proved environment by control of some or all of the space conditions of temperature, humidity, air motion, and air purity (dust, fume and vapor removal). Such systems can also provide needed make-up air and, by proper design, heat recovery and conservation. To provide the best yield on the investment, the systems must be effective, should be usable throughout the year, and must provide as much control of space conditions as practicable. This requires a high order of design technique and experience. General ventilation may be provided by the following methods:

1. Natural supply and natural exhaust.
2. Natural supply and mechanical exhaust.
3. Mechanical supply and natural exhaust.
4. Mechanical supply and exhaust.

Properly designed and applied, each of these systems will give good results. Some of the factors that must be considered in the selection and design are:

1. No supply system is complete without a complimenting exhaust system, nor can any exhaust system be effective without specific provision for the make-up air.
2. Simple general ventilation systems are not satisfactory for most work areas unless the climate is cool, and the internal heat loads, work loads, and worker population are low.
3. To provide effective general ventilation for heat relief by either natural or mechanical supply, the air must be delivered to the work zones with appreciable air motion as described under Local Relief, and sufficient exhaust must be provided to remove the heat liberated in the space. In addition to the heat relief supply systems, supplementary supply air may be required for this purpose (see the section Roof Ventilators).
4. Natural ventilation is best applied to high narrow buildings having sufficient heat load to create convective air flow. Care must be taken to avoid dead air spaces at the center of the building. See Chapter 24 of the 1961 GUIDE AND DATA BOOK.
5. Mechanical ventilation must be used to supply air to wide low buildings, particularly where there is insufficient localized convective force available. *Natural exhaust* may be suitable for such buildings, and in many cases will be adequate.
6. Supply air and exhaust air are *not* interchangeable in effectiveness. Supply air can be delivered where it is wanted at controlled velocity, temperature and humidity. Exhaust systems must be used to capture heat and fumes at the source.

Air Requirements for Adequate Ventilation

The rule-of-thumb criteria for ventilation such as air change rate, temperature rise and cfm per square foot are meaningless for providing effective heat relief unless the specific rate is established by means of successful existing systems, similar in all pertinent respects to the proposed installation. These criteria, properly interpreted, do serve as guides and checks of the ventilation design.

High air change rates in the upper levels of a building will not provide relief at the lower work zones. Such ventilation may even entrain hot ceiling air and drive it to the floor, actually creating an aggravated working condition.

Temperature rise has no bearing on heat relief. A rise of 50 or 60 F deg can be tolerated easily, particularly in spaces with high ceilings. Even a low temperature rise of 5 to 10 F deg may be inadequate to provide relief in hot weather, and such low limits of temperature rise require huge volumes of air. A well designed ventilation system will maintain the work zone within 1 to 3 F deg of the supply air temperature with *less* air and a *higher* average temperature rise. The temperature rise may be estimated by the following equation:

$$q = \frac{H}{1.08\Delta t} \qquad (8)$$

where

q = air supply, cubic feet per minute.
H = heat to be removed from space, Btu per hour.
Δt = temperature rise of the air, Fahrenheit degrees.

The quantity H must include all internal heat from such sources as equipment, process, lights, occupancy, and solar and roof transmission gains.

Ventilation is often expressed as cfm per square foot. This relationship also fails to evaluate the actual heat relief provided by a system, but it does give a relationship which is independent of building height. This is a more rational approach because, with the same internal load, the same amount of ventilation air, properly applied to the work zone with adequate velocity, will provide the desired heat relief quite independently of the ceiling height of the space, with few exceptions. Ventilation rates of 1½ to 3 cfm per sq ft have been found to give good results in many plants having internal loads of 100 to 125 Btu per sq ft. A rate of 2 cfm per sq ft is common in many such plants.

Frequently the requirements of the fume and dust exhaust systems for make-up air will set the supply air rates. These may range up to 5 or 6 cfm per sq ft and in rare cases, over 15 cfm per sq ft. For high rates two types of systems may be desirable: (1) to provide the low level distribution and velocity essential for heat relief in the work zones, and (2) a simple system with minimum distribution, such that make-up air may be provided without disturbance at hoods and process.

Roof Ventilators

Roof ventilators are basically heat escape ports located in the high section of a building and properly enclosed for weather-tightness. Stack-draft effect plus some wind induction are the motive forces for several common designs of continuous ventilators and round ventilators. The latter can be equipped with fan barrel and motor, thus permitting gravity operation, or motorized high capacity operation, at will.

Two other main designs are available: one is the low-type ventilator which consists essentially of a stack fan with a rainhood; the other contains a stack fan with a split butterfly closure that is floated to open position by the discharge air stream and is self-closing. Both employ minimum enclosures and have little or no gravity capacity.

Various types of roof ventilators may be listed in diminishing order of temperature differential and heat-removal capacity. Next to chimneys and stacks, the continuous ventilation monitor is most effective for removal of substantial and concentrated heat loads. This may be in the form of an elevated length of roof ridge with extended overhang and no rain louvers. Such structures are commonly employed over open hearth furnaces and soaking pit buildings but, in practice they give uncertain performance. A more efficient type is a streamlined, watertight monitor constructed of noncorrosive metals or protected metals. Its capacity increases with wind velocity and it can be readily closed in winter to conserve building heat. Both types have tremendous capacity and are limited only by roof area and proper relation of low-level air inlets.

Next in capacity are the (1) round gravity or windband ventilator, (2) round gravity type with fan and motor added, (3) low-hood powered ventilator, and (4) vertical upblast powered ventilator. Popular modifications of these include the rotary type and the turbine ventilator.

Minimum-capacity ventilators of the gravity type are applicable to warehouses with light heat loads, and to manufacturing areas having high roofs and light loads. Nonmechanical ventilators are desired here because the wide spacing makes electrical wiring and maintenance of fans and motors a matter of concern.

Streamlined continuous ventilators must be able to operate effectively in the absence of mechanical power. While it is difficult to predict performance accurately, it can safely be

said that efficient ventilator operation is generally obtained when difference in elevation between the average air inlet level and the roof ventilation is not less than 30 ft and the exit temperature is 25 F deg above the prevailing outdoor temperature. See Chapter 24 of the 1961 GUIDE AND DATA BOOK. Under these conditions and with a wind velocity of 5 mph, the ventilator throat velocity will be about 375 fpm. It will thus remove 10,000 Btu (per hr) (sq ft of throat area):

$$25 \text{ deg} \times 1.08 \times 375 \text{ cfm} = 10{,}000 \text{ Btu}$$

To insure this level of performance it is essential that sufficient low-level openings be provided for the incoming air; otherwise the gravity ventilator becomes starved for air and capacity falls off. The manufacturers recommend 250 fpm to 450 fpm inlet velocity. Lack of adequate inlet area is the most common cause of failure of gravity-type roof ventilators. A positive supply of air to insure direct ventilation around the hot equipment may be necessary within buildings of considerable area where the external wall inlets are remote from the equipment.

A decision between gravity and mechanical ventilators may be difficult to reach. The electrical power required for fan operation may be a deterring factor but this is offset by the advantage of constant ventilation capacity given by fan operation. Mechanical ventilators will function better with small inlets because they can create the pressure differential necessary for flow. However, it should be kept in mind that most roof fans lose capacity rapidly as the negative pressure exceeds 0.10 in. of water. High negative pressures are undesirable in buildings in any case because of door infiltration and other problems, and care should be taken in sizing the inlets. Preferably the inlet losses should be under 0.05 in. of water. In many cases there is justification for a mechanical system for make-up air which will positively supply air to the work zone.

Consideration should be given to the use of fusible link dampers in the roof ventilators or in roof trunk ducts in order to provide under-the-roof heat release in case of fire.

LOCAL RELIEF

General

The basic principle of effective local relief is that the air must be delivered directly to the work zone with sufficient air motion to provide cooling at the worker by means of convection and sweat evaporation. In most cases the objective is to provide reasonable or tolerable working conditions rather than complete comfort. In each case the methods described for local relief are based on the assumption that exhaust ventilation, radiation shielding, equipment insulation, and possible changes in process design have been fully utilized to minimize the heat loads. In addition, the supply air must not be blown on hot equipment nor through the layer of hot ceiling air before reaching the work zones. In the latter case huge volumes of hot air will be entrained and brought down to the worker.

Methods of Providing Relief

Two types of local ventilation are used:

General Ventilation: This might be termed *low level or displacement ventilation* because the supply air is delivered at the 8–12 ft level (10 ft is the most frequently used) and displaces the warm air rising from equipment, lights and occupants. The internal heat is picked up as the supply air leaves the work zone, and the work zone may be maintained within a few degrees of the supply air temperature with relatively low supply air volumes. Such low level systems should be applied to large work areas having high, uniform worker population. It should be noted that these systems are *local* in the sense that no attempt is made to maintain relief conditions in the upper levels of the building.

Local Area or Spot Cooling Ventilation: In buildings where only a few small work areas or relatively few work stations are required, it would be impracticable and wasteful to attempt to treat the complete building floor area. In such cases relief may be provided by these methods:

1. Provide a complete enclosure around the worker with separate ventilation in order to maintain cooler working conditions. This may be in the form of a control room, small shelter booth, or ventilated crane cab. In effect, this is "localized" general ventilation, differing only in the conditions of air temperature, humidity, and motion required.
2. Surround the worker with a relatively cool atmosphere by a direct supply of air introduced at a low level over a small area of the plant. In such cases we are not concerned with the temperature at higher levels in the space so long as adjacent structures do not become hot and thus return radiant heat into the work space.
3. Direct a high-velocity air stream at the worker to increase the evaporative cooling effect. This method, commonly called *spot cooling* will incorporate varying degrees of Method 2, depending upon the number of employees and the distribution of the work stations.

Method Number 1, in the form of a work station enclosure, is the most desirable because it permits complete control of the environment. The second method is effective in large areas with many work stations, such as machine shops and assembly lines. The last method is used to provide *spot cooling* in large spaces where scattered work stations and localized sources of heat make it highly impracticable to maintain a tolerable environment throughout the building.

Physiological Aspects of System Design

Two different situations in respect to heat load are encountered: (1) where radiant heat sources are not important, and (2) where radiant heat sources are important. These two situations must be treated differently in design.

Where Radiant Heat is Not Important. Where no important sources of radiant heat are located within or close to the work area, it is only necessary to introduce the relief air into the work space in such a way as to displace the hot air and thus surround the worker with an acceptable atmosphere with regard to temperature and air motion.

Where Radiant Heat is Important. Where important sources of radiant heat are present and cannot be entirely controlled by radiation shielding, the air supplied for relief must provide greatly increased heat removal by convection and sweat evaporation in order to offset the radiation load. In cases where the radiant load cannot be offset, intermittent work periods may be necessary, thus emphasizing the great need for all practical shielding to reduce the load. In other cases, the supply air temperature may be reduced by refrigeration or evaporative cooling to a level at which the worker can maintain body heat balance without undesirable strain.

Regardless of the heat source or load, if the temperature of the relief air exceeds skin temperature, a convective load is then added to any existing radiative load, and these, together with the metabolic heat, must be removed by sweat evaporation cooling. Additional air velocity over the worker simply increases the convective load, making the working condition less tolerable. While increased velocity will also increase sweat evaporation, a critical point is reached when the convective addition will exceed the removal of heat by sweat evaporation. At low velocities, below the critical point, maximum cooling may not occur because of incomplete sweat evaporation.[3,4] Again it becomes clear that the use of cool air is very important for high heat level conditions. This is the