easy access for equipment assembly, a trap door four feet wide and thirty-seven inches deep was cut in the tunnel floor and side at the center of the control room. A four foot opening on the tunnel side

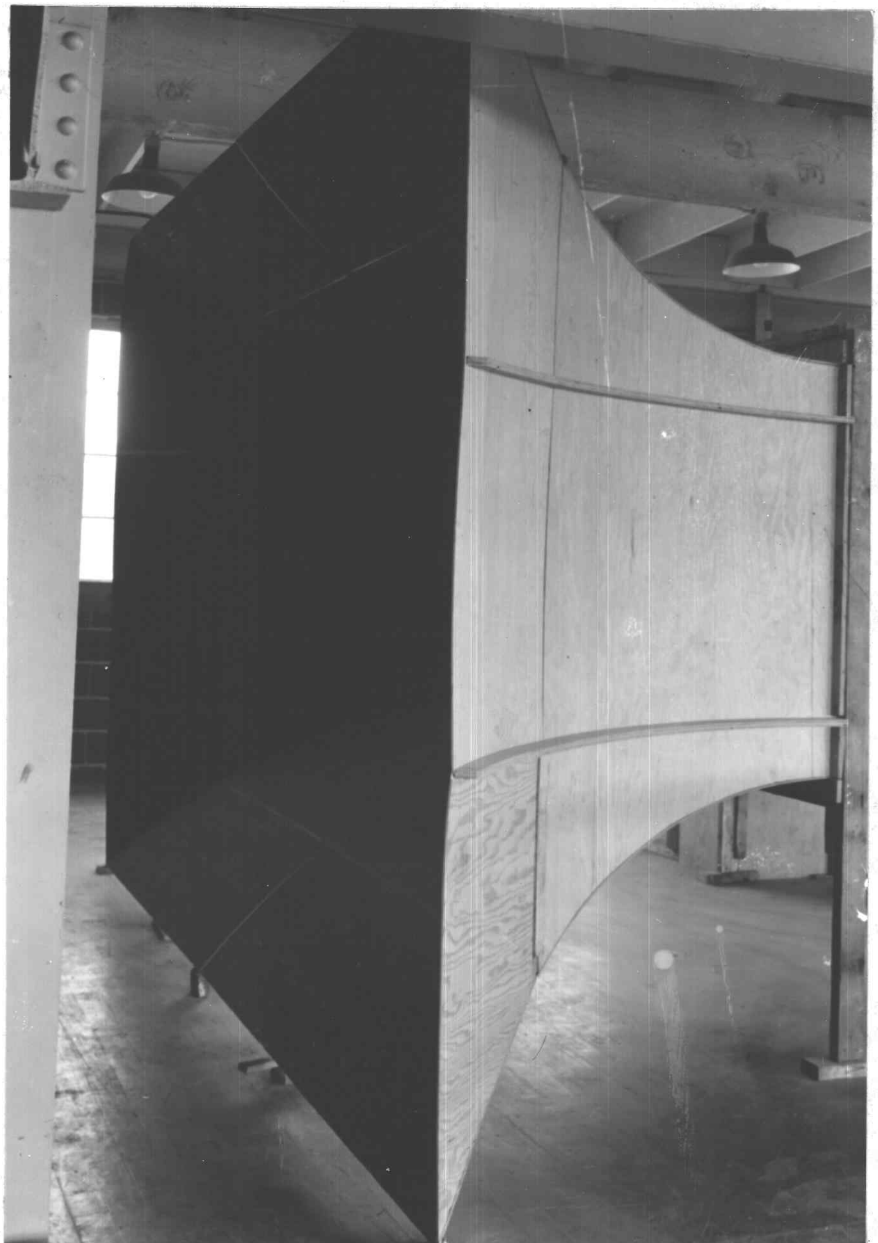

Figure 1. Wind Tunnel Entrance Bell

faced the control room for photographic purposes. This type of arrangement as shown in figure 2 worked successfully in the Texas Engineering Experiment Station tunnel.

The rectangular section continued twelve feet past the end of the control room to the fan assembly. Immediately preceding the fan, vertical steel shutters were installed to control the quantity of air flow.

The fan assembly immediately followed the shutters in an enlarged section as shown in figure 3. An eight foot, four-bladed fan was mounted in the center of the section. It was realized that this size fan would provide considerably more air moving potential than the anticipated velocities required, but again the future uses of the tunnel were considered where larger velocities might be needed. The pedestal for the fan was made of well braced four by four and four by eight inch lumber. It was secured to the floor independent of the tunnel section to decrease vibrations.

Power for the fan was provided by a five horsepower, three phase electric motor. The motor speed was 1800 RPM and the transmission ratio, through a double set of V belts, was 6.5 to 1.

When all the basic construction was completed, the inside joints were taped and the tunnel was spray-painted with flat black paint to provide a suitable background for photographs. A photo-flood lamp was installed in the roof of the test section and electrical connections were put in the control room.

The last component to be installed was the air-straighteners. Two by four foot Fluor cooling tower plastic grid packings joined together

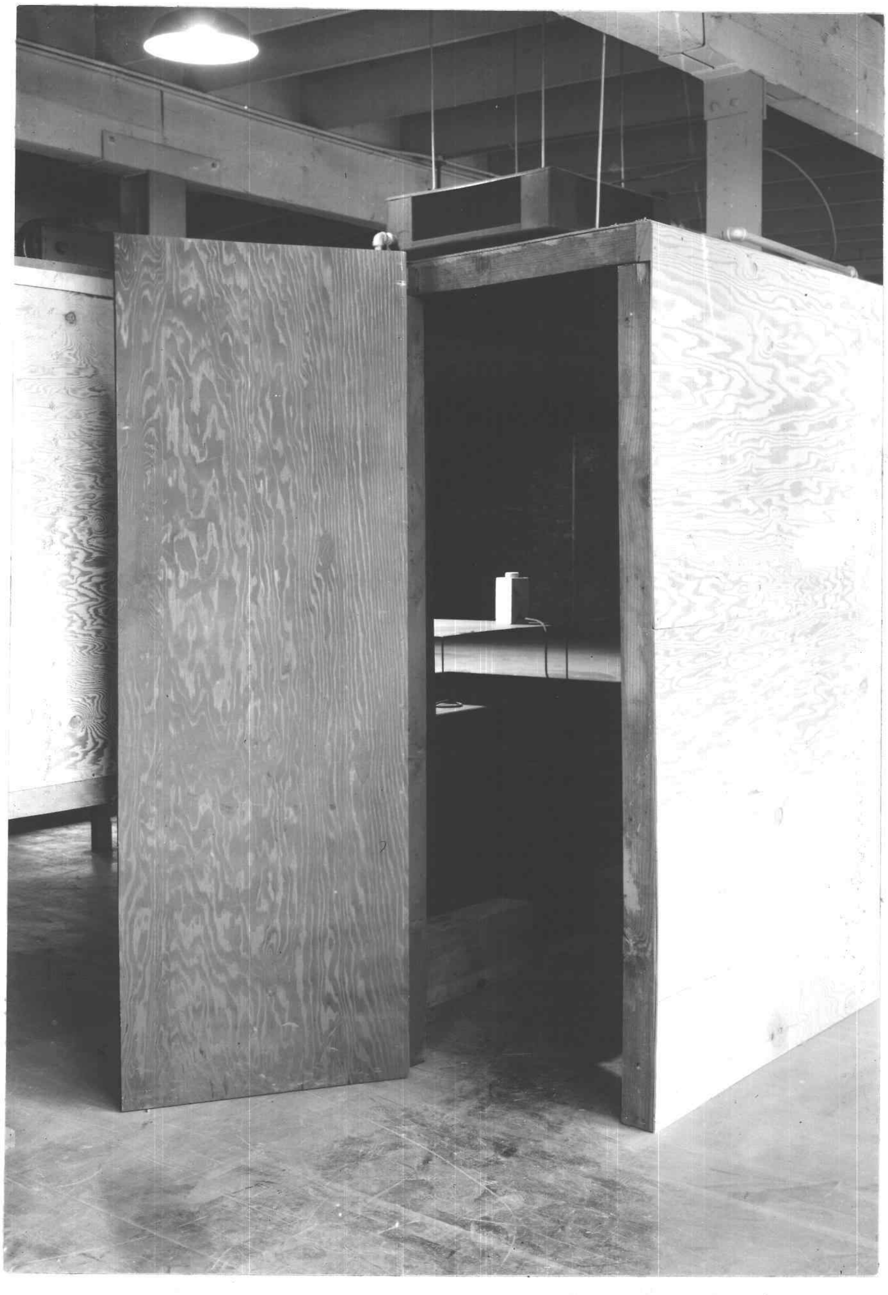

Figure 2. Wind Tunnel Control Room

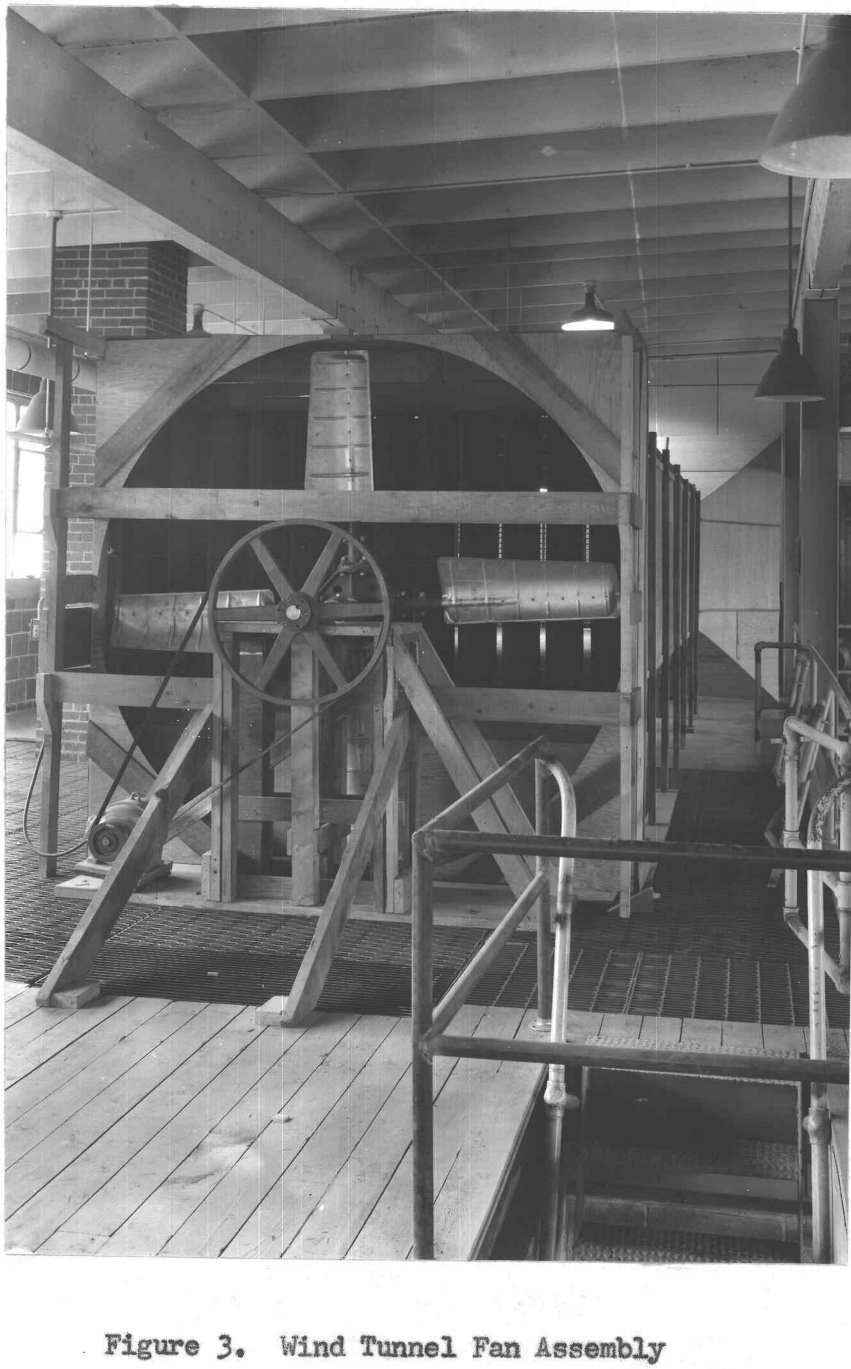

Figure 3. Wind Tunnel Fan Assembly

to form a solid bank seven and a half inches thick across the front of the tunnel directly behind the end of the entrance bell. The location of the components and overall dimensions of the tunnel are shown in figure 4.

Tests were then conducted to see if the desired velocity gradient could be obtained. Smoke tufts were first used to locate the most advantageous test section. The locality was defined within narrow limits by observation of the behavior of the smoke streams. At varied openings of the shutters a stop-watch was used in conjunction with the smoke to determine the approximate air velocity at various sections of the tunnel. The preliminary results indicated the test section should be in the area previously expected and the attainable velocity easily exceeded the velocities needed for this study.

To obtain precise measurements of the velocity gradient of the small area to be actually used for the models, a calibrated Anemotherm air velocity meter was used. At the maximum velocity to be used (15 miles per hour) the gradient varied the most but was still less than six per cent. At ten miles per hour the gradient was about four per cent, that is, the velocities at any point within the two foot cube where tests would be made, did not vary more than four per cent. The variance at five miles per hour was slightly less than four per cent. These results were most gratifying since the variance was within the limits established for similar investigations and was less than could be expected from natural prevailing winds. The velocity gradient curves for the most used velocity of ten miles per hour are shown in figure 5.

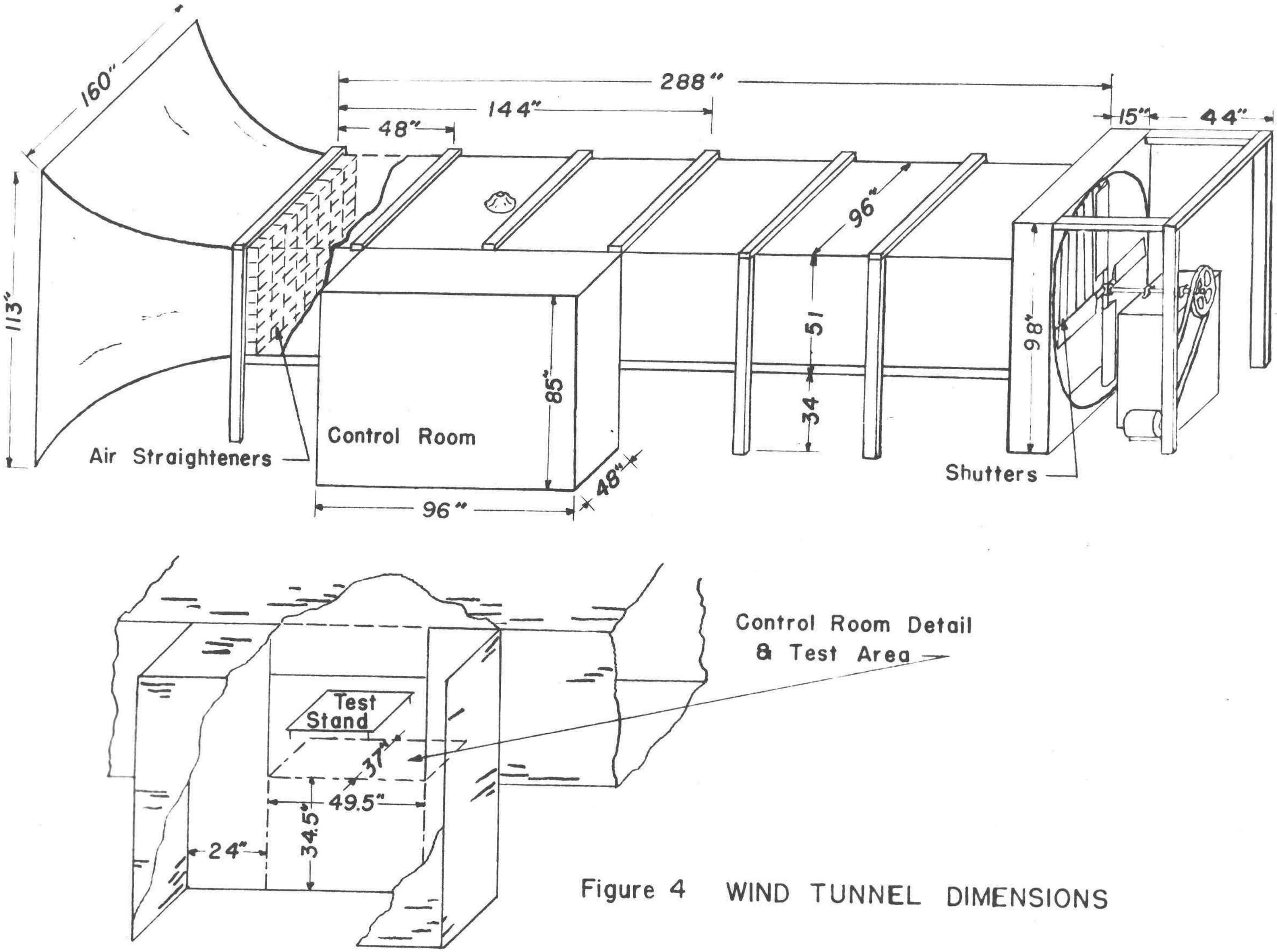

Figure 4 WIND TUNNEL DIMENSIONS

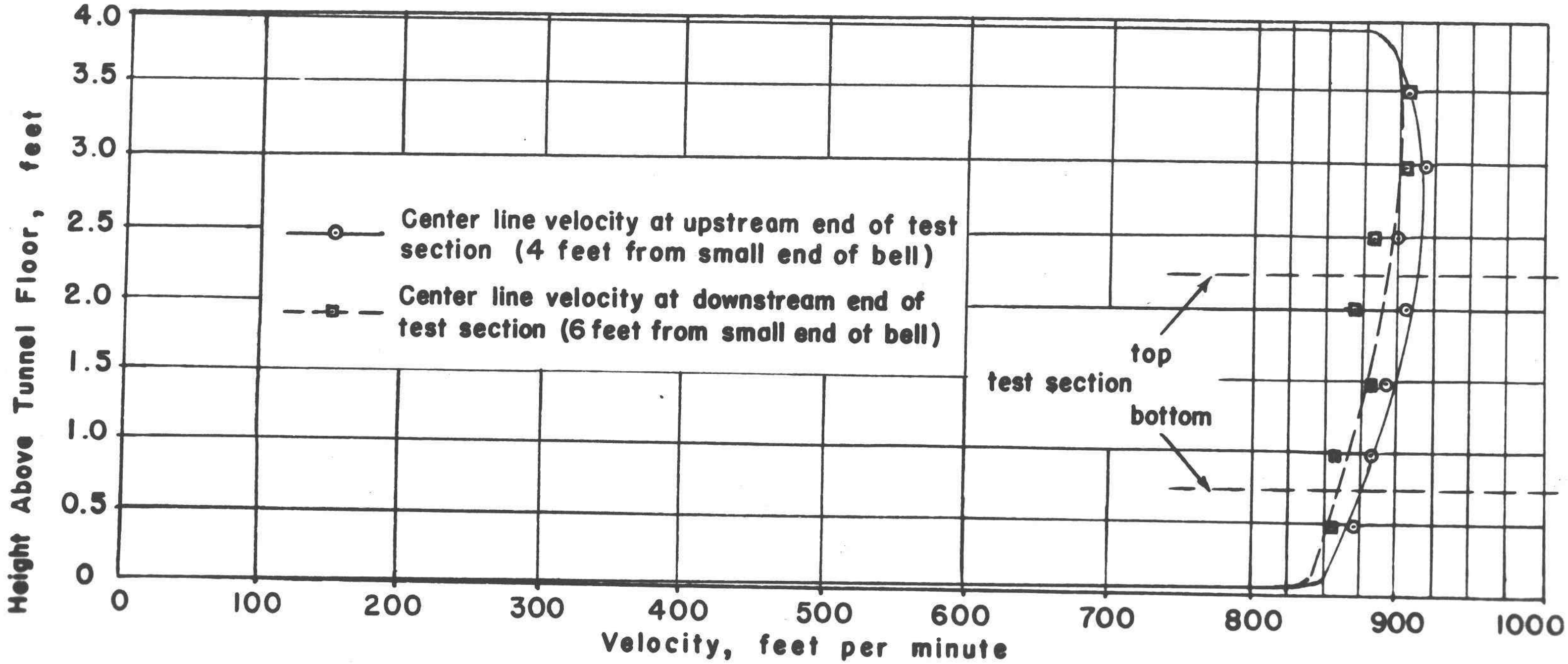

Figure 5 VELOCITY GRADIENT CURVES AT 10 MILES PER HOUR

SMOKE STUDY EXPERIMENTS

Equipment Description

Investigations involving the use of smoke for studying flow around obstructions have long been of recognized value. Flow visualizations of this type have been used to give rough approximations of design adequacies and to make more detailed studies where intricate high speed camera apparatus record the data.

Several different materials have been used as the smoke source. The researchers of the Collins Aeronautical Research Laboratory, which have done some outstanding work in the field of flow visualization for aircraft studies, have used the combustion of rotted wood but prefer evaporation of oil into a fine oil mist for their studies. A more common method is the use of chemical smoke where investigations are not as elaborate or at such high velocities as those of the aeronautical studies (11, vol.17, p.24-27).

For this investigation two types of chemical smoke were used. Ammonium hydroxide vapors bubbled through concentrated hydrochloric acid produced a dense, easily handled smoke that was used the most extensively. For particular cases titanium tetrachloride was used. The fumes from the latter produced adequately dense smoke for photography but could not be directed as easily as the former.

The equipment for smoke introduction may be seen in figure 6. In the foreground of the figure are the tube connected flasks which held the ammonium hydroxide and hydrochloric acid. The most expedient procedure for generating smoke from these chemicals was to blow air

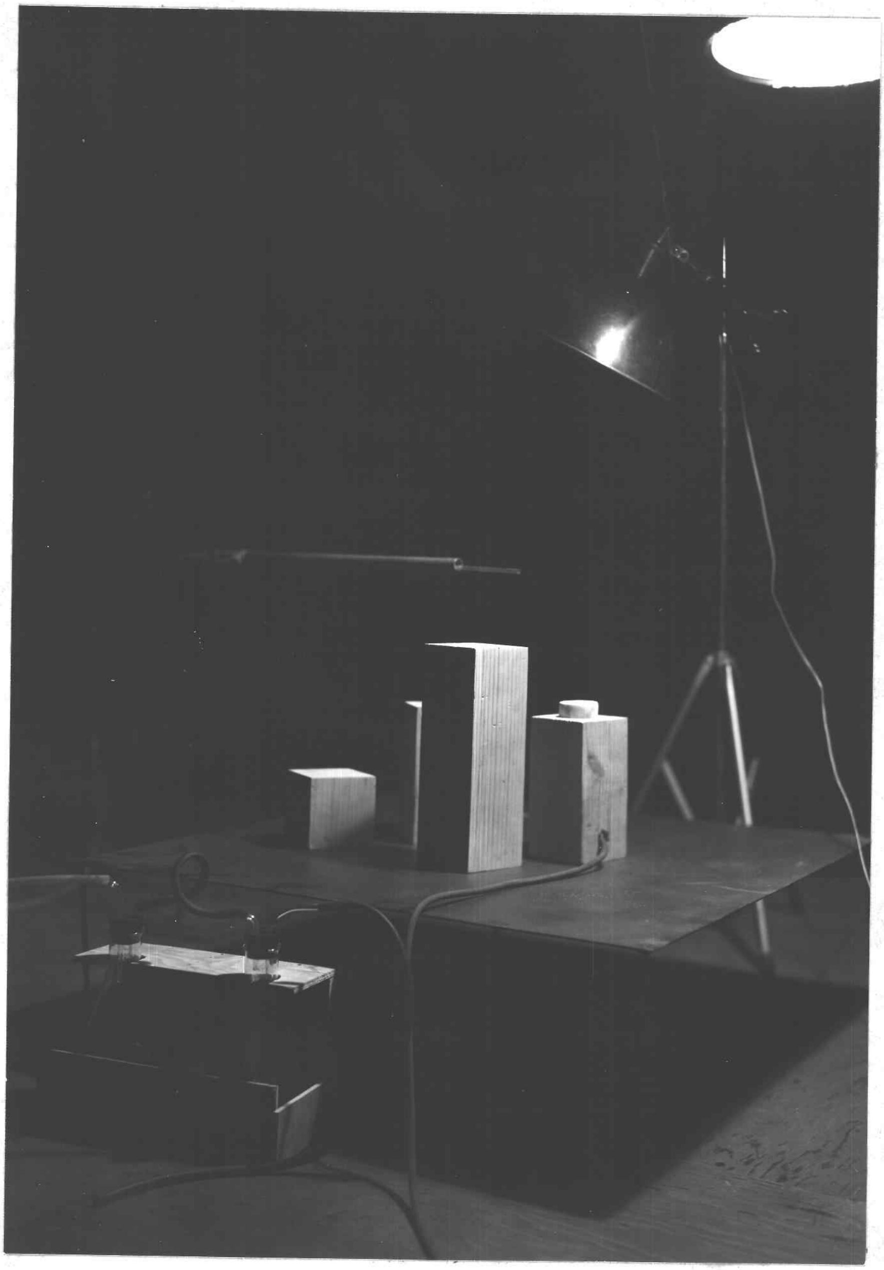

Figure 6. Smoke Study Equipment

through a tube submerged in the hydroxide and allow these vapors to bubble through the acid. The principal problem involved was the necessity of frequently cleaning the tubes due to solids precipitating out of the smoke. It was found that the clogging could be somewhat curtailed by quickly removing the conduction tubes from the flasks immediately after each test.

The smoke thus produced flowed through rubber tubing to the point of introduction in the tunnel. Hollow aluminum piping held the delivery tube parallel to the air flow in the throat section. The smoke stream was further defined by a small glass tube nozzle in the end of the rubber tubing.

When titanium tetrachloride was used, the compound itself was applied directly to the model.

The models used in this investigation were made of solid wood. They were designed on a basic increment of 3.6 inches which corresponds to a scale of sixty to one with an 18 foot prototype. Four different height to width ratios were used: a cube of 1:1 ratio, a 3:1 tall tower, a 2:1 medium-sized solid block, and a 2:1 model with a fan stack on top and an internal passage to deliver the smoke directly out of the fan stack. The sizes selected were believed to be well representative of actual industrial tower ratios. The model units are shown in figure 6.

In order that the testing area be in essentially constant velocity, the models were placed on a plate of one-eighth inch aluminum thirty inches square supported on slender posts eight inches above the floor. In use, this plate was centered between the walls and was four feet downstream from the small end of the entrance bell.

Testing Procedure

The smoke generating equipment previously described was used for the observation of flow patterns of a number of geometric configurations and for the photography of the configurations considered most pertinent to the investigation. Besides varying the combinations of models and their angles of attack to the approaching wind, the wind velocity was also varied by different settings on the tunnel shutters. By observation it was apparent that as the wind velocity increased over fifteen miles per hour, the tendency towards applicable smoke patterns diminished. Since winds of this magnitude are usually not a daily occurrence in actual installations and since other investigations of this nature have found the most deleterious conditions occur at velocities of 8 to 10 mph, this study was confined to wind speeds of 5, 10, and 15 miles per hour (17, vol.170, p.1209).

When a particular combination of model settings and wind velocity were deemed worthy of recording, photographs were taken. An additional photo flood lamp was placed downstream from the models being tested to supplement the light from the overhead lamp built into the tunnel. The photographs were taken from the control room with a 5 by 7 view camera. The distance from the model to the camera's lens was approximately four feet.

Analysis of Test Results

The intention of this study was to investigate the geometric ratios and placement of cooling towers in relation to varied winds that influence the tendency towards recirculation. Through the use of smoke patterns this study of the tendency towards recirculation took the form of combining the variables to produce observable differences in the smoke eddies in the lee of the models. Since the degree of recirculation is determined by the amount of exhaust vapor from the tower that tends to reenter the leeward intakes, it follows, that in a qualitative manner, the degree to which recirculation might occur can be judged by the flow of air from the top of the structure to the bottom intake section. This flow of air was illustrated by the insertion of smoke into the stream. It should be apparent then that the degree of recirculation would take on the observable characteristics of more or less dense concentrations of smoke flowing from the top of the model to the base. The more dense and violent eddies would thus be an indication of a greater ratio of recirculated air.

For purposes of analysis, the series of tests that constituted this investigation will be discussed in groups containing similar variables. Hereafter, models will be described by the ratio of height to width to length. For instance, M-2:1:3 would designate a height above the plate of 7.2 inches, a width of 3.6 inches, and a length parallel to the plate of 10.8 inches. The symbol for the model with the smoke exit in the fan stack will be M-2:1:1s. When a model is shown at an angle to the approaching wind, the angle of attack will follow the model symbol in parentheses. The wind speed will be designated by the symbol V with the velocity following in miles per hour. To illustrate a complete example, M-1:1:1 (45); V-10 mph means the model shown is a 3.6 inch cube set at an angle of 45 degrees to an approaching wind of ten miles per hour.

Figures 7 through 12 show single models with V-15 mph. The three views of M-3:1:1 are different only in the level of the tube introducing the smoke. Figure 8, with the tube level with the top, and figure 9, with the tube slightly below the top, show almost identical flow patterns while figure 7, with the tube considerably below the top, shows a flattened smoke pattern. Judging from the M-2:1:1s and models treated with titanium tetrachloride, the most consistent patterns are those made with the smoke introduction tube just slightly below the level of the top. It was also noticed in the M-3:1:1 that the smoke eddy did not reach to the ground level with any intensity. Figures 10 through 12 show the smoke eddy closer to the ground level and appear to indicate that the recirculation danger becomes more pronounced as the height to width ratio is decreased. The plume over M-2:1:1 and the plume from M-2:1:1s are almost identical which would seem to demonstrate that the vertical exit velocity from the tower has little effect on recirculation at higher wind velocities. However, it should be realized that the smoke from the M-2:1:1s does have an initial velocity perpendicular to the air stream, similar to the actual induced draft cooling tower, and this velocity component should be considered in quantitative studies. Only the observable effects of the leaving

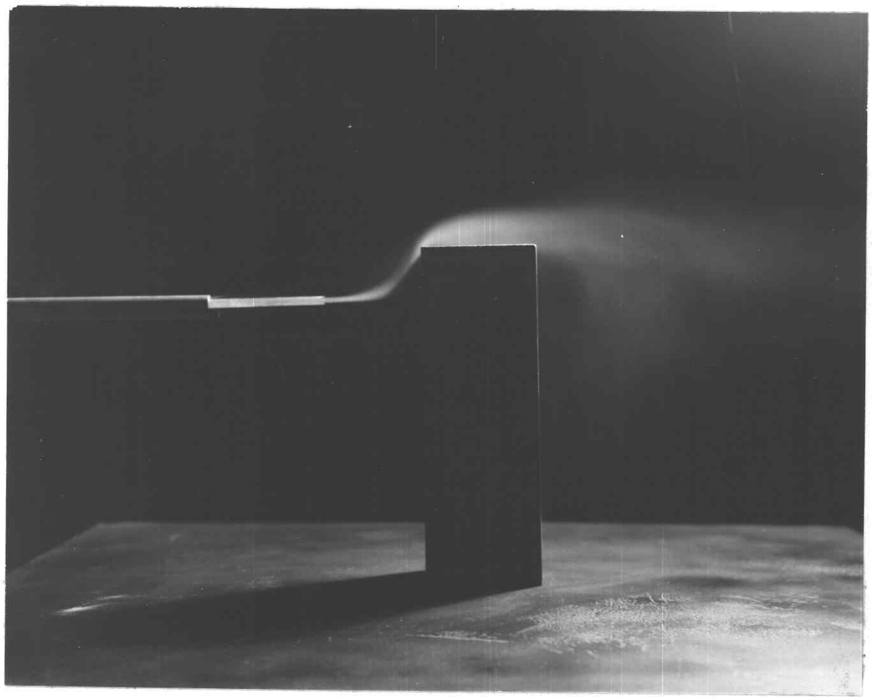

Figure 7. M-3:1:1; V-15 mph

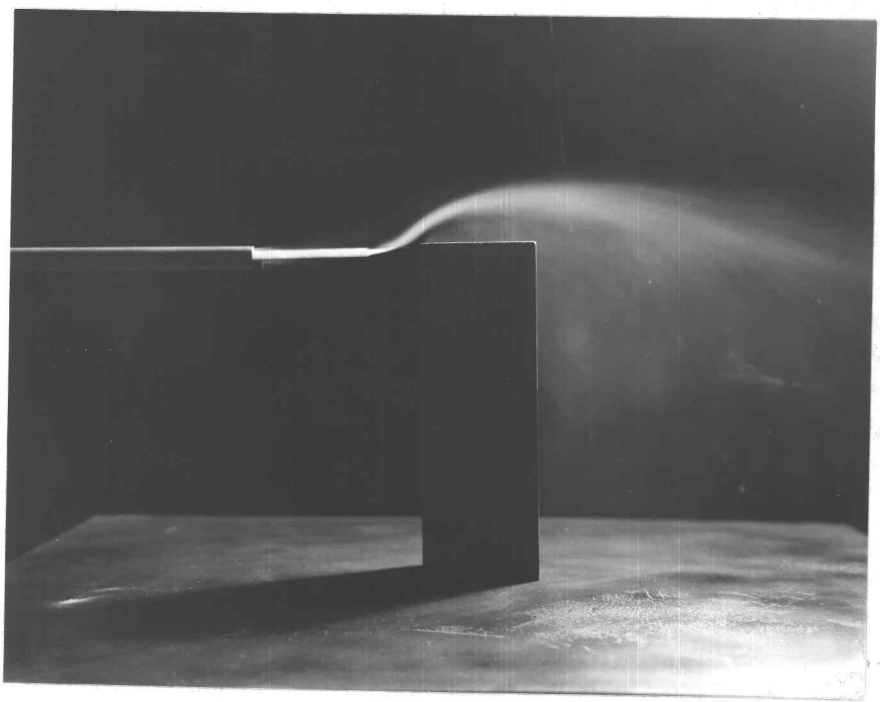

Figure 8. M-3:1:1; V-15 mph

Figure 9. M-3:1:1; V-15 mph

Figure 10. M-2:1:1; V-15 mph

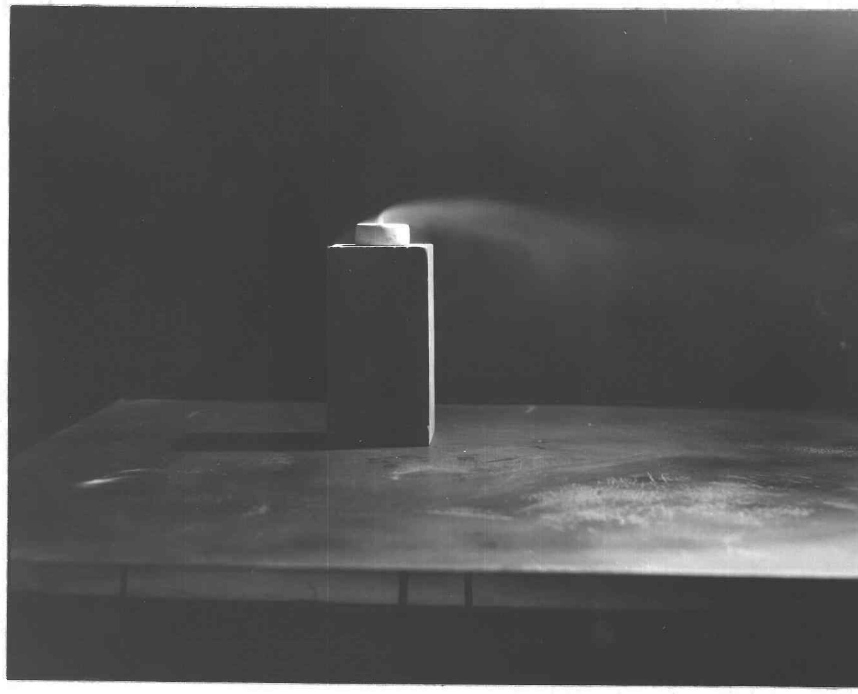

Figure 11. M-2:1:1s; V-15 mph

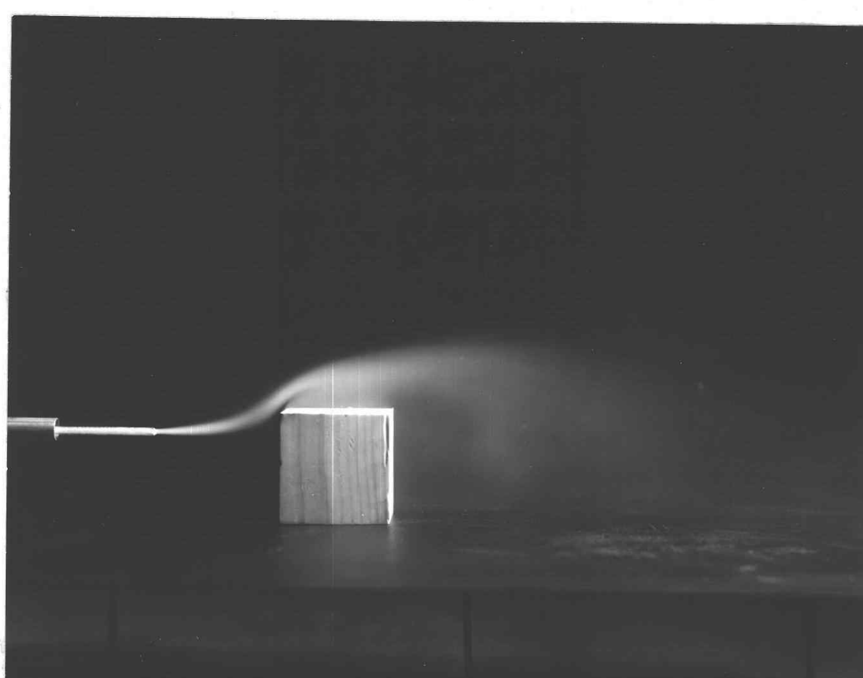

Figure 12. M-1:1:1; V-15 mph

velocity as it tends to influence the flow patterns will be discussed in this qualitative study.

In the next group, figures 13 through 17, at V-10 mph the intensity of the smoke near the base of the models is greatly increased. The M-2:1:1 and M-2:1:1s are again very similar and show a definite recirculation tendency. Figure 15 at M-2:1:1s (45) has a distinct pattern from the models at right angles to the approaching flow. As the photograph shows and as was observed in other tests, the plume retains its horizontal flow approximately twice as far as models perpendicular to the prevailing wind. The condition is at a maximum at an angle of attack of 45 degrees where it was photographed, and was observed to lessen as the angle approached zero. Figure 16 indicates that the M-1:1:1 has greater recirculation tendencies at V-10 mph than V-15 mph. Figure 17 demonstrates that the M-1:1:1 one width downwind from the M-1:1:3 has similar wind currents on both faces. Either or both models could be considered the cooling tower with the indication that recirculation would be increased due to the close proximity. The apparent increase in height of the plume is due to the angle from which it was photographed and because the titanium tetrachloride smoke was generated along the entire leading edge of the M-1:1:3.

The next group of pictures, figures 18 through 21, are at V-5 mph and show the four basic models. The decreased velocity of the wind is apparent in the feathery appearance of the smoke. In general, the recirculation as indicated by the smoke patterns appears to be

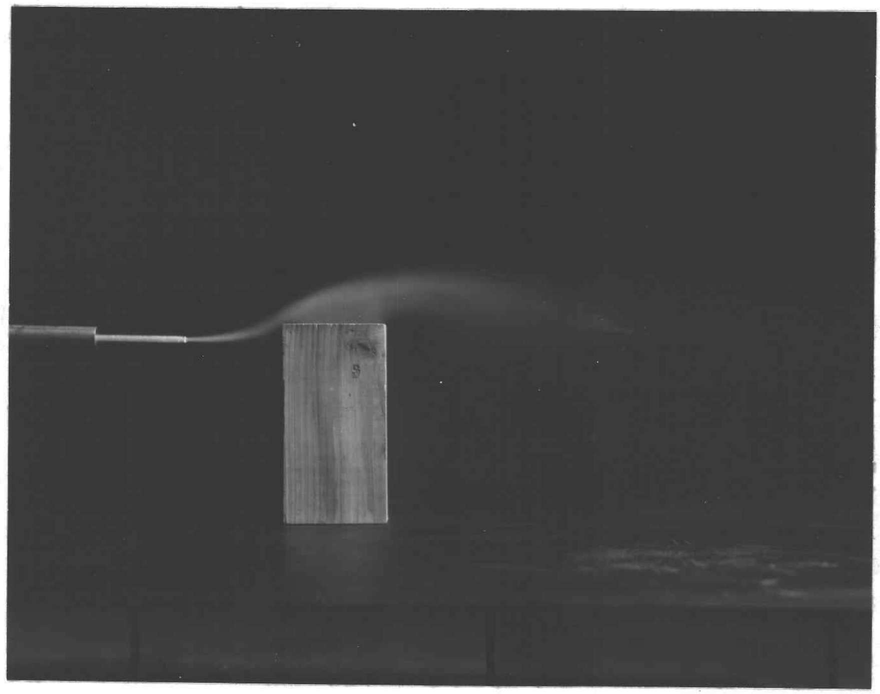

Figure 13. M-2:1:1; V-10 mph

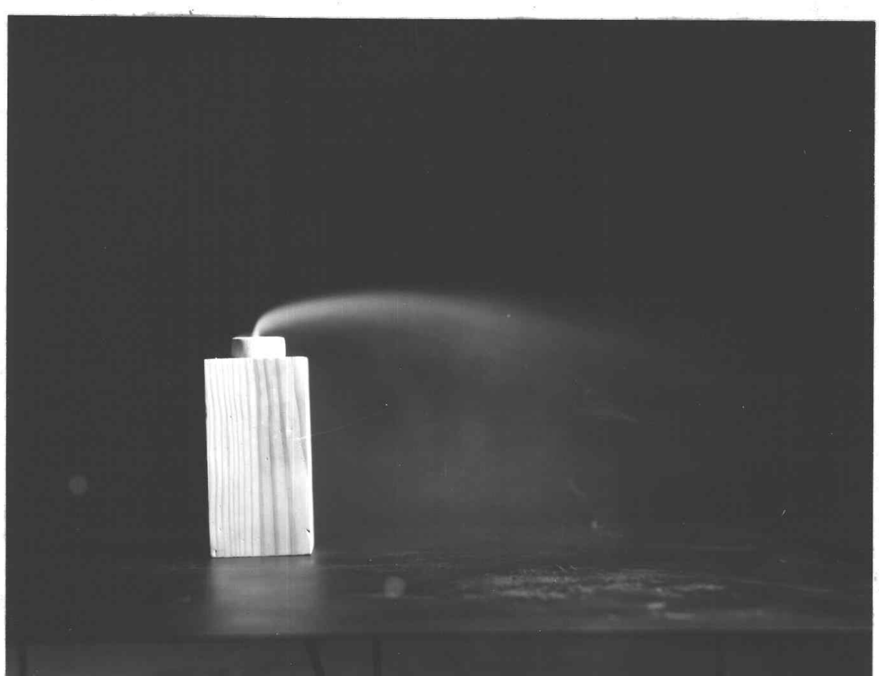

Figure 14. M-2:1:1s; V-10 mph

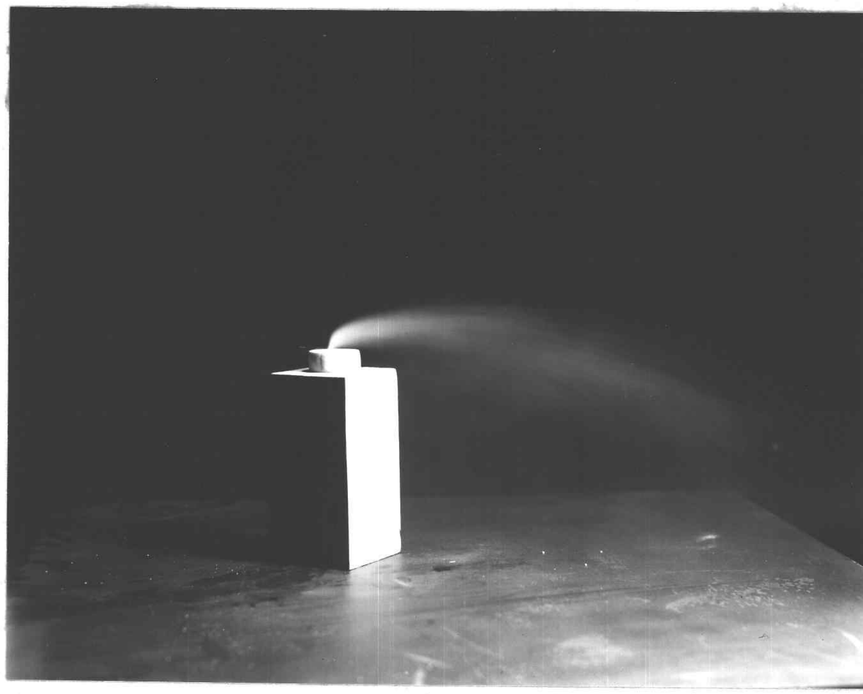

Figure 15. M-2:1:1s (45); V-10 mph

Figure 16. M-1:1:1; V-10 mph

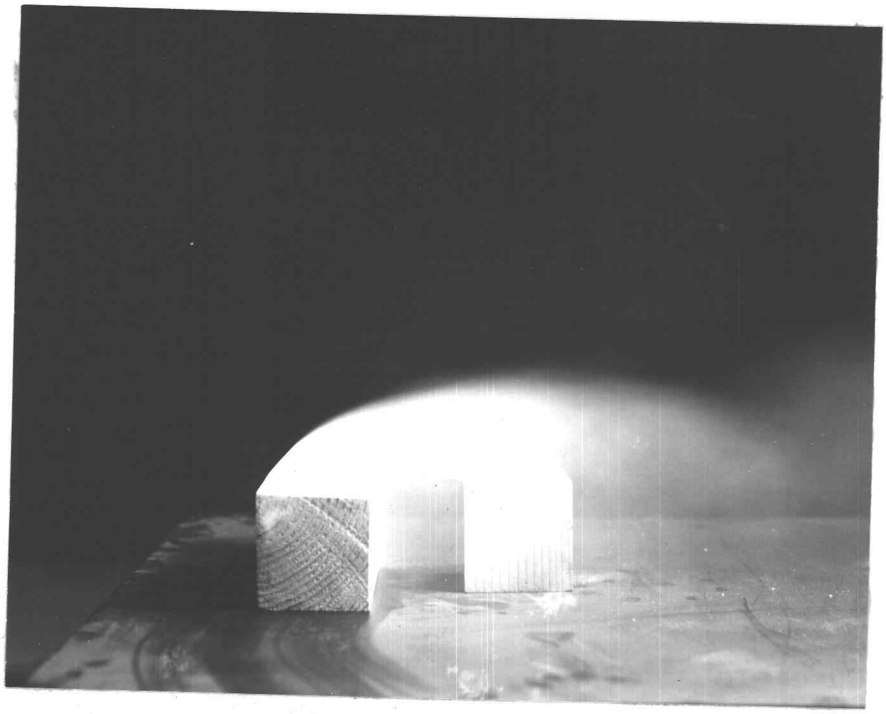

Figure 17. M-1:1:3; (1W); M-1:1:1; V-10 mph

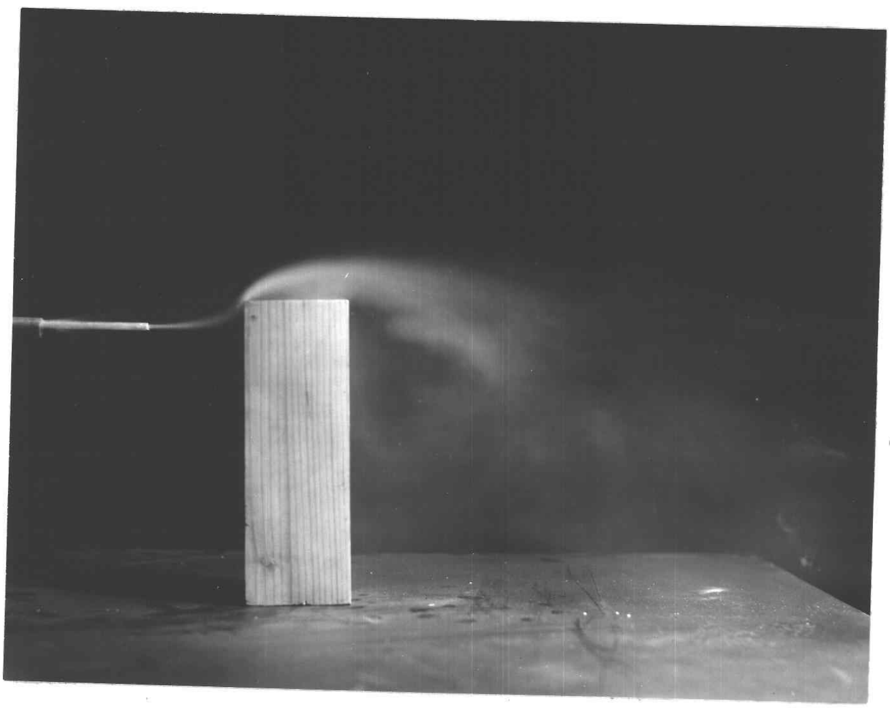

Figure 18. M-3:1:1; V-5 mph

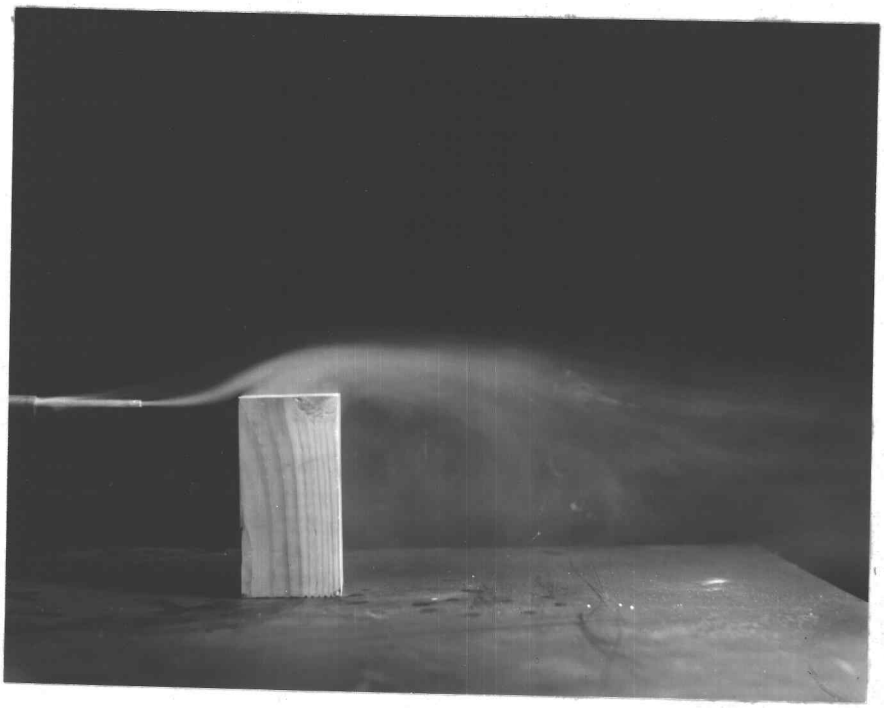

Figure 19. M-2:1:1; V-5 mph

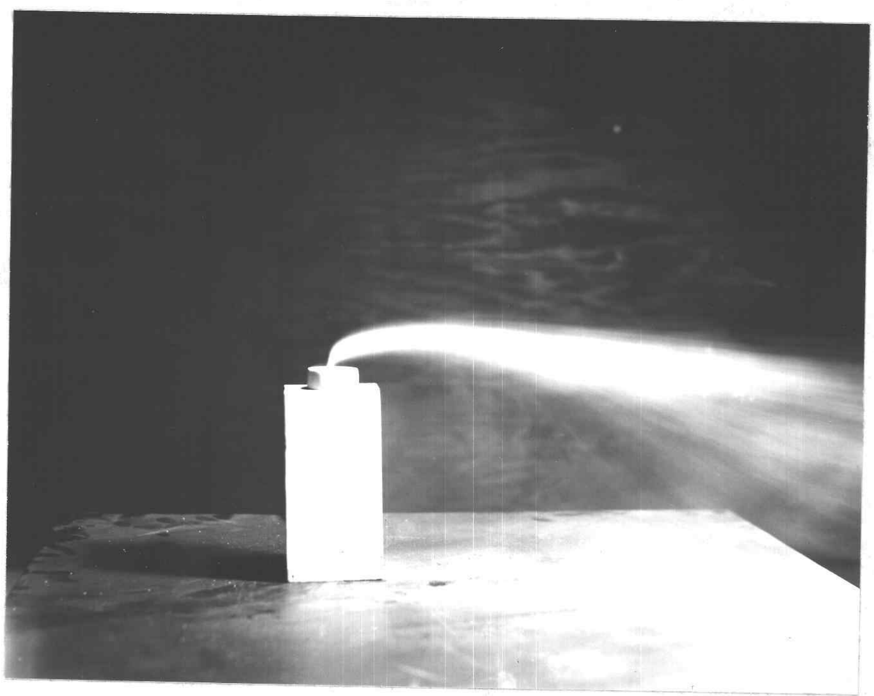

Figure 20. M-2:1:1s; V-5 mph

Figure 21. M-1:1:1; V-5 mph

greater than V-15 mph with the exception of M-1:1:1 which is about the same; and slightly less than V-10 mph since the smoke eddies do not appear as dense or pronounced. It can be seen that a smaller amount of the smoke is involved in the downwind swirls while a larger percentage flows smoothly past the model.

Before proceeding further, it should be mentioned that the comments made previously and those that follow are based on many observations of the smoke patterns and their interpretation as seen by the author. Proof of the analyses awaits a thorough quantitative study of the subject.

In the last test group are combinations of models that represent several of the most interesting groupings investigated. The symbol description employed lists the upstream model first, next a term designating the distance separating the models in basic widths, and the last term is the downstream model. For example, figure 22 has the notation M-3:1:1; (1W); M-2:1:1s and means a model with a 3.6 inch square base and 10.8 inches tall is 3.6 inches upstream from a model having a 3.6 inch square base that is 7.2 inches tall and has a fan stack. The wind velocity in figures 22 through 33 is ten miles per hour.

In figures 22 through 24, the M-2:1:1s is shown at three increments of 1W downwind from the M-3:1:1. Either model could be considered the cooling tower with similar analysis. In either case when the first model is 1W taller than the other, the recirculation tendency due to the air currents caused by the first obstacle decrease

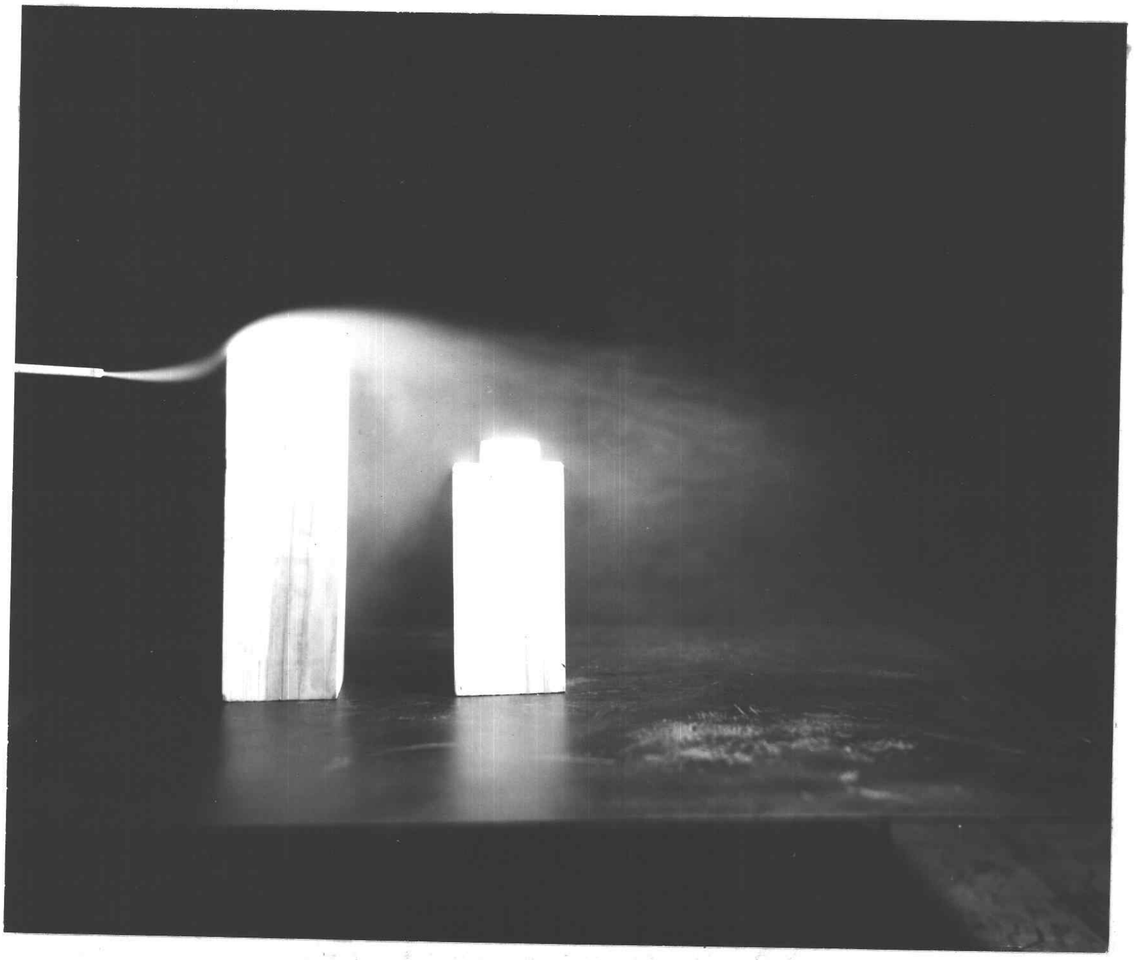

Figure 22. M-3:1:1; (1W); M-2:1:1s; V-10 mph

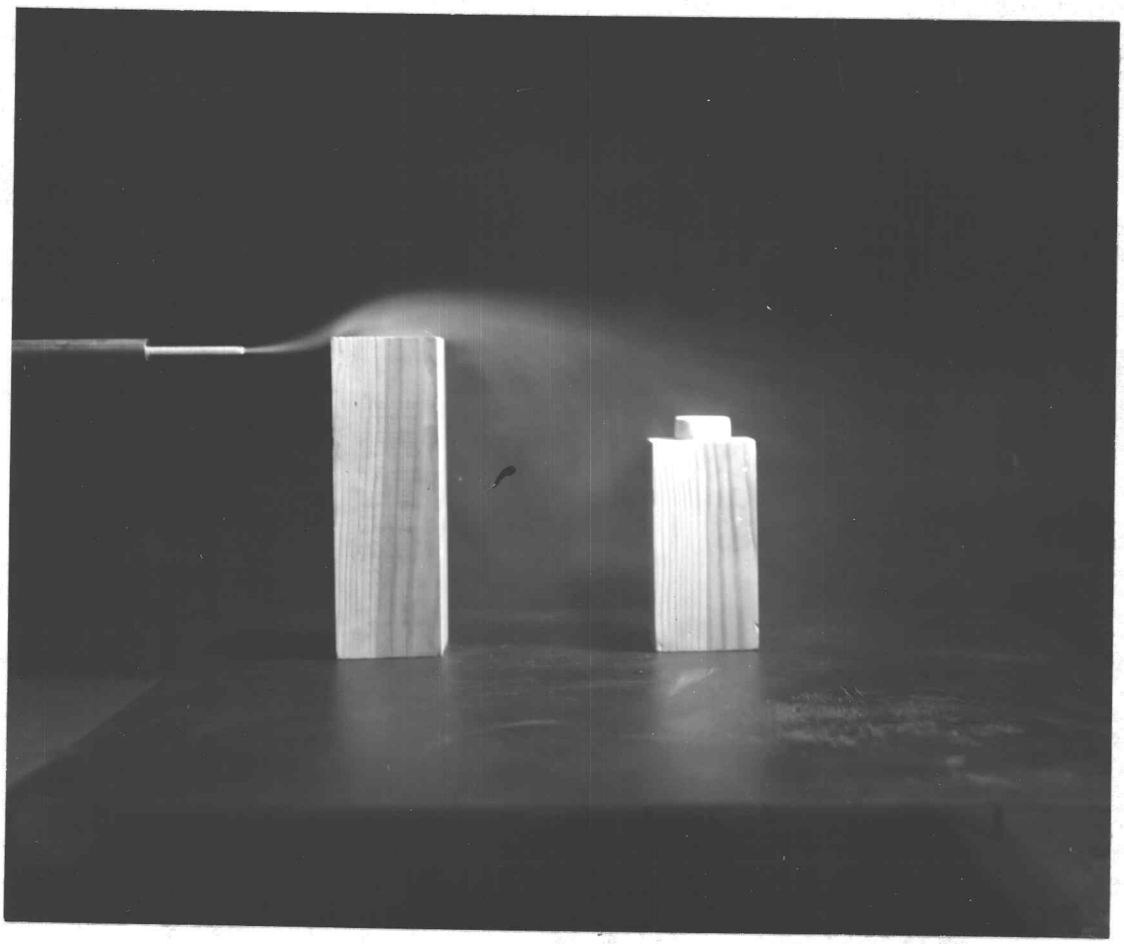

Figure 23. M-3:1:1; (2W); M-2:1:1s; V-10 mph

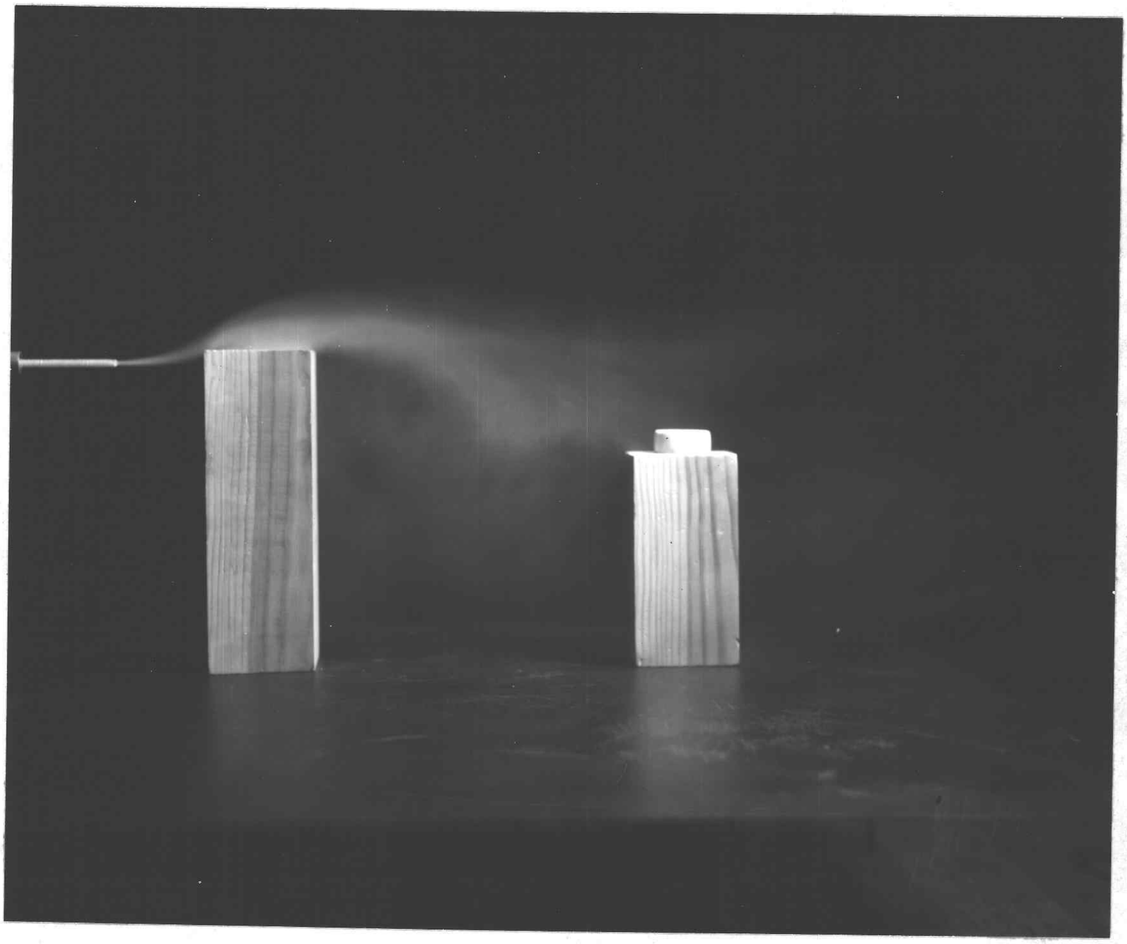

Figure 24. M-3:1:1; (3W); M-2:1:1s; V-10 mph

as the distance between them increases. At a distance of 3W the influence due to the front model is almost negligible. It was further observed that increasing the height of the front obstacle in proportion to the following model served to decrease the recirculation tendency as one would expect.

Smoke was introduced through the M-2:1:1s at 2W below the M-3:1:1 in figure 25. The plume noticeably tended towards recirculation in the M-2:1:1s.

The angle of attack for the M-3:1:2 was placed at 45 degrees to the M-2:1:1s for figures 25 and 26. In both cases the distance between the models was 1W which previously appeared to be the distance of maximum tendency towards recirculation. Also in both cases, the front edge of the M-3:1:2 was even with the back edge of the M-2:1:1s. The smoke plume of figure 26 is more nearly horizontal than figure 24 but was observed to curl back to the lee of the M-3:1:2. This tendency was seemingly confirmed in figure 27 where the smoke was introduced over the M-3:1:2. Recirculation appears to be present in this case but not to the extent of figure 22.

The M-2:1:1s (45) of figure 28, 2W directly behind the M-3:1:1, shows more violent air currents and seemingly greater tendency towards recirculation than the similar combination in figure 25.

Figure 29 demonstrates the M-3:1:1 has a lower ratio of recirculation when followed by a model proportionately shorter.

Figure 30 illustrates the M-1:1:1 is inclined towards increased recirculation when followed by a downwind obstacle. As might be anticipated, it was observed that the recirculation tendency increased

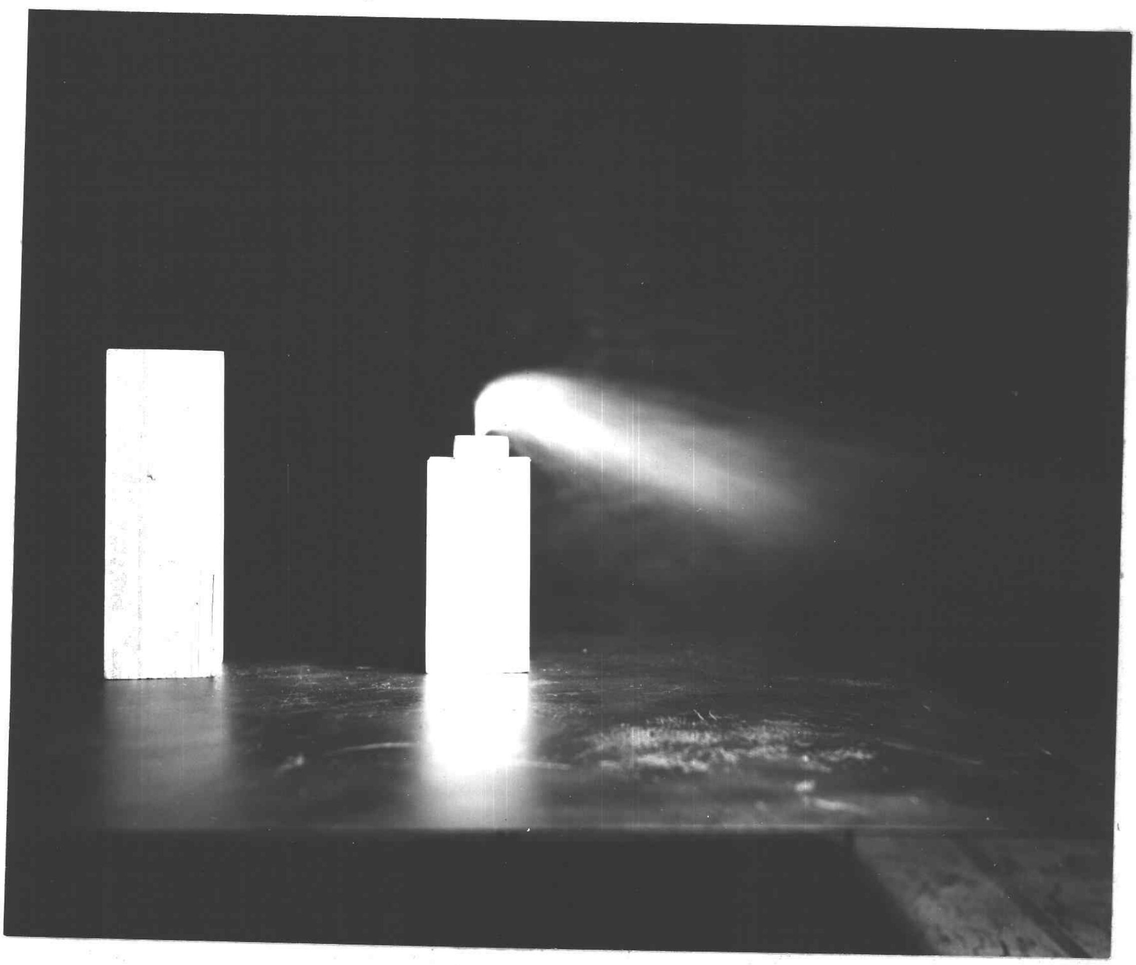

Figure 25. M-3:1:1; (2W); M-2:1:1s; V-10 mph

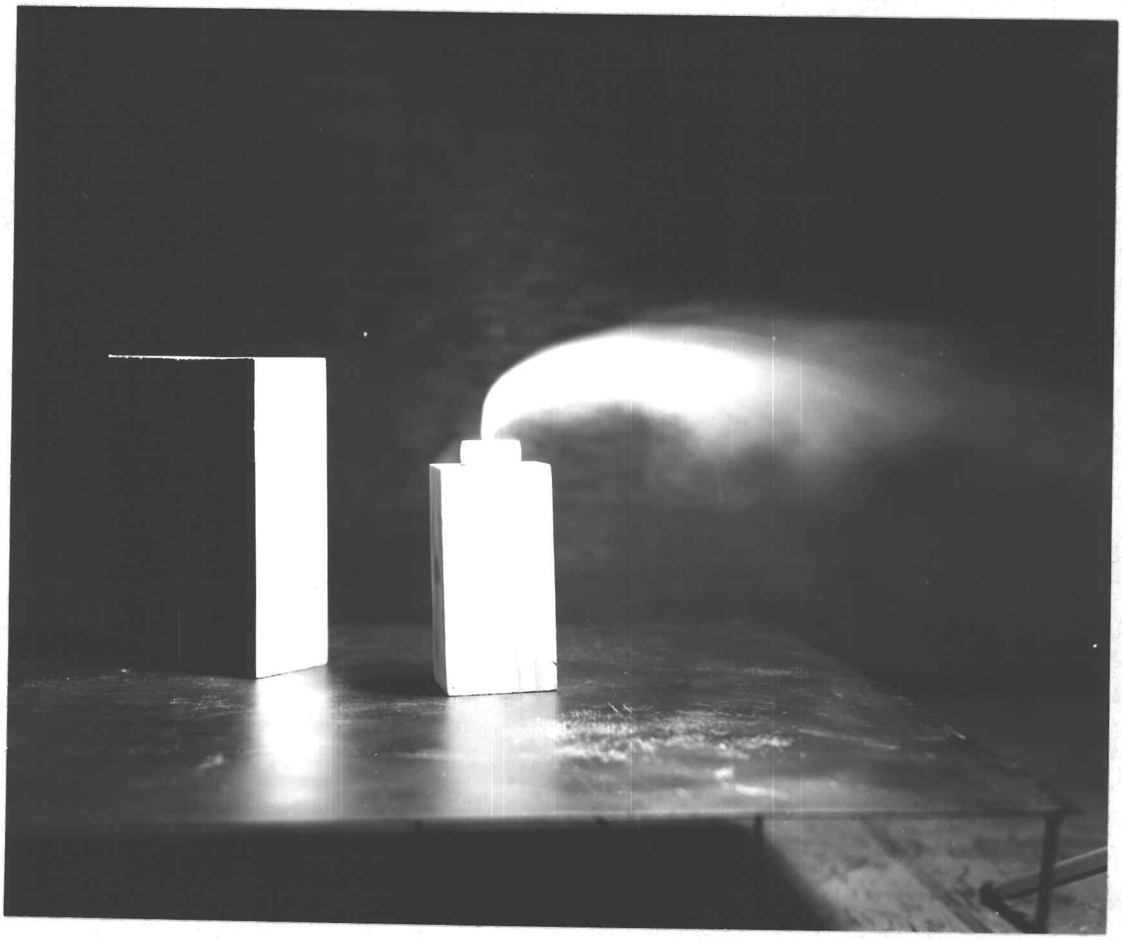

Figure 26. M-3:1:2 (45); (1W); M-2:1:1s; V-10 mph

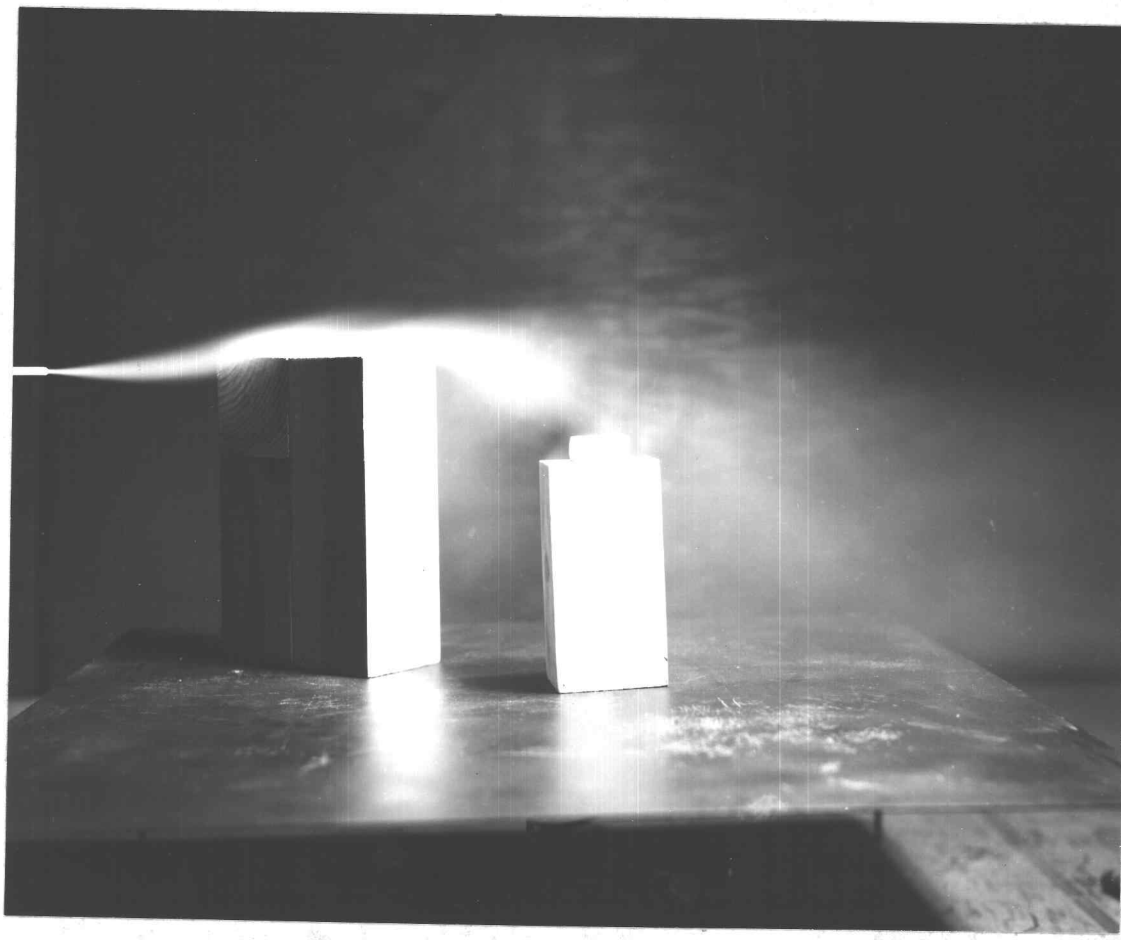

Figure 27. M-3:1:2 (45); (1W); M-2:1:1s; V-10 mph

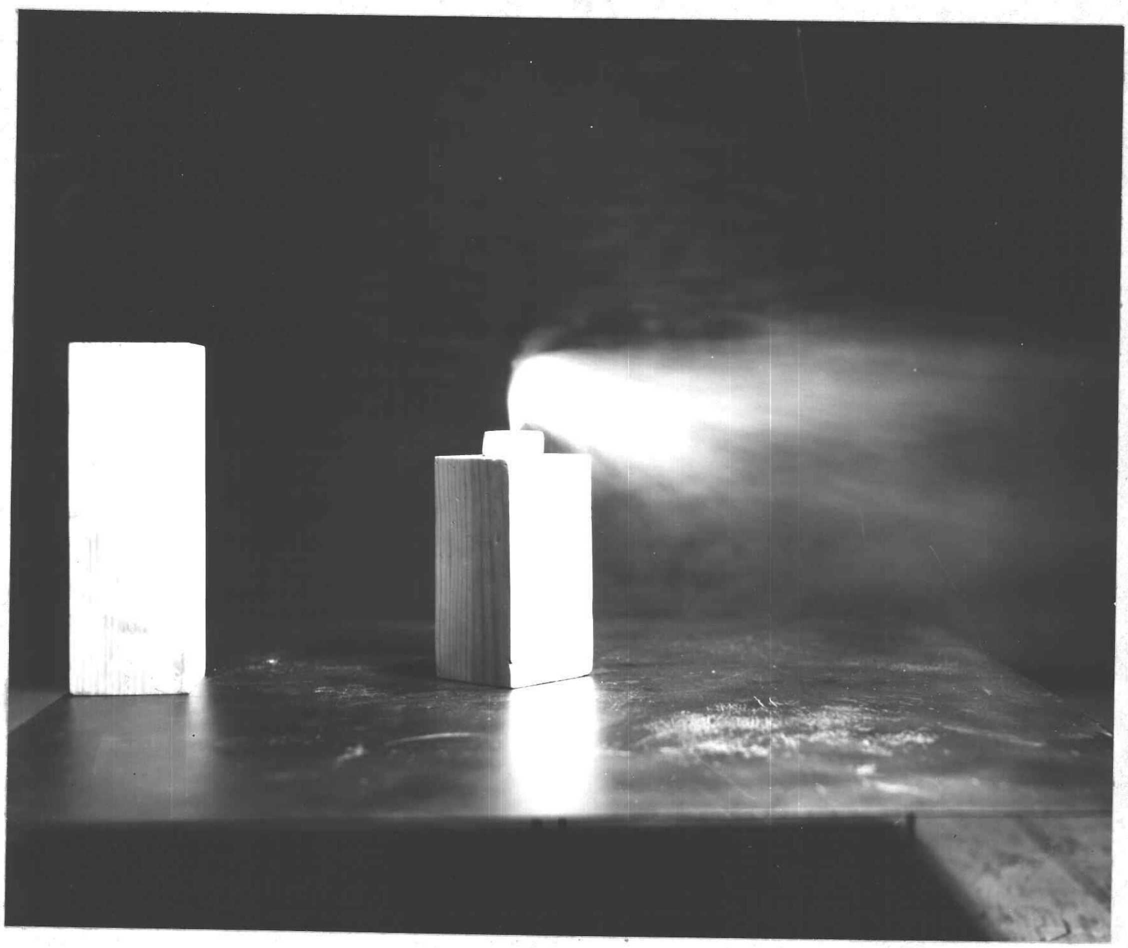

Figure 28. M-3:1:1; (2W); M-2:1:1s (45); V-10 mph

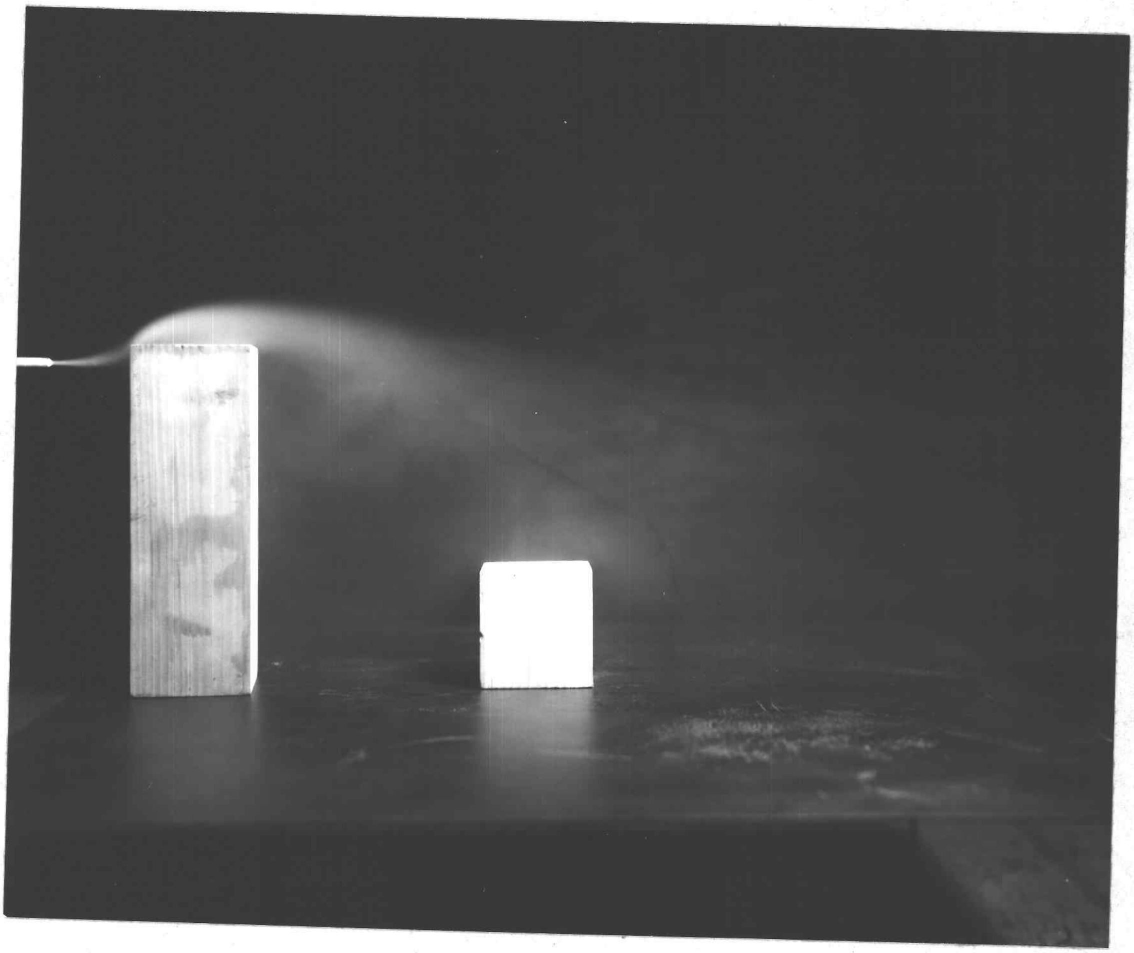

Figure 29. M-3:1:1; (2W); M-1:1:1; V-10 mph

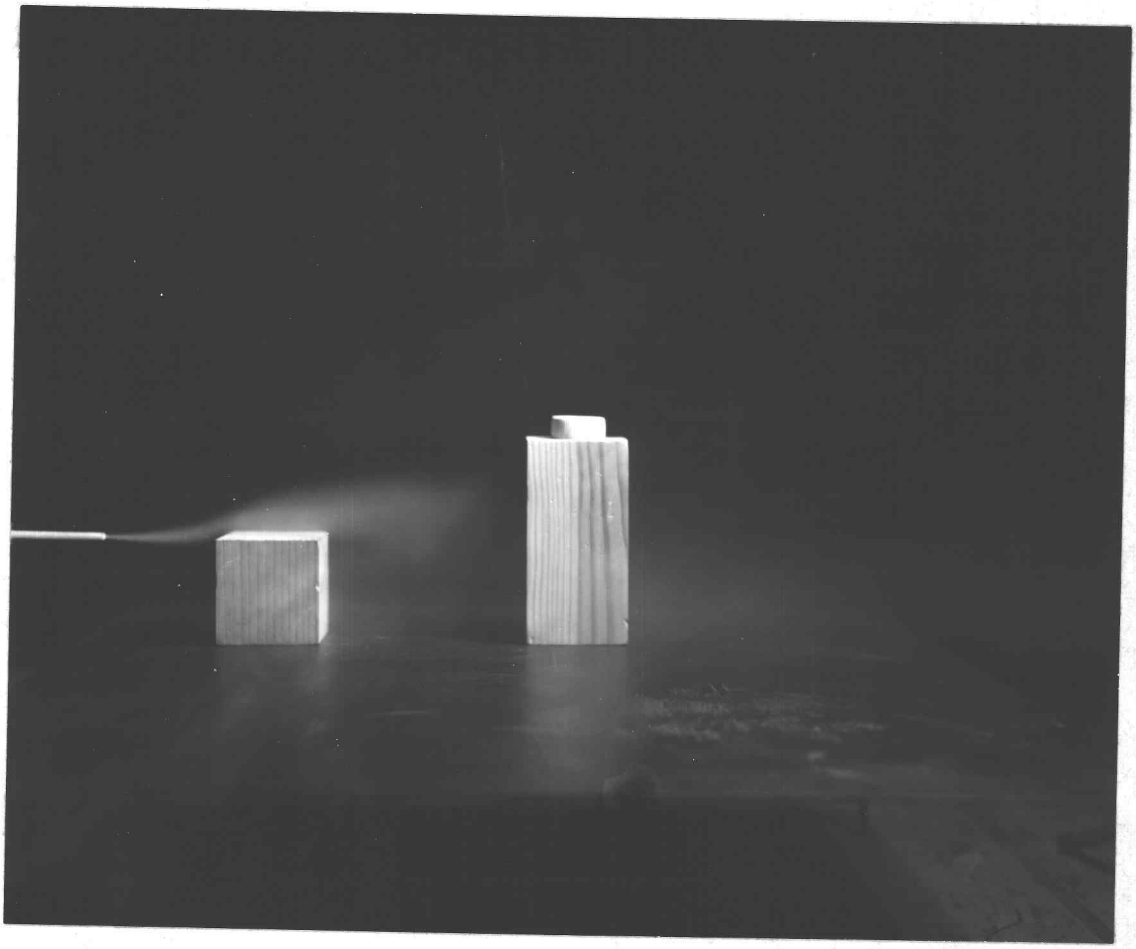

Figure 30. M-1:1:1; (2W); M-2:1:1s; V-10 mph

greatly as the downwind model approached the M-1:1:1. It can be seen that the currents caused by the upstream obstacle have little effect on the M-2:1:1s if it is considered as the cooling tower.

In figures 31 and 32, models of identical height are 2W apart. When smoke is introduced over the leading model the recirculation tendency in the M-2:1:1 is greater than if it were alone. However, when smoke is introduced from the M-2:1:1s as in figure 32, the plume is thin and almost horizontal showing little or no recirculation pattern. This pleasant condition was most pronounced at 2W and decreased to a more normal condition as shown in figure 14 when the distance was either increased or decreased.

Perhaps the most interesting picture is figure 33. This illustrates the only method of tower alteration that showed a definite decrease in recirculation tendencies. An inclined shield was mounted around the fan stack on the M-2:1:1s. For best results the shield angle was 45 degrees from the horizontal and had a height of twice the fan stack. When this figure is compared to figure 14, (taken at the same wind velocity) the very advantageous effects on recirculation patterns are obvious.

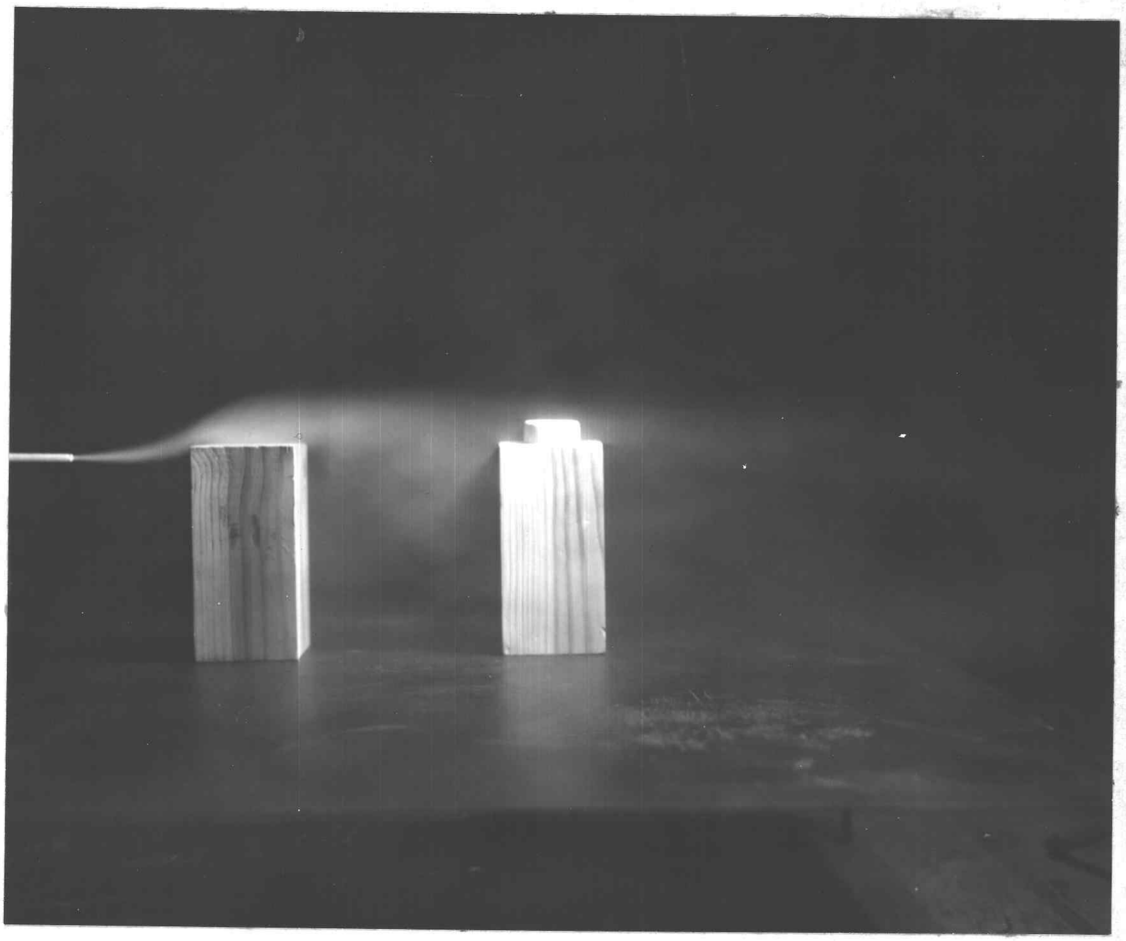

Figure 31. M-2:1:1; (2W); M-2:1:1s; V-10 mph

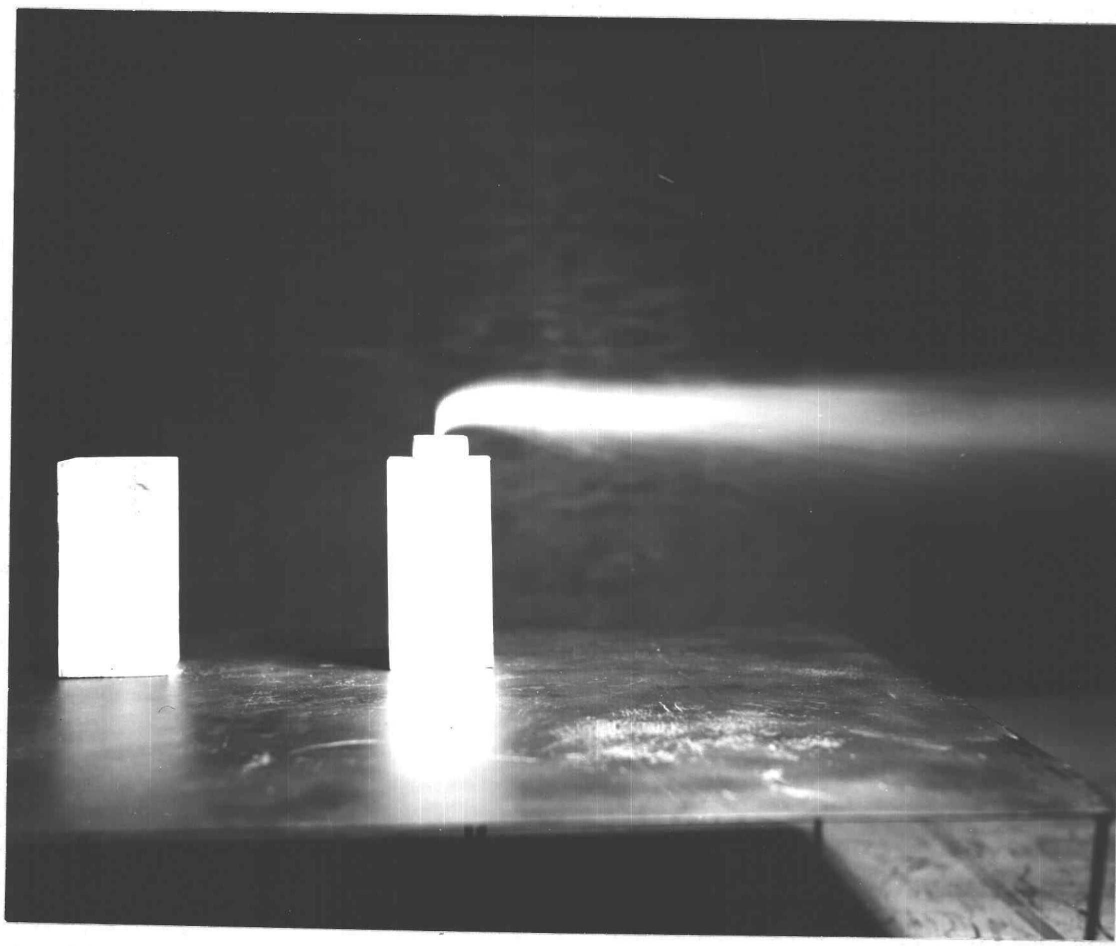

Figure 32. M-2:1:1; (2W); M-2:1:1s; V-10 mph

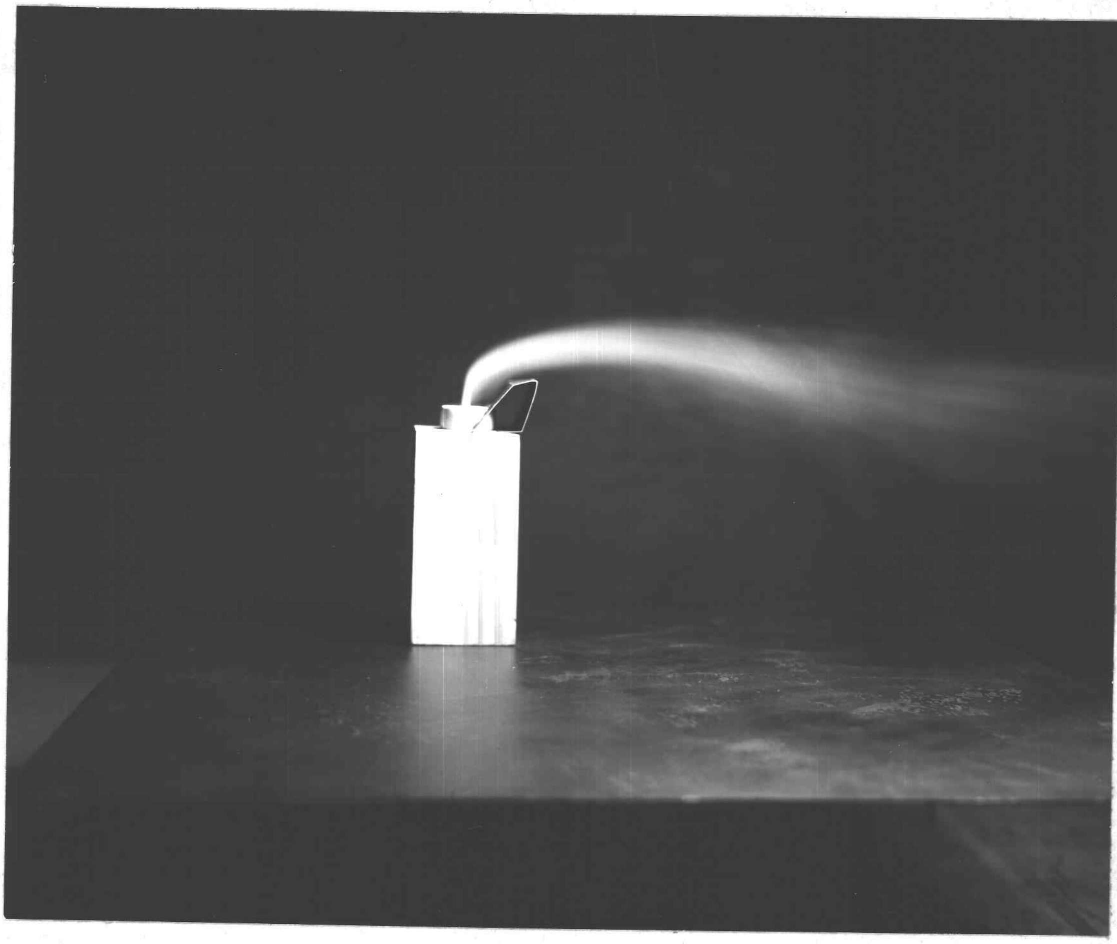

Figure 33. M-2:1:1s with Shield; V-10 mph

CONCLUSIONS AND RECOMMENDATIONS

Described in the foregoing pages are the considerations that led to the development of the test apparatus and test procedures for a qualitative study of recirculation in cooling towers. From the material presented the author feels that the following conclusions are warranted.

1. The usefulness of model investigations in wind tunnels for this type of study must be accepted in view of their flexibility and because prototype agreement has been established by other investigators.
2. The tendency towards recirculation of a given cooling tower is influenced by its location in relation to nearby structures and the direction of the prevailing winds. This tendency is greater as the distance decreases from a tower to an upwind structure of equal or greater height than the tower. Structures of less height than the tower have little effect.
3. The geometric ratios of a cooling tower and its angle of attack to the prevailing wind are contributing factors in recirculation tendencies. It appeared that increasing the height or the rotation of the tower to a maximum angle of 45 degrees with the air flow direction produced air patterns indicating less recirculation.
4. The addition of a wind shield on the tower stack appears to be a possible means of decreasing recirculation through tower alteration.

It must again be stated that the comments and conclusions stated in the context of this study are based upon the author's observation of numerous smoke patterns in relation to recirculation. This study should be considered a preliminary investigation which has helped to develop the tools and to define the limits for future studies of the problem.

The quantitative measurements of the recirculated portion of the exhaust air are, of course, the next step. The use of a tracer gas with appropriate measuring instruments, such as a CO_2 tracer and an interferometer as used by Takashi Shoda, will enable the investigator to determine the concentration of downwind stack gases (16, p.10). Such measurements should be made for many combinations of obstacles, towers, and wind speeds. Charts of the most common combinations should be prepared to enable users and manufacturers to anticipate the degree of recirculation for their choice of installation sites.

In addition to research into the tower location affecting its performance, the cooling tower itself must be subjected to intensive study. The effect of wind speed in relation to stack exit velocities should be studied. Quantitatively, models incorporating exit fans and heating coils with a tracer gas could be used, or qualitatively, proper buoyancy could be attained by injecting helium into the smoke supply. Based on the shown change of air flow due to the experimental stack device, more tower adaptations, such as stack shields, supporting stilts, or internal baffling of upwind air, should be developed and tested.

Let this study then, serve as the foundation upon which the further study of recirculation can be erected.

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