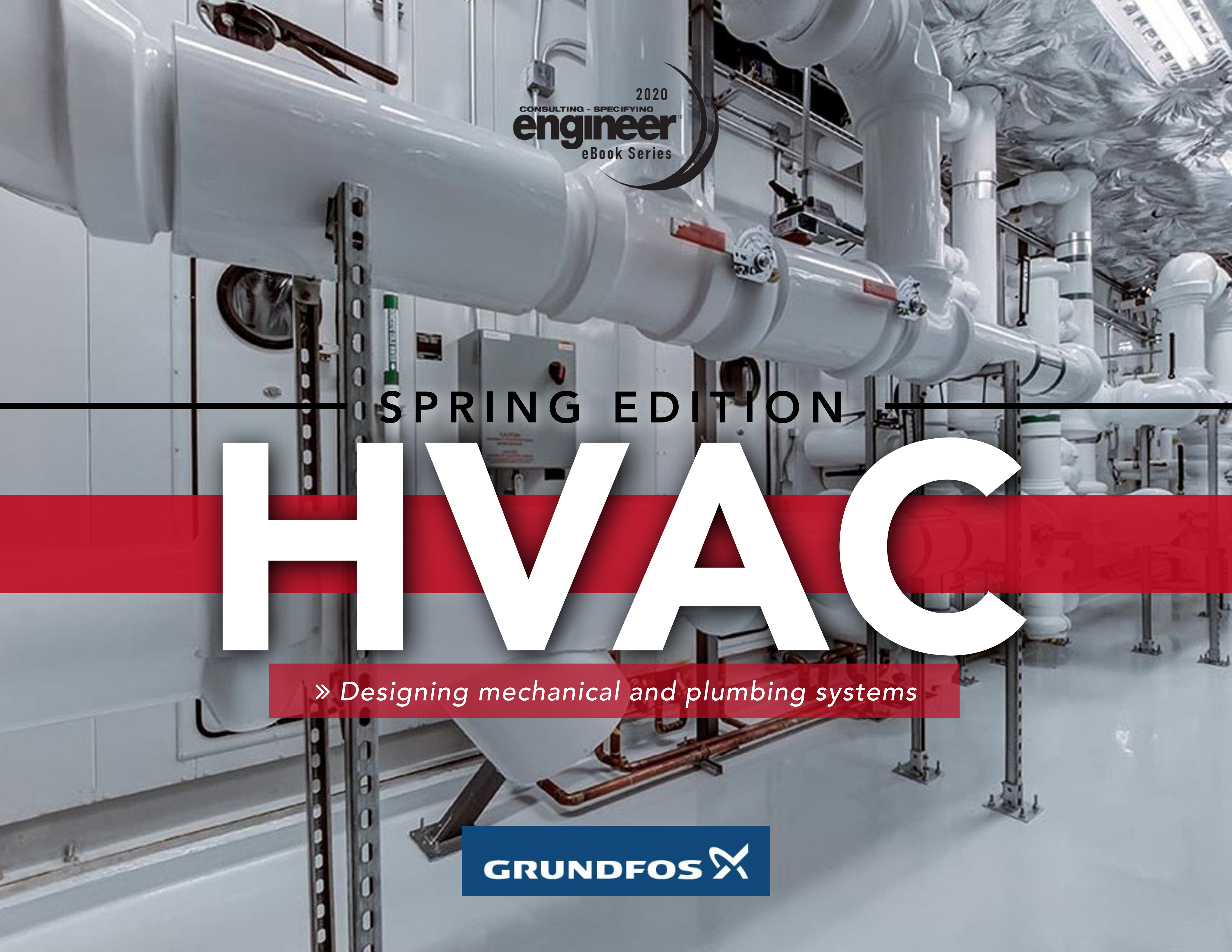

2020
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SPRING EDITION

HVAC

» *Designing mechanical and plumbing systems*

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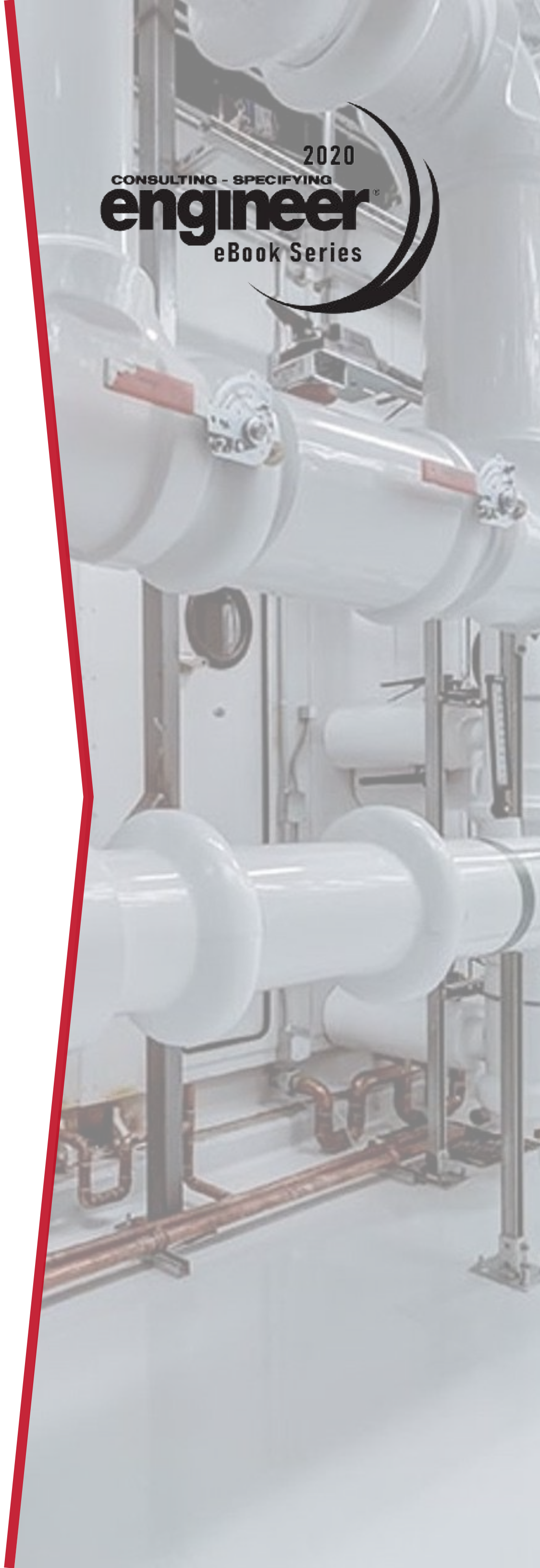

Pipe systems and materials: Design considerations

Choosing the right pipe system and design is essential to ensure excellence in mechanical, plumbing, fire protection and beyond

It's easy to forget about pipe systems. Once installed, they are rarely seen or thought about. But that belies their importance, especially when it comes to choosing the right pipe system and design to ensure excellence in mechanical, plumbing, fire protection and beyond.

Simply defined, pipes are pathways through which fluids are contained and flow in a system. The fluids may be water, glycol solution, fuel oil and refrigerant liquid. A network of pipes, fittings, joints, valves and supports is defined as a pipe system.

There can be multiple pipe systems on a typical project and they can be segregated by disciplines such as civil (domestic water, stormwater, sanitary, industrial water, wastewater, etc.); mechanical or heating, ventilation and air conditioning (chilled water, condenser water, hot water, steam, condensate, natural gas, fuel oil etc.); plumbing (domestic cold water, hot water, waste, vent, etc.); and fire protection (sprinkler water, compressed air, etc.).

Pipe system design is dependent on the requirements and design criteria that are specific of each discipline. The design of pipe systems is also governed by codes such as those published by ICC and standards and guidelines published by trade associations such as ASME, ASTM, NFPA, MSS, AWWA and ASHRAE.

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An optimum pipe system design is critical to the operation and longevity of the overall infrastructure and requires a multi-pronged approach. With appropriate maintenance, piping is typically expected to last the age of the building, while other equipment is replaced at the end of its service life. As pipe systems span multiple disciplines with varying requirements, developing an all-encompassing design guideline would be a monumental task.

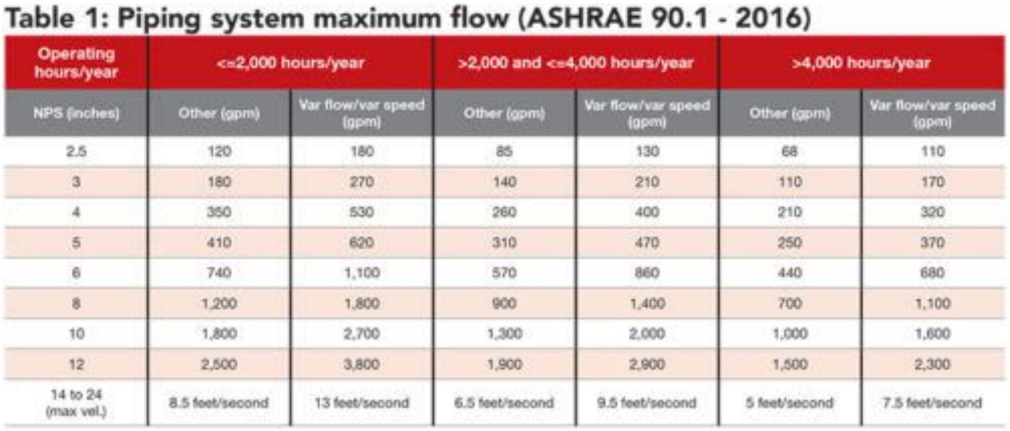

Table 1: Piping system maximum flow (ASHRAE 90.1 - 2016)

Operating hours/year	<=2,000 hours/year		>2,000 and <=4,000 hours/year		>4,000 hours/year	
NPS (inches)	Other (gpm)	Var flow/var speed (gpm)	Other (gpm)	Var flow/var speed (gpm)	Other (gpm)	Var flow/var speed (gpm)
2.5	120	180	85	130	68	110
3	180	270	140	210	110	170
4	350	530	260	400	210	320
5	410	620	310	470	250	370
6	740	1,100	570	860	440	680
8	1,200	1,800	900	1,400	700	1,100
10	1,800	2,700	1,300	2,000	1,000	1,600
12	2,500	3,800	1,900	2,900	1,500	2,300
14 to 24 (max vel.)	8.5 feet/second	13 feet/second	6.5 feet/second	9.5 feet/second	5 feet/second	7.5 feet/second

Table 1: *ASHRAE 90.1-2016 piping system maximum flow is shown. Based on the flow configuration and annual hours of operation, maximum flow for different pipe sizes is indicated for chilled water and condenser water application. Courtesy: ESD*

There are numerous factors that need to be considered when selecting a pipe system, such as:

- Type of fluid.
- Fluid pressure.
- Fluid temperature.
- Fluid flow rate.
- Code and authority having jurisdiction requirements.
- Service life.
- Project cost.

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- Project schedule.
- Local labor expertise.

Piping materials

Pipes can be broadly classified as metallic type and nonmetallic type. Commonly used metallic pipes are carbon steel, copper and ductile iron. Metallic pipes and fittings have been used for ages and continue to be used extensively.

Steel pipes manufactured in accordance with ASTM A53 standard specification are typically used in the mechanical industry. ASTM A53 covers nominal pipe size from 1/8 inch through 26 inches. Based on the manufacturing process and size, steel pipe can be classified as Type S (seamless), Type F (furnace butt weld) or Type E (electric resistance weld). Type F is available in Grade A while Type E and Type S are available in Grade A and B. The two grades have slightly different chemical composition of steel such as maximum percentage of carbon. Grade B is widely used due to its higher tensile strength.

The wall thickness of steel pipe is identified by schedule or weight class. Depending on size, steel pipe is typically available from schedule 5 through schedule 160 and wall thickness increases with schedule number. For example, 8-inch steel pipe has an outside diameter of 8.625 inches. However, the wall thickness varies from 0.109 inch (schedule 5) to 0.906 inch (schedule 160).

The working pressure of steel pipe increases with its schedule. ASME B31 identifies the criteria for calculating the working pressure of steel pipe systems. Calculations should

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include allowance for mill tolerance on wall thickness, corrosion allowance and cutting allowance if using threaded or cut-grooved joints. The ASHRAE Fundamentals Handbook is an excellent reference and it provides working pressure of commonly used steel pipe schedules from nominal pipe size 1/4 inch to 20 inches.

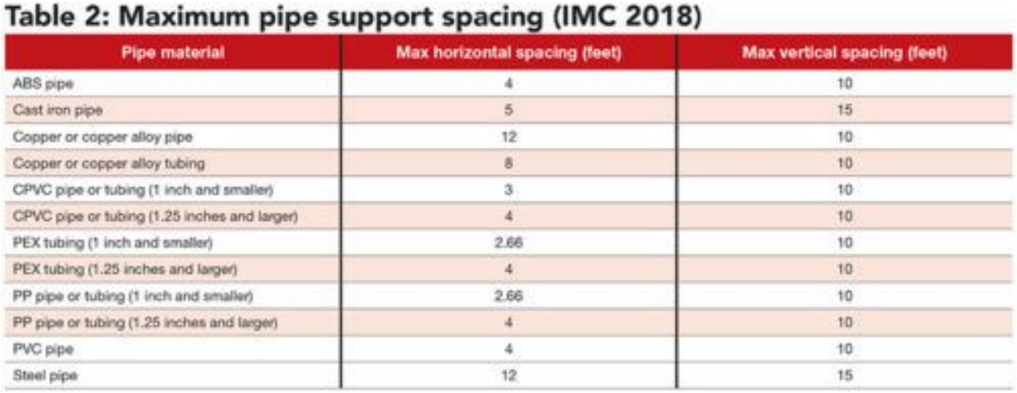

Table 2: Maximum pipe support spacing (IMC 2018)

Pipe material	Max horizontal spacing (feet)	Max vertical spacing (feet)
ABS pipe	4	10
Cast iron pipe	5	15
Copper or copper alloy pipe	12	10
Copper or copper alloy tubing	8	10
CPVC pipe or tubing (1 inch and smaller)	3	10
CPVC pipe or tubing (1.25 inches and larger)	4	10
PEX tubing (1 inch and smaller)	2.66	10
PEX tubing (1.25 inches and larger)	4	10
PP pipe or tubing (1 inch and smaller)	2.66	10
PP pipe or tubing (1.25 inches and larger)	4	10
PVC pipe	4	10
Steel pipe	12	15

Table 2: *This highlights the 2018 edition of the International Mechanical Code maximum support spacing for common pipe materials. Nonmetallic pipes require frequent supports compared to metallic pipes. Courtesy: ESD*

For the mechanical industry, commonly used steel piping is schedule 40 and schedule 80 for sizes 10 inches and below. Schedule 40, STD (standard weight) and schedule 80 are commonly used for pipe sizes 12 inches and above.

Steel pipes are typically joined by using welded, flanged, threaded or grooved-end fittings. A hybrid solution is common, such as using threaded fittings for pipes 2 inches and below and flanged fittings for sizes 2.5 inches and above.

Copper tubes manufactured in accordance with ASTM B88 standard specification for water service; ASTM B306 for drain, waste and vent service; and ASTM B280 for air conditioning and refrigeration service are typically used in the mechanical industry. A minimum of 99.9% pure copper is used for their production. Copper tubes are classi-

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fied as Types K, L, M and DWV depending on the wall thickness per ASTM standard B88 and B306. Wall thickness and working pressure reduces from Type K through DWV. For example, a 2–inch copper tube has an outside diameter of 2.125 inches. However, the wall thickness is 0.083 inch (Type K), 0.070 inch (Type L), 0.058 inch (Type M) and 0.042 inch (Type DWV).

Similar to steel piping, ASME B31 identifies the criteria for calculating the working pressure of copper tube systems. Copper tubes are available as hard-drawn (rigid) or annealed (bendable). Hard-drawn tubing has a higher working pressure compared to annealed tubing. Copper tubes are typically joined by using brazed, soldered, grooved-end or press-connect fittings. When brazing is used for joining hard-drawn copper tubing, the high temperatures associated with the joining process anneals copper at the joint and therefore the pressure ratings of annealed tubing are used.

Ductile iron pipe is used sparingly in the mechanical industry, though it is extensively used in plumbing and civil applications. AWWA C150 deals with DI pipe.

Common nonmetallic pipe systems used in the mechanical industry are polyvinyl chloride, chlorinated polyvinyl chloride, cross-link polyethylene (PEX), high-density polyethylene, polypropylene, acrylonitrile butadiene styrene and others. Nonmetallic systems continue to gain popularity in the mechanical industry and proprietary plastic blends continue to be developed.

Nonmetallic pipes offer several advantages such as low cost, light weight, inherent corrosion protection, immunity from galvanic effects, chemical inertness, low thermal conductivity, low friction losses and ease of installation.

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However, the application needs to consider the disadvantages, such as low baseline strength and severe degradation at elevated temperatures, high coefficient of expansion and limited ultraviolet resistance if installed outdoors. Nonmetallic pipes are typically joined by solvent, threaded and flanged connections.

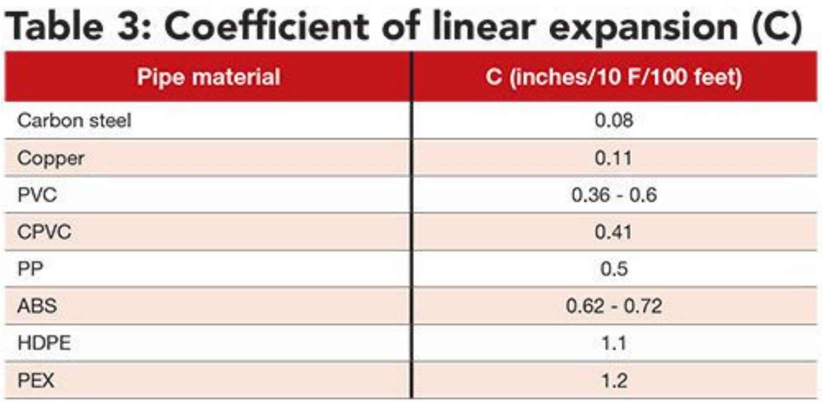

Table 3: Coefficient of linear expansion (C)

Pipe material	C (inches/10 F/100 feet)
Carbon steel	0.08
Copper	0.11
PVC	0.36 - 0.6
CPVC	0.41
PP	0.5
ABS	0.62 - 0.72
HDPE	1.1
PEX	1.2

***Table 3:** Coefficient of linear expansion is shown for different pipe materials. Nonmetallic pipes typically have significantly higher coefficient of expansion compared to metallic pipes. Courtesy: ESD*

Identifying the right pipe

The various pipe materials have inherent advantages and disadvantages. During design, it is critical that the attributes of pipe systems be reviewed in detail to ensure that the system that best satisfies the project requirements is selected.

Sizing

- For hydronic applications, velocity and pressure drop (due to friction losses) are the two primary factors that are considered for sizing pipes. The intent is to select the smallest possible pipe size while ensuring that velocity and pressure drop are within limits.

- The general recommendation is to limit fluid velocity to 10 feet per second for metallic pipes and 5 feet per second for nonmetallic pipes to minimize the impact

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of noise, erosion, cavitation and water hammer, depending on the application. Water hammer and pressure surges need to be specifically reviewed for nonmetallic pipes — hence the general recommendation to limit velocity to 5 feet per second. A minimum velocity of 2 feet per second is recommended for closed–loop systems to ensure that entrained air can flow to the air–separation device and be vented from the system.

- Another general recommendation is to limit pressure drop to 4 feet water column per 100 feet of pipe to ensure that pump head and power requirement are reasonable. Charts are available to help size pipes of various materials and they are typically used for most calculations. For complex applications requiring detailed analysis, pressure drop through

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piping can be calculated by using the fundamentals of hydraulics and equations such as Darcy-Weisbach and Hazen-Williams. The impact of fittings and pipe accessories such as valves can be accounted as equivalent pipe length or pressure drop equations that use loss coefficients. In addition, standards such as ASHRAE Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings also dictate pipe sizing. See Table 1 for chilled water and condenser water pipe sizing requirements per ASHRAE 90.1-2016.

Pipe supports

- Pipe supports must be designed to support the static and dynamic loads anticipated during operation. Static loads include weight of pipe system (pipe, valves, fittings, insulation, etc.), weight of fluid and weight of supporting elements. Dynamic loads include wind loads (for piping installed outdoors), seismic loads and forces generated by thermal expansion and contraction.

- The impact of these loads and means of support should be coordinated with the building structure. Standards such as ASME B31.9 and MSS SP-58 provide pertinent information related to design and installation of pipe supports. In addition, building codes such as the International Mechanical Code also have requirements associated with supporting pipes. Table 2 indicates the maximum support spacing of common pipe materials as mandated in IMC 2018. Note that nonmetallic pipes require frequent supports compared to metallic pipes.

Pipe expansion

- Pipe length alters with changes in its temperature. For an unrestrained pipe, the magnitude of change depends on the pipe material (coefficient of thermal ex-

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pansion), original pipe length and magnitude of temperature change. Table 3 indicates the coefficient of thermal expansion of common pipe materials. As is evident, nonmetallic pipes typically have significantly higher coefficients of thermal expansion compared to metallic pipes.

- Significant movement is possible for piping systems operating at high temperatures or in long runs of piping. Failure to account for thermal expansion and associated stresses can lead to failure of pipe supports, equipment connections and pipe joints. It is imperative that the pipe system be adequately flexible to accommodate pipe movement throughout its operating temperature range while keeping the internal stresses and anchoring forces within reasonable limits. Expansion compensation can be incorporated by using L-bends, Z-bends or U-bends at strategic locations along the pipe to increase flexibility or by using fittings such as bellows expansion joints and braided hose assemblies. Pipe stress analysis software can be used for complex applications.

Pipes are essential to civilized life. The idea that choosing the right system and design ensures all of us will be better off is a lead-pipe cinch.

Saahil Tumber, PE, HBDP, LEED AP, ESD, Chicago
Saahil Tumber *is technical authority at ESD. He is responsible for the overall design of mechanical systems for data centers, trading areas and other mission critical facilities requiring high availability. He is a member of the Consulting-Specifying Engineer editorial advisory board.*

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For a growing chemical processing and distribution company that was experiencing downtime and costly repairs, Grundfos' Hydro MPC BoosterpaQ — featuring the new CR 95 — offered the perfect solution.

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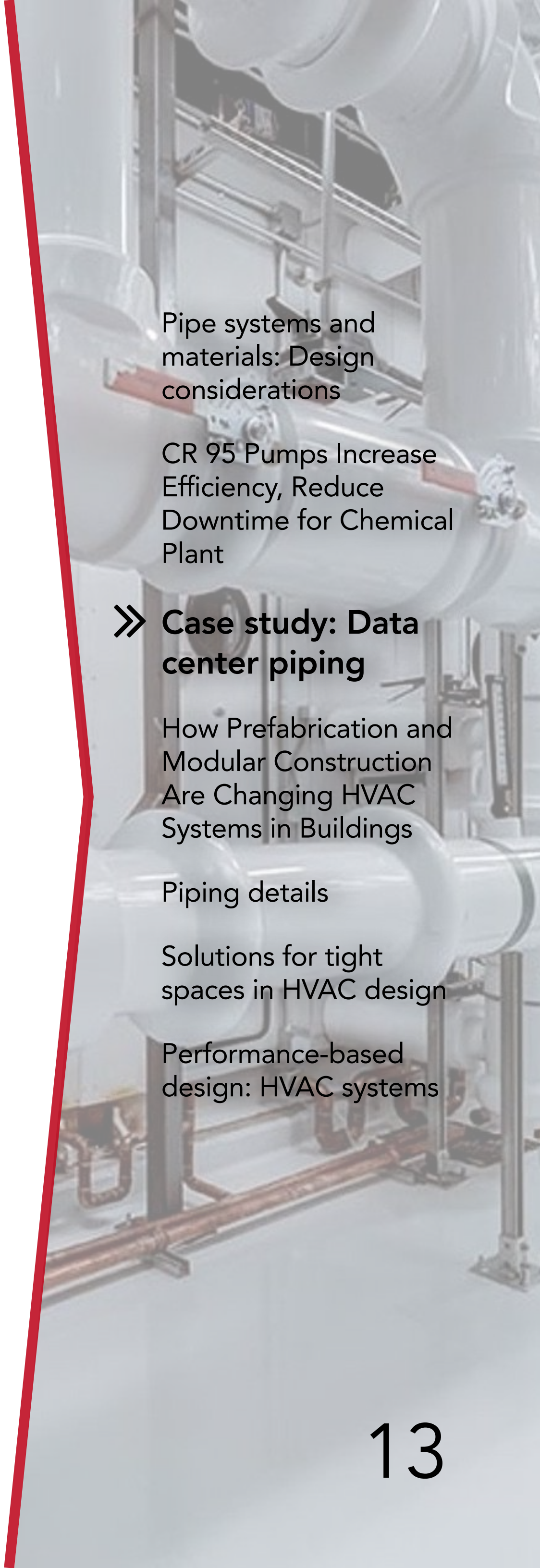
Case study: Data center piping

A data center required robust piping to transfer chilled water for cooling

A data center located in the Midwest was undergoing expansion. The project involved a new data hall with an initial load of 1,300 kilowatts and capability to scale up to an ultimate load of 2,600 kilowatts. An air-cooled chilled water plant was designed to serve the expansion space. The plant comprised of three 225-ton chillers piped in parallel to provide N+1 redundancy with the capability to add two additional 225-ton chillers in the future.

The heat transfer fluid was 40% ethylene glycol for freeze protection; each chiller featured a design flow of 380 gallons per minute and the chilled water pumping configuration was variable flow. The day one design flow was 760 gallons per minute and the ultimate design flow was 1,520 gallons per minute. Design chilled water temperature was 60 F supply and 76 F return. The system design pressure was 150 pounds per square inch gauge.

It was critical that the piping system serving the data center be robust. A piping system comprised of 8–inch schedule 40 steel pipe (ASTM A53, Grade B, Type E) with welded joints and fittings was used to create chilled water supply and return pipe loops beneath the raised access floor. The 8–inch pipe loops incorporated lugged butterfly valves at strategic locations to ensure that the piping system was concurrently maintainable — i.e., pipe segments could be isolated for maintenance activities without impacting the critical loads. Flanges were limited to valve and equipment connections. Figure 1 indicates the 8–inch chilled water supply and return loops. Also visible is 3–inch chilled water branch piping and ¾–inch condensate piping from the computer room air handling units.



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The piping system above the suspended ceiling was supported from the roof structure by using clevis hangers and metal framing system was used to support the piping system on slab beneath the raised access floor. Pipe supports were provided every 10 to 12 feet in compliance with the applicable code. Additional supports were provided at heavy pipe accessories such as air separators per manufacturer requirements. Figure 2 indicates the lugged butterfly valves at the 8–inch chilled water loops and the supports for the piping system beneath the raised access floor.

Figure 1: *Chilled water pipe serving the data center is shown. Branch piping to computer room air handling units and condensate piping is also visible. Courtesy: ESD*

Based on day one design flow of 760 gallons per minute, the maximum flow through an 8–inch pipe segment was 380 gallons per minute during normal operation, which corresponded to a pressure drop of 0.3 feet water column per 100 feet of pipe and a velocity of 2.4 feet per second. Based on ultimate design flow of 1,520 gallons per minute, the maximum flow through a pipe segment was 760 gallons per minute during normal operation, which corresponded to a pressure drop of 1 feet water column per 100 feet and a velocity of 4.9 feet per second.

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In the event a pipe segment had to be isolated for maintenance during an ultimate design condition, the maximum flow through the active pipe segment was 1,520 gallons per minute, which corresponded to a pressure drop of 3.9 feet water column per 100 feet and a velocity of 9.8 feet per second. In all scenarios, the pressure drop and velocity were within the recommended limits.

Figure 2: *Shown are metal struts for supporting piping systems on slab. Lugged butterfly valves at the chilled water supply and return loops are also visible. Courtesy: ESD*

Thermal expansion of the pipe system was reviewed. During normal operation, the minimum chilled water temperature was 60 F. In the event the data center was offline for an extended period and the chilled water system was disabled, the maximum water temperature was anticipated to be 95 F — i.e., the maximum temperature differential was only 35 F and the pipe loops had adequate capability to accommodate thermal stresses.

There were multiple locations where dissimilar pipe connections were necessary. For example, the CRAH units serving the data center had copper pipe connections. To reduce the potential of galvanic corrosion, dielectric flanges were used to connect steel pipe to copper.

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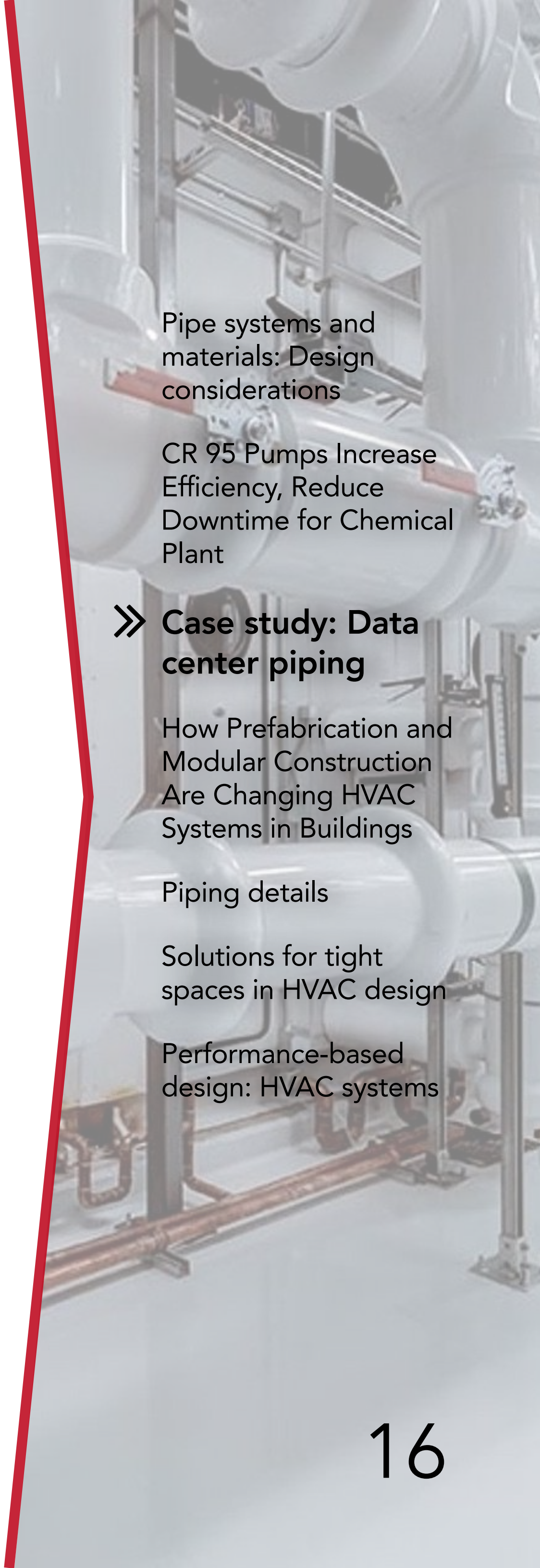
Chlorinated polyvinyl chloride was initially considered for condensate drain piping from the CRAH units. However, few CRAH units were equipped with an integral humidifier and the units also used the condensate piping for humidifier blowdown. Due to the potential of elevated water temperature in the pipe, CPVC was deemed to be unsuitable for the application and 1–inch copper pipe (ASTM B306 Type DWV) was used per CRAH unit.

The closed–loop system incorporated expansion tanks to accommodate fluid expansion, air separator to vent air from the system, glycol feeder to fill the system with glycol solution, side-stream filter to remove suspended solids from the system and chemical feeder for periodic injection of water treatment chemicals such as biocides, scale inhibitors and corrosion inhibitors.

Pipe connections with isolation valves and blind flanges were provided to ensure that future chillers and CRAHs could be incorporated without disabling the system. Pipe deadlegs were limited to 2 feet in length.

Saahil Tumber, PE, HBDP, LEED AP, ESD, Chicago
Saahil Tumber *is technical authority at ESD. He is responsible for the overall design of mechanical systems for data centers, trading areas and other mission critical facilities requiring high availability. He is a member of the Consulting-Specifying Engineer editorial advisory board.*



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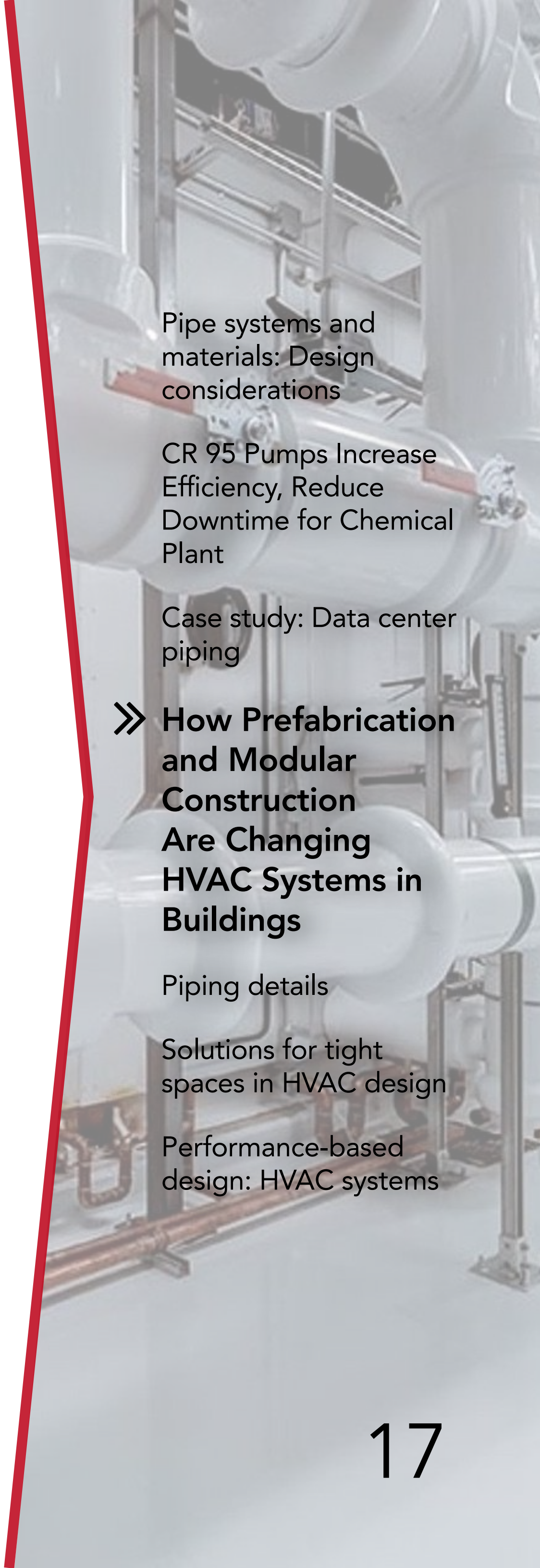
How Prefabrication and Modular Construction Are Changing HVAC Systems in Buildings

The positive impact on HVAC design, installation and overall efficiency

Prefabrication and modular construction have grown over the last few years as a solution to the problem of trade workforce shortages. These building methods are almost universally agreed to be advantageous because they improve:

- Productivity
- Quality
- Schedule certainty
- Cost predictability
- Waste reduction
- Client satisfaction
- Safety performance

As a result, the use of these methods in all aspects of construction is only expected to increase. According to the Prefabrication and Modular Construction 2020 SmartMarket Report from Dodge Data & Analytics, contractors are looking for both architects and engineers to leverage prefabrication and modular construction in more of their designs, but most of them only have experience with traditional, on-site construction practices. Regarding projects with Electrical, Mechanical and Plumbing (EMP)-oriented trade assemblies for HVAC, plumbing and electrical racks, risers and other assemblies, 64 percent of general contractors/construction managers (GCs/CMs) and 77 percent of



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trade contractors have used prefabricated systems — in stark contrast to just 39 percent of architects and engineers.[1]

In other words, prefabricated systems are well positioned to become the new industry standard, with demand driven by contractors and trades, but there is a lag in adopting these methods during project design. GCs/CMs forecast that 23 percent of projects over the next three years will include prefabricated systems for multi-trade assembly products — a 10-point increase from where we are today. Architects and engineers forecast prefabrication in only 19 percent of these upcoming projects — a 12-point increase from today's adoption.[2]

Prefabrication and Modular Construction Trends

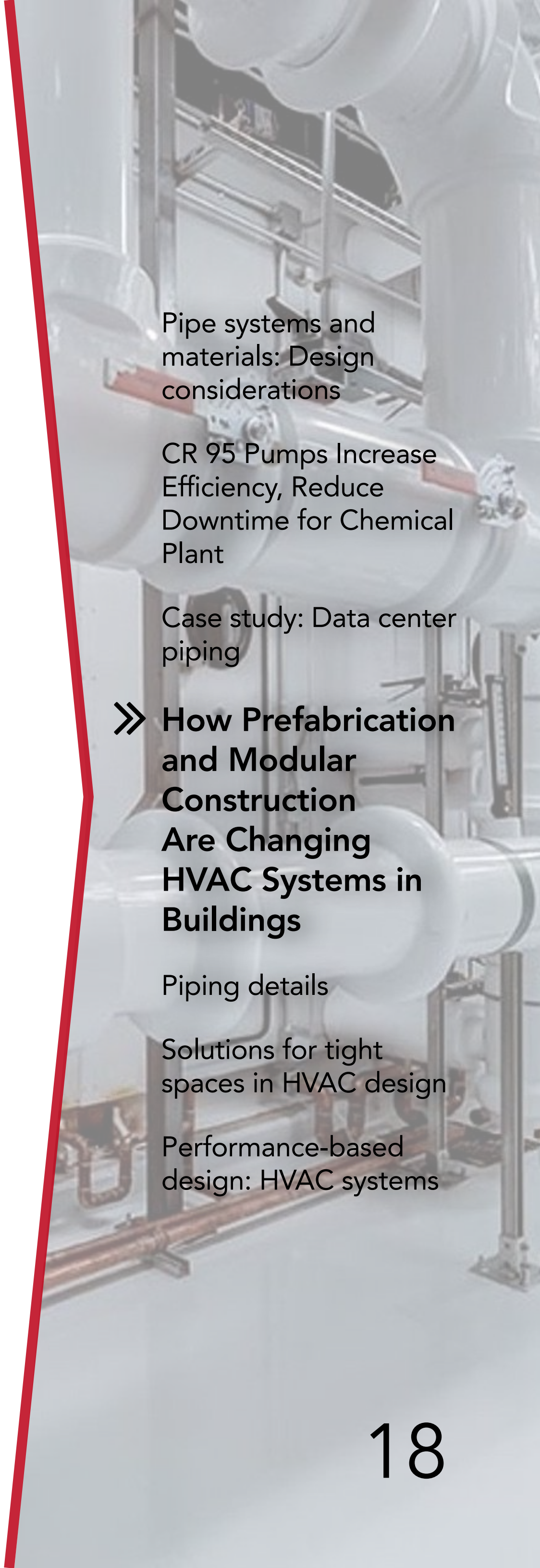
Prefabrication and modular construction are two ways of approaching off-site construction. The difference is what is built off-site.

What Is Prefabrication?

"Construction World" magazine defines prefabrication as "the practice of assembling a variety of components of a structure at a manufacturing site and transporting those sub-assemblies to the location of the construction jobsite." [2] Prefabricated units range from wall and floor panels to stairwells and more. Projects that are considered "on-site construction" often utilize prefabrication.

What Is Modular Construction?

In modular construction, the entire building is prefabricated. According to the Modular Building Institute:



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> *Modular construction is a process in which a building is constructed off-site, under controlled plant conditions, using the same materials and designing to the same codes and standards as conventionally built facilities — but in about half the time. Buildings are produced in "modules" that when put together on site, reflect the identical design intent and specifications of the most sophisticated site-built facility — without compromise.* [4]

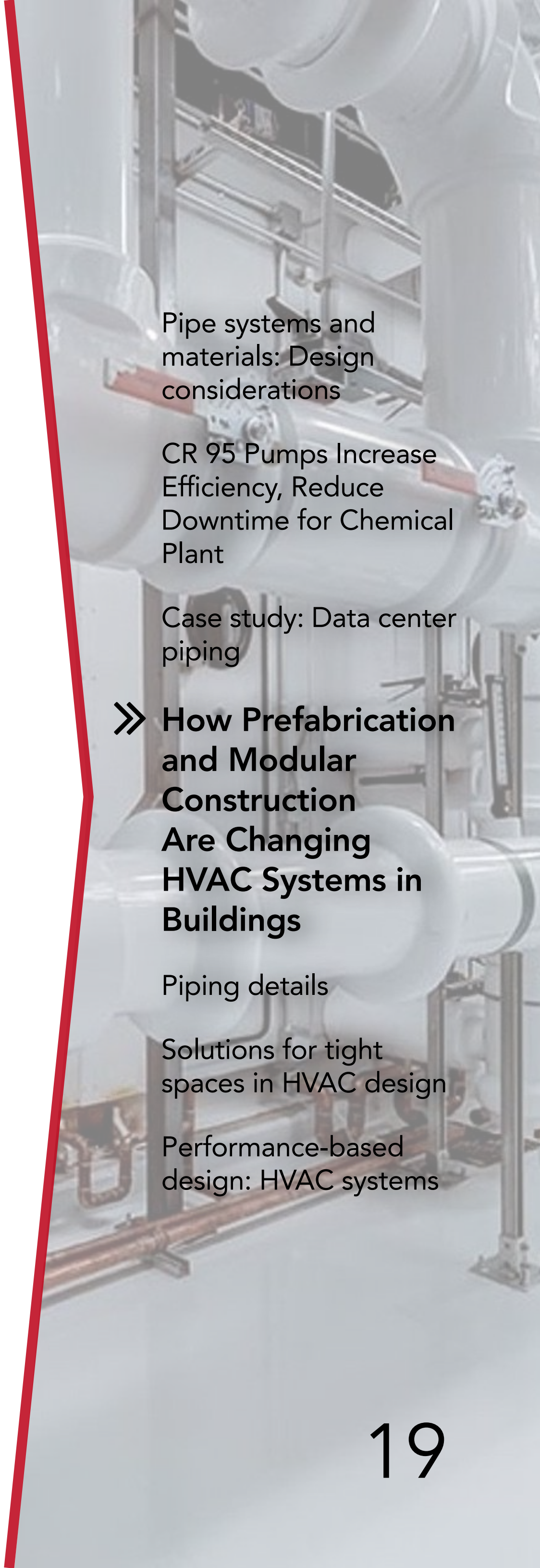
There are two types of modular construction: permanent modular construction and relocatable buildings.

Permanent modular construction (PMC) involves modules, or pods, that take the form of completed rooms or even complete hotel rooms with all the finishes. These modules are delivered to the job site and pieced together like building blocks.

Relocatable buildings (RBs) are what comes to mind for most people when they think of modular construction because examples are often seen traveling down the highway, bearing "wide load" signs. An RB is a partially or completely assembled building that complies with any applicable codes and/or regulations and is designed to be reused or repurposed multiple times. RBs are commonly seen at schools, medical clinics and construction sites.

Market Adoption and Forecast

The survey on which the SmartMarket Report is based shows that the various forms of prefabrication and modular construction have reached different levels of adoption in the United States. Among the survey respondents: [1]



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- 94% have used prefabrication in the last three years
- 38% have used permanent modular construction
- 28% have used relocatable modular construction

GCs/CMs agreed that the top obstacle to using prefabrication in more projects is its lack of inclusion in designs.

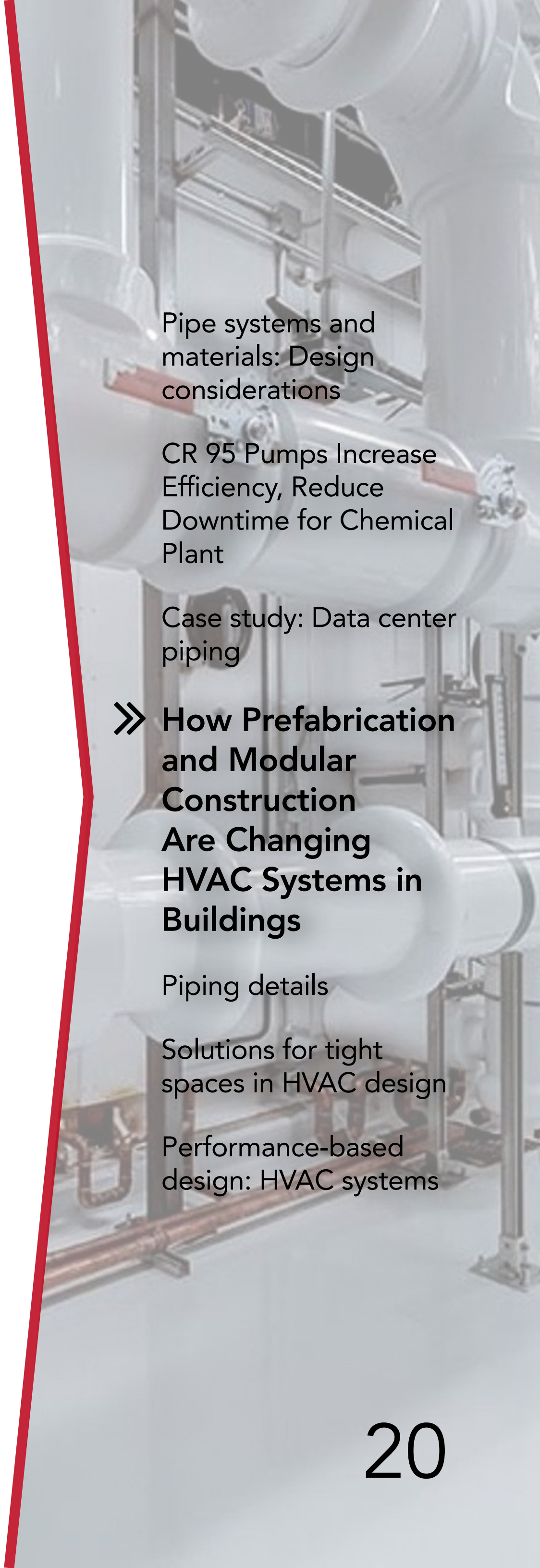
Survey respondents said that over the next three years, they expect to see more prefabrication and modular construction used in these building types:

- Health care facilities
- Hotels and motels
- Multifamily
- College buildings and dormitories
- Low-rise offices (1–4 stories)
- K–12 schools

Prefabrication in HVAC Systems

HVAC systems are vital for buildings. They must be reliable, efficient and designed to help the facility team optimize system performance, because HVAC impacts far more than human comfort. The optimal indoor climate raises people's productivity by up to 10 percent. A five- to eight-degree variance from the optimal temperature can decrease productivity by five to 10 percent.

A building's HVAC system is made up of many components. The most important pieces



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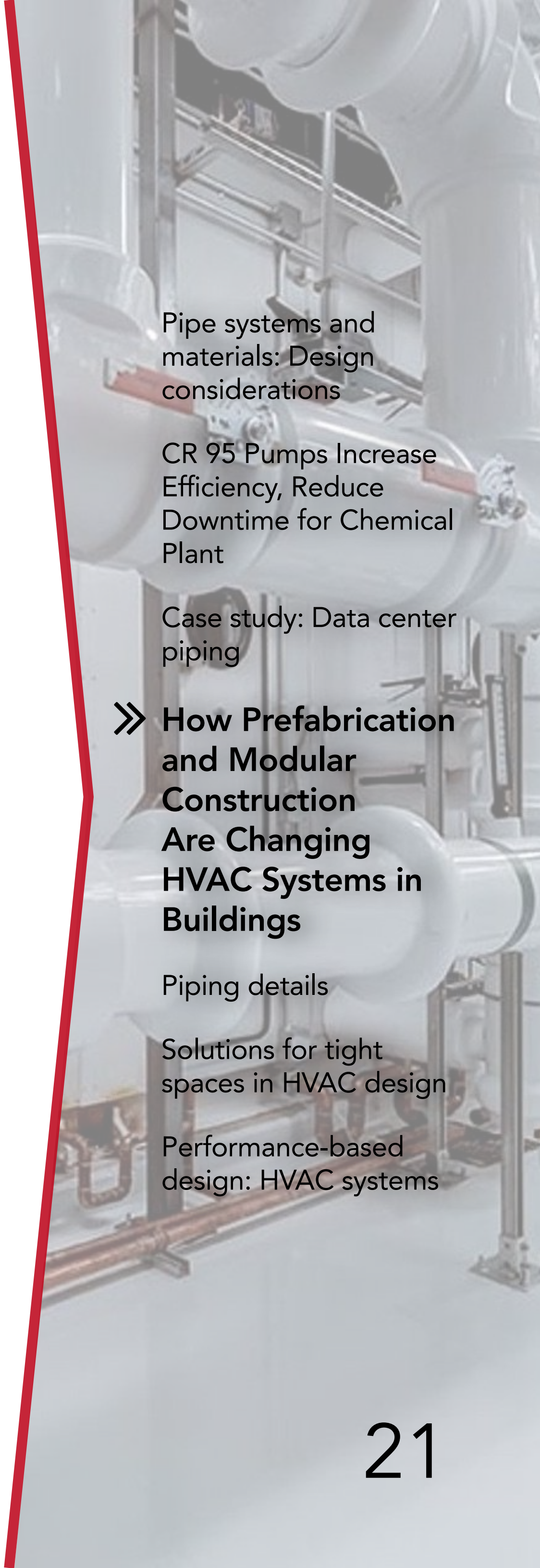
are the chiller and the air handling unit (AHU), which circulates air throughout a building to provide heating and cooling — both of which comprise many parts.

The HVAC industry has used prefabrication to overcome installation and commissioning challenges for many years. For example, when chillers were first introduced to the market, all the components were supplied individually: compressors, condensers, evaporators, expansion valves, power and controls units and other ancillary items. But now, chillers are sold as complete packaged systems. Likewise, AHUs are now sold as packaged systems made of many integrated components: filters, heating and/or cooling coils, humidifier, mixing chamber, blower/fan, balancing, heat recovery device, controls, vibration isolators, sound attenuators and more. The industry depends on chiller and AHU manufacturers to apply their expertise and design skills to build these important systems in factories for optimal efficiency and performance, rather than expecting contractors to do this work on-site. If the assemblies aren't sized, selected and built correctly, the building has problems.

But, for some reason, this logic doesn't extend to most HVAC pumping systems. The pump is the heart of the HVAC system, moving valuable and expensive chilled water throughout a building to maintain comfort for all. It serves as a water handling unit (WHU) for the entire building. Yet most pumping systems are still stick-built, requiring contractors to source and assemble multiple parts at the construction site. As an industry, it's time to recognize the value of prefabricated HVAC pumping systems.

The Value of Prefabricated Pumping Systems

Prefabrication offers the HVAC industry some of the same benefits of modular con-



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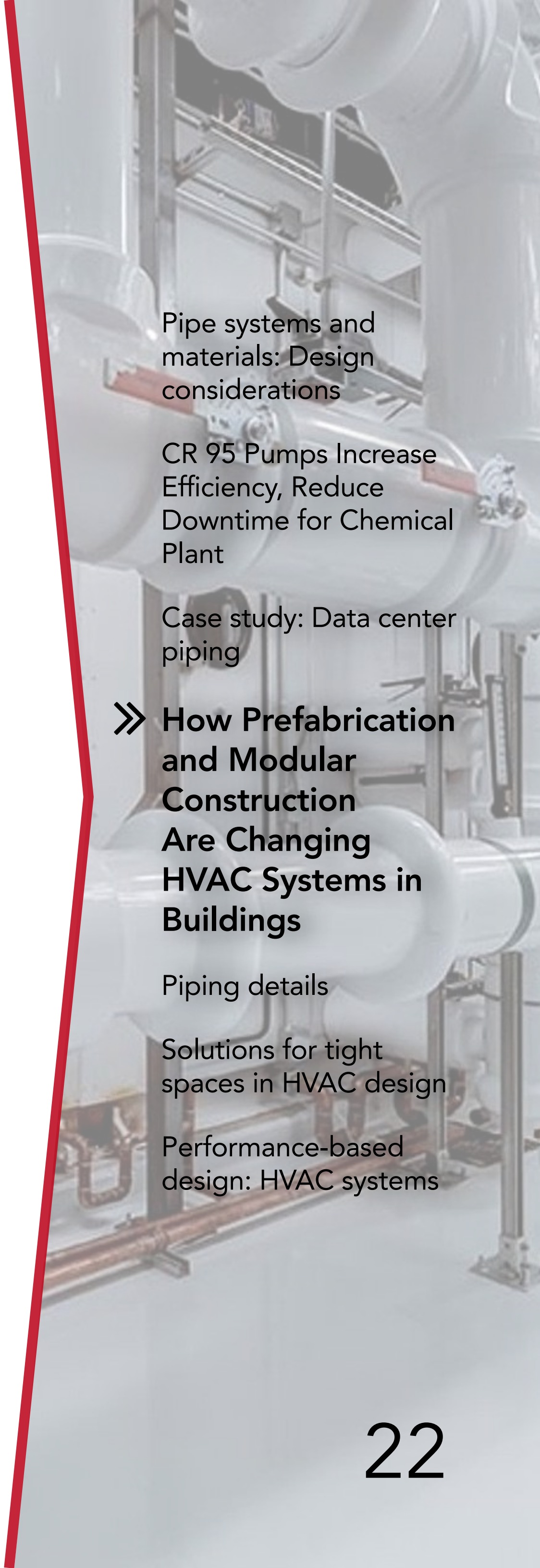
struction overall: the quality of a factory-controlled construction environment, and faster project completion.

The Quality of the Factory-controlled Environment

In the modular construction industry, factory-controlled builds allow for tighter construction, due to fewer site disturbances and less waste generation. Prefabrication and modular construction are considered green building approaches because materials can easily be recycled within the factory. In addition, manufacturers are able to control inventory and protect materials. An added safety benefit for the workers is improved air quality, and materials stay dry — nearly eliminating the chance of moisture being trapped inside the new building.

The same benefits can be achieved in the HVAC industry by using prefabricated pumping systems. The pumps, motors, drives and controls can be installed on a base frame, along with all the isolation valves, check valves, gauges and sensors. Everything can be pre-wired, -programmed and -commissioned to job-site requirements within the factory. This approach saves many hours of job-site labor, both mechanically and electrically, allowing for repeatability and ensuring the highest quality of work.

When assembling systems on-site with pumps, drives and controls from different manufacturers, it's not always easy to achieve optimum controls curves. And connecting two or more pumps in parallel, which is often required to maximize efficiency in the building, adds another level of difficulty, as the controls need to be set up for redundancy and/or cascade operation. But with an experienced single-source pumping system manufacturer, the assembly and design are optimized, and control programming maximizes operation efficiency.



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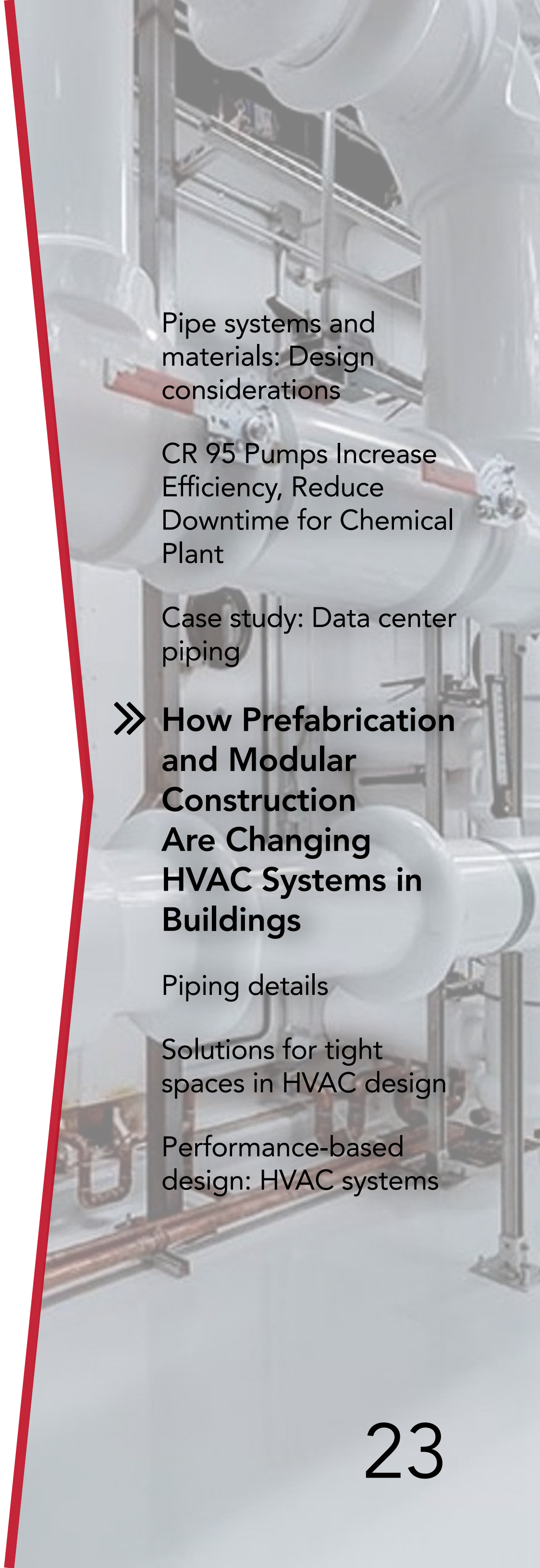
Additionally, packaged pumping systems can come with sensors on the inlet and outlet manifolds (or differential pressure sensors) and can be programmed to provide either proportional or quadratic pressure control. Any setpoint changes can be made on a single pump controller either at the control panel or through the building management system (BMS) for easy use.

Faster Project Completion

In modular construction, module assembly and site foundation work happen simultaneously, allowing projects to be completed 30 to 50 percent faster than with traditional construction methods. Since 60 to 90 percent of the construction is completed inside a factory, weather does not impact the construction timeline. Buildings can be occupied sooner, creating a faster return on investment.

The Modular Building Institute shared an example timeline illustrating these potential savings: [5]

Using prefabricated equipment helps drive efficiencies in the permits & approvals stage by simplifying design and streamlining the submittal process between the MEP



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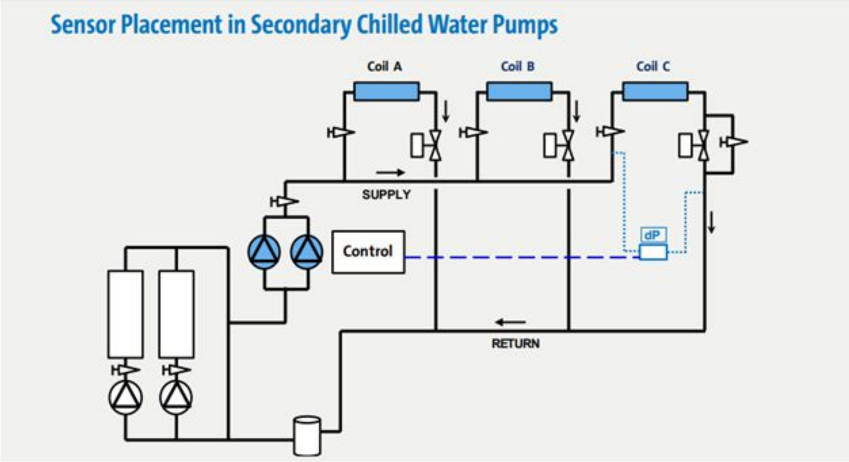
and mechanical contractors. Additionally, in the install & site restoration stage, time is saved because the systems can be sourced more easily and simply dropped in at the site, ready to go with a flip of the switch.

Figure 1



In the HVAC industry, when using off-the-shelf or configured prefabricated pumping systems, the manufacturer can source, build, pre-wire, pre-test and pre-commission the system while other building construction tasks happen. Once the system is delivered, contractors just have to make the piping connections and plug it in. The pre-testing and pre-commissioning ensure there are no surprises or delays.

Additionally, built-in, pre-programmed sensors and control equipment allow for data- and performance-driven system control.

Sensors for More Accurate Pump Control

The most common best practice in HVAC pump control is also the most intrusive and expensive: remote-mounted differential pressure sensors. Sensors allow the pumping system to react efficiently to changes in system flow requirements. Illustrated in Figure 1 is a remote-mounted, differential pressure sensor system that measures the pressure

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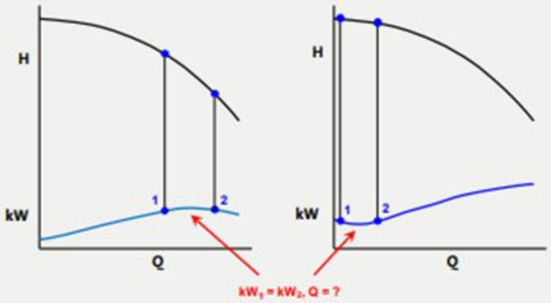
loss through the coil, control valve and balancing valve.

Figure 2



Power-based Control and Relation to Pump Performance Curve

Controlling pumps based on the pump's power consumption can intersect the pump curve at multiple points, as demonstrated by points 1 and 2.

But the difficulty in locating and installing this sensor (or sensors) leads to questionable decisions when the system is commissioned. This difficulty has led to many systems operating far below their intended efficiency. When there is indecision around correct sensor placement, sensors get mounted improperly in the system, in the mechanical room or across from the pump system itself. Utilizing normal control methodologies, none of these alternate locations are ideal, and they will not deliver the pumping efficiency that was intended when the system was designed. Some have suggested removing the sensor altogether and letting the pump, motor and drive figure out where to run. This type of power-based pump control can work for a system with a constant load, but it struggles to perform when system conditions aren't actually as designed or there is a dynamic variable load. Advancements in pump system control allow for a pump system–mounted sensor, but this must be planned for. Let's evaluate the effect of each control strategy on overall system efficiency.

Control Strategies: With & Without Sensors

Power-based Pump Control: No Sensor Used

Power-based pump control, in which controls operate without sensors or any direct feedback (data) from the system, has gained in popularity over the last 10 years. In this

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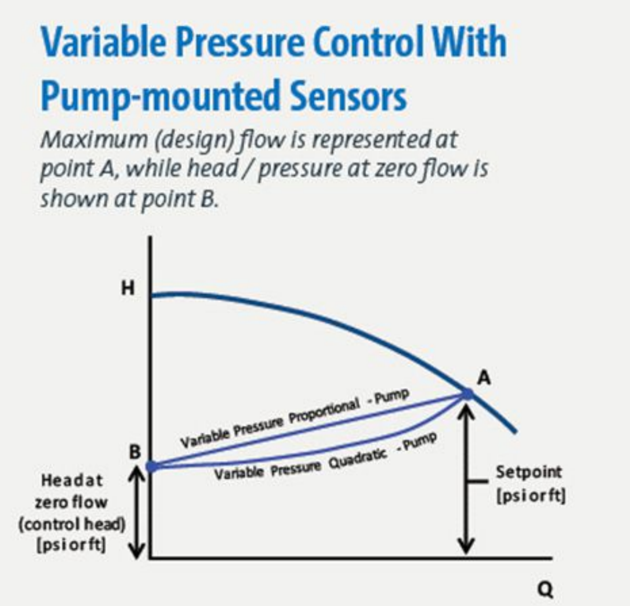
method, pump performance curves are loaded into the pump control, and both pressure and flow are estimated using the power consumed by the motor and drive. Caution must be taken when using power-based control, as this method does not work for all pump types. Since the only thing being measured is motor input power (via the variable frequency drive), there may be two points on the pump curve that require the same power. An example is shown below in Figure 2.

Figure 3


Variable Pressure Control With Pump-mounted Sensors

Maximum (design) flow is represented at point A, while head / pressure at zero flow is shown at point B.

Proportional Pressure: Pump-mounted Sensors

There's a common misconception that if a pump-mounted sensor is used, the pump can only operate in constant pressure mode. This is incorrect, as current pump technology allows proportional and/or quadratic pressure control, even in systems with pump-mounted sensors.

When pump-mounted sensors or power-based control are used (see Figure 3), there must be two setpoints: head/pressure at design (or maximum) flow (A), and head/pressure at zero flow (B). These two settings define the control curve characteristics. To properly set these parameters during commissioning, the head at zero flow (i.e., fixed head or control head) needs to be determined. For a hydronic circulation system, like

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the example illustrated in Figure 1, the fixed head would also represent the control head required if a remote-mounted differential pressure sensor were used.

Conclusion

Prefabrication and modular construction are growing trends with staying power, well-positioned to transform the building industry. These methods can be implemented for nearly any aspect of construction, based on the needs of the building. Prefabricated HVAC pumping systems offer benefits not only for the HVAC system itself, but also for the overall building, depending on the application and building needs.

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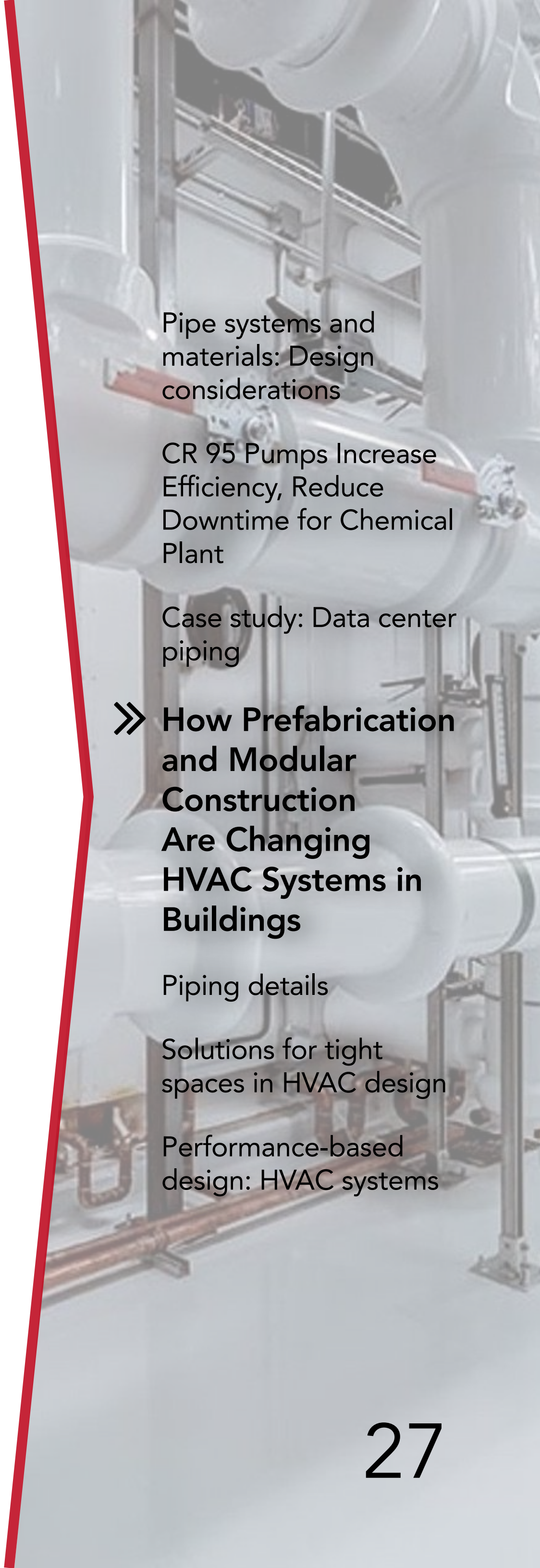

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Understand the various types of pipe and their applications

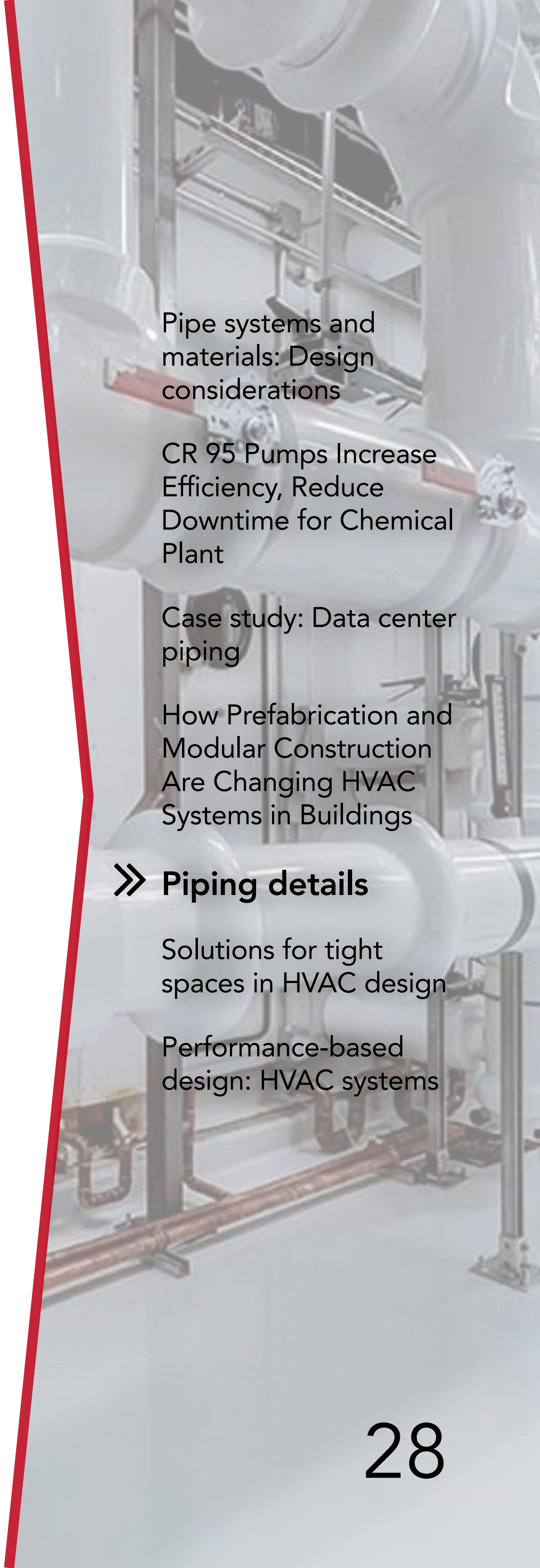
Acrylonitrile butadiene styrene pipe is strong and impact-resistant. It is occasionally used for drain, waste and vent applications. ASTM standards D2661 and D3965 deal with ABS pipes.

Chlorinated polyvinyl chloride has similar properties to PVC and is rated for higher pressures and temperatures. CPVC pipes and fittings are available with flame/smoke index less than 25/50 and therefore can be used in air plenums.

When using CPVC pipes and fittings, it is critical that manufacturer data sheets be reviewed in detail, as not all pipe sizes and fittings are listed to meet the flame/smoke index threshold mandated by building codes. CPVC pipes are extensively used for industrial water applications associated with evaporative cooling systems such as those serving data centers. ASTM standards D1784 and D1785 deal with CPVC pipes.

Cross-linked polyethylene (PEX) incorporates cross-link bonds in the structure of polyethylene. PEX pipe is strong and durable and can be used for fluids up to 200 F. Depending on the manufacturing process, PEX is classified as Type A (peroxide method), Type B (silane method) and Type C (electronic irradiation method) and properties such as flexibility, strength, thermal stability, repairability, etc. vary for each type. PEX is commonly used for radiant heating and cooling applications. ASTM standard F876, F877 and F2023 deal with HDPE pipes.

Polyethylene and high-density polyethylene pipes are flexible, lightweight and durable. They are frequently used for underground water and drain applications. ASTM



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standard D2239 deals with PE and ASTM standard D3350 deals with HDPE pipes.

Polypropylene pipe is lightweight and resistant to chemicals and can be used for higher-temperature applications compared to PVC. They are frequently used for corrosive and drainage applications. ASTM standards F2830 and F2389 deal with polypropylene pipes.

Shown are metal struts for supporting piping systems on slab. Lugged butterfly valves at the chilled water supply and return loops are also visible. Courtesy: ESD

Polyvinyl chloride is a commonly used pipe material due to its low cost. One of the big disadvantages of PVC is its inability to meet the flame/smoke index threshold of 25/50 as mandated by building codes for use in air plenums. ASTM standards D1784, D1785 and D2665 deal with PVC pipes.

Saahil Tumber, PE, HBDP, LEED AP, ESD, Chicago

Saahil Tumber *is technical authority at ESD. He is responsible for the overall design of mechanical systems for data centers, trading areas and other mission critical facilities requiring high availability. He is a member of the Consulting-Specifying Engineer editorial advisory board.*

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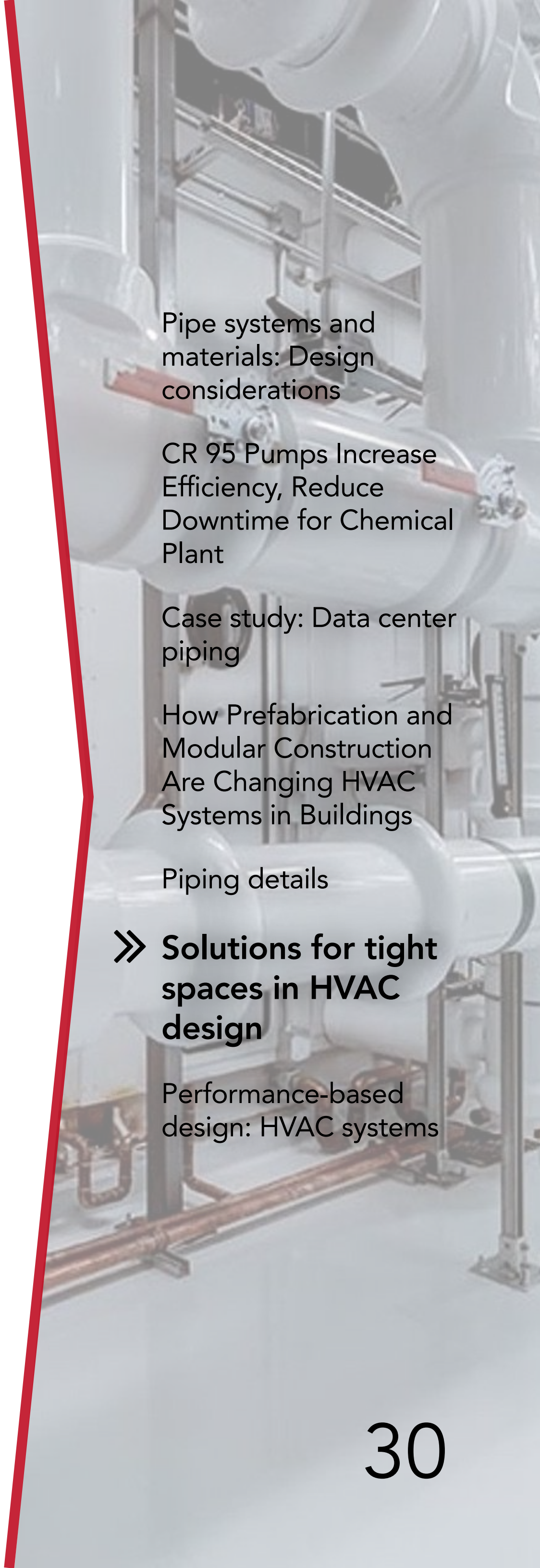
An historic university building had tough mechanical space requirements. Here's how these challenges were met.

The mechanical systems employed in the Marston Hall at Iowa State University (ISU) in Ames renovation provided more than the energy efficiency being sought for the project. The chilled beam/radiant heat with dedicated outside air system (DOAS) and associated mechanical infrastructure also met the goal of physically integrating 21st century systems within a facility that was not intended to house them—and still retain as much of the original building architecture as possible.

Specifically, the chilled water and steam piping and the ducting of the DOAS unit required much less space for transferring the cooling and heating energy compared to that required for a traditional central AHU system relying on air for heating, cooling, and ventilating. The reduced space requirements of the chosen systems were a perfect fit for Marston Hall.

The early 20th century, Second Empire-style building structure was characterized by low floor-to-floor heights, tall windows, and an original masonry system that integrated air supply and relief shafts within thick corridor walls. A hot deck/cold deck tunnel (split top/bottom) ran under the ground floor central corridor and fed a series of vertical masonry shafts within the structural walls that served individual upper spaces throughout the building's four floors. The original mechanical design—a pneumatically controlled multizone system—was impressive for a 1903 building.



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A similar utility distribution strategy was employed in the renovation to bring the modern and energy-efficient systems into the building. The hot deck/cold deck tunnel below the ground floor hallway was cleared out to create a walkable service corridor. A majority of the mechanical, electrical, and plumbing (MEP) ducts, pipes, and associated services, which originate from central mechanical rooms in the basement, are distributed in this lower level to five main vertical chase locations throughout the floor plate. This allowed the horizontal distribution on each occupied floor to be minimized and contained within small zones on each floor. This allowed ceiling heights to remain higher than if larger utilities had been piped and ducted across the floor plate on each occupied level (see Figure 7). Cutouts within the steel beams for utility routing further enabled maintaining higher ceilings.

Figure 5: *Marston Hall's DOAS unit provides the minimum ventilation air required by code. To the right—above and below the walkway—is the location of the former hot deck/cold deck tunnel. Courtesy: IMEG Corp.*

Figure 6: *This pre-renovation photo shows Marston Hall's existing tunnel stub looking west. Courtesy: IMEG Corp.*

The DOAS unit also required much less space compared to bringing in a much larger central air handling unit (AHU). Even so, to get the new DOAS unit into the basement, the team designed and installed a new, precisely sized opening in the existing exterior wall—with

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clearances down to the inch.

Another important space-fitting solution was required to maintain the architectural integrity in the east and west vestibules, where substantial amounts of outside air entering the building precluded the practicality of using chilled beams. Instead of chilled beams, the engineering team employed fan coil units in these areas; however, there was not sufficient room for ducting the supply air over the vestibule entry doors.

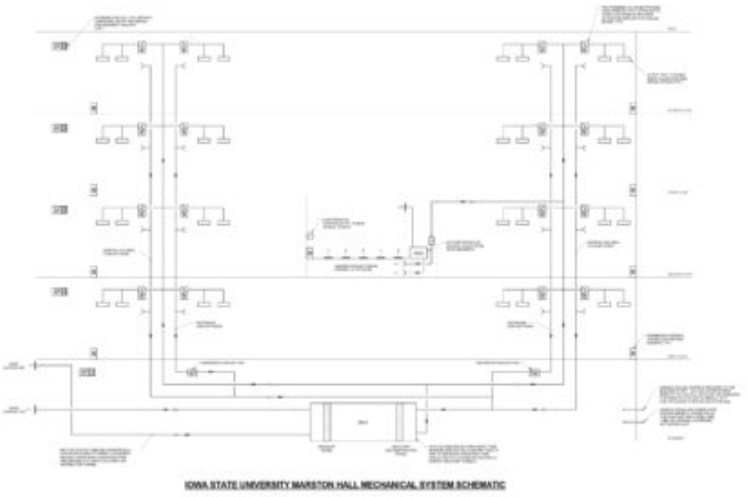

Figure 7: *The Marston Hall mechanical system schematic is shown. Courtesy: IMEG Corp.*

To solve this problem, the team custom-designed a supply louver/service door (referred to on the project as an SLS door) to solve the supply air distribution challenge and provide excellent service access to the equipment. In each vestibule, the fan coil unit was housed directly behind a full-size, architecturally compatible hinged access door. A louver in the door acts as the supply grill, with a small duct plenum on the back side of the door that mates up with the supply duct from the fan coil unit when the door is closed. Return air is then ducted in the wall cavity to the floor landing above.

Allowing space for access to the mechanical systems for operation and maintenance also was integral to the Marston Hall design:

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- The DOAS unit, main mechanical pumps, and heat exchangers are all located in the mechanical space in the building's reconfigured basement. Exterior access is available through the new door built for the DOAS installation, and interior access available via the mechanical room elevator and stair. Adequate space is provided for coil pulls, filter changes, and regular maintenance.

Figure 8: *To get the new DOAS unit into Marston Hall's basement, the team designed and installed a new, precisely sized opening in the existing exterior wall. Courtesy: IMEG Corp.*

- The air handler serving the auditorium is located in a mechanical room adjacent to the auditorium, on floor level off of the central corridor.

- Fan-powered variable air volume (VAV) boxes are located above accessible ceilings for filter changes.

- Chilled beams and perimeter radiant convectors only require periodic cleaning and are accessible throughout the building.

Figure 9: *An underfloor air displacement system for cooling and ventilation is employed in Marston Hall's large auditorium, where chilled beams would not be practical. Courtesy: IMEG Corp.*

During the construction of the project, the design team, contractors, and owner worked together to

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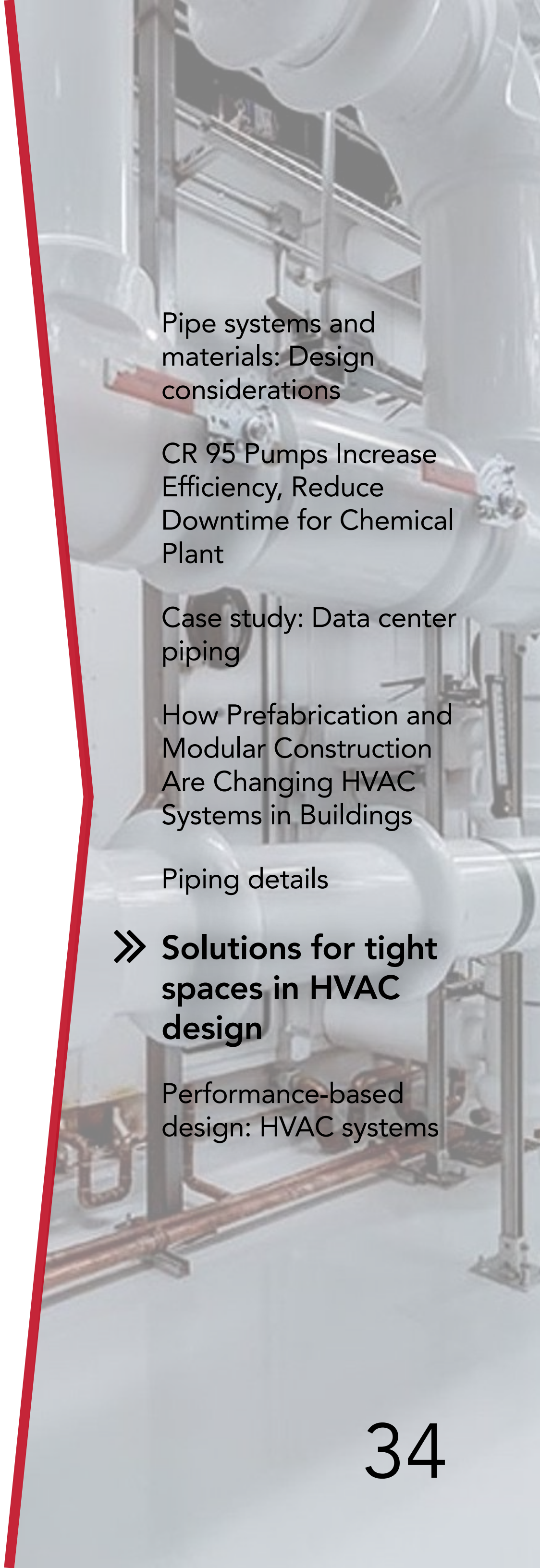
place and map isolation valves and control valves for optimized access and clearance. The isolation, control, and drain valves serving the perimeter heating system in the auditorium are located behind an access panel at floor level, as opposed to above the high auditorium ceiling.

Lincoln Pearce, PE, LEED AP, BEAP, IMEG Corp, Des Moines, Iowa
Lincoln Pearce *is a senior principal and client executive for IMEG Corp. where he leads the firm's commissioning team. He has been with IMEG his entire career, serving as project executive, project manager, systems concept engineer, and lead mechanical engineer for many of the firm's large, complex, and unique projects.*



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Many consulting engineers base their designs on performance, thus the focus on performance-based design in many specifications.

At its essence, all engineering design is performance-based. If we don't have a performance goal, what are we aiming for? Measuring our success against? How do we even start without such a goal?

What are we getting at within the topic of performance-based heating, ventilation and air conditioning design? In current parlance, performance-based HVAC design covers three broad spectrums:

1. Design solutions that do not meet prescriptive code/standard approaches or requirements; e.g., energy cost budget design under ASHRAE 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings.
2. Design to specific metrics that may be viewed as nonstandard; e.g., designing to meet specific indoor air quality criteria.
3. Operational performance targets; e.g., designing to a specific energy use intensity target.

Prescriptively noncompliant design

The first spectrum is likely the one most engineers are familiar with — at one time or another most mechanical, electrical or plumbing engineers have either done this or

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run into it as a potential hurdle in design aspirations. Energy code prescriptive requirements are generally the most common aspect that warrants exploration of performance-based alternatives.

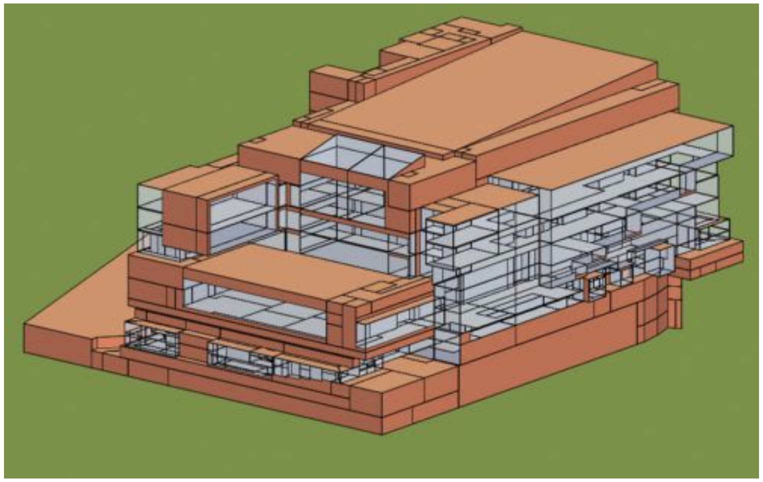

Figure 1: *This displays a whole building energy model, which on large projects can get extremely complex. Courtesy: Arup*

While each locale, climate and building typology each have its own drivers and common exceptions, these two are fairly common code variances:

- Economizer requirements for small cooling systems that impose significant infrastructure costs and constraints if implemented in most interior locations.
- Energy recovery requirements for air handling units that mandate air-to-air energy recovery systems.

When we look at alternative pathways for noncompliant MEP components, the engineer must find either an alternative solution that has equal performance or look to superlative performance in another area to offset the desired deficiency. The big non-MEP driver of performance-based energy code compliance is noncompliant building envelope performance; this is perhaps one of the biggest drivers of performance-based code compliance analysis. When the envelope is deficient, the MEP and lighting systems typically are called to offset the envelope’s shortcomings, eroding

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overall project energy performance.

Regardless of the root cause, the solution for most of these analyses is to run a whole building energy model that demonstrates that the proposed design meets or exceeds the performance of the code or standard reference design. How we as engineers come up with these solutions is where our creativity gets called into play — the solutions are as varied as the projects we undertake.

Figure 2: *A computational fluid dynamics comfort analysis allows for a detailed look at comfort conditions throughout the space. Courtesy: Arup*

A common solution is simply specifying equipment with higher than code performance, e.g., condensing gas boilers, higher efficiency chillers, etc. Alternative solutions include different solution approaches than code, such as the use of water-to-water heat pumps and exhaust air energy recovery coils for heat recovery in lieu of direct air-to-air recovery approaches.

However, one of the big challenges is that the codes and standards are catching up to our favorite solutions and making them mandatory. Performance targets are ever-evolving and require constant re-evaluation of previous solutions and approaches. Engineers have a societal duty toward sustainability — which generally means doing better than code minimum. Engineers should be always leading the code and doing better; the legal minimum should not be our legacy.

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A possible future is to incorporate those items resisted in the past and allow the systems that offset those past losses to be tomorrow's gains. How might that be done? Let's take the first item on the list — small cooling systems. For the most part, those systems end up serving data closets — 24-hour loads that require constant cooling. In many climate zones an economizer makes a lot of sense for such a load — and is required by code. So how does one get that done right?

Perhaps the easiest way is to work with the architect and the client to get the initial programing locating those rooms along or near the exterior of the building. With nice, short duct runs the cost and spatial impedance arguments really fall away and we are left with a better design. The old solution (higher efficiency cooling systems) can then be harnessed to make our overall building better than code, not just break–even.

Design to specific metrics

The specific design metrics seen most frequently are those around indoor environmental quality. IAQ, thermal comfort and acoustics are areas where designers are often asked to meet specific performance-based targets. Of these, acoustic design is probably the most common of the IEQ design requirements and HVAC engineers often rely on acoustical consultants for input and analysis of our designs to meet the project performance targets — interior noise criteria and exterior noise ordinance requirements.

Performance-based IAQ design typically references the IAQ Procedure of ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality. In this method, the engineer designs the system to meet specific pollutant concentration criteria rather than using more generically derived ventilation rates. While not typically used, this proce-

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dure gives the designer the flexibility to determine the pollutants of concern and design to specific concentration levels. Some of the drivers for this approach include:

- Indoor pollutant sources that are atypical for the space type (e.g., if furnishings are known to contain excessive volatile organic compound content).
- Space or use types not covered under the prescriptive ventilation rate procedure.
- Owner or process requirements.
- Outdoor air conditions that require more detailed analysis.

Regardless of the driver, the analysis approach is consistent — a mass balance analysis examining internal source emissions, outdoor concentrations and filtration effectiveness. The solutions can include modifying the amount of outside air brought in, additional source control measures, providing improved filtration within normal HVAC equipment or using recirculating air cleaners. One caution that is warranted in this approach is to always keep in mind pollutant sources that are not part of the specific analysis. In general, it is not recommend lowering base ventilation rates below the ASHRAE 62.1 prescriptive rates unless it is well-known that indoor pollutant sources are, and will remain, as analyzed or any specialized filtration covers the full range of indoor pollutants.

Thermal comfort is perhaps a bit unusual to list as an atypical performance-based design metric. However, the industry tends to design to air temperature conditions, not comprehensive thermal comfort for the occupants as defined by ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy. A comprehensive design for thermal comfort involves analysis of not just the air temperature, but also humidity, average air speed, the mean radiant temperature and direct solar radiation incident on

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the occupants. The code typically does not mandate true thermal comfort design; in general, the code uses only air temperature and most designers follow suit with a set of design criteria that at best look at air temperature and humidity.

Figure 3: *At the Kirsch Center for Environmental Studies, Cupertino, California, a variety of methods were used to achieve net zero. Energy modeling is critical to success of projects like this. Courtesy: Arup*

Compliance with ASHRAE 55 is more complicated than just air temperature at a thermostat and requires a more detailed evaluation of the HVAC system performance to consider average air speed and air temperature across the space, not just a room average condition. Compliance also requires evaluation of the building envelope performance — surface temperatures (for mean radiant temperature calculation) as well as direct solar radiation penetration and incidence on occupants.

Envelope performance for comfort is different from energy evaluation — the spatial specifics and solar geometry come into play with potentially greater impact to comfort than overall energy use. ASHRAE 55-2017 includes new requirements for accounting for the direct solar radiation impacts on comfort that require much more considered attention to glass orientation and shading device performance. While the standard has some prescriptive tabular options for glass and interior shading device performance,

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many conditions will require more detailed analysis. This analysis requires more specialized tools and consideration of different sun angles that may not coincide with peak HVAC load conditions (e.g., winter low sun angle conditions).

Operational performance targets

Designing to operational performance targets is relatively uncommon but increasing in popularity, whether for net zero energy projects or simply owners who wish to have an operational performance guarantee. Some codes also are allowing an outcome-based code compliance path as well (which in some jurisdictions comes with financial performance bonds for the owner). This is a topic and task complex enough to warrant its own article (and more). The contractual requirements typically focus around energy performance, though water performance also is occasionally required.

Unlike code compliance or U.S. Green Building Council LEED energy modeling, getting the right prediction is fundamental to the team's contractual and operational success. Uncertainty analysis is one of the foundational approaches to having confidence in the design solution and compliance with the performance target. There is not just one answer coming out of one energy model, like for code compliance. The engineer's role is to work with the team to evaluate many different possible energy model predictions to determine whether the design meets the performance threshold and the level of contractual risk is acceptable.

For most buildings, the uncertainty should consider the following aspects, at a minimum:

- Climate variability.
- Occupancy patterns and usage.

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- Internal load variations.
- Equipment and envelope performance variations/degradation.

The importance of uncertainty analysis cannot be overstressed when committing to an outcome-based performance target. There are so many variables that affect overall building energy consumption and so many of them are out of the design team's control that they need to be assessed for sensitivity. Those aspects that have a high sensitivity need to be controlled, either from a design perspective or contractually. Uncertainty analyses can help inform the contractual language around the performance guarantee by identifying those highly sensitive aspects of performance and regulate their risk.

Regardless of the type of performance-based design or its drivers, as HVAC engineers we need to be cognizant of the increased risk and responsibility that accompanies such design goals. We are at risk of code compliance, LEED certification status, IAQ compliance or even whole building energy performance and base most of that risk on analytical solutions. In many cases the analysis itself needs to be designed to ensure it is robust enough — a robust workplan that tests for uncertainty, sensitivity and risk and that includes rigorous checking. Most certainly it is more effort, but has the potential to bring about greater design freedom, success and higher overall performance.

Peter Alspach, PE, LEED AP

***Peter Alspach** is the director of design performance at NBBJ and was previously a principal at Arup. His expertise includes high-performance building engineering design and analytics.*

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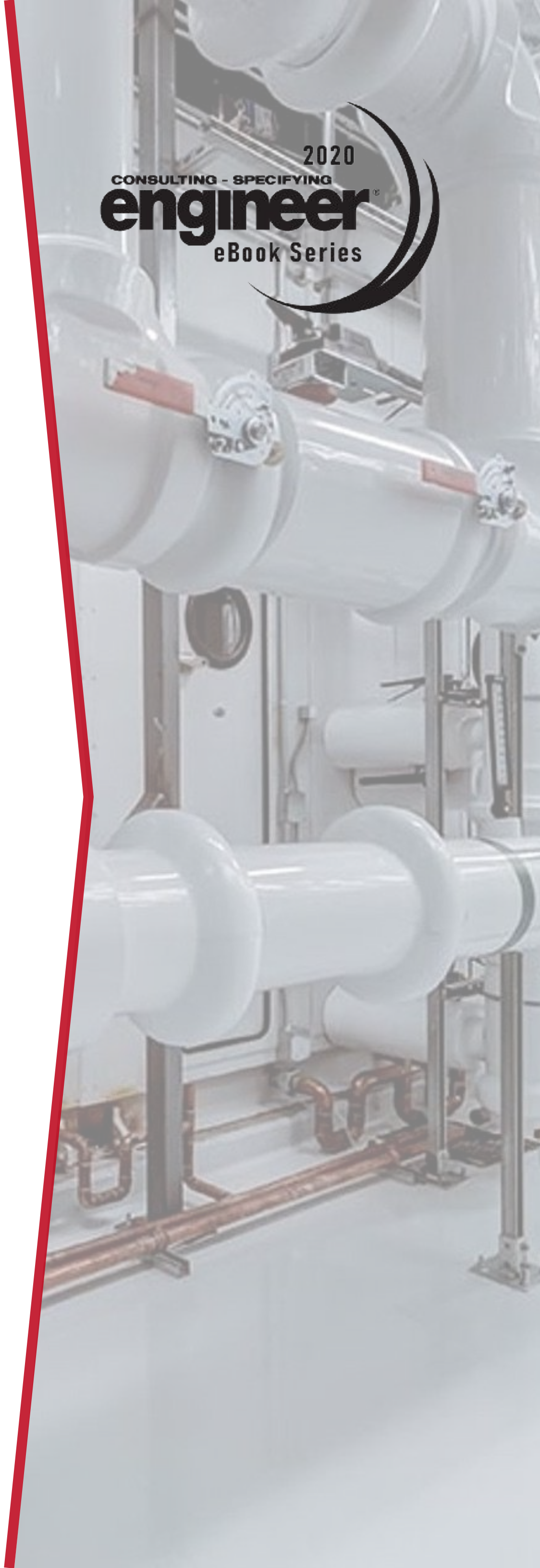

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