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HVAC Layout and Design: What Every Mechanical Engineer Should Know Course 1 of 4

by

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Understanding and implementing the HVAC layout and design process requires knowledge of the building use, applicable Codes and Standards, effects of HVAC on human comfort and/or process needs, primary equipment and system design application, primary equipment selection as well as ductwork, piping and terminal equipment design. With so many design choices, project execution strategies, coordination items and workflows it can be difficult for engineers to efficiently execute their designs. This is Course 1 in a four-part series that will provide key insights and knowledge I have accumulated over my 25+ years in the industry.

Over the years, I have successfully completed HVAC and mechanical designs for various market sectors including Residential, Light Commercial, Commercial, K-12, Higher Education, Healthcare, Pharmaceutical, Food & Beverage, Refrigerated/Warehousing and Industrial Manufacturing. Each market sector represents a different building use and function thereby creating unique design challenges. Project execution strategies vary by market sector which directly affects the HVAC design process and approach. This first section of Course 1 will: 1.) provide clear definition of each market sector; 2.) describe typical HVAC equipment and system applications for each; and 3.) briefly describe common project execution strategies for each market sector.

These descriptions will serve as our basis for discussion moving forward. The second section Course 1 will further describe the various project delivery and execution strategies. The third section of Course 1 will describe applicable Codes and Standards that should be applied to HVAC design given the building use. A summary will be provided tying the three topics together and descriptions provided for subsequent Courses 2, 3 and 4.

MARKET SECTORS

Residential is defined as a single dwelling unit occupied by a single family and may be single story or multi-story. The dwelling unit may include a finished or unfinished basement and attached or detached garage. Typical HVAC consists of residential DX Split System (Photo 1)[1] utilizing supply air diffusers in each room with return air grilles in each space and/or common spaces. The DX Split system consists of an indoor fan-coil unit and outdoor, air-cooled condensing unit or heat pump. The indoor fan-coil unit (or furnace) is single wall, lined with insulation and may have gas heating, electric heating or may rely on heat pump operation for heating depending upon the climate. Larger, multi-story single family dwelling units may include

PHOTO 1: TYPICAL RESIDENTIAL DX SPLIT SYSTEM

multiple DX Split Systems, single DX Split System with Zone Damper Control or combination of both. For example, it is common for homes over ~4,000 square feet to include a separate DX Split System for the upstairs and have a Zoned Damper Control System for the First Floor and Basement served by a single DX Split System. Each zone includes a separate zone thermostat. Sheet metal ductwork is typically low velocity, extended plenum design with supply/return air devices. Restrooms are provided with constant volume exhaust fans that operate via interlock with light switch. Ductwork distribution design and more detailed Control descriptions for these various systems will be included in Course 3.

Other HVAC system and equipment types for Residential applications include ground-source, geothermal heat pumps with distribution ductwork and air devices, radiant heating/cooling, high velocity central air conditioning systems, residential air-cooled chillers serving indoor air handling units (AHU's) and heating only systems with window mounted packaged terminal air-conditioners (as required) in temperate climates. Heating only systems may include fuel oil and/or natural gas fired boilers producing steam or hot water. The steam or hot water is distributed to floor mounted radiators or other terminal units. Further descriptions of each system type will be included in another Course 4.

For cooling, Residential projects in the Midwest, Climate Zone 4A, generally require 12,000 Btuh (1 Ton)[2] of cooling for every 600-850 sq. ft.. This is referred to as 600 s.f./ ton or 850 s.f./ton. Unless it is a walk-out, basements are not generally figured into the calculation. The smaller the home, the less square foot per ton figured. For example, a 1,000 sq. ft. home with no basement (occupiable space) may be provided with a nominal 2 ton Split System (rounded up from 1.67 tons because manufacturer's may not offer a 1.67 ton unit). A 3,200 sq. ft. home with no basement (occupiable space) may be provided with a nominal 4 ton unit. Supply airflow is estimated to be (on average) 400 cubic feet per minute (CFM)/ton. So, a nominal 4 ton unit would supply ~1,600 CFM. It takes 69,440 Btuh of heating (52.1 MBH) to heat that amount of air from 45F to 85F. This is calculated using the Equation (1):

$$Sensible\ Heat[Btuh] = SA\ Airflow[CFM]\ x\ 1.085\ x\ \Delta T[°\mathrm{F}]$$

Using an 85% AFUE Gas Furnace, this unit would require 81,694 Btuh input (69,440 Btuh/.85). Again, this figure is rounded up to the standard product offering of 100,000 Btuh (100 MBH) input. So, where does the 45F and 85F come from? For this climate region, 85F SA temperature can maintain 75F inside the dwelling unit considering heat that is dissipated through the walls, glass, doors and roof. The external "skin" of the dwelling unit is referred to as fenestration. The

45F represents set-back temperature that the furnace may need to recover from (if the occupants go on vacation).

The dwelling unit heating and cooling loads can be calculated by hand on a space by space basis and can be modeled using Load Analysis software which will be discussed in Course 2.

Residential project delivery usually consists of a general contractor or builder working with the Owner and directly employing sub-contractors. HVAC equipment and systems are routinely sized/designed by the HVAC installer (design-build). For larger dwelling units, fully custom homes or units located in larger metropolitan areas, HVAC permit drawings may be required. A residential building permit is normally required, and the Authority Having Jurisdiction (AHJ) will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances.

Light Commercial includes smaller scale business construction such as small office buildings, restaurants, free-standing retail buildings, strip malls, banks, etc. These facilities are usually single story and HVAC consists of light commercial DX Split Systems and/or light commercial packaged DX HVAC units. Packaged DX HVAC units may be pad or roof mounted with horizontal supply/return air openings or may be roof mounted with vertical supply air/return air (SA/RA) openings The industry refers to both types of DX HVAC units as "rooftop" units (RTU's) even if mounted at grade. Rooftop units are usually $\leq$ 240,000 Btuh ($\leq$ 20 tons)[2] in nominal cooling capacity and may be provided with natural gas or electric heat. RTU's are also offered in Heat Pump and/or High Efficiency unit configurations with both factory and field installed options. RTU's are single wall construction with open or foil faced insulation lining. Typical options include factory mounted GFCI service outlets, non-fused disconnect switch, factory curb and hail guards. Depending upon the size of the facility, packaged HVAC units may be procured with field or factory installed dry bulb economizer for "free cooling" operation during mild weather. Units can be provided with barometric relief or powered exhaust.

Systems may include the use of Variable Volume & Temperature (VVT) air terminal units with system bypass. VVT systems include an air terminal "box" mounted in the sheet metal ductwork serving each HVAC zone. Each zone includes a space temperature sensor that sends a "vote" to the VVT control system. After the votes are counted by the control system, the RTU is commanded to operate in heating (~85F SA) or cooling (~55F SA). Each VVT air terminal unit then modulates open or closed to maintain its zone temperature sensor set point. A system bypass box located in the ductwork near the RTU SA main, modulates to maintain duct static pressure where SA is bypassed to the return air plenum or return air ductwork. The VVT air terminals are pressure dependent which means as duct static pressure fluctuates, the VVT air terminals airflows will also fluctuate. Coupled with the fact that not all zones will be fully satisfied from a temperature stand-point, control can be somewhat erratic as the various VVT air terminals modulate their control dampers. This is a fair compromise considering the option of: a.) not having any zone control; or b.) the cost associated with full variable air volume (VAV) with reheat system and controls described below. VAV Systems are typically too costly for Light Commercial projects. HVAC zones may also be furnished with terminal VAV air diffusers in each space which can be provided with space heating/cooling temperature control. Restrooms, Locker Areas, Break Rooms and Kitchens are provided with constant volume exhaust fans that operate based upon building occupancy or via interlock with light switch.

Outside air and exhaust air steams may be supplied with a fixed plate sensible or rotating sensible or total energy recovery device (or “wheel”). As the descriptions suggests, this equipment is designed to transfer energy between the two airstreams. With total heat recovery wheels, in the summer months, there is an energy exchange from the outside airstream to the exhaust airstream thereby reducing the dry bulb/wet bulb temperatures entering the cooling coil. In the winter months, there is an energy exchange from the exhaust airstream to the outside airstream thereby increasing the dry bulb temperature and humidity entering the heating coil. Sheet metal ductwork is typically low velocity extended plenum or equal friction design with supply and return air devices. RA may be plenum or fully ducted. Ductwork distribution design and Control descriptions for these various systems will be included in Course 3.

Other system and equipment types include ground-source/water-source geothermal heat pumps with distribution ductwork, air-cooled chillers with chilled water air-handling units (AHU’s) and/or terminal fan coil units (FCU’s), radiant heating/cooling and DX Variable Refrigerant Flow (VRF) with Dedicated Outside Air Systems (DOAS). DOAS units provide conditioned ventilation air to each space while the terminal DX unit provides space sensible and latent cooling. VRF systems are also available in Heat Pump configuration for space heating.

For cooling, Light Commercial projects in the Midwest, Climate Zone 4A, generally require 450-650 s.f./ton cooling. The building usage drives the estimate load intensity. For example, a 1,200 sq. ft. retail business in a strip mall may be provided with a nominal 2 ton RTU (based on 550 s.f./ton). A 1,200 sq. ft. nail salon in a strip mall may be provided with a nominal 3 ton unit (450 s.f./ton with increased OA load). Again, supply airflow is estimated to be (on average) 400 CFM/ton. So, a nominal 2 ton unit would supply ~800 CFM. It takes 26,040 Btuh of heating (26.0 MBH) to heat that amount of air from 55F to 85F. Using an 85% AFUE Gas Furnace, this unit would require 30,635 Btuh input (26,040 Btuh/.85). Again, this figure is rounded up to the standard product offering of 40,000 Btuh (40 MBH) input. So, where does the 55F and 85F come from? For this climate region, 85F SA temperature can maintain 75F inside the business considering heat that is dissipated through the fenestration. The 55F represents set-back temperature that the gas heating may need to recover from. If we were to select electric heating for this unit, the input/output requirement would be 7.6 KW (26,040 Btu/3.412). This unit would be provided with a 10KW heater.

The Light Commercial heating and cooling loads can be calculated by hand on a space by space basis and can also be modeled using Load Analysis software which will be discussed in Course 2. Building permit officials may require output data from Load Analysis software and may require ComCheck documentation depending up on the jurisdiction.

Light Commercial project delivery usually consists of a general contractor working with the Owner and directly employing sub-contractors. HVAC equipment and systems are routinely sized/designed by the HVAC installer (design-build). There may be an Architect working with the Owner in which case the project may have design drawings provided as part of a classic plan and spec, bid/build process. Alternatively, the Architectural drawings may be used as part of a design-build project execution. A building permit is required in most jurisdictions and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances.

Commercial projects include office buildings, libraries, banks, convention centers, hotels, multi-family housing, large retail centers, fire-stations, court buildings, etc. These projects range in size from ~10,000 sq. ft. to several thousand square feet. Projects may include multiple buildings on a single campus (e.g., office park). Projects can be single story, multi-story or hi-rise and there is a wide range of equipment options that may be selected depending upon project size, use and function. Projects up to ~24,000 sq. ft. typically utilize DX equipment ($\leq$ 60 Tons). DX equipment may include Commercial Split Systems, VRF, multiple Constant Volume RTU's or single Variable Air Volume RTU with VAV air terminal units utilizing Electric or Hot Water Reheat (Photo 2)[3].

PHOTO 2: VAV BOX WITH ELECTRIC REHEAT

Variable Air Volume systems include an air terminal "box" mounted in the sheet metal ductwork serving each HVAC zone. Each zone includes a control temperature sensor that controls operation of each VAV air terminal to maintain space temperature set point. The HVAC system delivers ~55F SA primary air to each VAV air terminal inlet. During cooling operation, the VAV air terminal damper modulates open and closed (min/max) to maintain space cooling. If the space requires heating, the VAV air terminal damper modulates to minimum heating position and electric or hydronic reheat is engaged. The electric or hydronic reheat modulates to maintain space heating set point. VAV air terminals are pressure independent devices which means as the duct static pressure fluctuates, the VAV air terminals will constantly modulate to maintain proper minimum/maximum airflow as measured by the on-board sensing ring. VAV systems require robust controls, programming and start-up to function properly. The equipment and infrastructure are more costly than VVT systems, however, each zone will receive optimal temperature control.

VAV systems may include Series or Parallel Fan-Powered terminal units. These air terminals include a fan located in series or parallel with primary airflow. The fans are used to increase airflow for large spaces (e.g., Conference Rooms) or perimeter zones. With Series Fan-Powered terminals units, the primary air is induced into the fan inlet and mixed with primary air. The fan runs continuously, provides tempered air to the zone and boosts system pressure. With Parallel Fan-Powered terminal units, the fan only comes on when there is a call for heating and acts as the first stage of heating. Parallel Fan-Powered terminal units do not use as much fan energy, however, the noise generated by the fan can be perceived and can therefore become objectionable.

Larger, commercial RTU's are more efficient than light commercial RTU's are also offered in Heat Pump and/or High Efficiency unit configurations with both factory and field installed options. RTU's are single wall construction with insulation lining or full 2" or 4" double wall. Typical options include factory mounted GFCI service outlets, non-fused disconnect switch, factory curb, hail guards, factory installed dry bulb or enthalpy controlled economizer for "free cooling" operation during mild weather, barometric relief or powered exhaust. Additional options include hot gas reheat, enhanced control options, hinged access doors, factory variable speed drives, building pressure controlled powered exhaust fan option, dehumidification controls/functions, VAV system controls…the list goes on. Many large scale RTU's are configurable to include integral heat reclaim wheels, final filtration, and chilled water, hot water or steam coils (Photo 3)[4].

PHOTO 3: VAV ROOFTOP UNIT

Depending on the application, projects of this size may utilize small, Air-Cooled Chillers with AHU's and/or terminal FCU's (e.g., multi-media or conference centers). AHU's are usually double wall, modular construction rated to 6" W.C. IT Closets are typically cooled with dedicated, DX ductless Split Systems designed to operate year round. These consist of an indoor, wall hung or ceiling mounted FCU with outdoor, air-cooled condensing unit. Computer Rooms are cooled with Computer Room Air Conditioning Units (CRAC's). The CRAC units may have outdoor, air-cooled condensing units or air-cooled condensers. Condensing units include the compressor whereas condensers do not. CRAC's are also available with water-cooled options for redundancy and are designed to operate down to low ambient conditions. Building entrances and vestibules may include electric or hydronic heating. It is common to utilize Air Curtains for loading dock doors and large vestibules utilizing sliding doors. Air Curtains may be heated or non-heated. Toilets, kitchens and other spaces requiring exhaust are provided with constant volume exhaust fans that operate based upon building occupancy.

Projects between ~24,000 sq. ft. and ~140,000 sq. ft. may utilize combinations of the above equipment and systems. Larger commercial spec-office building projects typically utilize High Performance VAV Systems including DX RTU's, VAV Air Terminals and optimized controls. Hotels may utilize DX Split Systems or Packaged Terminal Air-Conditioning (PTAC) Units. Large meeting spaces may include chilled water AHU's so utilizing chilled water/hot water hi-rise FCU's would make sense. Pool areas are handled by Poolroom equipment designed especially for the harsh environment and equipped with accessories specific to pool areas (e.g., pool heaters). Multi-family apartments may use DX Split Systems. Surgery Centers may use DX RTU's with Hot Gas Reheat and VAV. Larger healthcare and municipal buildings will usually utilize air-cooled or water-cooled chillers (Photo 4)[5] with VAV AHU's and VAV air terminal units. Heating is accomplished with Central Hot Water or Steam Boilers. These larger facilities generally include parking garages which must be ventilated properly.

PHOTO 4: WATER-COOLED CHILLER

Buildings >140,000 sq. ft. typically use water-cooled chillers associated with a chiller plant located inside the building or in a remote Central Utility Building (CUB) or Central Utility Plant (CUP). Water-cooled chillers reject heat via cooling towers or evaporative coolers located outside. The chiller plant may also include heat reclaim chillers which can produce chilled water and 140F water used in VAV Reheat systems. Chillers may have free-cooling water-side economizers or the chiller plant may include a free-cooling HX. Multiple buildings located on a campus may use chilled water/hot water (or steam) campus loop systems. With campus loop systems, each building generally includes booster pumps serving AHU's with VAV air terminal units. Complete descriptions of these systems will be included in Course 4.

Sheet metal ductwork is typically medium and low velocity equal friction design with supply and return air devices. RA may be plenum or fully ducted. Ductwork may be design using the static regain method so engineers must analyze any renovation projects they undertake. Ductwork distribution design and Control descriptions for these various systems will be included in Course 3.

Other system and equipment types include ground-source/water-source geothermal heat pumps with distribution ductwork, self-contained vertical FCU's, underfloor air distribution, displacement air distribution, radiant heating/cooling (Chilled Beam), DX variable refrigerant flow (VRF/VRV) with dedicated outside air systems (DOAS), evaporative cooling. Ancillary systems may include humidification systems, UVGI lights, high efficiency filtration, cabinet unit heaters (CUH), electric entrance heaters, finned tubed radiation (FTR) and both low intensity and high intensity radiant heating. Large atriums will require make-up air (MAU) and smoke evacuation systems. In some cases, this will require an engineered ventilation system for smoke control. Hi-rise buildings require stairwell and egress corridor ventilation and smoke evacuation. The HVAC design will have close interaction with the Fire Control/Command Center. In most cases, egress passageways, corridors and stairs require dedicated HVAC systems. Elevator shaft and elevator equipment rooms must be treated separately from an HVAC standpoint. Commercial kitchens require sufficient MAU and special exhaust systems.

For cooling, Commercial projects in the Midwest, Climate Zone 4A, generally require 300-500 s.f./ton cooling. The building usage drives the estimated load intensity. For example, a 25,000 sq. ft. spec office building with limited conference rooms may be provided with a nominal 60 ton VAV RTU (based on 400 s.f./ton and 90% load diversity). Again, supply airflow is estimated to be (on average) 400 CFM/ton. So, a nominal 60 ton unit might supply ~22,000 CFM and may require some 17% OA (3,740 CFM). A 25,000 sq. ft. conference center may be provided with a nominal 70 ton unit (300 s.f./ton with increased OA load and 85% load diversity). This would result in a ~25,000 CFM unit and may require ~30% OA. Another way to approach the estimated equipment sizing is based upon delta enthalpy(Δh) using the following Equation (2):

$$Total\ Capacity[Btuh] = SA\ Airflow[CFM]\ x\ 4.5\ x\ \Delta\text{Enthalpy}[\text{Btu}/lb_{AIR}]$$

In Climate Zone 4A, it is typical for a spec office building requiring 17% OA to have a Δh of ~7.5. This is based on OA condition of $95F_{DB}/78F_{WB}$, mixed air condition of $78.5F_{DB}/66F_{WB}$, RA condition of $75F_{DB}/62.5F_{WB}$ and SA condition of $\sim 55F_{DB}/54F_{WB}$. Using this equation, we come up with 742,500 Btuh (742.5 MBH_{TOT} or 61.9 Tons). For a VAV application, this would again be a nominal 60 ton VAV RTU. A more detailed description of how these numbers are calculated will be provided in Course 2.

The heating load needs to be evaluated based on two scenarios: 1) Percentage of OA when majority of VAV boxes are in heating mode; and 2) Morning warm-up. For the first scenario, our 60 Ton RTU may be supplying 8,000 CFM in the winter months as the VAV boxes operate at heating CFM position. The ventilation and make-up OA CFM may be 3,740 CFM. This results in 47% OA. In this scenario, it takes 182,280 Btuh of heating (182.3 MBH) to heat the total, mixed air from 34F to 55F. Using an 85% AFUE Gas Furnace, this unit would require 214,447 Btuh input (214,447 Btuh/.85). Again, this figure is rounded up to the standard product offering of 225,000 Btuh (225 MBH) input. So, where does the 36F and 55F come from? For VAV applications, the RTU is designed to supply 55F air. This value may be reset to 60F or even 65F based on ambient conditions (and the building use), but I generally estimate worst case for preliminary design. The VAV Air Terminal unit reheat coils will then re-heating this 55F to their design leaving air temperature (LAT). If Fan-Powered Terminal Units are utilized, this equipment will also reheat the primary air to their design LAT. For this climate region, 85F LAT temperature can generally maintain 72F inside the business considering heat that is dissipated through the fenestration. 80F LAT can generally maintain 72F for interior zones. The 34F represents the mixed air temperature entering the gas furnace based on 0F ambient and 72F return air temperature (RAT).

For the second scenario, the RTU must recover the building temperature during a morning warm-up cycle. During this cycle, the VAV Air Terminal units are 100% open, and their heating is off. If Fan-Powered Terminal Units are utilized, their fans will be running. It takes 477,400 Btuh of heating (477 MBH) to heat that amount of air from 65F to 85F.

Equation (1): $477{,}400[Btuh] = 22{,}000[CFM]\ x\ 1.085\ x\ 20[°F]$

Using an 85% AFUE Gas Furnace, this unit would require 561,647 Btuh input (477,400 Btuh/.85). Again, this figure is rounded up to the standard product offering of 600,000 Btuh (600 MBH) input. So, where does the 55F and 85F come from? For this climate region, 85F SA temperature can maintain 75F inside the business considering heat that is dissipated through the fenestration. The 65F represents set-back temperature that the gas heating may need to recover from.

After completing the analysis for both scenarios, this nominal 60 ton unit needs to be provided with a 600 MBH input gas heating section. If we were to utilize electric heating, this unit would require 140KW and would be selected with a 140KW or 150KW heater depending on the manufacturer's standard product offerings. Depending on the application, the morning warm-up scenario may not always define the required RTU heating capacity so this analysis must always occur.

The Commercial heating and cooling loads are typically modeled using Load Analysis software and may include CFD analysis, both of which will be discussed in Course 2. Building permit officials may require output data from Load Analysis software and may require ComCheck documentation depending up on the jurisdiction.

Commercial building Owners and Managers may sub-contract HVAC and Control System Maintenance. Large commercial facilities employ knowledgeable facility maintenance staffs that monitor equipment operation, optimize operation for energy savings and maintain equipment.

As you can see, there are many equipment and system options to choose from and many special applications to design for. It is up to the engineer to suggest equipment and system options suitable for the application at hand, in keeping with regional trends and compliant with all Code requirements. Final system selection is developed in collaboration with the Owner, Architect and Construction Manager (CM)/General Contractor (GC) (as applicable) based on several criteria:

1. Project First Cost
2. HVAC System Life Cycle Costs (ROI)
3. Sustainability Goals (LEED, Green Building, etc.)
4. Owner Preference
5. Terms of Ownership
6. Reliability of System
7. High Performance Building Design Goals
8. Aesthetics/Sound
9. Site Requirements/Constrictions
10. Future Cost of Energy
11. Building Resiliency
12. Maintenance Staff Knowledge Base

Commercial project delivery methodologies vary by Client and market. Owners may employ an Architect to develop a complete set of plan and spec documents. The Architect may hire

Mechanical, Electrical (low-voltage and line-voltage), Plumbing, Fire Protection and Special System engineers. The documents are bid to General Contractors (GC's) who procure pricing from sub-contractors. Owners may choose to partner with a Construction Manager or GC earlier in the project. The Owner may execute the project on a Design-Build basis. And finally, the Owner may wish to pursue an Integrated Design Delivery team for project execution. Full descriptions of each delivery model are included in section two of this Course.

A building permit is required in most jurisdictions and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances. Special inspections will likely occur for deep underground, foundations, seismic, compliance with sound and light pollution ordinances, etc. The project may be executed with multiple drawing packages requiring multiple permits to facilitate project schedule.

K-12 Schools represent public and private educational facilities and learning centers. This category also includes Early Childhood Centers (ECC's). Buildings may include administrative offices, classrooms, multi-function areas, conference rooms, data rooms, computer labs, vocational learning spaces (e.g., auto-shops, woodworking shops), gymnasiums, cafeterias, commercial kitchens, libraries, auditoriums, natatoriums, museums, security stations, weight rooms, locker rooms, storage areas, chemistry labs, biology labs, mechanical rooms, loading dock areas, orchestra pits and staff lounges. There are several design conditions to contend with and many require unique HVAC design techniques. We will break these down by area and learning center type.

ECC's can range in size from 5,000 sq. ft. to several thousand square feet. Most will have larger, activity areas, quiet sleep/play areas, small administrative/break areas, restrooms and limited kitchen. In many cases, the students are fed snacks in their classroom. Young students produce more heat than adults so load density and ventilation can become a challenge for ECC's. Most ECC's are designed for 80-100 sq. ft. per child. Many are designed as Light Commercial buildings with special filtration or energy recovery devices to handle the higher percentage of outside air. Another option may include VRF with DX DOAS unit. The DOAS may be geothermal. Unless associated with a School District, ECC's do not have a maintenance staff to service the equipment so this is handled by a local service contractor.

K-12 schools consists of different age group facilities. Kindergarten through 5th or 6th grade elementary schools, 6th, 7th and 8th grade middle schools and 9th thru 12th grade high schools. Elementary schools may be small, neighborhood schools or single, larger elementary schools that serve an entire community. In both cases, it is common to have administrative areas (including the Teacher's Lounge) in the front of the building with classroom wings established for each grade or similar grades. These are usually single story and may be multi-story based on number of students and age of the facility. Cafeteria and gymnasium are treated separately from an HVAC standpoint. In the 40's, 50's and 60's, elementary schools were provided with steam systems serving steam radiators, classroom unit ventilators (UV's), cabinet unit heaters (CUH's) and/or finned tubed radiation (FTR) or hot water boilers and UV's for heating the classrooms (Photo 5)[6]. The UV's or operable windows were used for cooling and ventilation. Gymnasiums and Cafeterias were heat-only with operable windows for ventilation. Heating was accomplished using unit heaters or central heating AHU's. Some facilities had separate gas-fired RTU's for heating these spaces.


PHOTO 5: CLASSROOM UNIT VENTILATOR

In the 70's, 80's and early 90's, many schools started to utilize 2-pipe hot water/chilled water UV's with 2-pipe FCU's in Administrative areas. Chillers were added to existing systems with DX equipment being added to Cafeterias and Gymnasiums. New schools of that time also utilized 4-pipe chilled water/hot water systems with AHU's serving Cafeteria's and Gymnasiums as well as multi-zone AHU's serving administrative offices. Multi-zone DX RTU's were also used in certain regions. In the mid-late 90's, several schools started to utilize packaged DX RTU's with VVT, VAV or single zone. Ventilation was always the challenge so various techniques were used to reduce or treat the OA load including energy recovery wheels, carbon filtration, run-around ductwork systems, etc. Self-contained DX UV's were also used to retro-fit existing schools that wanted to eliminate their antiquated piping systems.

In addition to the above systems and equipment, elementary schools today are utilizing several new technologies including chilled beam, VRF with DOAS, FCU with DOAS, radiant heating displacement cooling, ground-source or water-source geothermal heat pumps with DOAS. Today's commercial RTU's can condition large amounts of OA and maintain space humidity via hot-gas reheat. As such, it is common to see DX RTU's used for elementary schools today – single zone or VAV. Kitchen areas are provided kitchen make-up air and exhaust. Change-rooms and Restrooms are provided with constant volume exhaust fans that operate off of time-clocks or are tied to the central Building Automation System (BAS). The BAS may also be referred to as the Building Management System (BMS).

Middle schools and high schools include the additional spaces described previously and HVAC system designs are more challenging. Larger multi-function areas and conference rooms require more ventilation air and have more latent load due to occupancy densities. Energy recovery is commonly utilized. Data rooms may be quite large requiring dedicated computer room air-conditioning. Computer Labs have high sensible loads and typically require separate or dedicated HVAC units as they are maintained at lower temperatures. Autos shops and woodworking shops require special exhaust systems, MAU and increased air change rates of 8-10 ACH. Auto shops may be equipped with welding equipment and will require welding hoods and make-up air. Woodworking shops require dust collection systems design per NFPA Guidelines. The dust collection system ductwork will likely require sprinkler protection.

Large scale facilities may include full auditoriums which must be designed as a theater with varying occupancies. Special attention is paid to the stage area, proscenium and orchestra pit if so equipped. I have had the opportunity to design a large work-out/weight room which was used by alumni in off-hours. These spaces require more ACH (6-10 ACH) and exhaust along with humidity control. Modern schools are equipped with very sophisticated science and chemistry labs. The labs are supported by solvent/chemical storage cabinets requiring dedicated venting and/or exhaust, specimen storage rooms requiring 10-12 ACH and dedicated exhaust and equipment rooms housing water purification/filtration systems, bottled gases, refrigerators and freezers. These spaces need additional cooling and exhaust to remove heat generated by equipment.

The labs themselves include fume hoods which require MAU and increased ventilation and ACH's. Careful consideration must be given to design of overhead HVAC system near fume hood sashes to maintain proper capture vortices within the hoods during operation. FPM must be maintained at the sash opening (~100 FPM) through all sash positions and air devices must be unidirectional flow or located ~48" away from hood openings. Hoods are provided with lab exhaust fans generating 40'-60' plume heights. The fan is equipped with bypass dampers and VAV nozzle cones to maintain proper exhaust and plume height.

Larger high schools will include central receiving and trash rooms. Air curtains should be provided to minimize infiltration of pests. These areas are usually heated and ventilated with exhaust provided above trash collection bins. Similar to elementary schools, kitchen areas are provided kitchen make-up air and exhaust. Change-rooms/locker rooms and restrooms are provided with constant volume exhaust fans. Locker rooms include shower facilities that must be exhausted separately per Code.

For all ECC's and smaller elementary schools, sheet metal ductwork is typically low velocity extended plenum or equal friction design with supply/return air devices. For larger elementary schools, middle schools and high schools, sheet metal ductwork is typically medium and low velocity equal friction design with supply and return air devices. RA may be plenum, fully ducted or a combination of both. Ductwork may be designed using the static regain method so engineers must analyze any renovation projects they undertake. Ductwork distribution design and Control descriptions for these various systems will be included in Course 3.

For cooling, K-12 projects in the Midwest, Climate Zone 4A, generally require 300-450 s.f./ton cooling. The use and function define the estimated load intensity. For example, a 1,200 sq. ft. classroom may be provided with a nominal 3.5 Ton, Constant Volume RTU with Hot Gas Reheat. (350 s.f./ton). A 3,200 sq. ft. library may require a nominal 7.5 ton RTU (450 s.f./ton). For chilled water systems, each space cooling requirement is totaled, and appropriate diversity factory applied. For large middles schools, an 85% diversity may be appropriate.

For early design and budgeting purposes, the heating load needs to be evaluated based the Light Commercial or Commercial criteria described above. Student populations give off a lot of heat, so the heating calculation is forgiving. K-12 heating and cooling loads are typically modeled using Load Analysis software and may include CFD analysis, both of which will be discussed in Course 2. Building permit officials may require output data from Load Analysis software and may require ComCheck documentation depending up on the jurisdiction.

As technology and training become more prevalent, large school districts employ facility maintenance staffs that monitor equipment operation, optimize operation for energy savings and maintain a comfortable and safe environment for students to learn. Some districts track energy use and take predictive measures to usage.

Again, there are several system choices to choose from. The engineer must collaborate with the design team to optimize system selection based on the same criteria described for Commercial projects.

K-12 projects usually employ an Architect to develop a complete set of plan and spec documents. The Architect may hire Mechanical, Electrical (low-voltage and line-voltage), Plumbing, Fire Protection and Special System engineers. The documents are bid to General

Contractors (GC's) who procure pricing from sub-contractors. This delivery model is typically a requirement since public monies are being used. A building permit is required in most jurisdictions and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances.

Higher Education facilities include private and state funded community colleges, colleges and universities. These facilities may contain all components described for high schools (above) and more. Major universities may also include recreation centers, dormitory buildings, apartment buildings for on or off-campus housing, parking garages, daycare centers, teaching hospitals and more extensive lab buildings. The functions are generally divided up into individual buildings (administration, lab, classroom, etc.).

These facilities use the same types of HVAC equipment and systems described for Commercial, ECC and K-12 facilities above. Large universities typically include a campus utility loop system with CUB (or CUB's) located on campus. Each building contains steam/hot water converter, chilled water and hot water circulation pumps, chilled water/hot water AHU's with VAV systems, FCU's, MAU's, DOAS's, etc.

Preliminary loads, HVAC distribution, facility maintenance, project execution strategy and construction permitting are essentially the same as K-12 only private universities have the choice of negotiating work, executing design-build or integrated design projects.

Healthcare buildings may include medical office buildings (discussed previously as Commercial), imaging, urgent care facilities, outpatient clinics/ambulatory care facilities, skilled nursing care, outpatient surgery facilities (e.g., orthopedic clinic) and/or 24/7 in-patient hospitals. Buildings may include rooms and spaces for exam, change, treatment, triage, Operating Room (OR), OR prep, patient recovery, intensive care, psychology, nurse stations, medication, patient holding, patient check-in, soiled utility, soiled holding, patient corridors, patient rooms, patient ICU, patient isolation, administrative, reception, waiting rooms, storage, files, restrooms, decontamination, sterilization, labs (e.g., pathology, tissue, etc.), invasive procedure, non-invasive procedure, radiology, imaging, physical therapy, mechanical, electrical, IT, Data Center, security, conference, laundry, kitchen, serving/cafeteria and gift shop. Like K-12, there are several design conditions to contend with and many require unique HVAC design techniques. We will break these down by area and healthcare building type and function

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Medical office buildings (MOB's) may house MRI's, LINAC, CT's or PET imaging equipment or may specialize in imaging services. These facilities are treated as commercial buildings with special equipment provided for the procedure room (non-invasive), control and mechanical room(s). Special equipment includes magnet chillers, cryo-vent for helium around MRI magnet and several control panels or mechanical room panels that give off heat. A CRAC unit is required to cool the mechanical room and additional sensible load for control room. The procedure room must be protected with wave guides and aluminum ductwork to avoid interaction with metal objects outside the room, or to protect the surrounding spaces from release of neutrons and electrons (LINAC). Proper temperature control and HVAC ductwork design is required to maintain high quality performance of the equipment and image quality. These systems are typically fully ducted return. The procedure room equipment provider will furnish start-up technicians to verify proper installation of all systems interacting with their equipment and proper function of their chiller, control panels, etc. The remaining building is treated as a Commercial building in terms of HVAC design.

Medical office buildings may be constructed as Light Commercial or Commercial projects. Projects with imaging equipment usually employ an Architect to develop a complete set of plan and spec documents that comply with American Institute of Architect (AIA), Facility Guidelines Institute (FGI) and ASHRAE/ASHE 170 design guidelines/standards. The Architect may hire Mechanical, Electrical (low-voltage and line-voltage), Plumbing, Fire Protection and Special System engineers. The documents are bid to General Contractors (GC's) who procure pricing from sub-contractors. This delivery model is typically a requirement since public monies are being used. A building permit is required in most jurisdictions and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances.

Urgent care facilities are essentially an MOB with waiting room, reception area (which serves as the administrative area), patient check-in, patient intake space (for vitals), triage room, exam rooms and restrooms. No procedures or blood draw occurs as urgent care are not accredited health services facilities. There is a licensed practical nurse (LPN) on staff assists with stabilizing patients for transport to other healthcare facilities as required.

Urgent care facilities are typically constructed as Light Commercial projects. It is recommended that triage rooms, exam rooms and restrooms be designed with FGI and ASRAE/ASHE 170 recommend ACH rates (OA, SA, RA and EA); however, this is not always the case.

A building permit is required in most jurisdictions and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances. There are no inspections from Joint Commission on Accreditation of Healthcare Organizations (JCAHO) or other accreditation service providers. This is an organization involved with inspecting and providing accreditation for healthcare facilities in the United States.

Outpatient clinics, also known as ambulatory care facilities, are facilities that provide services and procedures that do not require an overnight stay. Physicians, nurses, administrative and other support staff work in these buildings which may include any of the spaces described above (e.g., waiting room, exam rooms, etc.). These facilities may include imaging equipment, pathology labs, tissue labs and do not include central laundry or sterilizer rooms. Depending upon size, these building may include kitchens and serveries and usually only include a vending area with light break room for staff.

HVAC equipment and systems are similar to Commercial buildings with the most common being DX RTU with VAV and Electric or Hydronic Reheat. RA is typically ducted return due to Health Insurance Portability and Accountability (HIPAA) privacy concerns.

As with Commercial projects, delivery methodologies vary by Client and market. Regardless of plan & spec, design-build, or integrated project delivery (IPD), all spaces must be designed per American Institute of Architect (AIA), Facility Guidelines Institute (FGI) and ASHRAE/ASHE 170 design guidelines/standards. An Airflow Summary must be included on the plans and some jurisdictions require Pressure Mapping.

A building permit is required and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances. Outpatient clinics and ambulatory care facilities are accredited so JCAHO style inspections are required prior to final occupancy and operation.

Skilled nursing care facilities may be part of a graduated care campus including apartment buildings, single and duplex single family homes, memory care housing facilities, assisted living facilities/nursing homes. Skilled nursing facility residents require a higher level of medical supervision and care. LPN's administer medication, provide physical therapy and oversee telemetry monitoring as required. Rooms include administration, storage, clean linen storage, soiled holding, nurse stations, medication, IT closets, electrical rooms, security, restrooms, wash/tub rooms, shower facilities, loading dock, janitor closets, waiting rooms and gift shops for visitors. Laundry services are usually out-sourced. Residents may be monitored with CCTV systems and bracelet monitors such that the staff can better track their location.

HVAC equipment and systems are similar to Commercial buildings with the most common being DX Packaged units, DX Split Systems, VRF or a combination of these. Exhaust and make-up air are important to control odor, so DOAS units are quite common as well. Large campuses with multiple facilities (described above), may implement campus chilled water/hot water loops serving AHU's, FCU's, etc. Temperatures are generally kept warmer in resident rooms (~77F) whereas staff areas are maintained at cooler temperatures (~72F).

Skilled nursing facilities are governed by a different set of laws and regulations as they are licensed and accredited differently from hospitals. The Joint Commission (JHACO) also provides accreditation services for these facilities.

Project delivery approaches and permitting are the same as outpatient clinics with more emphasis on design-build project execution.

Outpatient surgery centers are similar to outpatient clinics in terms of use and function only they also provide surgical procedures that can be completed without requirements of an overnight stay. Examples would be orthopedic procedures, plastic surgery bariatric procedures, etc. Family medicine is not practiced in outpatient surgery facilities as practitioners are specialists. Additional rooms include change, procedure, OR, OR prep, patient recovery, patient corridors, nurse stations, medication, soiled utility, soiled holding, clean storage, administrative, reception, waiting rooms, storage, files, restrooms, decontamination, sterilization, labs, mechanical, electrical, IT. Larger facilities may also include data center, conference spaces, kitchen and serving/cafeteria.

Again, HVAC equipment and systems are similar to Commercial buildings with the most common being DX RTU's serving high performance VAV with electric or hydronic reheat. Pressurization relationships must be maintained to mitigate risk of airborne pathogens. Infection control is particularly important for surgery suites, and this can further be mitigated by maintaining proper humidification. It is common to utilize duct mounted dispersion tube systems with electric generating, terminal humidification equipment. Airflow serving critical spaces must be filtered to Minimum Efficiency Reporting Value (MERV) 14 (~85% Eff.) with terminal HEPA filtration in OR's.

OR's and some procedure rooms also require low wall return to reduce mixing of contaminates within the space. Unidirectional air is introduced over the operating arena at 35-40 feet per minutes (FPM). This filtered air then exists the operating arena and is captured by the low wall return openings. A portion of the return air may be collected at the ceiling level depending upon room size. Some procedures require 100% exhaust. RA for these facilities is typically ducted return due to Health Insurance Portability and Accountability (HIPAA) privacy concerns.

As with Commercial projects, delivery methodologies vary by Client and market. Regardless of plan & spec, design-build, or integrated project delivery (IPD), all spaces must be designed per American Institute of Architect (AIA), Facility Guidelines Institute (FGI) and ASHRAE/ASHE 170 design guidelines/standards. An Airflow Summary must be included on the plans and some jurisdictions require Pressure Mapping. Pressure mapping illustrates direction of airflow to/from each space and balances the airflows for the test and balance (TAB) contractor. A building permit is required and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances. Outpatient clinics and ambulatory care facilities are accredited so JCAHO inspections are required prior to final occupancy and operation.

Hospitals are designed for patient care and monitoring for more than 24 hours. Hospitals include all rooms described above and may include pharmaceutical suites where pharmaceutical compounding may occur. These spaces are designed per United States Pharmacopeia (USP) 797 guidelines for sterile preparation. Hospitals may have central laundry and sterilization areas with terminal sterilization within the OR suite. RA for these facilities is typically ducted return due to Health Insurance Portability and Accountability Act (HIPAA) privacy concerns.

Hospitals utilize chillers, steam boilers, steam/hot water converters, chilled water/hot water (or steam) AHU's. AHU's can be double-wall modular style units rated to 6" W.C. or may be fully custom units rated to 10" W.C. These units likely include integral humidifiers. AHU's may be constant volume for VAV serving high performance VAV and constant air volume (CAV) systems with hot water reheat. Custom AHU's can be built with up to 4" thick insulation, can include vestibules, energy recovery devices and a host of other options. They can be built for any CFM the facility needs and are designed to last well over 30 years.

For cooling, Healthcare projects in the Midwest, Climate Zone 4A, must be analyzed on a space by space basis. Many spaces must operate 24 hours. MOB's, clinics, portions of ambulatory care may be considered Commercial areas. Typically, larger healthcare facilities or facilities containing procedure and operating rooms are analyzed using the delta enthalpy approach. Loads are driven more by internal loads, and it is typical for a healthcare facility to have a Δh of 8.5-9.5. This is driven by the larger percentage of OA typically required and lower LAT dewpoints. For example, it is common for AHU LAT's to be designed for ~$48F_{DB}/47F_{WB}$

such that OR's can be maintained at 68F and 45% RH. The space conditions must be clearly defined in early design as these low LAT greatly impact equipment sizing and cost.

Each space must be analyzed, and proper delta enthalpy applied. Hospitals typically use chilled water and may require as low as 42F chiller leaving water temperature. Chiller plant design usually includes spare capacity which will be discussed in Course 4.

For larger healthcare facilities, the hot water load may be calculated in Btuh using Equation (1). The CFM is estimated to be 35% of the total SA CFM, mixed air entering temperatures are calculated using ASHRAE winter design conditions -5F (may be -10F in some climates) and 85F LAT. If laundry services and central sterilizer rooms are included, large mass, steam boilers will be sized for these loads and building heating needs. More of this will be covered in Course 4.

The Commercial heating and cooling loads are typically modeled using Load Analysis software and may include CFD analysis, both of which will be discussed in Course 2. Facility engineers require Airflow Analyses to be submitted for final approval as this is related to accreditation. Building permit officials may require output data from Load Analysis software and may require ComCheck documentation depending up on the jurisdiction.

Large healthcare facilities employ knowledgeable facility maintenance staffs that monitor equipment operation, optimize operation for energy savings and maintain equipment. Utility metering and sub-metering are common in the healthcare industry as large facilities have a significant net Energy Use Intensity (NEUI). This is defined as source energy – renewable on-site energy consumed over the square footage of building space. For example, I was involved with a large hospital campus that saved $1.1Mil over a three year period in energy bills by implementing equipment and system control upgrades. This facility had an 8,000 ton chiller plant with several buildings. Meters were installed on all buildings and Operator staff constantly monitored weather patterns to predict HVAC equipment needs.

Again, there are many equipment and system options to choose from and many special applications to design for. It is up to the engineer to suggest equipment and system options suitable for the application at hand, in keeping with regional/industry trends and compliant with all Code requirements. Final system selection is developed in collaboration with the Owner, Architect and CM/GC (as applicable) based on the criteria described above. The surgeons have significant contribution to this conversation as the OR suites generate large amounts of revenue for hospitals. OR's need to be reliable and the OR suite must maintain the proper environment (temperature, humidity, pressurization) for a project to be considered successful.

As with Commercial projects, delivery methodologies vary by Client and market. Regardless of plan & spec, design-build, or integrated project delivery (IPD), all spaces must be designed per American Institute of Architect (AIA), Facility Guidelines Institute (FGI) and ASHRAE/ASHE 170 design guidelines/standards. An Airflow Summary must be included on the plans and some jurisdictions require Pressure Mapping. A building permit is required and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances. Outpatient clinics and ambulatory care facilities are accredited so JCAHO inspections are required prior to final occupancy and operation.

Pharmaceutical facilities may be divided up into various categories including liquid injectables manufacturing, dry product manufacturing, biological/viral material manufacturing, filling, packaging, warehousing, conditioned storage and refrigerated storage. Active Pharmaceutical Ingredients (API's) may contain or be mixed with a viral, biological, toxic or radioactive component. The Food and Drug Administration (FDA) ensures that facilities are developing Quality Risk Management (QRM) for safety and produce quality. The FDA also monitors the industry for compliance with current good manufacturing (cGMP) facilities, manufacturing, packaging, product handling/transport and product storage processes. Like any process, manufacturing consists of raw material transport, blending/mixing, reaction (in some cases), product extraction, purification, filling and packaging. HVAC is part of the cGMP process that ensures these activities comply with Owner QRM's.

Pharmaceutical manufacturing occurs in controlled spaces that must meet certain temperature, humidity, pressurization and contaminant level design criteria. Potential contaminants may be viable (contain biological material) or non-viable (e.g., graphite dust). Air inside these controlled spaces is sampled, and particles counted to predict the potential risk for product contamination. The sampling can occur while the room is at rest (i.e., no workers present, and process equipment may be running) or in operation (workers are present and process equipment may be running). After construction is complete, each space must be classified through a validation procedure to ensure it meets the requirements. The validation procedure includes test and balance activities, pressure tests, temperature/humidity verification, air sampling, smoke tests to verify unidirectional airflow at the work surface, etc. A pressure cascade is established whereby airflow exfiltrates the cleanest spaces and migrates towards the non-classified spaces. This is a multi-step process including verification of installation quality (IQ) and operational quality (OQ). The HVAC system is an integral part of these test procedures.

In the United States, the FDA uses Grades to define the cleanliness level of rooms. In the European Union, they use the Pharmaceutical Inspection Convention/Scheme (PIC/S) which include Grades and reference ISO Classes to define the cleanliness level of rooms. Table 1 is summary of these designations, based on in the "in operation" condition.

FDA Grade	PIC/S ISO 14644	PARTICLE COUNT 0.5µm	5µm[1]	AIR SAMPLE[2] cfu/cu. meter	ACH[3]
A	5	3,520	20	< 1	> 500[4]
B	7	352,000	2,900	10	70
C	8	3,520,000	29,000	100	30
D	N/A	N/D	N/D	200	20
CNC2[5]	N/A	N/A	N/A	N/A	6
CNC1[6]	N/A	N/A	N/A	N/A	6
NC	N/A	N/A	N/A	N/A	4

N/A = Not Appliable
N/D = Not Defined
CNC = Controlled, Non-Classified
NC = Non-Classified

NOTES: 1. Not Measured in US
2. Colony forming unit (cfu)
3. Airlocks tyipcally have +10 ACH
4. Typically design for 100% unidirectional airflow at 70 fpm
5. Areas where product ingredient transport may occur
6. Includes primary gowning only

TABLE 1: GRADE/ISO CLASSFICIATIONS - IN OPERATION

Any space that may have open containers or ingredients that may potentially come in contact with pharmaceutical products (e.g., vials) and are open to the ambient environment, must exist within a classified space (Grade A/B). If these items exist inside of a non-contained piece of process equipment, the product and ambient space must be separated with a Restricted Access Barrier System (RABS). If these items exist in a fully contained piece of process equipment, the equipment must be housed in a classified space as only one Grade change may occur at a time. HVAC equipment and systems must be designed to meet or exceed recommended air changes for each space and maintain the pressure cascade. If enhanced gowning techniques are being used or if the process is automated and does not require operators, the ACH rates may be reduced. The design pressure differentials define the amount of outside air required. The EU requires minimum 0.04" W.C. (10.0 Pa) between Grade spaces so we generally design for 0.06" W.C. (15.0 Pa). Many Owners have their own design guidelines established which may exceed recommended minimum ACH rates and step pressurization.

Product and personnel transport between Grade spaces requires a Personal Airlock (PAL) or Material Airlock (MAL). These are generally designed to cascade from cleaner spaces to spaces that are less clean (e.g., Grade B to Grade C). When dealing with cyto-toxic or biological material, airlocks must be introduced that create "sinks" and "bubbles". These airlocks contain the product while maintaining aseptic (or clean) manufacturing conditions. After defining the process, product and personnel flow, Classification, Pressurization and HVAC Zoning documents are created for cGMP compliance. These documents are used during validation and must be presented, along with Airflow Diagram (AFD's) the FDA inspector(s).

In addition to designing for Grade spaces, blending may include the use of volatile solvents, alcohols and other materials that may need to be stored in rooms carry a H-3 or H-4 Hazard Classification. Some of these spaces may also carry Electrical Classifications. Many facilities have Clean Space, Technical Spaces within Clean Spaces (for Autoclaves and other equipment) as well as Mechanical Room space required to support the process equipment. Additional rooms or areas include gowning, lockers, restrooms, office, QC labs, product sample labs, conference, receiving warehouse, shipping warehouse, storage warehouse, cold storage, electrical, Data and Interstitial. Most pharmaceutical production facilities are built with Interstitial space for installation of control devices, particle counters, terminal air devices, air control valves, airflow monitoring stations, reheat coils and in some cases AHU's.

Smaller Pharmaceutical manufacturing facilities, Contract Development and Manufacturing Organization (CDMO's) and CMO's may receive pre-manufactured raw materials and API's from other sources. Their focus is on filling, packaging, warehousing and receiving/shipping. It is common to find these facilities served by DX equipment and treated as Commercial buildings…particularly if their product transport is disposable.

Large-scale Pharmaceutical manufacturing is designed with chilled water, steam or hot water AHU's serving low velocity ductwork. MAU can be delivered to each AHU or AHU's can be designed to bring in OA directly. AHU's are generally fully custom units rated for 10" W.C. Grade A/B, C and D spaces require SA Terminal HEPA or ULPA Filters to deliver unidirectional airflow into each space at maximum 70 fpm. Return air is collected down low and may include filter grilles depending upon the process. The Terminal HEPA/ULPA units may be fed directly with pre-filtered air via low pressure ductwork or may be Fan-Powered HEPA Terminal Units that exist within a SA Plenum. With this scenario, the AHU's supply pre-filtered, conditioned air into the plenums and extra RA from the plenums (usually over the low wall return openings).

Regardless of how the MAU and SA are fed to each space, the SA and RA airflows must be controlled and monitored. These systems can be designed as constant volume completely hard balanced, or they can be designed as dynamically controlled systems based on airlock and space pressurization needs. The benefit of designing hard balanced systems is the simple fact that there is less equipment and maintaining the pressure cascade requires little maintenance. The draw-back is that every time an alteration is made, a part of the plant is shut down for extensive equipment repairs/replacement or there is an addition to any part of the cascade, the entire cascade must be re-balanced. This effort can require days of production shut-down. With dynamically controlled system designs, the pressurization cascade is essentially self-correcting. The draw-back is that more equipment and controls are required to make it work properly. This means more validation time, more programming time and most importantly, more calibrations after the facility is put into operation. Each return air valve will need calibrated frequently to keep them from drifting out of specification.

Pharmaceutical HVAC designs have separate HVAC zones for Grade A/B, Grade C, Grade D, CNC, etc. It is typical to segregate zones to prevent cross-contamination (particularly if dealing with harmful components). Mixing levels of cleanliness are avoided and all systems are fully ducted SA and RA.

Sheet metal ductwork may be galvanized or stainless steel (304L or 316L if exposed in a Grade space). Clean rooms are routinely cleaned and wiped down with harsh cleaners that may contain hydrogen peroxide. These chemicals will discolor and destroy galvanized coatings. RA ductwork drops are cleaned and wiped down on the inside to eliminate risk of particles accumulating and then falling into the clean room. If exposed, the ductwork should be 316L to avoid discoloring over time as the hydrogen peroxide will attack carbon steel. Closed processes require minimum 304L stainless steel for the vaporized hydrogen peroxide (VHP) cleaning process. It is very important to fully understand the cleaning chemicals being used, the cleaning process and VHP cycles that need exhausted. Sheet metal ductwork is typically low velocity equal friction design with certain systems designed based on feet per minute (FPM) velocity. Ductwork distribution design and Control descriptions for these various systems will be included in Course 3.

Additional HVAC equipment associated with pharmaceutical facilities would be similar to commercial buildings, although nearly every space is conditioned in the pharmaceutical industry. Special exhaust may be required including the use of HEPA filter banks. Equipment and system reliability are paramount as a single equipment failure could result in severe financial losses. I was involved with a facility producing a batch of product every three days with a profit of over $1.5mil. Every piece of mechanical equipment had full redundancy.

For cooling, Pharmaceutical projects must be analyzed on a space by space basis. Many spaces require 24 hour operation. Packaging, warehousing and office areas may be considered as Commercial spaces. Typically, Grade spaces are analyzed using the ACH method, sensible load calculated, and then sensible heat ratio (SHR) applied to develop total load for each space. OA

Ventilation load is handled separately based on pressurization requirements. The SHR is defined as the Sensible Load divided by the Total Load. These facilities may have 0.85 SHR for high occupancy areas and as little as 0.95 SHR in automated packaging and production spaces. By decoupling the ventilation load, one can gain insight as to the sensible load density. It is not uncommon to see production spaces at 250 s.f./ton without ventilation and 175-200 s.f./ton with ventilation. Lower LAT dewpoints are also required. For example, it is common for AHU LAT's to be designed for ~48F_{DB}/47F_{WB} such that dry products production areas can be maintained at 68F and 40% RH. I was involved with a large-scale manufacturing project whereby the production space had to be maintained at 7% RH due to lyophilization (freeze-drying). This required desiccant drying and cooling which is common for buffer rooms, sterile cores dealing with dry products and areas where products undergo lyophilization and come in contact with ambient air. Each space conditions must be clearly defined in early design as these low LAT greatly impact equipment sizing and cost.

Pharmaceutical typically requires 38F-42F chilled water and 25F-30F cold process water. The HVAC design may be asked to help design the process cooling system and will need to account for cooling tower water needs when sizing the cooling tower systems. The hot water load in Btuh is calculated using Equation (1). The CFM is estimated to be 100% of the total SA CFM serving process spaces (Constant Volume) and 35% of the total SA CFM serving non-Grade spaces (VAV). mixed air entering temperatures are calculated using ASHRAE winter design conditions -5F (may be -10F in some climates) and 70F LAT for process spaces, 85F LAT for non-Grade spaces. Large mass, steam boilers will be sized for the process loads (CIP skids, Clean Steam Generators, Humidifiers) and building heating needs.

The Pharmaceutical heating and cooling loads are typically calculated using spreadsheets (initially) and then modeled using Load Analysis software. Critical Grade spaces may include CFD analysis. These techniques will be discussed in Course 2.

Large Pharmaceutical facilities employ knowledgeable facility maintenance staffs that monitor equipment operation, optimize operation for energy savings and maintain equipment. Utility metering and sub-metering are common in the pharmaceutical industry for trouble-shooting purposes. Typically, there is a dedicated Instrument and Electrician (I&E) staff, PLC Controls staff to maintain the process controls and Mechanical staff to maintain HVAC equipment as well as the HVAC Building Management System (BMS) and Environmental Control System (EMS). The EMS is data-logged as per FDA compliance in the Pharmaceutical industry.

As with Commercial projects, delivery methodologies vary by Client and market. Regardless of plan & spec, design-build, or integrated project delivery (IPD), all spaces must be designed per cGMP and FDA design guidelines/standards. The project delivery methods may follow typical commercial standards or may implement a stage-gate (FEL) method of project delivery. These will be discussed later in this Course.

Depending on the jurisdiction, a building permit may be required for the building and infrastructure only. I have been involved with many projects where the AHJ did not get involved with the process or HVAC design. Large pharmaceutical projects typically have an Environmental Permit that needs to be adhered to. Careful consideration must be made to Cooling Towers, Lab Exhausts, building exhaust, etc.

Food & Beverage may include production of baked goods, cereal bars, pet food, meat processing, food supplements (a.k.a. Nutraceuticals), soda, tea, beer and other spirits. The process production is similar to Pharmaceutical in that we have raw material handling, blending, mixing, forming/filling and packaging. The difference is that products must be brought to temperature (145F to 185F) per FDA requirements. Also, many beverages require carbonation.

Spaces may include Class 1, Class 2, Class 3 or Non-Classified areas based on presence of food materials. Class 1 areas are full wash-down areas including walls, ceilings and floors. Cleaners include foam soaps and disinfectants. Class 2 areas have limited wash-down of equipment and floors. Walls and ceilings may be wiped down. Class 3 spaces are wipe-down as needed only, and non-classified areas only require routine dusting and cleaning. Understanding the Class Ratings for each space determines equipment selection and design. In addition, these areas may be cooled to low ambient temperatures and may have large amounts of latent load within them, particularly after wash-down. Formation of water droplets or condensation on the ceiling and walls is not acceptable so SA distribution strategies must be considered during normal operation and during recovery mode after room wash-down.

It is important to provide sufficient ACH rates to prevent condensation, furnish minimum MERV13 filtered air to these spaces and design enough capacity to cool each space to its required temperature and humidity set point. Below are some examples of specialty spaces that need to be considered when designing HVAC for any Food & Beverage facility.

Dry goods mixing will require dust collection hoods and exhaust systems. In some cases, the products are sticky so hoods have screens for capture of product and must be designed for full wash-down. These spaces may have temperature and humidity requirements to keep the product workable or flowable. Wet goods mixing likely has dry components that get introduced via eductors. This may be a closed process or partially open to the room in which case a small capture hood will be required. The rooms typically require a lot of wash-downs, so temperature and humidity levels are important.

Some facilities may have dough or product proofing rooms that require higher temperatures and much higher relative humidity. The heating/cooling loads fluctuate in these spaces, so designing HVAC systems that can adjust as needed is especially important. The product specific heat is used to calculate the load if the process is exothermic. It may be necessary to bring the temperature down at different rates during different time intervals of the proofing process.

Forming rooms may contain process equipment whereby the forming occurs in a contained environment, or the forming process may be partially open to the environment. Forming may require local exhaust capture hoods or connections to the equipment itself. Continuous process forming verses semi-automated batch forming must be understood as batch forming will usually involve open product containers and more personnel in the area.

Oven(s) may be contained in a single room or may be located in a large warehouse environment. I have worked on projects with multi-stage ovens stretching several hundred feet in length. Product loading and off-loading may include accumulators and spiral coolers on the outflow side of the oven. These represent areas where open product is giving off heat. Again, the specific heat and moisture content of the product must be understood at each stage of the process to properly size and design the HVAC system. It is likely undesirable to introduce cold , filtered air directly onto the product as this can affect product quality. These are questions that need to be asked during the early design process.

Wash-down rooms may be necessary for trays, carts, mixer parts, etc. The wash-down rooms are obviously very wet and provide an opportunity for microbial growth. For the meat industry, these rooms may also propagate the spread of airborne viruses. Capture hoods are generally located above washing equipment and sinks. Wash-down rooms may include areas for pre-drying trays before they are sent to the freezer or other storage area. This additional latent load should be considered when sizing HVAC systems.

Dehydration equipment may be included in the design. Like Pharmaceutical, products that are dehydrated may require lower humidity designs. The dehydration chambers will include exhaust. For continuous processes, accumulation tables may be required. For batch processes, trays and carts may be staged within these rooms upstream of the dehydration process.

Refrigerated/Frozen storage likely includes separate, packaged refrigeration equipment. Smaller facilities will utilize DX equipment whereas larger facilities may have Ammonia and/or CO2 refrigeration systems.

Support spaces include offices, conference rooms, tasting rooms, QC labs, raw material labs, restrooms, mechanical, electrical, PLC controls, IT, Data, security, battery charging, gowning, de-gowning, lockers, showers, warehouse/shipping, shipping docks and security. These can all be conditioned as described in other sections of this Course.

As for process spaces, smaller facilities may utilize Multi-stage DX equipment for process HVAC. Larger facilities will likely utilize air-cooled or water-cooled chillers with steam boilers serving AHU's with chilled water and hot water. AHU's are zoned for each space to maintain unique temperature and humidity control for each space. Steam boilers are typically required for CIP and other process skids, so steam will likely be part of the project regardless the use of DX equipment. As mentioned previously, AHU's are fully custom with wash-down capability. Some include stainless steel coils as well as full stainless steel liners, drain pans, etc.

For cooling, Food & Beverage projects must be analyzed on a space by space basis. Many spaces require 24 hour operation with 3-4 hour wash-down cycles each. Packaging, warehousing and office areas may be considered as Commercial spaces. Typically, process spaces are analyzed using the delta enthalpy approach. Loads are driven more by internal loads, and it is typical for spaces within a Food & Beverage facility to have a Δh of 8.5-10.5. This is driven by the larger percentage of OA typically required and lower LAT dewpoints. The space conditions must be clearly defined in early design as these low LAT greatly impact equipment sizing and cost. It is not uncommon to see production spaces at 250 s.f./ton without ventilation and 175-200 s.f./ton with ventilation.

All RA/EA ductwork serving these spaces is typically 304 Stainless Steel for corrosion protection. RA for these facilities is ducted return due to wash-down needs. SA ductwork is usually galvanized

As with Commercial projects, delivery methodologies vary by Client and market. Regardless of plan & spec, design-build, or integrated project delivery (IPD), all spaces must be designed per FDA design guidelines and standards. The project delivery methods may follow typical commercial standards or may implement a stage-gate (FEL) method of project delivery. These will be discussed later in this Course.

Depending on the jurisdiction, a building permit may be required for the building and infrastructure only. I have been involved with many projects where the AHJ did not get involved with the process or HVAC design. Large Food & Beverage projects typically have an Environmental Permit that needs to be adhered to. Careful consideration must be made to Cooling Towers, Lab Exhausts, building exhaust, etc.

Refrigerated/Warehousing market has become extremely popular with on-line products and foods. Warehouses range in size from 35,000 sq. ft. to over 1mil sq. ft. They are manufactured using tilt-up, concrete walls, insulated metal panels (IMP) and un-insulated metal panels (pre-fabricated metal buildings). They are used for storage of food/non-food items and manufacturing associated with various industries.

Besides the warehouse itself, spaces or areas may include shipping offices with offices, restrooms, breakroom, etc. that are treated as Light Commercial spaces. There may be other offices, locker rooms, break rooms to support the Operators of the facility. These areas are treated as Commercial spaces. These facilities usually have an area for fork truck battery charging. Depending on the batteries used, exhaust may be required in this area at 1.0 CFM/sq. ft. Other spaces include fire pump room and electric room which also require heat and vent. The water entrance and plumbing mechanical room may be designed with its own room so heat and vent this space as well.

Dry-goods are typically stored at ambient conditions in the Midwest. Heat and Vent warehouses require 0.60 CFM/sq. ft. of OA and heating is usually designed to handle ventilation, skin loss and infiltration due to operation of the various dock doors. Heating and Ventilation air may be accomplished with roof mounted, gas-fired MAU's and airflow is circulated internally using high-volume low speed (HVLS) fans or destratification fans. Air is then exhausted to achieve the desired pressurization. An alternative would be to utilize floor mounted, air-turnover units. These take up floor space; however, save roof penetrations and can be fitted with cooling coils.

Products may be stored or manufactured in conditioned warehouses. These facilities may include multiple DX RTU's and DOAS units with HVLS or destratification fans and exhaust fans. For larger facilities, chilled water and hot water may be used in conjunction with roof mounted AHU's or floor mounted Air turnover units.

Refrigerated Spaces (above or below freezing) may be built-out within a large Warehouse using IMP walls and roof or be built integral to the Warehouse roof by using IMP walls and OSB roof sheathing (wooden roof structure in some cases). Freezers need to be provided with insulated and sometimes heated floors to prevent condensation from accumulating and freezing underneath the floor. Individual DX Split systems are used up to ~350 tons. Refrigeration systems above 350 tons are typically built-up skid units that may utilize HCFC Refrigerant, CO2 or Ammonia as a circulated refrigerant to the evaporators. Evaporators are installed high in the space and distribute horizontally ~50' to 75' (Photo 6)[7]. Larger systems may be roof mounted and ducted to throw the SA up to 150'.

PHOTO 6: REFRIGERATION EVAPORATOR

For large-scale, central systems, the compressor skids may be grade or roof mounted. Heat is rejected via Adiabatic Coolers, Air-Cooled Condensers or Cooling Towers. Distribution piping becomes part of the HVAC design and must be treated as process design complying with ASME B31.3 and ASME B31.5.

Dry goods, heat and vent warehouse design can be accomplished using a spreadsheet. The support offices, etc. are typically designed as previously described for Light Commercial and Commercial spaces.

For conditioned Warehouses with moderate loading/unloading (incoming product at ~85F) and maintaining ~75F, projects in the Midwest, Climate Zone 4A, generally require 650-850 s.f./ton cooling. The building usage drives the estimate load intensity as incoming product temperatures and frequency of overhead door usage greatly affect the load. Manufacturing processes (such as Chocolate manufacturing) may have significant equipment and process loads that need to be considered.

These Warehouse loads can be modeled using Load Analysis software which will be discussed in Course 2. Building permit officials may require output data from Load Analysis software and may require ComCheck documentation depending up on the jurisdiction. Refrigerated warehouses are typically modeled using a specialty program designed for this purpose. These programs consider defrost cycles, redundant units required for swing loads, etc.

Refrigerated/Dry-Goods warehouse project delivery usually consists of a general contractor working with the Owner and directly employing sub-contractors. HVAC equipment and systems are routinely sized/designed by the HVAC installer (design-build). There may be an Architect working with the Owner in which case the project may have design drawings provided as part of a classic plan and spec, bid/build process. Alternatively, the Architectural drawings may be used as part of a design-build project execution.

A building permit is required in most jurisdictions and the AHJ will perform inspections during construction to ensure all systems are being installed per local Codes and ordinances.

Industrial Manufacturing may include petroleum plants, chemical plants, plants that produce raw materials or produce a wide range of products. This section of the Course is meant to describe large facilities with multiple buildings housing the process. In some cases, the process is outside.

HVAC may be used for spot comfort cooling within manufacturing facilities. In many cases, the buildings only require heating for freeze protection and ventilation to meet minimum OSHA requirements of 4 ACH. Additional exhaust and filtration may be appropriate to support process needs. Spot cooling is accomplished with DX equipment and is for Operator comfort only. Chilled water, cooling towers and boiler systems used for process needs may be designed by HVAC Design Engineers; however, that is outside the scope of this Course. These design opportunities exist and will require development of process P&ID’s, spool/fabrication drawings and other detail drawings that are typically outside the scope of normal HVAC Design and Engineering.

Industrial manufacturing facilities will routinely include offices, labs, testing labs, warehousing, kitchens, serveries, locker room, showers and other facilities described under Commercial buildings. By in large, these systems are DX and may utilize process steam, process hot water, etc. There exists a demarcation between process utility and utilities required for comfort cooling and heating. It will be up to the plant to update and modify their P&ID’s to account for additional services that are not process related. To that end, HVAC for Industrial facilities is typically kept separate from any process utilities.

The HVAC may need to be designed such that the facility can maintain and trouble-shoot it. The plant may have standardized with certain OEM products and may not accept factory installed devices such as variable speed drives (VSD’s), control devices, circuit breakers, disconnects, etc. In some cases, the plant may want to control the HVAC equipment with their PLC control systems. Sometimes called process control system (PCS) or digital control system (DCS), these protocols are not in keeping with HVAC industry standards. The most they can communicate is ModBus RTU using RS-485 communication bus. BacNet, Lonworks and other communication protocols described in Course 3 are completely foreign to these systems. This author has been involved with projects whereby factory controls were removed such that DCS controls could be installed. This voided the equipment warranty and created a significant project cost increase. I have also been involved with projects involving chillers where the factory rupture discs were removed and replaced with pressure safety valves (PSV's) such that the vessels could be part of the Site Pressure Vessel Maintenance program.

Alternatively, many industrial facilities sub-out maintenance for their Commercial HVAC systems and keep these devices completely off their DCS. In these cases, I encourage Owners to install additional monitoring devices such as additional space sensors, fan current switches, etc. to independently monitor the HVAC equipment. This seems to be a successful strategy and maintains separation between the two control systems, maintenance programs, etc.

The project delivery is unique for these facilities. The plant engineer or project manager overseeing the project execution may hire an Architect to develop a set of bid drawings. The Owner may choose to handle the design and installation as a design-build project. Either way, the project will likely undergo funding and execution typical with larger industrial plants. This multi-step, stage-gate process is described in the next section.

A building permit is required in most jurisdictions and the AHJ should perform inspections during construction to ensure all systems are being installed per local Codes and ordinances. This is not always the case. Plant access is difficult to obtain with Site training, safety training, etc. Many times, the AHJ does not perform Site inspections.

PROJECT EXECUTION STRATEGIES

The first part of this Course referred to several project execution strategies including:

1. Plan & Spec, Bid/Build (PSBB)
2. Design-Build (D/B)
3. Integrated Project Delivery (IPD)
4. Stage-Gate/FEL (FEL)

In addition to these project execution strategies, I have also been involved with Design-Assist (D/A) which is similar to IPD but does not include the same contractual relationship. As noted, Residential, Light Commercial, Commercial and Refrigeration/Warehousing projects tend to utilize D/B and may implement the classic PSBB. The K-12, Higher Education and Healthcare market sectors tend to utilize PSBB more often and may execute D/B or IPD in certain regions. D/B and IPD are more prevalent when working with privately funded institutions.

Pharmaceutical is a mixed bag depending on the Client, size of project and complexity. Industrial Manufacturing commonly utilizes FEL or D/B.

The Plan & Spec, Bid/Build (PSBB) market has been extremely popular over the years. The project is linear and broken up into major deliverables as follows:

PA/PD: Preliminary Assessment and Design
- Energy Reports
- Rough Sketches
- Budget Reports
- GMP Proposal if CM is involved

SD: Schematic Design
- S/D Narrative
- Preliminary Load Summary
- Cost Modeling

D/D: Design Development
- D/D Document Set
- Refined GMP Proposal if CM is involved
- Detailed Scope Documents

C/D: Construction Documents
- Could Include Progress Sets Including
  - 30%, 60%, 95%
  - Permit
- 100% IFC (many times used for Permit)
- Separate Specification Binder
- Bid Document Development and RFP's

Bidding:
- Bid Tabs

- Bid Clarifications
- Issue Addendum

C/A: Construction Administration

- Provide Comments on Submittals and Shop Drawings
- Respond to RFI's
- Field Observation Reports
- Field Punch List Reports

Cx: Commissioning Support

- Respond to Cx Agent Comments

Close-Out:

- TAB and Start-up Report Comments
- Final For-Record Documents

We will look at each project phase associated with PSBB execution strategy and further understand the primary team members involved and HVAC design tasks that occur at each phase.

During PA/PD, team members include Principal Level Owners, Managers and Project Managers (PM's) from the A/E Team, Owner's Team and CM/GC as applicable. During this phase, the building use and function are being defined along with project goals, overall budget and schedule. Zoning and site analysis are underway. HVAC Design team is brainstorming HVAC equipment and system ideas that fit the Owner's goals, performing option analyses, developing comparative energy studies/reports, providing high level information for each system including equipment sizes and locations and offering high level equipment and system budgets on a $/sq. ft. basis. The information provided in the first part of this Course can provide guidance during this phase of project development.

SD team members are the same and may also include senior level designers. The building type, location and general size and shape are defined during this phase. The architect has developed some rough bubble diagrams defining interior spaces. The team is working on the Schematic Design narrative which includes final preliminary load analyses for one or two options. The final HVAC system selection may not be finalized, but information is provided to allow for an informed decision by the Owner. Mechanical spaces are defined, shafts and exterior openings are located (as required), equipment weights are furnished and building structure is finalized. Seismic and wind design categories are confirmed at SD. Electrical coordination includes definition of HVAC systems required to be on stand-by or emergency power, short circuit current rating limitations and location of major electrical rooms related to mechanical equipment. Plumbing coordination includes need for floor drains, non-potable water and storm drainpipe routing/scheme.

During D/D, Principal level team members begin to hand off design responsibility to the A/E Team who begins to involve more senior level team members. The Owner expects the A/E Team and CM/GC team to drive the process and is still there to answer key questions to keep the process moving. The CM/GC or A/E Team may develop a detailed cost estimate at this phase.

By the completion of D/D, mechanical rooms should be laid out, major equipment selections and schedules completed, Code analysis complete, and final loads completed based on the selected system. All HVAC zones are defined and ready for Owner sign-off. Sheet metal and piping mains are located with terminal air devices located on the drawings. Preliminary coordination is occurring with all trades and disciplines. Final equipment weights are shared with the structural engineer and shaft detailing occurs. The preliminary motor data table (MDT) is shared with electrical design team. All cable tray and main conduit routing are coordinated with the electrical engineer. Coordination occurs with regards to disconnect switches, factory GFCI outlets, etc.

Early in the C/D Phase, senior engineers are involved with the design and begin to hand things off to the designers. The designers begin to detail the drawings and build content into the model. The Owner continues to answer question related to interior finishes, access control, Owner provided equipment, equipment access requirements, etc. The Owner has verified all building programming, ceiling heights and room cards by 30% C/D phase.

By 60% CD's, the HVAC design team coordinates final location of ceiling air devices, completes sheet metal and piping design layouts. Several notes are added to the drawings to clarify scope and project specific details completed. Final roof framing is confirmed with the structural engineer. The final MDT is provided to the electrical designers, plumbing drains coordinated, section cuts are established, control sequence of operation and final technical specifications is completed for all equipment and systems. If a CM/GC is involved, a detailed cost estimate for the project may be updated at this phase. By 95% CD's, section detail completed along with preliminary Clash detection and clash reports with resolution occurring through 100% IFC's. The HVAC design team needs to carefully study electrical, plumbing and architectural drawings to ensure proper coordination.

Bidding is heavily driven by project PM's and all bids are received lump sum. Prospective bidders will receive and review documents, attend pre-bid walk-thru's and develop RFI's. RFI's are passed along to senior engineers and designers for response. The A/E team works to issue bid Addenda such that complete and concise bids can be produced. The goal is to significantly reduce construction RFI's and provide all clarification to the bidders. During this phase, the 100% IFC plans & specifications may actually be issued as a "Permit Set" to the AHJ with Permit applications. This allows the design team to issue 100% IFC with all bid addenda and permit comments addressed. Alternatively, these comments will be picked up as Revision 1 Bulletin to the 100% IFC Set.

Once CA begins, The PM's becomes more involved with day to day execution of the project. The A/E Team typically performs an internal hand-off as junior engineers will begin to perform shop drawing and submittal reviews. The junior engineers are heavily involved with project walk-thru's developing reports and responding to RFI's. Designers hand-off the model to the construction team such that they can complete Clash detection and resolution. The construction team develops fabrication drawings and shop drawings for team review.

Cx support and project close-out occur simultaneously from a design standpoint. Final punch list visits occur, TAB reports reviewed, and the A/E Team receives field red line drawings for production of the For Record drawings.

Design-Build projects may involve architects from Architectural firms or may include Architects employed by the CM/GC. MEPFP sub-contractors may execute their designs in-house or hire consulting engineers. The process is very similar to PSBB with a few key differences as follows:

1. If the CM/GC is utilizing in-house Architects, or if the MEPFP subs are hiring consultants, there may be a conflict of interest
2. The project typically has a compressed design and construction schedule
3. PA/PD is typically completed by pre-construction teams and folded into early design efforts
4. SD and D/D are typically non-existent from a formal deliverables perspective – usually goes straight into CD phase with more packages
5. Equipment procurement occurs during early CD phase so 100% IFC's include equipment specific schedules
6. Model coordination occurs during design, so clash detection starts at ~75% CD

There are several benefits to the design-build approach including:

1. Compresses overall schedule and typically saves cost
2. Brings construction knowledge to design documents (prefabrication, construction sequencing)
3. More accurate project pricing earlier in the design phase
4. No finger pointing if problems occur during construction
5. Typical value engineering or value add ideas are smoked out early and changes incorporated into the design without significant design rework
6. Fewer team members to communicate with
7. Continuity of team member from design through the end of construction

From an Owner's perspective, there are some drawbacks to executing a project using design-build partners. The Owner loses a third party perspective that may present challenging questions that can lead to more collaboration and creative solutions. Specifications may not be as complete leaving room for some ambiguity. The Owner may not have clarity with regards to equipment, system scope or control scope. This makes it difficult to discern exactly what is in the lump sum or guaranteed maximum price (GMP). With regards to project pricing structures, there are a few options with design-build. During pre-construction, the CM/GC may develop a project budget with subs that includes design fees, construction fees, project construction GMP and contingencies. The overall GMP may be negotiated as cost-plus, meaning all costs will be exposed to the Owner with negotiated mark-ups, or it may be carried as a project GMP that will be converted to Lump Sum at some point during the design. Design and construction fees may be held (billed) separately or rolled into the Lump Sum. The Owner may carry remaining contingencies at that point in the design or allow the CM/GC to carry all contingencies and handle with change-order at the end of the project. There are many options to consider. It all comes down to the relationship, level of trust and expertise.

Design-Assist projects are a unique combination between PSBB and D/B. With this model, there is a CM/GC involved early in the design process. The A/E Team takes the project through SD and early DD. The project is then bid out to prospective D/A partners who will be responsible for completing the design. The A/E Team remains on the overall design/construct team as advisors. They review all drawings, specifications, Cx plans, etc. and provide advice to the Owner. Negotiations typically occur with regards to scope and price as the design continues to completion.

The Owner experiences all of the D/B benefits and has the advantage of a third party perspective and reviewer of the design. The A/E Team can also influence the level of detail included on the drawings. The project bares the cost of additional team members and gains the benefits. During construction, if the D/B firm experiences resource challenges, the A/E Team can step in to fill the gap thereby reducing project schedule risk. The D/B firms typically take design responsibility and signs/seals the drawing packages. A GMP is established early in the design and there is an incentive for design/construct team members to decrease the GMP. There is a shared savings for all team members if project costs can be reduced. At 100% IFC, the project is converted to Lump Sum and agreement is reached for no contractor change orders. The savings are held as contingency until the end of the project. If all parties perform successfully, the savings are shared equitably. I was involved with design of the new Busch Stadium in St. Louis using this project execution strategy. I found this to be very collaborate and successful approach.

Integrated Project Delivery (IPD) is similar to Design-Assist only there is a contractual agreement between all parties for shared savings during PA/PD. Once a project opinion of probable cost is established that the Owner accepts, the team is challenged to reduce overall building costs through project development, design, construction and occupancy. Energy savings after occupancy may be part of the agreement as each agreement is project specific based on the teams' plan.

Since all team members are party to the contract, collaboration is promoted as there is no benefit to creating dispute or "finger pointing" to protect one's financial position. Everyone on the team ensures the right people are at the project meetings such that information is freely shared, and decisions can be made quickly and efficiently. All team members have equal say in the negotiations. If disputes arise or agreements cannot be reached, the issues are elevated to an executive team that performs an internal mediation to resolve issues. BIM is commonly used to help track the decision making process, identify challenges/conflicts and document solutions that help all stake-holders.

It is common for the design/construction team to verify proper operation of HVAC systems to prove modeled energy savings are actually being realized by the team. In many cases, there are complications, programming and Commissioning (Cx) issues to work through, but once Cx efforts are complete, the buildings typically perform better than the load modeling suggests.

Stage-Gate/Front-end loaded (FEL) projects are typically associated with stage gate project execution. As the name suggests, design drawings are developed early in the project execution cycle and contain detailed information to facilitate accurate project cost models prior to construction begins. The phases of FEL project go by many names, I will share the naming convention we used while working at a major chemical plant in the Midwest.

We utilized a five step (or stage) process which started with Business Justification for the project. Business Justification phase identified the following items:

1. Project Scope Description
2. Opinion of Probable Cost which usually consisted of a +/- 30% Cost Model – engineering, equipment, construction and asset management were broken out
3. Suggested Design, Construction, Cx Schedule – broken up by annual quarters (e.g., 2Q2021)
4. Project need or justification – "how will this project save money, improve production, Operator safety or product quality?"

For maintenance replacement projects, we would typically perform a 5-why analysis to determine the root cause of process for equipment failure. Technology updates would sometimes occur, but for the most part maintenance replacement projects were like for like replacements to improve reliability and keep production running. These projects were typically justified with production up-time and history of work orders and maintenance costs. It was relatively simple to develop the preliminary cost models for these projects as my facility either performed the work in-house or partnered with a local contractor for larger projects involving rigging, etc. We had all of the rates and could estimate hours.

Small capital projects (≤$2.5Mil) were generally tied to process improvement, Operator safety and/or product quality optimization. Our Technology Innovation team, unit Operations staff, Maintenance Teams and/or I/E Techs would supply high level scope details. It was up to my department to fully develop the scope and Opinion of Probable Cost estimates. This could be accomplished by partnering with our local PM staff, DCN Control Technicians, equipment vendors, etc. For this stage of the project, management may ask for a Failure Mode and Effects Analysis (FMEA) or preliminary Risk Assessment. In some cases, management would ask for a full Hazard and Operability Analysis (HAZOP).

For larger capital projects, some engineering monies were required to fully define the scope and rough order of magnitude costs. We would approach management with project ideas and request "seed monies" (<$50K) to further develop the Business Justification. Larger projects required more rigor and larger teams to develop the Business Justification. We performed many of the same tasks required for small projects and may be asked to perform first steps associated with Design for Lean Six Sigma (DFLSS) or Define, Measure, Analyze, Improve and Control

(DMAIC) processes. These concepts are associated with Six Sigma, Many department leaders were Black Belts within my company.

Typically, this first round meeting would require follow up information be investigated, analyzed and presented. In some cases, we would receive engineering monies to proceed to Stage 2 known as the Cost Engineering Package (CEP). The CEP would be similar to 30% CD's with 100% PFD's/90% P&ID's complete and would also include a +30% / - 10% Detailed Cost model. All contingencies would be identified, and action plans presented to mitigate project risk. After CEP was completed, we would present to management for additional engineering monies and possibly equipment shop drawing procurement monies.

Again, the CEP phase was multi-step with the management team. This is the phase whereby multiple options were suggested to enhance the original concept. Each suggestion required rigorous analysis with additional engineering and costing. I had one project that required four CEP "pitches" before getting approved to the next stage. We had monthly meetings with management, so this delayed the original project execution schedule estimates considerably. Once approved, our project estimate would put on a priority list, we would be granted more engineering monies and we moved into Stage 3 of the process known as the Basic Engineering Package (BEP).

The BEP deliverable would be similar to a 95% CD package with 100% P&ID's. We may be able to present some equipment shop drawings and shared a +/- 10% Cost Model. Our company utilized a Management of Change (MOC) process, so the preliminary MOC assessment was presented. We would typically engage the DCN Control Technicians and several levels of Operations during BEP. It was important to also engage the Maintenance Team and I/E Techs during this stage of the process. Depending on the size of the project, this BEP phase may last 6 months to a year. I was involved with a large-scale project whereby this process took 1.5 years to complete.

The BEP presentation was to get final project funding approved such that remaining equipment and services can be approved. This did not ensure the project would actually get executed; however, it did all the project to move into Stage 4. During Stage 4, our task was to complete the drawings, develop pipe spool/fabrication drawings, get everything pre-fabricated, procure all remaining equipment and allocate external and internal resources to proceed with project execution. Additional tasks include develop of Standard Operating Procedures, execution of the MOC process (including Code Compliance, Safety Compliance, etc.) and start scheduling production interruptions or shut-downs to perform the actual installation. Our turnarounds (or large-scale production shut-downs) occurred every ~3 years so it was important to coordinate all piping tie-ins.

For capital project, we would meet with management during Stage 4 construction to provide updates and request confirmation of final, full project funding had gone through corporate. This process may take up to an additional six months. We needed to secure final funding before writing the final contracts with our installers. Once these contracts were completed, we were ready to move into Stage 5 which included completion of installation, development of control simulation modeling, project installation validation, coordination with our Reliability department, water batch testing, Operator training for each shift, process verification and asset entry.

The stage-gate process can be viewed by some as cumbersome but considering our facility's Maintenance and Capital Expenditure (CapEx) budget, the process was very necessary. Small, maintenance replacements took about 1 year to fully execute. Larger maintenance projects involving Code vessels took ~1.5 years to complete. I was involved with three (3) small CapEx projects, and each took about 1.5 to 2 years to complete. I was also involved with two (2) medium-sized CapEx projects (≤ $5Mil) and each one took about 2.5 years to complete. My portions of the larger project consisted of ~$15Mil. These three (3) projects were tied to a much larger initiative (~$45Mil). After 3 years, we were able to complete about half of the project and 100% of our piping tie-ins. Large scale projects can take up to 5 years.

As a comparison, Busch stadium ($360Mil) took a little less than 5 years to complete and Cx. Most Light Commercial projects can be fully completed in <8 months. Large Commercial projects (≤$100Mil) can typically be completed in <1.5 years. I was involved with a fairly large High School which included an Auditorium, that project was completed <1.5 years. Large-scale healthcare projects may take up to 5 years to complete. Additions to existing facilities can usually occur much more quickly. I Was involved with a hospital expansion involving 23 OR's and new, 4-story patient tower. This was design-build project and was completed in <2.5 years. Most commercial projects have a ~1.5 year design/construction cycle in the design-build world.

CODES AND STANDARDS

Codes and standards are put in place to protect the public, provide a standard for design of buildings and all systems that are contained within them and ensure equipment will meet minimum energy performance guidelines. Adopted Codes and standards are enforceable by law.

It is up the HVAC design engineer to read and understand these Codes such that they can be properly applied.

The first step to applying the correct Codes is to fully understand the building you are designing. The market sectors described in this Course provide a good start; however, this Course was intended to provide a brief overview and did not include Malls, Parking Garages, Theaters or Hazardous Storage Facilities to name a few. I encourage the reader to study the Codes that apply to each of the Market Sectors described and learn about special circumstances not discussed in this Course. For now, we will spend time understanding the basics of the International Code Councils codes, major sections to start with, interactions between the Codes and common changes or supplements states and large municipalities may issue. The ICC digital Codes can be accessed for free here: https://codes.iccsafe.org.

One can click on the "Find Your Codes" button and a category screen appears on the left side of the screen. Codes can be searched by type, state, year, etc. As you will find, there are several, interrelated Codes including International Building Code (IBC), International Mechanical Code (IMC), International Energy Conservation Code (IECC), International Fuels Gas Code (IFGC) and International Fire Code (IFC). This Course will focus on these Codes as they govern a majority of what the HVAC design engineer will encounter.

It is important to note that the Codes are updated and issued every three years. States may modify these Codes with Supplements or issue their own versions of the Code (e.g., New Jersey, California). Municipalities adopt Codes, make modifications to them or issue their own versions via state and local ordinance. Some states, like New York, utilize different versions of the Codes depending on the project type. One of the first steps to applying the proper Code is to understand which version of these Codes are valid for the project at hand. In some cases, adoption of a Code supplement or newer version of the Code may occur during the course of design. To that end, it is also important to open a dialogue with your local Code officials or Authority Having Jurisdictions (AHJ's) to ensure to be abreast of upcoming changes and potentially coordinate adherence.

This also applies to standards and guidelines referenced within the Codes. Codes present a definition of compliance. Standards and guidelines give engineers the "how to". Standards and guidelines are not Codes; however, they must also be studied, and measures taken to adhere to them. Many standards are written in code language and some states have adopted them separately. Common standards to review are ASHRAE 15, 30, 62.1, 90.1; ASME B31.5, B31.9; FDA Title 21; NEC 70, 99; SMACNA and UL.

The HVAC design engineer should spend time studying the architectural drawings and become familiar with the building. IBC, Chapter 3 deals with Building Use Group and Occupancy Classifications. There are ten occupancy classifications as follows:

1. Section 303, Assembly Groups A-1 through A-5
2. Section 304, Business, Group B
3. Section 305, Educational, Group E
4. Section 306, Factory and Industrial, Group F-1 and F-2
5. Section 307, High Hazard, Groups H-1 through H-5
6. Section 308, Institutional, Groups I-1 through I-4
7. Section 309, Mercantile, Group M
8. Section 310, Residential, Groups R-1 through R-4
9. Section 311, Storage, Groups S-1 and S-2
10. Section 312, Utility and Miscellaneous, Group U

Most of the market sectors included in this Course correspondence to these occupancy classifications and may include multiple classifications within the same building (mixed occupancy). Residential dwelling units have their own Code, The International Residential Code (IRC). Below are some classifications that may be associated with the remaining market sectors:

1. Light Commercial: B
2. Commercial: A-3, B, M, R-1 through R-4
3. K-12: A-1, B, E
4. Higher Education: A-1, A-3, B, I-4, R-3
5. Healthcare: A-3, B, I-1, I-2, I-3, I-4
6. Pharmaceutical: B, F-1, F-2, H-3, H-4, S-1, S-2
7. Food & Beverage: B, F-1, F-2, H-3, S-1, S-2
8. Refrigerated/Warehousing: B, H-1, H-2, H-3, H-4, S-1, S-2
9. Industrial Manufacturing: B, F-1, F-2, H-1, H-2, H-3, H-4, S-1, S-2

Primary occupancy may contain other occupancies and the building may not be classified as mixed use. It is up the HVAC design engineer to still comply with occupancy classification requirements for each space based on use and function (IBC, Ch. 5). We are not architects; however, we should study the architectural drawings and understand the materials of construction, fenestration and special equipment being used.

IBC, Chapter 5 covers building heights and areas based on construction types and protections. This chapter also covers Mezzanines which are particularly important with Pharmaceutical as well as Food & Beverage projects. Construction types are discussed in Chapter 6. Construction classifications are different than occupancy classifications. Protected and un-protected buildings have different wall constructions and ratings which directly affect the HVAC design. IBC, Chapter 16 covers Seismic and Wind Use Groups. This chapter references a publication developed by the American Society of Civil Engineers, ASCE 7. This publication defines restraints and design procedures that may be required for buildings as well as HVAC equipment and system components within the building. These sections allow development of the architectural partition schedule, egress routes and life safety plan. All of these documents directly affect the HVAC design.

IBC, Chapter 4 contains several sections on special detailed requirements. These are specific requirements for different occupancy classifications that must be adhered to during HVAC design. This section contains several specific references to NFPA Standards, sections of the International Fire Code (IFC), etc. All related sections should be read to develop the interaction between these Codes and Standards.

IBC, Chapter 7 includes definitions and required protections for various partition/wall types such as vertical openings (712), shaft enclosures (713) and air transfer openings (717). These design elements will be identified on the architectural drawings and the architect may seek guidance from the HVAC design engineer in terms of suitable protections for each scenario.

IBC, Chapter 9 is all about Fire Protection Systems that may be required within the different occupancy classifications. Topics include alternative automatic fire-extinguishing systems (904), fire alarm and detection systems (907), smoke control systems (909), fire command center (911), fire pumps (913) and carbon monoxide detection (915). The HVAC equipment and systems designs may interact with a number of these sections.

IBC, Chapter 10 describes means of egress and include special HVAC requirements for some. Categories the HVAC design engineer should become familiar with include corridors (1020), interior exit stairways and ramps (1023), exist passageways (1024), horizontal exits (1026) and assembly (1029).

And finally, IBC, Chapter 12 includes two sections directly related to the HVAC design. Ventilation (1202), temperature control (1203) and sound transmission (1206) may apply to your project designs.

As an HVAC design engineer, one should become completely familiar with the International Mechanical Code (IMC). Key Chapters include:

Chapter 3 – General Regulations
Chapter 4 – Ventilation
Chapter 5 – Exhaust Systems
Chapter 6 – Duct Systems
Chapter 7 – Combustion Air
Chapter 8 – Chimneys and Vents

Again, there are several references to sections within IMC, sections in IBC, NFPA and other standards. All references should be read, and fully understood. The engineer may find duplication and/or conflicts between the sections. I have found that reading Code Commentary is very helpful as this commentary explains the technical requirements of the Code. Below are other Code sections to become familiar with (indicated for each):

International Plumbing Code (IPC):
Chapter 3 – General Regulations
Chapter 8 – Indirect/Special Waste

International Fuel and Gas Code (IFGC):
Chapter 3 – General Regulations
Chapter 4 – Gas Piping Installations
Chapter 5 – Chimneys and Vents

International Fire Code (IFC):
Chapter 3 – General Regulations
Chapter 9 – Fire Protection Systems
Chapter 10 – Means of Egress

International Energy Conservation Code (IECC):
Chapter 3 – General Requirements
Chapter 4 – Commercial Energy Efficiency
Chapter 5 – Existing Buildings

Some observations I have established over the years:

1. IBC Sections 712, 713, 714, 716 and 717 links with IMC Section 607
2. IBC Chapter 10 links with IFC Chapter 10
3. IPC Chapter 3 and IMC Chapter 3 have a lot of duplication
4. IMC Chapter 8 and IFGC Chapter 5 have a lot of similarities

5. Several aspects of IBC Chapter 9 relate to IBC Chapter 4

One has to spend time reading the Codes to become familiar with their formatting. Exceptions only apply to sections they are included in, certain requirements may only apply to sub-sections and not overall content of particular chapters, etc. It is imperative that project specific Code searches occur during early design to identify scope items and ensure the budget includes equipment to address all requirements.

SUMMARY

This Course was intended to familiarize the reader with HVAC equipment and system choices associated with various market sectors, describe project execution strategies that may be implemented and outline specific Code sections that may apply to each building type. There are several equipment and system options available to the HVAC design engineer. It is important that the proper discovery occur early in the design process to fully understand project goals and priorities (schedule, cost, complexity/efficiency). Once defined, the HVAC engineer can provide options, make further evaluations (e.g., Code, energy consumption, etc.) and make recommendations in a manner appropriate with the project execution strategy. This aspect of Consulting sets the stage for Code compliant, successful project layout and design.

The budgeting phase is the most important part of any project. Clear communication is key to developing a complete scope and establish expectations. Courses 2, 3 and 4 will provide more tools to help the HVAC designer better define system design requirements. This information will allow for better collaboration reducing coordination issues, design rework ("churn") and errors.

Course 2 will include three sections: 1.) Comfort Cooling Factors, Design Fundamentals and Psychrometric analysis; 2.) Load Input/Output Information and Procedure; and 3.) System Comparisons and Economic Analysis required for early design decisions. This Course will help establish the basis for design and identify design risks.

Course 3 will describe typical HVAC Zoning for various applications, ductwork design strategies, ductwork layout practices and describe DX system control components. This Course will also include chilled water/hot water systems and control strategies. This is the "how-to" of HVAC design.

Course 4 will include three sections: 1.) DX vs. Chilled Water and Relative $/sq. ft. Costs for Each; 2.) Chilled Water/Hot Water Plant Design; 3.) Geothermal and Other Technologies. A deeper dive into these topics will further equip the HVAC designer with key knowledge needed to communicate effectively with the design/construct team.

COURSE NOTES AND PHOTO CREDITS

(1) Photo 1, Daikin Residential Split System provided by Daikin Comfort
(2) 12,000 Btuh = 1 Ton of Cooling. It is a quantity approximately equal to the latent heat of fusion or melting of 1 ton (2,000 lb) of ice, from and at 32F. ASHRAE Technical Committee (TC) 1.6 https://www.ashrae.org/technical-resources/authoring-tools/terminology
(3) Photo 2, Titus VAV Box with Electric Reheat provided by Titus
(4) Photo 3, Daikin RPS, VAV RTI provided by Daikin Applied
(5) Photo 4, Carrier centrifugal chiller provided by Carrier Corporation
(6) Photo 5, Daikin Unit Ventilator provided by Daikin Applied
(7) Photo 6, Century Evaporator provided by Century Refrigeration