Implementing a BACnet Network

BY TOM LEACH

As HVAC systems transition to network control, the approach of how to lay out and start up these systems is different. This article does not go into the control side of BACnet, but addresses the systematic approach to starting up a BACnet network. The focus of the article is quality control and testing versus control theory.

Building Overview

The building is a 30-story hotel for a national brand in New York City. The building has 100,000 ft^2 (9290 m^2) of space with 150 guest rooms that use water source heat pumps (WSHP) for climate control. Guest room control was not in our scope of work and is not covered in this article.

The control system discussed in this article handles all the common systems in the building. The systems controlled are:

- **Boilers.** Three boilers connected as a unified system;
- **Cooling Towers.** Two 150 ton (528 kW) towers with two 7.5 hp (5.6 kW) fans;
- **Condenser Water.** Two 15 hp (11 kW) pumps;
- **Domestic Hot Water.** Two 10 hp (7 kW) pumps;
- **Hot Water.** Two 10 hp (7 kW) pumps; and
- **Heat Pump.** Two 30 hp (22 kW) pumps.

Specifications

When we bid on the project, the design had been value engineered multiple times, and the system was a base level design. The control contractor's work is the last step to get equipment running; we are one of the "usual suspects" to blame for things not working properly. Rather than bemoan the situation, we engineer the system anticipating problems and plan accordingly.

Old Style

The old style of control would have the contractor buy subsystems for the different elements (boiler, pumps, AC) and then connect the right-colored wire to the right terminal. We have installed more than enough systems where the control of an AC unit was simply connecting R, G, Y, W, and common and breaking the right leg at the time clock.

In that style of control, we started with systems that had been engineered and tested by the vendor in multiple situations.

New Style

In the new style, everything is custom and is created for the first time. The importance of this concept cannot be overstated. Now, instead of getting a proven, tested system, there is a collection of components. It is roughly the same as buying a new car at the showroom versus going to the auto supply store and buying a list of parts.

Quality

Table 1 shows all the connections in the hotel system. Every control wire has two ends with which to make a mistake. For the complex systems, we had panels fabricated by an outside shop that is UL certified. *Table 1* shows the custom panels with their internal wiring and the wired connections required in the field (energy

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recovery ventilator [ERV], corridor AC [CAC], makeup air [MUA], vertical heat pump [VHP]).

Across the six fabricated panels with 1,184 total connections in the wiring, there were four errors, or an error rate of 0.33%. That doesn't sound terrible, but there was a fault in four panels out of six, or a 66% error rate.

Our incoming inspection consists of tests on every panel before field installation. The front panel control with the diagnostic software performs all the following tests:

- Read every switch input;
- Set every light output;
- Test audio signal output;
- Read every contact input, on and off;
- Read every thermistor input (decade resistor box, simulate expected temperature span);
- Read every voltage input (0–10 V reference ±0.1%, test entire span with multiple settings);
- Set every relay output;
- Set every voltage output (test multiple levels with a 4.5 digit digital voltmeter); and
- Verify MS/TP address and device ID.

All tests are conducted to the panel's terminal strip.

We believe in the following statement: "Any time an error is missed, it costs 10 times more to fix at the next step."

As each panel is a complex product, we track every problem and revision we have done to the panel; we attach a sheet of paper to the front of the panel and log every issue and change for revision control. It is heartbreaking to have to troubleshoot a problem twice because a fix wasn't applied.

Testing

The testing of the system is methodical and is performed in stages. You have to be confident in the base system to be able to troubleshoot more complex problems later.

We test the network communication wires multiple times, even before there is power in the building, using a technique called time domain reflectometry (TDR). It amounts to injecting signal pulses into a bare piece of wire. The equipment measures the time it takes for the reflection to return and calculates how many feet away the break occurred.

We take TDR measurements from both ends of the cable. If the measurement comes back the same, and

TABLE 1 Custom panels with internal wiring and wired connections required in the field.

NAME	INTERNAL POINTS	EXTERNAL POINTS
Elevator Room		38
Gym		26
ERV 1		92
ERV 2		92
ERV 3		92
CAC 1		62
CAC 2		44
HPWP Panel	140	78
Condenser Panel	187	96
Domestic and Heat Panel	233	110
Boiler Control Panel	280	120
Valve Panel	204	78
Cooling Tower Control		72
AC1		38
AC2		36
VAV 16		28
VAV 17		28
VAV 19		28
VAV 21		28
VAV 22		28
VAV 23		28
VAV 24		28
VAV 25		28
VAV 26		28
VAV 28		28
VAV 29		28
Fan Panel	132	80
MUA 1		82
MUA 2		62
MUA 3		80
VHP, BACnet-Compatible Thermostat		22
CHP A, BACnet-Compatible Thermostat		22
CHP B, BACnet-Compatible Thermostat		22
VHP 1, BACnet-Compatible Thermostat		22
VHP 2, BACnet-Compatible Thermostat		22
HHP B, BACnet-Compatible Thermostat		22
VHP 4, BACnet-Compatible Thermostat		22
Communications/JACE Panel	8	24
Boiler Panel		24
	1,184	**1,888**

what we expect in distance, we know we have a good wire from end to end. If the numbers don't match, we can track down the problem before the wire gets covered up. If there is a problem, we can discover it as soon as possible.

Phased Start-Up

We break the testing into discrete steps and never try to "just throw the switch." The order of testing is as follows:

- Incoming test of panels;
- Connect controllers to the BACnet network ("Can we talk to the controller?");
- Manual test of connected panels ("Can we see the sensors and cause actuator action?");
- Manual running of fans and pumps using the override switch with the embedded override software;
- Test of automatic loops; and
- Tuning of loops.

The biggest improvement we made on this project was to add a cellular remote connection. We can remotely log into the building and operate it from our office. After our field technicians make connections to controllers, we log in and test operation. We make a list of fixes required to be made by field technicians for the next day. Software fixes are done in the office and remotely loaded.

Old and New Versus All New

Stand-Alone Requirements

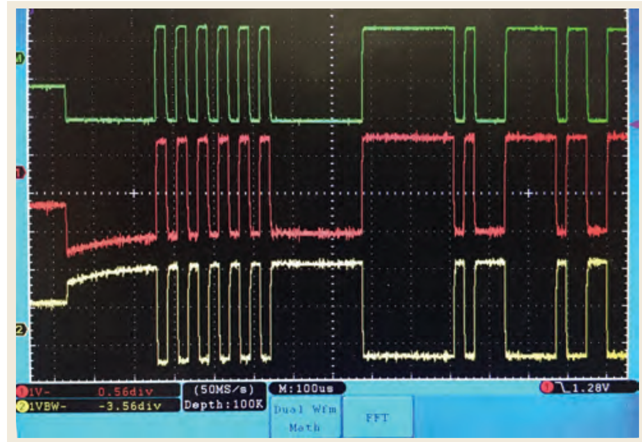
The design required that each subsystem had to be independent and that the failure of the network would not affect its operation. This increased the cost and complexity of the wiring because a common parameter such as outside air temperature could not be shared across controllers.

All the pumps are run in a lead/lag configuration with fail-over. The stand-alone operation requirement did not allow using BACnet network signals to directly control the VFD operation of the pumps. Each controller had dedicated wiring to the VFDs they operated. The downside is that the VFD controller has many pieces of information (volts, amps, power) that are not accessible to the system.

Design for Failure

Things are going to fail; it is what entropy promises. As the BMS contractor is in charge of the control

PHOTO 1 This oscilloscope photo shows the two network wires (red and yellow) and the calculated difference (green trace).



implementation, we can decide how we want the system to react when components fail. Our guiding principle is for the system to fail to a safe state; if possible, we also want it to fail in a manner that allows occupants to use the building.

Hardware Design

We always want a failure of a component to place the system into a safe state. If we are monitoring a contact closure, we want the active state to be closed. If a wire breaks, the system will go into fault mode. The operation of a VFD allowed for either a NO (normally open) or an NC (normally closed) contact to signify a fault. We chose the NO to signify a fault, as it is a more robust signal that the VFD is operating properly.

Network Design

The network specified was BACnet, which is an ASHRAE standard. The BACnet system used for this hotel is MS/TP on EIA-485 twisted pair wire. A network wire pair connects to every controller on the network in a daisy chain fashion. The designation MS/TP stands for master slave/token passing. Masters can ask and answer questions, while slaves can only answer. If you provide a clean signal, the controllers will handle all the details of the protocol and move information around the network.

Data rates for BACnet can be between 9,600 baud (roughly, "baud" means bits/second) up to 115.2K baud. We set the speed to 38,400 baud, which is a reasonable trade-off of speed versus reliability for the network. For troubleshooting the communications network, we use a 100 MHz digital oscilloscope to measure the quality of the signal to make sure the system is at a peak signal to noise ratio.

BACnet on twisted pair is a differential signaling system. The information signal is the difference between the positive and the negative wires. This is designed to cancel out the common noise on the two wires.

Photo 1 shows the two network wires and the calculated difference. The middle red image is the positive wire, and the bottom yellow signal is the negative wire. The top green trace is the calculated difference between the positive wire and the negative wire. Notice how the common noise on both wires is "differenced" out in the top green trace.

We always add terminating resistors and bias resistors on each network segment, per the BACnet standard. We have found this gives us a cleaner signal and is worth the effort.

It is amazing how hard it is to troubleshoot a cable when it is in the ceiling, in conduits, and behind walls. Our poor wire has been cut, stretched, pinched, and burned with a solder torch after it was installed.

On an earlier system, we used wire that was certified for the EIA-485 standard. We paid $0.20/ft ($0.66/m) for the wire. After solving multiple wire problems in a smaller hotel, we changed to a wire with a better grade of insulation that costs $1.20/ft ($3.94/m), and it is worth every penny. Communication wire is not a good place to scrimp.

It is best to divide and conquer a problem, and a BACnet network is no different. For the hotel, rather than having a single network wire going through the entire building, we used a separate wire segment on each floor. A fault on the second floor will not affect operation of the network on the ninth floor. The central controller used for BACnet control is referred to as a Java application control engine (JACE). We fitted the JACE with four EIA-485 port connections so it could address four independent network wires.

Even if the network is completely down, the design of the system enables each of the controllers to do its job, as every controller was designed to operate stand-alone.

Software Design

The same rules apply to the software design: in the case of a fault, we make sure the system goes to a safe state. If a pump faults, we disable the faulted pump and enable the spare pump.

The system can detect when it has lost communications from other points in the network. A good example is occupancy status. Our designs on the loss of communication to a central schedule always fail back to the occupied state. While it might use more energy, the building space is still usable.

The controllers can also spot when a sensor has gone inoperative and will make do with either the last valid reading or fault to a backup sensor. An example is an outdoor sensor for temperature. If a sensor fails, we read the information from another sensor in the network or from the Internet's local weather service.

System Diagnostics

The HVAC control for the hotel is implemented in dedicated controllers. We create schematics of components in them to implement the control function. Each controller can hold 200 blocks. A block is an internal resource in the controller. It can be anything from a proportional–integral–derivative (PID) function to an AND gate.

In most subsystems we do not require the full 200 blocks; when possible, we add system diagnostics to assist in troubleshooting. For all temperatures, we record the minimum, maximum, and average reading. We also monitor the action of the control outputs of the system. Our job is to anticipate problems and to collect the data that will assist problem resolution.

In a previous project, we were controlling the radiant heat system. We monitored the supply temperature, the return temperature, and controlled the state of the mixing valve. We recorded the 24-hour average of each of the sensors and the mixing valve.

The problem: despite the control keeping the valve in the 100% open position, the return temperature never reached setpoint. An additional pump was added, which solved the problem. With diagnostics, it is easier to pinpoint the real cause of the problem.

Table 2 shows the different diagnostic blocks we use through the HVAC system.

We time-stamp measurements when they occur. The time stamps help us correlate different events to determine if there is a cause and effect between separate parts of the building.

During the commissioning phase, we always place the time stamp diagnostic on critical signals such as the Fire

Safety Input. In normal operation, the Fire Safety control provides the HVAC system with a contact closure informing us that the building is *not* in a fire condition, and the HVAC systems can operate.

The Event Time Stamp diagnostic block will capture the first time the Fire Safety opened, the most recent time it opened, and how long it was open. We also count the number of times the event occurred. If we see a high count of events within a short length of time, our first inclination is that a bad connection exists. A low count with a long signal would indicate a problem with the fire safety system.

TABLE 2 Diagnostic blocks used through the HVAC system.

NAME	FUNCTION	TYPE INPUT	TYPE OF READINGS
Trend_8	8 Sample with Time Stamps	Analog	Temperatures, VFD Speed, Static Pressure
Average_24	24 Hour Average	Analog	Temperatures, VFD Speed, Static Pressure
Maximum	Max. Reading with Time Stamp	Analog	Control Outputs, Temperatures
Minimum	Min. Reading with Time Stamp	Analog	Control Outputs, Temperatures
Event_Time_Stamp	Mark First and Last Events	Binary, On/Off	Fire Safety, Break Glass, Dirty Filters, Alarms
Length	Measure Time Length of Event	Binary, On/Off	Fire Safety, Break Glass, Dirty Filters, Alarms
Count	Count Number of Events	Binary, On/Off	Fire Safety, Break Glass, Dirty Filters, Alarms

In this case, the diagnostics were monitoring message integrity for months before the hotel was opened. Intermittent problems are the toughest issues to solve, and the diagnostic circuit is a valuable tool to troubleshoot them.

The main system controller, the JACE, has the ability to log data. We have the JACE start logging the main systems (heat pump water pump supply temperature, return temperature, cooling tower temperature, pump speeds) on five-minute intervals. By being able to see how the systems are reacting over time, we can spot problems and solve them. When tuning PID loops, we often increase the update speed to get better resolution. We have run tests with three second updates with five to six variables with no issues.

Heat Pump Water Pump (Water Loop for WSHPs)

Often, we need to be able to start a pump before we have all of the sensors in place to have a complete system. On all of the control systems, we add a "loop override" switch internal to the panel, which breaks the control loop and will run the pump at a fixed setting.

For this project, we started the heat pump water pump (HPWP) loop pump, keeping the pump at 60% of rated speed. While it was in this state, we found out the differential pressure sensor had issues and needed to be upgraded. We don't let systems go to fully automatic mode until we know all of the pieces are working.

In the next stage, we enable the control loops. We are now testing if the dynamics of the system are correct. We are cognizant that while we read back sensors properly in the first step it doesn't mean that that the supply and return sensors weren't accidently swapped.

Figure 1 shows the system's differential pressure response at the end of the loop versus the HPWP pumps speed. We use this information to set the offset bias for each of the PID loops for the pumps.

Software Phase One

During panel checkout and first operation at the site, we ran a diagnostic version of the software. All the valves, VFDs, and fans can be manually controlled from the panel. This allows simple operation in the early phases of start-up.

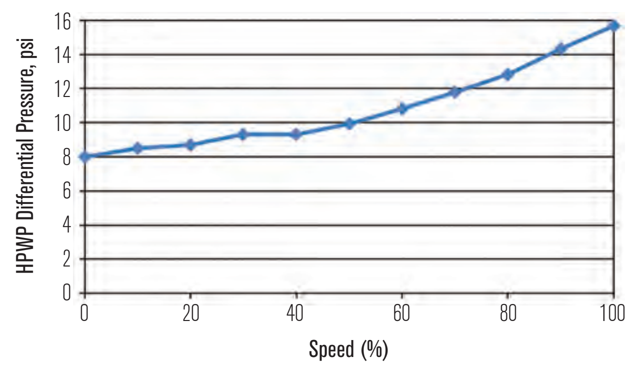
The panel also allows field personnel to read all of the sensors connected to the panel, temperatures, pressures, and status inputs. This allows fast feedback as soon as the field technician makes the connections, if the wiring is correct. This is all part of the 100% test philosophy, along with the multiple levels of test. Waiting until the end to test subsystems is a recipe for frustration.

When starting up, remember that in a new building nothing is stable. We had dedicated circuit breakers, we labeled them as critical, we taped them over, and we put notes on the circuit panels, but nothing prevented the breakers to our computer from being flipped off. Starting on the next project, we will put in battery backup on the main JACE computer and sense when we lose power and send an email alert.

Heat Pump Loop

The heat pump water loop pump runs 24 hours per day, 365 days per year. The control logic determines if

FIGURE 1 Differential pressure reading for different speeds of the HPWP pump.



the system requires heat from the boiler or needs to reject heat through the cooling tower.

The temperature response to the control operation of the heat pump loop is illustrated in *Figure 2*. The "mode" signal when high indicates that the system is in heat injection mode. As the boilers weren't functional at this point, the chart doesn't include the state of the injection valve, as it would be full open the whole time. The building is self heating during this time period.

When the heat pump loop return temperature rises above the 77°F (25°C) threshold, the system goes into heat rejection mode, the heat injection valve is turned off, and the cooling tower is activated. While in heat rejection mode, the fans in the cooling tower are modulated to maintain a 75°F (24°C) setpoint.

When the temperature drops below the 72°F (22°C) threshold, the loop will go into heat injection mode. The cooling tower will be shut down. The control will modulate the heat injection valve to maintain the 75°F (24°C) setpoint.

In this example, the building is under construction, and it is a small load. When it goes to heat rejection mode, the capacity of the cooling tower brings the temperature down quickly through the 75°F (24°C) setpoint and through the lower threshold (72°F [22°C]), pushing the system back into heating mode.

The building needs to reject heat as the return temperature is higher than the supply temperature, but this control strategy disables the cooling tower. This method of determining heating/cooling mode has some inefficiency.

Figure 3 adds the change in temperature from the supply to the return to better illustrate if the building should be injecting or rejecting heat. The second signal from the top shows the temperature change in the loop offset by the dashed line. Above the dashed line, the loop is gaining heat, and below the line, the loop is losing heat. The chart shows a brown status signal on top

FIGURE 2 Temperature of the heat pump loop, showing the system changing between heat rejection and heat injection mode.

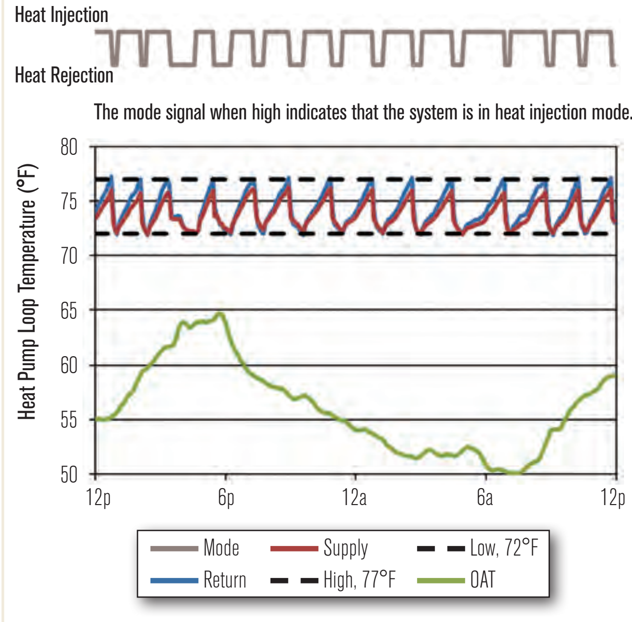
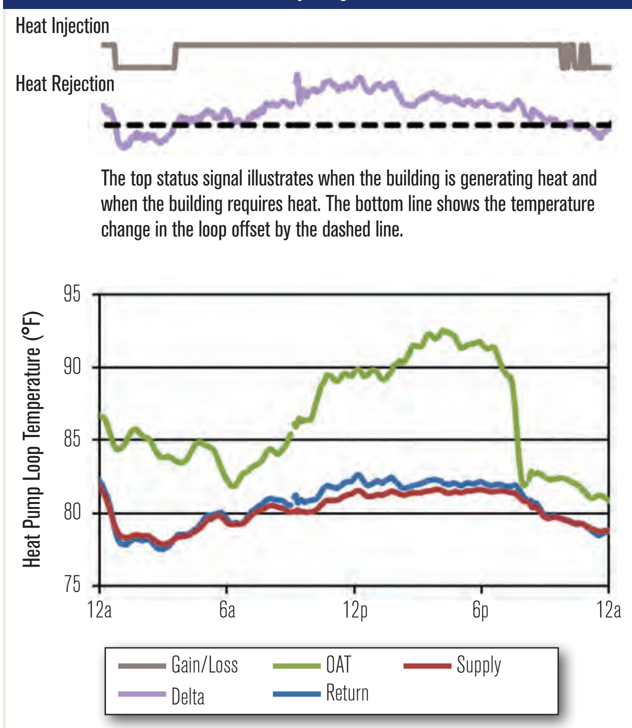


FIGURE 3 Temperature of the heat pump loop, showing the system rejecting heat when it should have been injecting heat.



to illustrate when the building is generating heat and when the building requires heat. A "low" level on the top brown line shows the building requires heat.

Figure 3 also shows the supply, return, and the outside air temperature. Even though the temperature of the loop stays above the lower threshold of 72°F (22°C), it can be seen from the status line that the return temperature is sometimes lower than the supply temperature, meaning that the heat pumps are extracting heat from the loop. In this case, the HVAC system is throwing away money in two ways:

1. The cooling tower is rejecting heat that the building needs. The heat pumps will have to work harder to extract heat from a lower temperature water loop.
2. A 15 hp (11 kW) pump and two 7.5 hp (5.6 kW) fans are being run to throw away heat we want.

The main issue is that the two-threshold strategy to determine heat/cooling mode, while simple, isn't fast enough to catch the shift in the building's needs across the daily swings. A better method of control is part of the upgrade proposal to the building owners.

Condenser Water and Cooling Towers

The cooling system is two 150 ton (528 kW) cooling towers acting as a single system. There are two 7.5 hp (5.6 kW) fans driven by VFD drives. The speed of the 15 hp (11 kW) condenser water pump is slaved to run at the same speed as the heat pump loop. The specification requires holding the condenser water temperature at 76°F (24°C).

What we found during commissioning is that it is hard to hold to the 75°F (24°C) setpoint under light load conditions. While the system has VFD drives on both the fans and the pump feeding the cooling tower, there is a 25% lower limit on the speed of the pumps and the fans.

The cooling tower OEM states that more cooling is generated for less energy with two fans at 25% versus running a single fan at 50%. The current sequence of operation uses a single fan under light load. We will implement the specified sequence of operations, but we will propose that the building owners modify the sequence to a more energy-efficient algorithm.

Conclusion and Changes for the Next Project

We were pleasantly surprised that the start-up met our expectations. We were ecstatic about the performance and reliability of the cellular network connection. The remote connection transformed the job experience.

Following are lists of things we plan to do the same on the next project.

1. Use the best EIA-232 wire possible with multiple independent wire networks through the building. (We currently specify a wire that is plenum rated.)
2. Use a remote cellular access with added battery backup.
3. 100% testing of panels.
4. Diagnostic software in all panels.
5. Fault-tolerant design for hardware and software.

Things we will do differently on the next project.

1. Standardization of shielded cable for sensor inputs.
   - Shielded cable will reduce 60 Hz noise on thermistor inputs. We measured a higher common mode noise on unshielded sensor cables.
2. All field drawings will have standardized wire color coding.
   - Standardize wiring to reduce errors; field error rates of 3% to 4% on wiring are too high.
   - Standardized color codes will enable faster troubleshooting.
3. Change from resistive sense thermistors to platinum RTD 4-20 mA sensors for critical readings.
   - Platinum RTD temperature sensors have 1% system accuracy versus thermistors with 4% system accuracy. Measuring the temperature gain in the heat pump loop requires a lower system error budget than a thermistor can deliver.
   - 4-20 mA sensors also have a longer distance of operation versus thermistors.
4. Change from a dry contact input to a 110 V/24 V relay coil to sense when the building is in a fire situation. On the current project, the electrical contractor connected 110 V to the boiler control panel where a contact input was expected. That event destroyed all the control electronics. A more rugged solution is to have a 110 V input for the Fire Safety signal, which will now be our standard implementation.
5. We will add a temperature sensor at the end of every water loop. We have found multiple small piping mistakes occurred in this project that would have been easier to isolate if we knew the temperatures at the end of the different loops. ■