Related Commercial Resources

CHAPTER 15. INDUSTRIAL AIR CONDITIONING

THIS chapter addresses air-conditioning systems for industrial facilities such as manufacturing plants, laboratories, processing plants, and power plants. HVAC systems provide the process environment (including temperature, humidity, air motion, air quality, noise, and cleanliness) to facilitate industrial processes and provide for the health, safety, and comfort of personnel.

Many industrial buildings require large amounts of energy, in both manufacturing and maintaining building environmental conditions. This chapter provides system and building design guidance for energy conservation by using insulation, ventilation, and waste heat recovery.

1. GENERAL REQUIREMENTS

Typical temperatures, relative humidities, and specific filtration requirements for storage, manufacture, and processing of various commodities are listed in Table 1. Requirements for a specific application may differ from those in the table.

Table 1 Design Requirements for Industrial Air Conditioning[1]

Process	Dry Bulb, °C	rh, %
ABRASIVE		
Manufacture	26	50
CERAMICS		
Refractory	43 to 66	50 to 90
Molding room	27	60 to 70
Clay storage	16 to 27	35 to 65
Decalcomania production	24 to 27	48
Decorating room	24 to 27	48
Use high-efficiency (MERV 13 or better) in decorating room. To minimize the danger of silicosis in other areas, a dust-collecting system or medium-efficiency particulate air filtration may be required.		
DISTILLING		
General manufacturing	16 to 24	45 to 60
Aging	18 to 22	50 to 60
Low humidity and dust control are important where grains are ground. Use high-efficiency filtration for all areas to prevent mold spore and bacteria growth. Use ultrahigh-efficiency filtration where bulk flash pasteurization is performed.		
ELECTRICAL PRODUCTS		
Electronics and x-ray		
Coil and transformer winding	22	15
Semiconductor industry	21	45
Electrical instruments		
Manufacture and laboratory	21	50 to 55
Thermostat assembly and calibration	24	50 to 55
Humidistat assembly and calibration	24	50 to 55
Small mechanisms		
Close tolerance assembly	22[*]	40 to 45
Meter assembly and test	24	60 to 63
Switchgear		
Fuse and cutout assembly	23	50
Capacitor winding	23	50

Paper storage	23	50
Conductor wrapping with yarn	24	65 to 70
Lightning arrester assembly	20	20 to 40
Thermal circuit breakers assembly and test	24	30 to 60
High-voltage transformer repair	26	5
Water wheel generators		
Thrust runner lapping	21	30 to 50
Rectifiers		
Processing selenium and copper oxide plates	23	30 to 40

*Temperature to be held constant.
Dust control is essential in these processes. Minimum control requires medium-efficiency filters (MERV 11 or better). Degree of filtration depends on the type of function in the area. Smaller tolerances and miniature components suggest high-efficiency particulate air (HEPA) filters.

FLOOR COVERING

Linoleum		
Mechanical oxidizing of linseed oil*	32 to 38	
Printing	27	
Stoving process	70 to 120	

*Precise temperature control required.
Medium-efficiency particulate air filtration is recommended for the stoving process.

FOUNDRIES*

Core making	16 to 21	
Mold making		
Bench work	16 to 21	
Floor work	13 to 18	
Pouring	4	
Shakeout	4 to 10	
Cleaning room	13 to 18	

*Winter dressing room temperatures. Spot coolers are sometimes used in larger installations.
In mold making, provide exhaust hoods at transfer points with wet-collector dust removal system. Use 280 to 380 L/s per hood, with a target capture velocity of approximately 2.5 m/s. In shakeout room, provide exhaust hoods with wet-collector dust removal sys- tem. Exhaust 190 to 240 L/s in grate area. Room ventilators are generally not effective.
In cleaning room, provide exhaust hoods for grinders and cleaning equipment with dry cyclones or bag-type collectors. In core making, oven and adjacent cool- ing areas require fume exhaust hoods. Pouring rooms require two-speed powered roof ventilators. Design for minimum of 10 L/s of floor area at low speed. Shield- ing is required to control radiation from hot surfaces. Proper introduction of air minimizes preheat requirements.

FUR

Drying	43	
Shock treatment	−8 to −7	
Storage	4 to 10	55 to 80

Shock treatment or eradication of any insect infestations requires lowering the temperature to −8 to −7°C for 3 to 4 days, then raising it to 16 to 21°C for 2 days, then lowering it again for 2 days and raising it to the storage temperature.

Furs remain pliable, oxidation is reduced, and color and luster are preserved when stored at 4 to 10°C.

Humidity control is required to prevent mold growth (which is prevalent with humidities above 80%) and hair splitting (which is common with humidities lower than 55%).

GUM

Manufacturing	25	33
Rolling	20	63
Stripping	22	53
Breaking	23	47
Wrapping	23	58

LEATHER		
Drying	20 to 52	75
Storage, winter room temperature	10 to 16	40 to 60
After leather is moistened in preparation for rolling and stretching, it is placed in an atmosphere of room temperature and 95% relative humidity. Leather is usually stored in warehouses without temperature and humidity control. However, it is necessary to keep humidity sufficiently low to prevent mildew. Medium-efficiency particulate air filtration is recommended for fine finish.		
LENSES (OPTICAL)		
Fusing	24	45
Grinding	27	80
MATCHES		
Manufacture	22 to 23	50
Drying	21 to 24	60
Storage	16 to 17	50
Water evaporates with the setting of the glue. The amount of water evaporated is 8 to 9 kg per million matches. The actual match production rate must be known to determine the actual moisture load in the space.		
PAINT APPLICATION		
Lacquers: Baking	150 to 180	
Oil paints: Paint spraying	16 to 32	80
The required air filtration efficiency depends on the painting process. On fine finishes, such as car bodies, high-efficiency particulate air filters are required for the outdoor air supply. Other products may require only low- or medium-efficiency filters. Makeup air must be preheated. Spray booths must have 0.5 m/s face velocity if spraying is performed by humans; lower air quantities can be used if robots perform spraying. Ovens must have air exhausted to maintain fumes below explosive concentration. Equipment must be explosion-proof. Exhaust must be cleaned by filtration and solvents reclaimed or scrubbed.		
PHOTO STUDIO		
Dressing room	22 to 23	40 to 50
Studio (camera room)	22 to 23	40 to 50
Film darkroom	21 to 22	45 to 55
Print darkroom	21 to 22	45 to 55
Drying room	32 to 38	35 to 45
Finishing room	22 to 24	40 to 55
Storage room (black and white film and paper)	22 to 24	40 to 60
Storage room (color film and paper)	40 to 50	40 to 50
Motion picture studio	22	40 to 55
The above data pertain to average conditions. In some color processes, elevated temperatures as high as 40°C are used, and a higher room temperature is required. Conversely, ideal storage conditions for color materials necessitate refrigerated or deep-freeze temperatures to ensure quality and color balance when long storage times are anticipated. Heat liberated during printing, enlarging, and drying processes is removed through an independent exhaust system, which also serves the lamp houses and dryer hoods. All areas except finished film storage require a minimum of medium-efficiency particulate air filters.		
PLASTICS		
Manufacturing areas		
Thermosetting molding compounds	27	25 to 30
Cellophane wrapping	24 to 27	45 to 65
In manufacturing areas where plastic is exposed in the liquid state or molded, high-efficiency particulate air filters may be required. Dust collection and fume control are essential.		
PLYWOOD		
Hot pressing (resin)	32	60
Cold pressing	32	15 to 25
RUBBER-DIPPED GOODS		

Manufacture	32	
Cementing	27	25 to 30*
Dipping surgical articles	24 to 27	25 to 30*
Storage prior to manufacture	16 to 24	40 to 50*
Testing laboratory	23	50*

*Dew point of air must be below evaporation temperature of solvent.
Solvents used in manufacturing processes are often explosive and toxic, requir- ing positive ventilation. Volume manufacturers usually install a solvent recovery system for area exhaust systems

TEA		
Packaging	18	65

Ideal moisture content is 5 to 6% for quality and mass. Low-limit moisture content for quality is 4%.

TOBACCO		
Cigar and cigarette making	21 to 24	55 to 65*
Softening	32	85 to 88
Stemming and stripping	24 to 29	70 to 75
Packing and shipping	23 to 24	65
Filler tobacco casing and conditioning	24	75
Filter tobacco storage and preparation	25	70
Wrapper tobacco storage and conditioning	24	75

*Relative humidity fairly constant with range as set by cigarette machine.
Before stripping, tobacco undergoes a softening operation. TOXIC AGENTS/HAZARDOUS MATERIA

TOXIC AGENTS/HAZARDOUS MATERIALS		
Process areas	20 to 39	<65

[1] Filtration as discussed in the table should correspond to the following minimums as defined in ASHRAE *Standard* 52.2:

Low efficiency	MERV 7 to MERV 8
Medium efficiency	MERV 10 to MERV 12
High efficiency	MERV 13 to MERV 14
Ultrahigh efficiency	MERV 15
HEPA	MERV 17 to MERV 20

The process engineer and owner should determine the process and HVAC filtration specifications for the specific application.

Industrial processes or regulatory requirements may change over time; thus, systems should be able to provide for future requirements (to the extent practical).

Outdoor design requirements and indoor temperature, humidity, cleanliness, noise, and allowable variations should be established by agreement with the owner. A compromise between requirements for product or process conditions and those for comfort may optimize quality and production costs.

An environment that allows a worker to safely perform assigned duties without fatigue caused by temperature and humidity may enhance performance.

Special Warning: Some industrial spaces may contain flammable, combustible, and/or toxic concentrations of vapors or dusts under either normal or abnormal conditions. In spaces such as these, there are safety issues that this chapter may not completely address. Special precautions must be taken in accordance with requirements of recognized authorities such as the National Fire Protection Association (NFPA), the Occupational Safety and Health Administration (OSHA), the American Conference of Governmental Industrial Hygienists (ACGIH), and the American National Standards Institute (ANSI). In all situations, engineers, designers, and installers who encounter conflicting codes and standards must defer to the code or standard that best addresses personnel safety.

The cascade-ventilation-system design for toxic agents or similar hazardous materials is a potential fit for such facilities. This can include a once-through, "push-pull" system, drawing air from the highly toxic areas to lower ones, with air change rates varying from 10 to 60 ach; pressures from –808.6 Pa to –62.2 Pa; and temperatures of 10 to 38°C. Applicable federal, state, and industry codes, and standards must be applied in the design of these facilities.

Terminology

The **supply system** includes **air-handling units (AHUs)** with steam and hot water heating and chilled water cooling coils, ductwork, dampers, and accessories.

Transfer air (TA) assemblies consist of ductwork, dampers, blast valves, fast-actuating dampers, and accessories.

The **exhaust air filtration system** includes **exhaust air filter units (EAFUs)** with two HEPA filters and six charcoal filters to capture highly toxic agent vapors, ductwork, dampers, accessories, and stacks.

The HVAC units are powered by off-site and essential power, and the **instrumentation and facility control system (FCS)** are fed from **uninterruptible power supply (UPS)**. FCS is a **safety instrumented system (SIS)**.

2. PROCESS AND PRODUCT REQUIREMENTS

An industrial product or process may require control of the indoor environment if it affects one or more of the following factors.

Rate of Chemical Reaction

Some processes require temperature and humidity control to regulate chemical reactions. In rayon manufacturing, for example, pulp sheets are conditioned, cut to size, and mercerized. The temperature directly controls the rate of reaction, and the relative humidity maintains the solution at a constant strength and rate of evaporation.

In drying varnish, oxidizing depends on temperature. Desirable temperatures vary with the type of varnish. High relative humidity retards surface oxidation and allows internal gases to escape as chemical oxidizers cure the varnish from within. Thus, a bubble-free surface is maintained with a homogeneous film throughout.

Rate of Crystallization

The cooling rate determines the size of crystals formed from a saturated solution. Both temperature and relative humidity affect the cooling rate and change the solution density by evaporation.

In coating pans for pills, a heavy sugar solution is added to the tumbling mass. As water evaporates, sugar crystals cover each pill. Moving the correct quantity of air over the pills at the correct temperature and relative humidity forms a smooth, opaque coating. If cooling and drying are too slow, the coating will be rough, translucent, and have an unsatisfactory appearance. If the cooling and drying are too fast, the coating will chip through to the interior.

Rate of Biochemical Reaction

Fermentation requires both temperature and humidity control to regulate the rate of biochemical reactions. Many fermentation vessels are jacketed to maintain consistent internal temperatures. Fermentors are held at different temperatures, depending on the process involved. In brewing, typical fermentor temperatures range from 7 to 11°C. Because of vessel jacketing, tight control of room temperature may not be required. Usually, space temperatures should be held as close as practical to the process temperature inside the fermentation vessel.

Designing such spaces should take into account gases and other by-products generated by fermentation. Typically, carbon dioxide is the most prevalent by-product of fermentation in brewing and presents the greatest potential hazard if a fermentor overpressurizes the seal. Provide adequate ventilation in case carbon dioxide escapes the process.

In biopharmaceutical processes, hazardous organisms can escape a fermentor; design of spaces using those fermentors should allow containment. Heat gains from steam-sparged vessels should also be accounted for in such spaces.

Product Accuracy and Uniformity

Air temperature and cleanliness affect quality in manufacturing precision instruments, lenses, and tools. When manufacturing tolerances are within 5 µm, close temperature control (typically ±2.8 K) prevents expansion and contraction of the material; constant temperature over time is more important than the temperature level. Usually, conditions are selected for personnel comfort and to prevent a film of moisture on the surface. A high-efficiency particulate air (HEPA) or ultralow-penetration air (ULPA) filter may be required.

Product Formability

Manufacturing pharmaceutical tablets requires close control of humidity for optimum tablet formation. Tableting typically requires less than 40% rh at 20°C.

Table 2 Regain of Hygroscopic Materials[*]

			Relative Humidity								
Classification	**Material**	**Description**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Natural	Cotton	Sea island—roving	2.5	3.7	4.6	5.5	6.6	7.9	9.5	11.5	14.1
textile	Cotton	American—cloth	2.6	3.7	4.4	5.2	5.9	6.8	8.1	10.0	14.3
fibers	Cotton	Absorbent	4.8	9.0	12.5	15.7	18.5	20.8	22.8	24.3	25.8
	Wool	Australian merino—skein	4.7	7.0	8.9	10.8	12.8	14.9	17.2	19.9	23.4
	Silk	Raw chevennes—skein	3.2	5.5	6.9	8.0	8.9	10.2	11.9	14.3	18.3
	Linen	Table cloth	1.9	2.9	3.6	4.3	5.1	6.1	7.0	8.4	10.2

	Linen	Dry spun—yarn	3.6	5.4	6.5	7.3	8.1	8.9	9.8	11.2	13.8
	Jute	Average of several grades	3.1	5.2	6.9	8.5	10.2	12.2	14.4	17.1	20.2
	Hemp	Manila and sisal rope	2.7	4.7	6.0	7.2	8.5	9.9	11.6	13.6	15.7
Rayons	Viscose nitrocellulose	Average skein	4.0	5.7	6.8	7.9	9.2	10.8	12.4	14.2	16.0
	Cuprammonium cellulose acetate		0.8	1.1	1.4	1.9	2.4	3.0	3.6	4.3	5.3
Paper	M.F. newsprint	Wood pulp—24% ash	2.1	3.2	4.0	4.7	5.3	6.1	7.2	8.7	10.6
	H.M.F. writing	Wood pulp—3% ash	3.0	4.2	5.2	6.2	7.2	8.3	9.9	11.9	14.2
	White bond	Rag—1% ash	2.4	3.7	4.7	5.5	6.5	7.5	8.8	10.8	13.2
	Comm. ledger	75% rag—1% ash	3.2	4.2	5.0	5.6	6.2	6.9	8.1	10.3	13.9
	Kraft wrapping	Coniferous	3.2	4.6	5.7	6.6	7.6	8.9	10.5	12.6	14.9
Miscellaneous	Leather	Sole oak—tanned	5.0	8.5	11.2	13.6	16.0	18.3	20.6	24.0	29.2
organic	Catgut	Racquet strings	4.6	7.2	8.6	10.2	12.0	14.3	17.3	19.8	21.7
materials	Glue	Hide	3.4	4.8	5.8	6.6	7.6	9.0	10.7	11.8	12.5
	Rubber	Solid tires	0.11	0.21	0.32	0.44	0.54	0.66	0.76	0.88	0.99
	Wood	Timber (average)	3.0	4.4	5.9	7.6	9.3	11.3	14.0	17.5	22.0
	Soap	White	1.9	3.8	5.7	7.6	10.0	12.9	16.1	19.8	23.8
	Tobacco	Cigarette	5.4	8.6	11.0	13.3	16.0	19.5	25.0	33.5	50.0
Miscellaneous	Asbestos fiber	Finely divided	0.16	0.24	0.26	0.32	0.41	0.51	0.62	0.73	0.84
inorganic	Silica gel		5.7	9.8	12.7	15.2	17.2	18.8	20.2	21.5	22.6
materials	Domestic coke		0.20	0.40	0.61	0.81	1.03	1.24	1.46	1.67	1.89
	Activated charcoal	Steam activated	7.1	14.3	22.8	26.2	28.3	29.2	30.0	31.1	32.7
	Sulfuric acid		33.0	41.0	47.5	52.5	57.0	61.5	67.0	73.5	82.5

* Moisture content expressed in percent of dry mass of the substance at various relative humidities, temperature 24°C.

Moisture Regain

Air temperature and relative humidity markedly influence production rate and product mass, strength, appearance, and quality in manufacturing or processing hygroscopic materials such as textiles, paper, wood, leather, and tobacco. Moisture in vegetable and animal materials (and some minerals) reaches equilibrium with moisture in the surrounding air by **regain** (the percentage of absorbed moisture in a material compared to that material's bone-dry mass). For example, if a material sample with a mass of 2.5 kg has a mass of only 2.25 kg after thorough drying under standard conditions of 105 to 110°C, the mass of absorbed moisture is 0.25 kg, 10% of the sample's bone-dry mass. Therefore, the regain is 10%.

Table 2 lists typical regain values for materials at 24°C in equilibrium at various relative humidities. Temperature change affects the rate of absorption or drying, which generally varies with the thickness, density, and nature of the material. Sudden temperature changes cause slight changes in regain even with fixed relative humidity, but the major change occurs as a function of relative humidity.

Hygroscopic materials deliver sensible heat to the air in an amount equal to the latent heat of the absorbed moisture. The amount of heat liberated should be added to the cooling load if it is significant, but it is usually quite small. Manufacturing economy requires regain to be maintained at a level suitable for rapid and satisfactory manipulation. Uniform relative humidity allows high-speed machinery to operate efficiently.

Some materials may be exposed to the required humidity during manufacturing or processing, and others may be treated separately after conditioning and drying. Conditioning removes or adds hygroscopic moisture. Drying removes both hygroscopic moisture and free moisture in excess of that in equilibrium. Drying and conditioning can be combined to remove moisture and accurately regulate the final moisture content in products such as tobacco and textiles. Conditioning or drying is frequently a continuous process in which the material is conveyed through a tunnel and subjected to controlled atmospheric conditions. For more detail, see Chapter 24 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

Corrosion, Rust, and Abrasion

In manufacturing metal products, temperature and relative humidity must be kept sufficiently low to prevent hands from sweating, thus protecting the finished article from fingerprints, tarnish, and/or etching. Salt and acid in perspiration can cause corrosion and rust in as little as a few hours. Manufacture of polished surfaces and of steel-belted radial tires usually requires medium-efficiency to HEPA filtering to prevent surface abrasion.

Air Cleanliness

Each application must be evaluated to determine the filtration needed to counter the adverse effects on the product or process of dust particles, airborne bacteria, smoke, spores, pollen, and radioactive particles. These effects include chemically altering production material, spoiling perishable goods, and clogging small openings in precision machinery. See Chapter 29 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* for details.

Static Electricity

Static electricity is often detrimental in processing light materials such as textile fibers and paper, and extremely dangerous where potentially explosive atmospheres or materials are present. Static electric charges are generally minimized when relative humidity is above 35%. Room relative humidity may need to be maintained at 65% or higher because machinery heat raises the machine ambient temperature well above the room temperature, creating localized areas of low relative humidity. Such areas could be sources of static electricity. The parts assembly area of an ammunition plant should have design conditions of 24°C and 40 to 60% rh. In addition, air-moving equipment (fans) should be spark resistant.

According to NFPA *Standard* 77, humidification increases a material's surface conductivity, but the static electric charge dissipates only if there is a conductive path to ground.

However, humidification is not a cure-all for static electricity problems. Some insulators do not adsorb or absorb moisture from the air, and high humidity does not noticeably decrease their surface resistivity. Examples include uncontaminated surfaces of some polymeric materials (e.g., plastic piping and containers, films), and the surface of petroleum liquids. These surfaces can accumulate static electric charge even when the atmosphere has a humidity of 100%.

3. PERSONNEL REQUIREMENTS

Space conditions required by health and safety standards to avoid excess exposure to high temperatures and airborne contaminants are often established by the American Conference of Governmental Industrial Hygienists (ACGIH). In the United States, the National Institute of Occupational Safety and Health (NIOSH) does research and recommends guidelines for workplace environments. The Occupational Safety and Health Administration (OSHA) sets standards based on these guidelines, with enforcement usually assigned to a corresponding state agency.

Standards for safe levels of contaminants in the work environment or in air exhausted from facilities do not cover everything that may be encountered. Minimum safety standards and design criteria are available from U.S. Department of Health agencies such as the National Institute of Health, National Cancer Institute, and Public Health Service. The U.S. Department of Energy and Nuclear Regulatory Commission establish standards for radioactive substances.

Thermal Control Levels

Industrial plants are usually designed for an internal temperature of 16 to 32°C and a maximum of 60% rh. Tighter controls are often dictated by the specific operations and processes located in the building. ACGIH (2016) established guidelines to evaluate high temperature and humidity levels in terms of heat stress (Dukes-Dobos and Henschel 1971). See Chapter 9 of the 2021 *ASHRAE Handbook—Fundamentals* for a more detailed analysis of work rate, air velocity, rest, and the effects of radiant heat.

Temperature control becomes tighter and more specific if personnel comfort, rather than avoidance of heat stress, becomes the criterion. Nearly sedentary workers prefer a winter temperature of 22°C and a summer temperature of 26°C at a maximum of 60% rh. Workers at a high rate of activity prefer 18°C; they are less sensitive to temperature changes and can be cooled by increasing the air velocity. ASHRAE *Standard* 55 provides more detailed information.

Contamination Control Levels

Toxic and/or hazardous materials are present in many industrial plants and laboratories. Gases and vapors are found near acid baths and tanks holding process chemicals. Plating operations, spraying, mixing, abrasive cleaning, and other processes generate dust, fumes, and mists. Many animal and laboratory procedures (e.g., grinding, blending, sonication, weighing) generate aerosols. Air-conditioning and ventilation systems must minimize exposure to these materials. When airborne, these materials greatly expand their range and potential for affecting more people. Chapter 11 of the 2021 *ASHRAE Handbook—Fundamentals*, OSHA requirements, and ACGIH (2016) give guidance on the health effects of various materials.

Concentrations of gaseous flammable substances must also be kept below explosive limits. Acceptable concentrations of these substances are a maximum of 25% of the lower explosive limit. Chapter 11 of the 2021 *ASHRAE Handbook—Fundamentals* provides data on flammable limits and their means of control.

Instruments are available to measure concentrations of common gases and vapors, but specific monitoring requirements and methods must be developed for uncommon ones.

4. DESIGN CONSIDERATIONS

Required environmental conditions for equipment, process, and personnel comfort must be known before selecting HVAC equipment. The engineer and owner jointly establish design criteria, including the space-by-space environment in facilities, process heat loads and exhaust requirements, heat and cooling energy recovery, load factors and equipment diversity, lighting, cleanliness, etc. Consider separating dirty processes from areas that require progressively cleaner air.

Insulation should be evaluated for initial cost and operating and energy cost savings. When high levels of moisture are required in the building, the air-conditioning and structural envelope must prevent unwanted condensation and ensure a high-quality product. Condensation can be prevented by eliminating thermal short circuits, installing proper insulation, and using vapor barriers. See Chapters 25 and 27 of the 2021 *ASHRAE Handbook—Fundamentals* for further details.

Personnel engaged in some industrial processes may be subject to a wide range of activity levels for which a broad range of temperatures and humidities are desirable. Chapter 9 of the 2021 *ASHRAE Handbook—Fundamentals* addresses recommended indoor conditions for a variety of activity levels.

If layout and construction drawings are not available, a complete survey of existing premises and a checklist for proposed facilities are necessary (Table 3).

New industrial buildings are typically single story with a flat roof and ample height to distribute air and utilities without interfering with process operations. Fluorescent fixtures are commonly mounted at heights up to 4 m, high-output fluorescent fixtures up to 6 m, and high-pressure sodium or metal halide fixtures above 6 m; LED fixtures are used at all heights. Lighting design considers light quality, diffusion, room size, mounting height, and economics. Illumination levels should conform to recommendations of the Illuminating Engineering Society of North America.

Table 3 Facilities Checklist

Construction

1. Single or multistory
2. Type and location of doors, windows, crack lengths
3. Structural design live loads
4. Floor construction
5. Exposed wall materials
6. Roof materials and color
7. Insulation type and thicknesses
8. Location of existing inlet and exhaust equipment
9. Building orientation

Use of Building

1. Product needs
2. Surface cleanliness; acceptable airborne contamination level
3. Process equipment: type, location, and exhaust requirements
4. Personnel needs, temperature levels, required activity levels, and special workplace requirements
5. Floor area occupied by machines and materials
6. Clearance above floor required for material-handling equipment, piping, lights, or air distribution systems
7. Unusual occurrences and their frequency, such as large cold or hot masses of material moved indoors
8. Frequency and length of time doors open for loading or unloading
9. Lighting: location, type, and capacity
10. Acoustical levels
11. Machinery loads, such as electric motors (size, diversity), large latent loads, or radiant loads from furnaces and ovens
12. Potential for temperature stratification

Design Conditions

1. Design temperatures: indoor and outdoor dry and wet bulb
2. Altitude
3. Wind velocity
4. Makeup air required
5. Indoor temperature and allowable variance
6. Indoor relative humidity and allowable variance
7. Indoor air quality definition and allowable variance
8. Outdoor temperature occurrence frequencies
9. Operational periods: number per day and duration

10. Waste heat availability and energy conservation incentives
11. Pressurization required
12. Mass loads from the energy release of productive materials

Code and Insurance Requirements

1. State and local code requirements for ventilation rates, etc.
2. Occupational health and safety requirements
3. Insuring agency requirements

Utilities Available and Required

1. Gas, oil, compressed air (pressure), electricity (characteristics), steam (pressure), water (pressure), wastewater, interior and site drainage
2. Rate structures for each utility
3. Potable and fire water

Air-conditioning systems can be located on the roof of the building or (ideally) in an interior equipment room. Air intakes should not be located too close to loading docks or other sources of contamination. (See the section on Air Filtration Systems.) HVAC system installation must be coordinated with other systems and equipment that compete for building space, such as piping systems, electrical bus, fire sprinklers, lighting, cranes, structural elements, etc.

Operations in the building must also be considered: some require close control of temperature, humidity, and/or contaminants. A schedule of operations is helpful in determining heating and cooling loads.

Material Handling (MH) Airlock Interface

Material handling airlock interfaces can be used in facilities that process toxic agents or similarly hazardous materials. Each MH conveyor airlock has one in gate and one out gate. These gates are equipped with position switches that send signals to the FCS to indicate the gate positions (open/closed). When both gates are closed, continuous air purging is required; when either of the gates is open, sufficient capture velocity is required to prevent backflow. Both gates should not be open simultaneously.

Each MH airlock is provided with one set of inlet and outlet transfer air assemblies. The inlet assembly consists of one big and one small on/off isolation damper. The outlet assembly has a pressure control damper. The FCS opens both inlet isolation dampers and modulates the outlet pressure control damper to satisfy the design airlock pressure. When one gate is open, the FCS adjusts the positions of the isolation and pressure control dampers to allow an airflow rate that satisfies both ventilation and design capture velocity requirements.

Process Exhaust Interface with Exhaust System. Offgas treatment (OT) process exhausts are discharged from the process blowers into the HVAC exhaust air inlet headers. The FCS enables OT blower operation only when HVAC exhaust air inlet headers are maintained at the set negative pressure. Space pressure controllers of the adjacent rooms modulate the respective dampers in the supply air ducts to balance airflow and keep the downstream room at set negative pressure.

System Shutdown. The ventilation/filtration system of toxic areas is in continuous operation. If negative pressure cannot be maintained because of a loss of essential power off site, the system is automatically shut down via the FCS, and all normally open TA isolation dampers in the toxic areas of the cascading airflow paths are closed to prevent toxic vapor migration. The fast-actuating isolation valves remain open to keep the blast resistant rooms vented to the EAFUs.

5. LOAD CALCULATIONS

Table 1 and specific product chapters of this Handbook discuss product requirements. Chapter 18 of the 2021 *ASHRAE Handbook—Fundamentals* provides appropriate heating and cooling load calculation techniques.

Solar and Transmission

The roof load is usually the largest solar load on the envelope. Solar loads on walls are often insignificant, particularly because modern factory buildings tend to be windowless. Insulating the building walls and roof almost always benefits HVAC cost and performance. Because roof surfaces can become dirty, use a dark roof color in load calculations.

Internal Heat Generation

Internal heat generated by equipment and processes, as well as products, lighting, people, and utilities, may satisfy heating load requirements. Understanding equipment operating schedules allows an appropriate diversity factor to be applied to the actual power consumption. Using connected loads may greatly oversize the system. Processes tend to operate continuously, but may be shut down on weekends or at night. Heating to some minimal level without equipment and/or process load should be considered. Consult ASHRAE research project RP-1104 (White and Pahwa 2003) for further information.

The latent load in most industrial facilities is minimal, with people and outdoor air being the primary contributors, but some processes and products do generate a latent load, which can dominate the HVAC system design. Mist collectors serving operations that use heated washers or water-based coolants operating above the targeted space temperature can contribute excessive latent loading in wet machining operations. Quantifying the latent impact for each source can help determine which exhaust streams should be discharged outdoors and not recirculated back to the space. Moisture condensation on cold surfaces must be managed when the latent load becomes very large.

Stratification Effect

The cooling load may be dramatically reduced in a work space that takes advantage of temperature stratification. A stagnant blanket of warm air directly under the roof has little effect on occupants or equipment as long as it remains undisturbed. Heat sources near the stagnant air have little effect on the cooling load. When the ceiling or roof is high, 20 to 60% of the heat energy rises out of the cooling zone, depending on building construction and the temperature of heat sources. Switching to a return air location near the roof could be cost effective, because it takes advantage of higher temperatures at the roof.

Supply and return air ducts should be installed as low as practical to avoid mixing the warm boundary layers in cooling mode. The location of supply air diffusers generally establishes the stratified air boundary. Spaces with a low occupant-to-floor-area ratio adapt well to using low quantities of supply air with spot cooling for personnel.

Makeup Air

Makeup air provides ventilation and building pressurization. It must be filtered and conditioned to blend with return air and then distributed to the conditioned space. The quantity of makeup air must exceed that of the exhaust air to positively pressurize the building. Makeup air quantity may be varied to accommodate an exhaust system with intermittently operating elements. Heat and cooling recovery from the exhaust airstream can substantially reduce the outdoor air load.

Processes requiring an extensive amount of exhaust air should ideally be placed in an area of the plant provided with minimal heating and no refrigerated air conditioning. Ventilation air may be required to reduce the quantity of health-threatening fumes, airborne bacteria, fugitive aerosols, or radioactive particles. Minimum ventilation rates must meet the requirements of ASHRAE *Standard* 62.1. Consult the owner's industrial hygiene or engineering representative to determine if ventilation rates in excess of this standard may be warranted.

Economizers can take advantage of ambient conditions and possibly satisfy HVAC loads without added heating or cooling for much of the year.

Fan Heat

Heat is generated by fans that move and pressurize the air. This heat is not felt by the occupants but does add to the cooling load. The discharge air temperature of a draw-through cooling arrangement requires cooler air to the fan to accommodate the temperature increase of air passing through the fan. The increase is more significant in systems with higher discharge air pressures.

6. PRESSURIZATION

Room-to-room pressurization is an essential method for contamination control. Without pressurization, surrounding contamination (e.g., particulates, gases, hot or cold air, moisture) can enter the room by infiltration through doors, windows, cracks, pass-throughs and penetrations for pipes or ducts, etc. The cleanest room should have the highest room pressure, with decreasing pressure corresponding to decreasing cleanliness. A differential pressure around 12.5 or 25 Pa is often used.

Pressurization calculations can be performed by using the procedures and charts in Chapter 18 of the 2021 *ASHRAE Handbook—Fundamentals*, or those in Chapter 5 of Spitler (2009). Using the charts in Spitler, calculate the building exfiltration at designated room pressurization level. Also, in accordance with ASHRAE *Standard* 62.1, determine the required outdoor air rate using the actual number of occupants, and identify the total exhaust air volume from the building. The sum of exfiltration air volume plus exhaust rate (or required outdoor air, whichever is greater) is the total ventilation rate under the designated building pressurization.

To ensure the designated pressurization level, perform a leak test for exterior and interior walls, partitions, doors, and windows between two adjacent areas with different pressurization levels, roof, exterior doors and windows, connections between wall and roof, and any building elements between two areas with different pressurization levels. All major leaks must be eliminated before HVAC systems start-up.

If pressurization is a critical attribute for maintaining room cleanliness in areas such as plant process control rooms, computer rooms, etc., then the crack area may need to be estimated and the pressurization air quantity calculated using an equation such as Equation (11) or (12) in Chapter 54, where the crack is treated as an orifice and the required airflow is defined as a function of pressure differential. Adequate design margins should be incorporated in the pressurization system design to allow for building envelope seal degradation over the structure's life. If the pressurization is required for safety or code compliance, make provisions in the design for periodic surveillance and testing.

Explosion Management

Particularly in facilities that process toxic agents and other hazardous materials, the possibility of explosion should be addressed. Blast valve assemblies are installed at points of air transfer and exhaust air penetrations through the blast-resistant building envelope. An explosion-generated pressure wave of 103.5 kPa or greater immediately closes the affected blast valves (spring balanced pressure disks). The inlet and outlet blast valves close within 10 ms. The fast-actuating dampers are provided in series with the blast valve assemblies. On receiving alarms from explosion switches located within the affected blast-resistant rooms, the FCS automatically closes the corresponding fast-actuating isolation dampers, and fast-actuating isolation dampers powered by the nitrogen system close within 500 ms.

The blast valves are fully automatic in operation. After an explosion, when the room pressure decreases to the facility-specific set pressure, the FCS opens the exhaust-side fast-acting dampers first, and then opens those in the transfer air assemblies when the room pressure decreases to a lower (facility specific) set pressure, to restore the cascading ventilation path.

Any room involved in an explosion immediately raises all related upstream room pressures due to the cascading airflow blockage. Based on the room pressure control, the FCS automatically throttles the respective pressure dampers installed in the supply air ducts to minimize the pressure upset in the upstream rooms. The airflow blockage may create a ripple effect that causes the system header pressure controller to slow the fan speeds of the EAFU and supply AHU. In some rooms, there is a bypass exhaust pathway open to bypass exhaust to allow venting from rooms to the exhaust header.

7. SYSTEM AND EQUIPMENT SELECTION

Industrial air-conditioning equipment includes heating and cooling sources, air-handling and air-conditioning apparatus, filters, and an air distribution system. Components should be selected and the system designed for long life with low maintenance and operating costs conducive to low life-cycle cost.

Systems may consist of the following:

- Heating-only in cool climates, where ventilation air provides comfort for workers
- Air washer systems, where high humidities are desired and where the climate requires cooling
- Heating and evaporative cooling, where the climate is dry
- Heating and mechanical cooling, where temperature and humidity control are required and other means of cooling are insufficient

All systems include air filtration appropriate to the contaminant control required.

Careful evaluation should determine zones that require temperature control, especially in large, high-bay areas where the occupied zone is a small portion of space volume. ASHRAE *Standard* 55 defines the occupied zones as from the floor to 1.8 m high, more than 1 m from exterior walls or fixed conditioning equipment, and 0.3 m from interior walls.

8. HEATING SYSTEMS

Floor Heating

Floor heating is often desirable in industrial buildings, particularly in large, high-bay buildings, garages, and assembly areas where workers must be near the floor, or where large or fluctuating outdoor air loads make maintaining ambient temperature difficult.

Floors may be tempered to 18 to 21°C by embedded hydronic systems, electrical resistance cables, or warm air ducts as an auxiliary to the main heating system. Heating elements may be buried deep in the floor (150 to 450 mm) to allow slab warm-up at off-peak times, thus using the floor mass as heat storage to save energy during periods of high use.

Floor heating may be the primary or sole heating means, but floor temperatures above 29°C are uncomfortable, so such use should be limited to small, well-insulated spaces.

Unit and Ducted Heaters

Gas, oil, electric, hot-water, or steam-fired unit heaters with centrifugal or propeller fans are used for spot heating areas and may be arranged in multiples for heating an entire building. Temperatures can be varied by individual thermostatic control. Unit heaters should be located so that the discharge (throw) reaches the floor adjacent to and parallel with the outer wall, and spaced to produce a ring of warm air moving peripherally around the building. In industrial buildings with heat-producing processes, heat tends to stratify in high-bay areas. In large buildings, additional heaters should be placed in the interior so that their discharge reaches the floor to reduce stratification. Downward-discharge unit heaters in high bays and large areas may have a revolving discharge. Gas- and oil-fired unit heaters should not be used where corrosive vapors are present. Furthermore, care must be taken to avoid selecting a unit configuration wherein return air from the space is drawn through the combustion zone of any direct-fired gas burners, because unintended byproducts of combustion may result.

Ducted heaters include large direct- or indirect-fired heaters, door heaters, and heating and ventilating units. They usually have centrifugal fans.

Unit heaters and makeup air heaters commonly temper outdoor air that enters buildings through open doors. Mixing quickly brings the space temperature back to the desired setting after the door is closed. The makeup air heater should be applied as a door heater in buildings where the doors are large and open for extended periods, such as doors for large trucks or railroad cars. Such large doors often use ductwork drops across the top and along both sides of the door, with slotted diffusers to induce an air-curtain effect.

Unit heaters are also needed in buildings that have considerable leakage or a sizeable negative pressure. These units help pressurize the door area, mix the incoming cold air, temper it, and quickly bring the area back to the desired temperature after the door is closed.

Door heating units that resemble a vestibule operate with airflow down across the opening and recirculated from the bottom, which helps reduce cold drafts across the floor. These units are effective on high-usage doors under 3 m tall. Additional information on heating is given in Chapter 27 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

Infrared Heaters

High-intensity gas, oil, or electric infrared heaters transfer heat directly to the occupants, equipment, and floor in the space without appreciably warming the air, though some air heating occurs by convection from objects heated by the infrared heaters. These heaters are classified as either near- or far-infrared heaters, depending on how close the wavelengths they emit are to visible light. Near-infrared heaters emit a substantial amount of visible light.

Both vented and unvented gas-fired infrared heaters are available as either individual radiant panels or as a continuous radiant pipe. Pipe-type heaters include burners 4.5 to 9 m apart and an exhaust vent fan at the end of the pipe. Unvented heaters require exhaust ventilation to remove flue products from the building and to prevent moisture from collecting on the walls and ceiling.

Infrared heaters are common in the following applications:

- High-bay buildings, where heaters are usually mounted 3 to 9 m above the floor, along outer walls, and tilted to direct maximum radiation to the floor. If the building is poorly insulated, the controlling thermostat should be shielded to avoid influence from the radiant effect of the walls and the cold walls.
- Semi-open and outdoor areas, where people can be comfortably heated directly and objects can be heated to avoid condensation.
- Loading docks, where snow and ice can be controlled by strategic placement of near-infrared heaters.

Additional information on both electric and gas infrared heating is given in Chapter 16 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

9. COOLING SYSTEMS

Common cooling systems include refrigeration equipment, evaporative coolers, and high-velocity ventilation air.

For manufacturing operations, particularly in heavy industry where mechanical cooling cannot be economically justified, evaporative cooling systems often provide good working conditions, as discussed in Chapter 41 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*. If the operation requires heavy physical work, spot cooling by ventilation, evaporative coolers, or refrigerated air can be used. To minimize summer discomfort, high outdoor ventilation rates may be adequate in some hot-process areas. A mechanical air supply with good distribution is needed in all these operations.

Refrigerated Cooling Systems

The most commonly used refrigerated cooling systems are roof-mounted, direct-expansion packaged units. Larger systems may use chilled water distributed to air-handling units.

Central system condenser water rejects heat through a cooling tower. Refrigerated heat recovery is particularly advantageous in buildings with simultaneous need to heat exterior spaces and cool interior spaces.

Mechanical cooling equipment should be selected in multiple units. This lets the equipment match its response to fluctuations in the load and allows maintenance during off-peak operation periods. Packaged refrigeration equipment commonly uses positive-displacement (reciprocating, scroll, or screw) compressors with air-cooled condensers. When equipment is on the roof, the condensing temperature may be affected by warm ambient air, often 5 to 10 K higher than design outdoor air temperature. ASHRAE *Standard* 15 provides rules for the type and quantity of refrigerant in direct air-to-refrigerant exchangers.

Desiccant-based systems should be considered for processes that require dew points below 10°C (e.g., pharmaceutical processing).

Evaporative Cooling Systems

Evaporative cooling systems may be direct or indirect evaporative coolers or air washers. Evaporative coolers have water sprayed directly on wet surfaces through which air passes. Any excess water drains off. Air washers recirculate water, and the air flows through a heavily misted area. Water atomized in the airstream evaporates, cooling the air. For either type, using refrigerated water simultaneously cools and dehumidifies the air. For spaces that require an air washer and high relative humidities (e.g., tobacco and textile processing areas), heat provided to the sump should provide sufficient energy for humidification beyond that recovered in the return airstream.

Temperature and humidity of the exit airstream may be controlled by varying the temperature of the chilled water and reheat coil and by varying the quantity of air passing through the reheat coil with a dew-point thermostat.

It may be necessary to filter air entering the evaporative cooler to ensure that dust or lint does not accumulate and clog the nozzles or evaporating pads. Chemical treatment of the water may be necessary to prevent mineral build-up or biological growth on the pads or in the pans.

10. AIR FILTRATION SYSTEMS

Air filtration systems remove contaminants from the building supply or exhaust airstreams. Supply air filtration at the equipment intake removes particulate contamination that may foul heat exchange surfaces, contaminant products, or present a health hazard to people, animals, or plants. Gaseous contaminants must sometimes be removed to prevent exposing personnel to odors or health-threatening fumes. Return air with a significant potential for carrying contaminants should be recirculated only if it can be filtered enough to minimize personnel exposure. Return air should be exhausted if monitoring and contaminant control cannot be ensured.

The supply filtration system usually includes collection media or a filter, a media-retaining device or filter frame, and a filter housing or plenum. For more on filtration systems, see Chapter 29 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

Exhaust Air Filtration Systems

Exhaust air systems are either (1) general systems that remove air from large spaces or (2) local systems that capture aerosols, heat, or gases at specific locations in a room and transport them so they can be collected, inactivated, and safely discharged to the atmosphere. Air in a general system usually requires minimal or no treatment before being discharged to the atmosphere. Air from local exhaust systems can sometimes be safely discharged to the atmosphere, but may require contaminant removal before being discharged. Exhausted air must meet appropriate air quality standards when defined as a release point based on plant air permitting requirements. Chapters 31 and 32 of this volume and Chapter 30 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* have more information on industrial ventilation and exhaust systems.

In exhaust air emission control, fabric-bag filters, glass-fiber filters, venturi scrubbers, and electrostatic precipitators all collect particles. Packed-bed or sieve towers can absorb toxic gases. Activated carbon columns or beds, often with oxidizing agents, are frequently used to absorb toxic or odorous organics and radioactive gases.

Outdoor air intakes should be carefully located to avoid recirculating contaminated exhaust air. Wind direction, building shape, and location of effluent source strongly influence concentration patterns.

Air patterns from wind flowing over buildings are discussed in Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*. The leading edge of the roof interrupts smooth airflow, reducing air pressure at the roof and on the lee side. Exhaust air must be discharged through either a vertical stack terminating above the building turbulent-air boundary or a shorter stack with a high enough discharge velocity to project the effluent through the air boundary into the undisturbed air passing over the building. The high discharge prevents fume damage to both the roof and roof-mounted equipment, and keeps fumes away from building air intakes. A high vertical stack is the safest, simplest solution to fume dispersal.

Contamination Control

In addition to maintaining thermal conditions, air-conditioning systems should control contaminant levels to provide a safe and healthy environment, good housekeeping, and quality control for the processes. Contaminants may include gases, fumes, mists, or airborne particulate matter. They may be produced by a process in the building or contained in the outdoor air.

Contamination can be controlled by preventing the release of aerosols or gases into the room and by diluting room air contaminants. If the process cannot be enclosed, it is best to capture aerosols and gases near their source with a local exhaust system that includes a hood or enclosure, ducts, fan, motor, and exhaust stack.

Dilution controls contamination in many applications but may not provide uniform safety for personnel. High local concentrations of contaminants can exist despite a high overall dilution rate.

11. EXHAUST SYSTEMS

An exhaust system draws a contaminant away from its source and removes it from the space. An exhaust hood surrounding the point of generation contains the contaminant as much as is practical. The contaminant is transported through ductwork from the space, cleaned as required, and exhausted to the atmosphere. The hood inlet air quantity is established by the velocities required to convey the airborne contaminant. Chapter 33 has more information on local exhaust systems.

Design values for average and minimum face velocities are a function of the characteristics of the most hazardous material the hood is expected to handle. Minimum values may be prescribed in codes for exhaust systems.

Contaminants with greater mass may require higher face velocities for control. Design face velocities should be set carefully: too high a velocity can be as hazardous as one too low. Refer to ACGIH (2016) and ASHRAE *Standard* 110 for more information.

Exhaust ductwork should be sized to provide velocities high enough to keep contaminants in suspension. Velocities should exceed the settling velocities for the expected particle size distribution.

Selection of materials and construction of exhaust ductwork and fans depend on the nature of the contaminant, ambient temperature, lengths and arrangement of ducts, method of hood fan operation, and flame and smoke spread ratings. Exhausts containing acids, alkalis, solvents, or oils should address corrosion, dissolution, and melting.

Condensation in ferrous metal ducts may contribute to corrosion. Consider the dew point of process gases with respect to the surrounding ambient temperature. Condensation can be managed by reducing the dew point of the exhaust stream, by vapor barriers, or by using thermal insulation.

12. OPERATION AND MAINTENANCE

Equipment room layout should provide space for cleaning, servicing, and replacing components quickly to minimize system outages. Maintenance of refrigeration and heat rejection equipment is essential for proper performance without energy waste. Maintenance includes changing system filters periodically. Industrial applications are dirty, so proper selection of filters, careful installation to avoid air bypassing the filter, and prudent filter changing to prevent overloading and blowout are required. Dirt lodging on the tips of forward-curved fan blades appreciably reduces air-handling capacity. Fan and motor bearings require lubrication, and fan belts need periodic inspection. Direct- and indirect-fired heaters should be inspected annually. Steam and hot-water heaters have fewer maintenance requirements than comparable equipment with gas or oil burners.

For system compatibility, water treatment is essential. Air washers and cooling towers should not be operated unless the water is properly treated.

13. HEAT RECOVERY AND ENERGY CONSERVATION

The process industry often presents opportunities to recover heat from the exhaust airstream for use in preconditioning makeup air. Extreme care must be taken to ensure compatibility of heat exchanger components and materials with contaminants often found in exhaust streams. For example, brewery spaces are held between 1.7 and 10°C. Exhaust air passes over a heat recovery wheel to precondition outdoor makeup air, which in turn controls the level of carbon dioxide contamination. Coated aluminum heat recovery wheels can be subject to premature failure because of caustic cleaning materials conveyed in the exhaust system.

Additional consideration should be given to the assessment of risk associated with the heat recovery strategy. Frequently, downtime in large industrial facilities can exceed millions of dollars per hour. Costs associated with failure of a heat recovery device can easily overcome savings in energy costs if the result is a facility shutdown.

14. CONTROL SYSTEMS

Control systems for industrial processes and air-conditioning systems differ from commercial direct digital control (DDC) systems in important ways. Modern industrial control systems fall into three categories:

- **Programmable logic controller (PLC) systems.** These systems are chosen for industrial environments because of their inherent robustness and speed. They are rated to operate in environments of 50°C, as opposed to 40°C for DDC systems. Also, because the controller does not look up point information from a central database, the program scan speed is much greater: a total program scan time of less than 0.1 s is not unusual. Local display screens are available for field panel mounting; however, one of the following two systems is required to provide overall plantwide data gathering and reporting.

- **Distributed control systems (DCS).** Like commercial DDC systems, DCS systems are defined as shared logic controllers as opposed to programmable logic controllers. A shared logic controller shares the resources a common database of point names to provide point attribute data such as units (% rh, kPa, etc.), point range (0 to 100% rh, 0 to 690 kPa, etc.), logical point name, and software address. This information is shared across all controllers in a given network of controllers and then reported to the user through the graphical user interface (GUI). DCS systems can provide an embedded GUI like DDC systems do, or can work seamlessly with a third-party SCADA system.

- **Supervisory control and data acquisition (SCADA) systems.** SCADA systems are typically overlays that acquire and store data from subordinate DCS, PLC, or other systems. They provide the GUI and display operating system parameters. By contrast, commercial DDC or building management systems (BMS) have the graphic engine and data acquisition and storage system embedded into the base operating system. Industrial requirements typically preclude DDC systems to act as a SCADA system because of their limited data communication networks and inability to reliably handle large numbers (>10,000) of input and output points in a given system.

Industrial controllers can be installed, configured, and/or maintained by third-party providers (known as **system integrators**) or by the manufacturer themselves. They have open communication protocols and exchange information over various network protocols such as Modbus (North America) or Profibus (EU). These protocols allow communication between different brands of controllers and the overall network, with BACnet® capability for occasional integration with commercial DDC system where deemed necessary. Industrial systems also allow Ethernet-based protocol (TCP/IP) for data exchange in high-speed networks as well as remote Internet-based monitoring and control.

Industrial control systems are documented differently than commercial-based DDC systems. The American National Standards Institute (ANSI), in cooperation with International Society of Measurement and Control (ISA), established a standard that defines how engineering documents are prepared (e.g., process and instrumentation diagrams [P&IDs], instrument naming or tagging convention). Commercial systems generally are documented using standards defined by the system manufacturer, who installs and maintains the systems, and their technicians can operate across several facilities or in different cities.

Industrial instrumentation is also quite different from commercial DDC systems. Instruments are typically in housings listed for hazardous environments that also provide excellent protection from the moisture, dust, and dirt frequently found in an industrial environment. Signal types are usually 4 to 20 mA over the range of 0 to 100% of the transmitter span. Hazardous locations use instruments listed specifically for the hazard division and group. Intrinsic safety barriers provide a level of protection by limiting the amount of power consumed by these devices to 1 W or less.

15. LIFE AND PROPERTY SAFETY

Human life and property safety must be thoroughly considered in all types of industrial project design, construction, installation, start-up, testing, operation, and maintenance. The life and property safety concern should include (but not be limited to) hazards generated in the property and related prevention, effective fire and hazardous gas detection and alarm systems, active fire protection systems, room-to-room pressurization and smoke control, homeland security and emergency response plans, etc. Refer to related NFPA and ACGIH publications for detailed regulations.

Toxic Agent/Hazardous Materials Processing Facility

Fire. When the fire alarm control panel (FACP) receives alarm signals from local smoke/heat detectors, it sends signals to shut off the smoke/fire dampers (BDs) in the affected fire zone. The FACP also sends an alarm signal to the FCS. The position switch from each BD sends a feedback signal to FCS confirming that the BD has been fully closed; otherwise, a fault alarm is activated at the FCS. Due to airflow blockage, the cascading system upstream room pressure increases, and downstream room pressure decreases further. To minimize room pressure upsets, the FCS automatically throttles the upstream supply air pressure control dampers and downstream exhaust air pressure control dampers.

During the pressure surge transition, the cascading system pressures may rise at the supply air plenum and become more negative at the exhaust air inlet headers. FCS pressure feedback control automatically reduces the fan speed of the AHUs and EAFUs accordingly. If pressure surges are significant and occur faster than the FCS pressure control response, pressure and vacuum relief dampers in the supply and exhaust headers automatically open to protect ductwork from damage.

After the fire has been cleared, the smoke/fire dampers are manually reset to the open position from the FACP. Bypass exhausts are provided within fire zones and located strategically to mitigate pressure excursion resulting from a fire in critical process rooms. When the bypass mode is initiated, FCS closes the inlet transfer air isolation dampers to suppress fire spread, which prevents heat and smoke damage to the EAFUs; activates the bypass exhaust; and places pressure controllers into automatic pressure control mode to minimize pressure surge and airflow impact to surrounding rooms.

Loss of Power. During loss of off-site power, essential power is provided to EAFUs and AHUs by the dedicated generator and the standby generators to maintain the toxic areas at slight negative pressure relative to ambient to prevent toxic vapor escaping. The adjustable-speed drives (ASDs) of the fans of EAFUs and AHUs are programmed to allow fast ramp-up when power is restored. If a dedicated generator starts and standby generators fail, the FCS continuously monitors and controls the cascading ventilation system to maintain slight negative pressure with reduced flows. When all the generators fail to start, and the total exhaust airflow rate drops to 15% of the system design capacity, the FCS starts closing all TA isolation dampers to prevent toxic vapor migration from highly toxic areas to areas of lower concentrations.

Equalizing System Flows. Equalizing the flow rates of all the AHUs and EAFUs provides smooth operation of the HVAC supply and exhaust system in a cascade ventilation system to maintain varying differential pressures in the space. To accomplish this, an input from the pressure differential value set in the supply plenum and exhaust duct header are provided to the respective flow-indicating controllers (FICs) of the facility AHUs or EAFUs to maintain pressure at the supply plenum and the exhaust duct header. This input value going to the FICs, which is scaled from pressure differential value to flow value, corresponds to the respective supply plenum or the exhaust duct header pressure value. The outputs of the FICs go to the respective ASDs that control fan speed to maintain the supply plenum or the exhaust duct header pressure while equalizing the flow rates of all the AHUs or EAFUs.

Starting System Offline Unit. While starting the offline unit and shutting down the online unit, the oncoming AHU or EAFU is given a signal by the FCS that can sometimes cause flow through the unit to overshoot before stabilizing at the design flow rate, activating high-flow alarms. This can be prevented with following steps:

- The FCS provides an initial tracking signal for the FIC of the AHU or EAFU during unit startup.
- The initial tracking signal is calculated using the average of the FIC outputs of other operating units. This lower initial tracking signal prevents the oncoming unit from overshooting and reaching the high flow alarm value.
- The tracking mode will be released after the oncoming unit's FIC output remains constant for set time as determined during testing.

Once the oncoming EAFU or AHU flow is stabilized, then the FIC will transition from the startup control mode to the operating control mode.

16. COMMISSIONING

Several types of HVAC commissioning processes are used for industrial HVAC projects: (1) overall HVAC project commissioning, (2) construction HVAC project commissioning, and (3) existing-building HVAC commissioning (**retrocommissioning**). The process described here applies to both new construction and major renovations.

For new construction, commissioning should start at the project's inception during the predesign phase, and continue through design, construction, acceptance, training, operation, maintenance, and postacceptance.

The owner should retain an HVAC commissioning authority (CA) at the very beginning of the predesign phase. The CA develops the scope of the commissioning and reviews the design intent during predesign to ensure the project accommodates the commissioning process. The CA also coordinates with the owner, design engineer, and HVAC contractor during preparation of project design and construction documents; this includes the overall project execution schedule, preparation and issue of commissioning and construction specifications, and review of contractor submittals. This paves the way for commissioning, and the CA continues to carry out and complete the implementation of the planning commissioning process.

Participants include the start-up personnel listed during start up, the test and balance company, the process operators, the owner's project authorities, and the commissioning personnel.

Commissioning documents include the following:

- Certificates and warranties of system completion, along with a complete set of as-built drawings submitted by mechanical, electrical, plumbing, control, and fire protection contractors.
- If available, all major equipment installation, operation, and maintenance (IOM) manuals from equipment manufacturers.
- Records of significant problems and solutions that occurred during start-up and testing.
- Certified system test and balance reports, including verified major equipment models and capacities, and tested performance values conforming to system criteria.
- A complete room-to-room pressurization map submitted by the test and balance company.
- A control system IOM submitted by the control contractor.
- When applicable, a certificate of as-built cleanroom cleanliness. The report should be based on testing when the cleanroom facility is complete and all services are connected and functional, but without equipment and operating personnel in the cleanroom.
- If the contract scope requires, a certificate of cleanroom cleanliness with process running and with operating personnel in the facility.
- A commissioning report signed by all attendees.

Commissioning requirements for industrial air-conditioning systems (particularly central heating and cooling equipment such as chillers, boilers, air compressors, etc., or nonprocess air-handling systems) often can follow the procedures outlined in ASHRAE *Guidelines* 0 and 1.1, which use statistical evaluations to define the scope of commissioning activities. Most industrial applications, however, use full commissioning of each point instead of statistical evaluation, because of the process requirements for reliability and the basic functional requirements.

In facilities regulated by government agencies, **qualification** (or **validation**) of the air-conditioning systems may be required. In these cases, use the appropriate government and industry-specific guidelines instead of ASHRAE *Guidelines* 0 and 1.1. Qualification follows a more rigorous set of standards for acceptance than commercial commissioning:

- **Risk assessment** determines the level of qualification that a given system should undergo. It considers the severity the risk presents (e.g., loss of life or of the system) and the likelihood of occurrence (e.g., once during system life, once a year). The highest risks are those that have the greatest severity as well as the most likely occurrence. In those cases, the qualification requirements are the highest.

- **Life-cycle assessment** is most often used in industrial control systems. Required documentation typically consists of specifications for user requirements, functionality, and design, and the system is qualified under an installation qualification to verify the design specification. An operational qualification verifies the requirements of the functional specification, and the performance qualification verifies the requirements of the user requirement specification.

- **Testing plans and strategies** should reflect the results of the risk assessment and life-cycle assessment. The plans and strategies should also address the resources required to conduct the qualification, the documentation to be developed, and the appropriate owner team to accept the results. Most importantly, it defines the procedure to be followed when a discrepancy is found.

Testing documentation is developed to qualify the system so it can pass an audit by the regulatory agency or a third party retained by the owner.

For more information on commissioning, see Chapter 44 and ASHRAE *Standard* 202-2018.

REFERENCES

ASHRAE members can access *ASHRAE Journal* articles and ASHRAE research project final reports at technologyportal.ashrae.org. Articles and reports are also available for purchase by nonmembers in the online ASHRAE Bookstore at www.ashrae.org/bookstore.

ACGIH. 2016. *Industrial ventilation: A manual of recommended practice,* 29th ed. American Conference of Governmental Industrial Hygienists, Cincinnati, OH.

ASHRAE. 2019. The commissioning process. ASHRAE *Guideline* 0-2019.

ASHRAE. 2007. HVAC&R technical requirements for the commissioning process. ASHRAE *Guideline* 1.1-2007.

ASHRAE. 2022. Safety code for mechanical refrigeration. ANSI/ASHRAE *Standard* 15-2022.

ASHRAE. 2020. Thermal environmental conditions for human occupancy. ANSI/ASHRAE *Standard* 55-2020.

ASHRAE. 2022. Ventilation for acceptable indoor air quality. ANSI/ASHRAE *Standard* 62.1-2022.

ASHRAE. 2016. Method of testing performance of laboratory fume hoods. ANSI/ASHRAE *Standard* 110-2016.

ASHRAE. 2018. Commissioning process for buildings and systems. ANSI/ASHRAE/IES *Standard* 202-2018.

Dukes-Dobos, F., and A. Henschel. 1971. The modification of the WNGT Index for establishing permissible heat exposure limits in occupational work. U.S. Public Health Service *Publication* TR-69.

NFPA. 2014. Recommended practice on static electricity. *Standard* 77. National Fire Protection Association, Quincy, MA.

Spitler, J.D. 2009. Infiltration. Ch. 5 of *Load calculation applications manual*. ASHRAE.

White, W.N., and A. Pahwa. 2003. Heat gain from electrical and control equipment (RP-1104). ASHRAE Research Project, *Final Report.*

BIBLIOGRAPHY

Azer, N.Z. 1982. Design guidelines for spot cooling systems. Parts 1 and 2. *ASHRAE Transactions* 88(2):81-95 and 88(2):97-116. *Papers* HO-2667 and HO-2668.

Gorton, R.L., and H.M. Bagheri. 1987. Verification of stratified air conditioning design. *ASHRAE Transactions* 93(2):211-227. *Paper* 3067.

Gorton, R.L., and H.M. Bagheri. 1987. Performance characteristics of a system designed for stratified cooling operation during the heating season. *ASHRAE Transactions* 93(2):367-381. *Paper* 3077.

ISPE. 2008. *GAMP® 5: A risk-based approach to compliant GxP computerized systems.* International Society for Pharmaceutical Engineering, Tampa, FL.

ISA. 2009. Instrumentation symbols and identification. ANSI/ISA *Standard* 5.1-2009. International Society of Automation, Research Triangle Park, NC.

NFPA. 2018. Flammable and combustible liquids code. *Standard* 30. National Fire Protection Association, Quincy, MA.

NFPA. 2018. National fuel gas code. *Standard* 54. National Fire Protection Association, Quincy, MA.

NFPA. 2017. Standard for fire and explosion prevention during cleaning and purging of flammable gas piping systems. *Standard* 56. National Fire Protection Association, Quincy, MA.

NFPA. 2016. Standard for the productions, storage, and handling of liquefied natural gas (LNG). *Standard* 59A. National Fire Protection Association, Quincy, MA.

NFPA. 2015. Boiler and combustion systems hazards code. *Standard* 85. National Fire Protection Association, Quincy, MA.

NFPA. 2018. Life safety code®. *Standard* 101. National Fire Protection Association, Quincy, MA.

NFPA. 2017. Standard for the prevention of fires and explosions in wood processing and woodworking facilities. *Standard* 664. National Fire Protection Association, Quincy, MA.

NFPA. 2016. Standard on disaster/emergency management and business continuity programs. *Standard* 1600. National Fire Protection Association, Quincy, MA.

West, D.L. 1977. Contamination dispersion and dilution in a ventilated space. *ASHRAE Transactions* 83(1):125-140.

White, W. 2010. Heat gain from electrical and control equipment in industrial plants, part II (RP-1395). ASHRAE Research Project, *Final Report.*

Yamazaki, K. 1982. Factorial analysis on conditions affecting the sense of comfort of workers in the air conditioned working environment. *ASHRAE Transactions* 88(1):241-254. *Paper* HO-2677.