CHAPTER 15: Control Systems and Sequences

Learning Objectives

Upon completion of this chapter, you will be able to:

1. **Understand** fundamental control logic types and their applications
2. **Analyze** heating control sequences according to CSA B149.1
3. **Explain** the operation of combination heating and cooling systems
4. **Design** basic zone control systems for residential and commercial applications
5. **Configure** advanced control systems including outdoor reset and building automation
6. **Troubleshoot** complex control system problems systematically
7. **Interpret** control sequences and timing diagrams
8. **Verify** proper control system operation and safety interlocks
9. **Diagnose** common control system failures
10. **Apply** control theory to practical HVAC applications

Introduction

Control systems are the brain of modern HVAC equipment, orchestrating the complex interaction between components to maintain comfort and safety. From simple on-off thermostats to sophisticated building automation systems, gas technicians must understand how controls sequence equipment operation, manage safety interlocks, and optimize system performance.

This chapter explores control theory and practical applications, emphasizing:

- Safety sequences mandated by CSA B149.1
- Integration of heating and cooling systems
- Zone control strategies
- Advanced control technologies
- Systematic troubleshooting approaches

Understanding control systems enables technicians to:

- Properly commission new equipment
- Diagnose complex system problems
- Optimize system performance
- Ensure safe equipment operation
- Interface with building automation systems

15.1 Basic Control Logic

On-Off Control

Principle of Operation: On-off control, also called two-position or binary control, is the simplest form of automatic control. The controlled device is either fully on or fully off, with no intermediate positions.

Characteristics:

- Simple and reliable
- Low cost
- Easy to understand and troubleshoot
- Some temperature swing inherent
- Cycling wear on components

Components:

1. **Sensing Element**
    - Temperature sensor
    - Pressure sensor
    - Humidity sensor
    - Flow sensor
2. **Controller**
    - Thermostat
    - Pressure switch
    - Humidistat
    - Aquastat
3. **Final Control Element**
    - Gas valve
    - Relay contacts
    - Damper motor
    - Pump/blower

Temperature Control Example:

```
Setpoint: 20°C (68°F)
Differential: 1°C (2°F)

Heat ON at: 19.5°C (67°F)
Heat OFF at: 20.5°C (69°F)
```

Advantages:

- Simplicity
- Reliability
- Low initial cost

- Easy maintenance
- Fail-safe operation possible

Disadvantages:

- Temperature swing
- Equipment cycling
- Reduced equipment life
- Less precise control
- Potential comfort issues

Staged Control

Multi-Stage Operation: Staged control provides intermediate capacity levels between off and full capacity, improving comfort and efficiency.

Two-Stage Heating Example:

Stage 1 (Low Fire):

- First stage activates at setpoint minus 0.5°C
- Provides 40-60% of full capacity
- Maintains temperature during mild conditions

Stage 2 (High Fire):

- Activates if temperature continues dropping
- Typically 1-2°C below setpoint
- Provides 100% capacity
- Quick recovery from setback

Staging Methods:

1. **Time-Based Staging**
    - Fixed time delay between stages
    - 5-10 minutes typical
    - Prevents short cycling
    - Simple implementation
2. **Temperature-Based Staging**
    - Based on temperature differential
    - More responsive to load
    - Better comfort control
    - Requires sophisticated thermostat
3. **Outdoor Temperature Staging**
    - Stages based on outdoor temperature
    - Prevents unnecessary high fire

    - Improves efficiency
    - Requires outdoor sensor

Commercial Multi-Stage Example:

```
4-Stage Rooftop Unit:
Stage 1: 25% capacity at SP-0.5°C
Stage 2: 50% capacity at SP-1.0°C
Stage 3: 75% capacity at SP-1.5°C
Stage 4: 100% capacity at SP-2.0°C

Staging Down:
Stage 4 OFF at SP+0.5°C
Stage 3 OFF at SP+1.0°C
Stage 2 OFF at SP+1.5°C
Stage 1 OFF at SP+2.0°C
```

Benefits of Staging:

- Improved comfort (smaller temperature swings)
- Better humidity control
- Increased efficiency
- Reduced equipment cycling
- Longer equipment life
- Quieter operation at low fire

Modulating Control

Continuous Capacity Control: Modulating control provides infinite capacity adjustment between minimum and maximum, maintaining precise temperature control.

Types of Modulating Control:

1. **Proportional Control**
    - Output proportional to error
    - Simple implementation
    - May have offset from setpoint
2. **Proportional-Integral (PI)**
    - Eliminates steady-state error
    - More complex tuning
    - Common in commercial systems
3. **PID (Proportional-Integral-Derivative)**
    - Fastest response
    - Anticipates changes
    - Requires careful tuning
    - Used in critical applications

Modulating Components:

Modulating Gas Valves:

- 0-10VDC or 4-20mA signal
- Turndown ratio 5:1 to 10:1
- Smooth capacity adjustment
- Electronic feedback

Variable Frequency Drives (VFDs):

- Control motor speed
- Energy savings
- Soft start/stop
- Precise airflow control

Electronic Expansion Valves:

- Precise refrigerant control
- Superheat optimization
- Wide operating range

Control Signals:

- 0-10VDC: Common in HVAC
- 2-10VDC: Allows off position
- 4-20mA: Industrial standard
- PWM: Pulse width modulation
- Digital: BACnet, Modbus

Throttling Range: The temperature range over which the control modulates from minimum to maximum.

Example:

```
Setpoint: 20°C
Throttling Range: 2°C
Maximum output at: 19°C
Minimum output at: 21°C
```

Setpoint and Differential

Setpoint: The desired control point for the system.

Types of Setpoints:

1. **Fixed Setpoint**
   - Manually set
   - Remains constant

2. **Adjustable Setpoint**
   - User adjustable
   - Limited range
3. **Remote Setpoint**
   - Set by BAS
   - Can be scheduled
4. **Reset Setpoint**
   - Varies with outdoor temperature
   - Optimizes efficiency

Differential (Deadband): The difference between cut-in and cut-out points.

Mechanical Differential:

- Fixed by design
- 1-3°C typical
- Not adjustable

Electronic Differential:

- Adjustable
- 0.5-5°C range
- Optimizable for application

Differential Considerations:

Narrow Differential:

- More precise control
- Increased cycling
- Better comfort
- More equipment wear

Wide Differential:

- Less cycling
- Longer equipment life
- Greater temperature swing
- Potential comfort complaints

Optimal Differential Selection:

```
Residential: 1-2°C (2-3°F)
Commercial: 2-3°C (3-5°F)
Industrial: 3-5°C (5-10°F)
Storage: 5-10°C (10-20°F)
```

Anticipation

Purpose: Anticipation prevents overshoot by shutting off heating/cooling before reaching setpoint.

Types of Anticipation:

1. **Heat Anticipation**
   - Small heater in thermostat
   - 0.1-1.2A adjustable
   - Turns heat off early
   - Prevents overshoot
2. **Cool Anticipation**
   - Fixed resistor
   - Not adjustable
   - Prevents overcooling
3. **Electronic Anticipation**
   - Algorithm-based
   - Self-adjusting
   - Learns system response
   - No physical anticipator

Cycle Rate Adjustment: Number of cycles per hour affects comfort and equipment life.

Recommended Cycles Per Hour (CPH):

```
Gravity warm air: 1-2 CPH
Low mass radiation: 3-4 CPH
Forced air: 4-6 CPH
Electric heat: 6-9 CPH
High mass radiation: 2-3 CPH
```

Adaptive Control: Modern thermostats use adaptive algorithms:

- Learn system response time
- Adjust anticipation automatically
- Optimize for comfort and efficiency
- Reduce overshoot and undershoot

15.2 Heating Control Sequences

Simple Thermostat Call for Heat

Basic Sequence of Operation:

1. **Thermostat Initiation**
    - Room temperature drops below setpoint
    - Thermostat contacts close (R to W)
    - 24VAC signal sent to furnace
2. **Control Board Response**
    - Receives W call
    - Initiates safety checks
    - Begins ignition sequence
3. **Pre-Purge** (if applicable)
    - Inducer motor starts
    - Proves venting path clear
    - 15-30 second purge
4. **Ignition Sequence**
    - Ignition source activated
    - Gas valve opens
    - Flame established
5. **Flame Proving**
    - Flame sensor confirms ignition
    - Safety timer satisfied
    - System continues operation
6. **Blower Operation**
    - Fan-on delay (30-90 seconds)
    - Blower starts on heat speed
    - Circulates warm air
7. **Continuous Operation**
    - Maintains flame
    - Monitors safety controls
    - Cycles on limit if needed
8. **Satisfaction**
    - Thermostat satisfied
    - W signal removed
    - Gas valve closes
9. **Post-Purge**
    - Inducer continues (15-30 seconds)
    - Clears products of combustion
10. **Fan-Off Delay**
    - Blower continues (90-180 seconds)
    - Removes residual heat
    - Prevents heat exchanger stress

Ignition Sequences per CSA B149.1

CSA B149.1 Requirements:

Mandatory Safety Features:

1. **Proof of Closure**
   - Gas valve must be proven closed
   - Before ignition attempt
2. **Ignition Trial Time**
   - Maximum trial periods:
   - Main burner direct: 15 seconds
   - Pilot ignition: 90 seconds
   - Direct spark: 15 seconds
   - Hot surface: 30-60 seconds
3. **Flame Supervision**
   - Continuous monitoring
   - 0.5-4 seconds response
   - Immediate gas shutoff on failure
4. **Lockout on Failure**
   - After failed ignition attempts
   - Requires manual reset
   - Or automatic after timeout

Standing Pilot Sequence:

1. **Pilot Valve Opens**
   - Thermocouple must be proven
   - 750°C minimum temperature
   - 25-30 mV typical
2. **Main Valve Operation**
   - Only after pilot proven
   - Continuous supervision
   - Immediate shutdown on failure

Intermittent Pilot Sequence (IPI):

```
Time 0: Thermostat call (W)
Time 1s: Inducer starts (if present)
Time 15s: Pressure switch proves
Time 16s: Spark starts
Time 17s: Pilot valve opens
Time 20s: Spark stops (flame proven)
Time 21s: Main valve opens
Time continuous: Flame monitoring
On failure: Immediate gas shutoff
After 3 failures: Lockout (manual reset)
```

Direct Spark Ignition (DSI):

```
Time 0: Thermostat call
Time 1s: Inducer starts
Time 15s: Pressure proves
Time 16s: Spark activation
Time 17s: Gas valve opens
```

```
Time 20s: Flame proven or retry
Trial time: 15 seconds maximum
Retries: 3-5 attempts
Lockout: After final failure
```

Hot Surface Ignition (HSI):

```
Time 0: Thermostat call
Time 1s: Inducer starts
Time 15s: Pressure proves
Time 16s: Igniter energizes
Time 45s: Igniter at temperature (870°C)
Time 46s: Gas valve opens
Time 50s: Flame proven
Time 51s: Igniter de-energizes
If no flame: Close valve, retry
Maximum trials: 3-4 attempts
```

Flame Sensing Methods:

1. **Flame Rectification**
   - AC applied to sensor
   - Flame conducts DC component
   - 0.5-10 microamps DC typical
   - Most common method
2. **Flame Rod Requirements:**
   - Minimum 1 μA for proof
   - 2-10 μA typical reading
   - Ground area 4x rod area
   - Proper positioning critical
3. **UV Sensors**
   - Ultraviolet detection
   - Commercial/industrial
   - Self-checking capability
   - Fail-safe design
4. **Infrared Sensors**
   - Detects IR radiation
   - High-temperature applications
   - Less affected by contamination

Blower Control (Heating Mode)

Fan Control Methods:

1. **Temperature-Activated**
   - Bimetal fan switch
   - Opens at 38°C (100°F)
   - Closes at 49°C (120°F)
   - Simple and reliable

2. **Time-Delay Control**
    - Electronic timer
    - Fixed or adjustable delay
    - 30-90 seconds on
    - 90-240 seconds off
3. **Integrated Control Board**
    - Programmed delays
    - Multiple speed control
    - Diagnostic capability
    - Variable timing

Blower Speed Selection:

Heating Speed:

- Lower CFM than cooling
- 350-400 CFM per ton typical
- Prevents cold drafts
- Increases temperature rise

Speed Tap Selection:

```
PSC Motor Typical:
Black: High (cooling)
Blue: Medium-high
Yellow: Medium-low (heating)
Red: Low
White: Common
```

Temperature Rise Calculation:

```
ΔT = (Output BTU/h) / (1.08 × CFM)

Example:
80,000 BTU/h furnace
1200 CFM airflow
ΔT = 80,000 / (1.08 × 1200) = 62°F
```

Acceptable Temperature Rise:

- Manufacturer specifications
- Typically 30-70°F (17-39°C)
- Higher rise = lower CFM
- Must stay within limits

Limit Control Operation

Primary Limit Switch:

Purpose:

- Prevent overheating
- Protect heat exchanger
- Ensure safe operation
- Manual reset type

Operation:

1. Normal: Closed circuit
2. Over-temperature: Opens at setpoint
3. Stops gas flow immediately
4. Requires manual reset
5. Investigate cause before reset

Typical Settings:

```
Residential Furnace:
Open: 200°F (93°C)
Manual reset required
Location: Above heat exchanger
```

Secondary/Auxiliary Limits:

Auto-Reset Limits:

- Open: 160-180°F
- Close: 130-140°F
- Automatic reset
- Cycling protection

Rollout Switches:

- Detect flame rollout
- Multiple locations
- Manual or auto reset
- 200-300°F typical

Location Requirements:

- Hottest air location
- Not in direct radiant path
- Proper airflow sensing
- Accessible for service

Testing Limit Switches:

1. Continuity when cold
2. Opens at rated temperature
3. Proper reset function
4. Secure mounting
5. Proper location

Safety Lockout Procedures

Types of Lockout:

1. **Soft Lockout**
    - Automatic reset
    - After time period (1-3 hours)
    - Or power cycle
    - Minor faults
2. **Hard Lockout**
    - Manual reset required
    - Safety-critical faults
    - Requires investigation
    - Reset button/power cycle

Common Lockout Conditions:

Ignition Failure Lockout:

```
Sequence:
1st attempt: 15-30 seconds trial
2nd attempt: After 30s wait
3rd attempt: After 30s wait
4th attempt: Final try
Lockout: No flame after all attempts
Reset: Manual after 1-3 hours
```

Flame Failure Lockout:

- Flame loss during operation
- Immediate gas valve closure
- Retry attempts (1-3)
- Lockout if continuous failure

Limit Switch Lockout:

- Primary limit open
- Manual reset only
- Must investigate cause
- Check for:
    - Dirty filter

- Blocked vents
- Blower failure
- Overfire condition

Pressure Switch Lockout:

```
Typical sequence:
5 attempts to prove pressure
2-minute wait between attempts
Lockout after 5 failures
Check:
- Blocked vents
- Inducer operation
- Pressure tubing
- Switch calibration
```

Lockout Reset Procedures:

1. **Identify Fault**
    - Check diagnostic LEDs
    - Read fault codes
    - Review sequence
2. **Correct Problem**
    - Clear blockages
    - Replace failed parts
    - Verify operation
3. **Reset Method**
    - Press reset button (hold 1-2 seconds)
    - Or power cycle (off 30 seconds)
    - Clear fault memory if needed
4. **Verify Operation**
    - Complete heating cycle
    - No fault recurrence
    - Document repair

Diagnostic LED Codes:

```
Common Patterns:
1 flash: System lockout
2 flashes: Pressure switch stuck closed
3 flashes: Pressure switch open
4 flashes: Open limit
5 flashes: Flame sense failure
6 flashes: Rollout switch open
7 flashes: Gas valve error
Continuous: Normal operation
```

15.3 Combination Systems

Heating and Cooling Integration

Dual-Function Systems: Modern HVAC systems integrate heating and cooling functions, requiring careful control coordination to prevent simultaneous operation and ensure efficient changeover.

Common Terminal Designations:

```
R: 24V power from transformer
C: Common (24V return)
W/W1: First stage heat
W2: Second stage heat
Y/Y1: First stage cooling
Y2: Second stage cooling
G: Fan
O: Reversing valve (cool)
B: Reversing valve (heat)
```

System Integration Requirements:

1. **Single Transformer**
   - Powers both heating and cooling
   - 40-75VA typical
   - Sized for maximum load
2. **Interlock Controls**
   - Prevent simultaneous heat/cool
   - Thermostat logic
   - Time delays between modes
3. **Blower Speed Control**
   - Different speeds for heat/cool
   - Automatic switching
   - Relay or electronic control

Control Board Integration: Modern integrated control boards manage:

- Mode selection
- Safety interlocks
- Blower speeds
- Staging sequences
- Diagnostic functions
- Communication protocols

Furnace with Air Conditioning

System Components:

1. **Furnace (Heating)**
   - Gas burner system

- Heat exchanger
- Integrated blower
- Control board

2. **Air Conditioner (Cooling)**
    - Outdoor condensing unit
    - Indoor evaporator coil
    - Refrigerant lines
    - Condensate management

Control Sequence - Cooling Mode:

```
1. Thermostat calls for cooling (Y)
2. Furnace control receives signal
3. Blower relay energizes (high speed)
4. Y signal passed to outdoor unit
5. Compressor contactor pulls in
6. Condenser fan starts
7. Compressor starts (time delay)
8. Continuous operation until satisfied
9. Thermostat satisfied (Y off)
10. Outdoor unit stops
11. Blower continues (90 seconds)
12. System off
```

Control Sequence - Heating Mode:

```
1. Thermostat calls for heat (W)
2. Standard heating sequence initiates
3. Inducer starts (if present)
4. Ignition sequence
5. Gas valve opens
6. Flame established
7. Blower on (low/medium speed)
8. Continuous operation
9. Thermostat satisfied
10. Gas valve closes
11. Blower off delay
```

Blower Speed Configuration:

DIP Switch Settings (Typical):

```
COOL (Tons) | HEAT (BTU) | ADJUST
2.0         | 60,000     | +10%
2.5         | 75,000     | Normal
3.0         | 90,000     | -10%
3.5         | 105,000    | -20%
```

Airflow Requirements:

- Cooling: 400 CFM/ton

- Heating: Based on temperature rise
- Continuous fan: Medium speed
- Dehumidification: -15% CFM

Heat Pump with Gas Backup

Dual-Fuel Systems: Combines heat pump efficiency with gas heating reliability.

Components:

1. Heat pump outdoor unit
2. Gas furnace with coil
3. Dual-fuel thermostat
4. Outdoor temperature sensor
5. Fossil fuel kit (control module)

Operating Modes:

Heat Pump Only (Above Balance Point):

```
Outdoor > 35°F (2°C):
- Heat pump primary heat
- High efficiency operation
- No gas usage
```

Dual Operation (Transition):

```
20-35°F (-7 to 2°C):
- Heat pump with gas auxiliary
- Based on outdoor temperature
- Or time/temperature algorithm
```

Gas Only (Below Balance Point):

```
Below 20°F (-7°C):
- Gas furnace only
- Heat pump locked out
- Maximum heating capacity
```

Control Logic:

Balance Point Determination:

- Heat loss calculation
- Heat pump capacity curve
- Intersection point
- Adjustable in thermostat

Switchover Methods:

1. **Outdoor Temperature**
   - Fixed setpoint
   - 25-40°F typical
   - Simple control
2. **Economic Balance**
   - Compares operating costs
   - Real-time pricing
   - Optimizes for cost
3. **Comfort Priority**
   - Switches on recovery time
   - Maintains temperature
   - User preference

Wiring Configuration:

```
Dual-Fuel Terminal Usage:
R: 24V power
C: Common
Y1: Compressor stage 1
Y2: Compressor stage 2
W1: Gas heat (backup)
W2: Gas heat stage 2
O/B: Reversing valve
G: Fan
E: Emergency heat
S1/S2: Outdoor sensor
```

Lockout Logic:

- Heat pump OFF when gas runs
- Prevents compressor damage
- Time delay between modes
- Emergency heat override

Changeover Controls

Automatic Changeover: System automatically switches between heating and cooling based on temperature.

Requirements:

- Auto mode on thermostat
- Deadband between modes
- Time delays
- Temperature averaging

Changeover Deadband:

```
Example Settings:
Heat setpoint: 68°F (20°C)
Cool setpoint: 75°F (24°C)
Deadband: 7°F (4°C)

Operation:
Heat ON below 68°F
All OFF 68-75°F
Cool ON above 75°F
```

Manual Changeover: User manually selects heating or cooling mode.

Advantages:

- Prevents unwanted switching
- User control
- Energy savings
- Simpler control

Commercial Changeover: Often based on outdoor temperature:

```
Outdoor > 65°F: Cooling only
55-65°F: Auto changeover
Outdoor < 55°F: Heating only
```

Emergency Heat

Purpose: Backup heating when heat pump fails or cannot maintain temperature.

Activation Methods:

1. **Manual Selection**
    - EM HEAT switch
    - Bypasses heat pump
    - Direct gas/electric heat
    - User activated
2. **Automatic Activation**
    - Heat pump failure
    - Low pressure lockout
    - Defrost malfunction
    - Compressor fault

Control Sequence:

```
1. Emergency heat selected/activated
2. Heat pump locked out
3. W2 or E terminal energized
```

```
4. Auxiliary heat operates
5. Higher energy consumption
6. Alert indicator activated
```

Staging with Emergency Heat:

- Stage 1: Auxiliary heat only
- Stage 2: Additional elements/capacity
- No heat pump operation
- Full backup capacity

Return to Normal:

1. Manual: Switch back to normal
2. Automatic: After fault cleared
3. Time delay before compressor
4. Verify heat pump operation

15.4 Zone Control Systems

Multiple Zone Damper Systems

System Components:

1. **Zone Control Panel**
    - Central brain
    - Receives thermostat inputs
    - Controls dampers
    - Manages equipment
2. **Zone Dampers**
    - Motorized dampers
    - Spring return or power close
    - End switches
    - Various sizes
3. **Zone Thermostats**
    - Individual zone control
    - Standard wiring
    - Programmable options
4. **Bypass Damper**
    - Pressure relief
    - Barometric or motorized
    - Prevents high static
5. **Equipment Interface**
    - Staging control

    - Speed control
    - Safety interlocks

Zone Panel Operation:

Priority Logic:

```
First Priority: Any heating call
Second Priority: Any cooling call
Third Priority: Fan only call
Staging: Based on number of zones
```

Typical 3-Zone Sequence:

```
Zone 1 calls for heat:
1. Zone panel receives W signal
2. Opens Zone 1 damper
3. Closes Zones 2 & 3 dampers
4. Damper end switches prove
5. Sends W to equipment
6. Normal heating sequence
7. Zone 1 satisfied
8. Equipment stops
9. Dampers return to normal
```

Multiple Zone Calling:

```
Zones 1 & 2 call for heat:
1. Both dampers open
2. Zone 3 closes
3. Equipment operates
4. First zone satisfies
5. Its damper closes
6. Bypass opens partially
7. Second zone continues
8. All satisfied - system off
```

Multiple Circulator Systems

Hydronic Zone Control: Each zone has dedicated circulator pump.

Components:

1. **Boiler**
    - Central heat source
    - Aquastat control
    - Multiple temperature capability
2. **Zone Circulators**
    - Individual pumps
    - 1/12 to 1/6 HP typical

    - Isolation valves
3. **Zone Controls**
    - Relay panels
    - Thermostat inputs
    - Pump outputs
    - Priority control

Control Methods:

Zone Relay Panel:

```
Typical 4-Zone Panel:
- 4 thermostat inputs (T1-T4)
- 4 pump outputs (C1-C4)
- Boiler demand contact
- Priority capabilities
- LED indicators
```

Operation Sequence:

```
1. Zone thermostat calls
2. Relay panel energized
3. Zone circulator starts
4. Boiler demand made
5. Boiler fires
6. Water circulates in zone
7. Zone satisfied
8. Circulator stops
9. Last zone satisfied
10. Boiler demand removed
```

Zone Valve Alternative:

- Single circulator
- Multiple zone valves
- 2-way or 3-way valves
- End switch feedback
- Similar control logic

Control Strategies

Temperature Control Strategies:

1. **Single Setpoint**
    - All zones same temperature
    - Simple control
    - Limited flexibility
2. **Individual Setpoints**
    - Each zone independent

- Maximum comfort
   - Energy savings potential
3. **Scheduled Setpoints**
   - Time-of-day control
   - Occupied/unoccupied
   - Night setback
4. **Adaptive Control**
   - Learns zone characteristics
   - Anticipates demand
   - Optimizes runtime

Equipment Staging Strategies:

Demand-Based Staging:

```
1 zone calling: Stage 1 (40%)
2 zones calling: Stage 1 (40%)
3 zones calling: Stage 2 (70%)
4+ zones calling: Stage 3 (100%)
```

Time-Based Staging:

- Fixed time delays
- Prevents short cycling
- 5-10 minute stages

Temperature-Based Staging:

- Based on supply temperature
- Or return temperature
- Or outdoor temperature

Load Matching: Modern systems modulate capacity:

- Variable speed equipment
- Matches exact load
- Maximum efficiency
- Optimal comfort

Bypass Requirements (Air Systems)

Purpose of Bypass: Maintains minimum airflow when zones close.

Types of Bypass:

1. **Barometric Bypass**
   - Weighted damper

    - Opens on pressure
    - Self-regulating
    - No power required
2. **Motorized Bypass**
    - Controlled by static pressure
    - Variable position
    - Better control
    - Requires power
3. **Dump Zone**
    - Always open zone
    - Common area
    - Hallway/basement
    - No damper required

Bypass Sizing:

```
Bypass CFM = Total CFM - Minimum Zone CFM

Example:
System: 1200 CFM
Smallest zone: 400 CFM
Bypass needed: 800 CFM
Bypass duct: ~14" round
```

Static Pressure Control:

- Monitor with manometer
- 0.5" W.C. maximum typical
- Adjust bypass damper
- Verify all conditions

Problems Without Bypass:

1. High static pressure
2. Reduced airflow
3. Icing of coil
4. Compressor damage
5. Heat exchanger stress
6. Noise issues
7. Comfort problems

Bypass Installation:

```
Location: Supply to return
Before zones: After coil
After zones: Before return drop
Distance: Minimum 10 feet
Damper type: Barometric/motorized
```

Alternative: Variable Speed Blower

- ECM motor
- Constant CFM
- Adjusts to static
- Eliminates bypass need
- Higher initial cost
- Better comfort

15.5 Advanced Controls

Outdoor Reset Controls

Principle: Adjusts supply water temperature based on outdoor temperature - warmer water when mild, hotter water when cold.

Benefits:

- Improved efficiency (10-30%)
- Better comfort
- Reduced cycling
- Lower return temperatures
- Condensing boiler optimization

Reset Curve:

```
Outdoor Temp | Supply Temp
-20°C (-4°F) | 82°C (180°F)
-10°C (14°F) | 71°C (160°F)
0°C (32°F)   | 60°C (140°F)
10°C (50°F)  | 49°C (120°F)
15°C (59°F)  | 38°C (100°F)
```

Reset Ratio: Temperature change ratio between outdoor and supply.

```
Reset Ratio = ΔSupply / ΔOutdoor

Example:
Supply changes 60°F (180-120)
Outdoor changes 40°F (-4 to 36)
Ratio = 60/40 = 1.5:1
```

Control Components:

1. **Outdoor Sensor**
   - North wall mounting

    - Away from sun/exhaust
    - 10K thermistor typical
    - Weather resistant
2. **Supply Sensor**
    - Strapped to pipe
    - Under insulation
    - 12" from boiler
    - Good thermal contact
3. **Reset Controller**
    - Analog or digital
    - Adjustable curve
    - Min/max limits
    - Display capabilities

Programming Parameters:

- Design outdoor temperature
- Design supply temperature
- Warm weather shutdown
- Minimum supply temperature
- Maximum supply temperature
- Reset curve shape

System Types:

Boiler Reset:

- Most common application
- Works with any boiler
- Best with condensing
- Requires mixing valve protection

Mixing Valve Reset:

- Boiler constant temperature
- Valve modulates
- Good for cast iron boilers
- Protects against condensation

Injection Pumping:

- Variable speed injection
- Primary/secondary piping
- Precise control
- Complex installation

Boiler Management Systems

Multi-Boiler Control:

Purpose:

- Stage multiple boilers efficiently
- Rotate lead boiler
- Optimize efficiency
- Provide redundancy

Staging Strategies:

1. **Sequential Staging**
    - Fixed order
    - Simple logic
    - Uneven wear
2. **Rotation Staging**
    - Lead boiler rotates
    - Even wear
    - Daily/weekly rotation
3. **Efficiency Staging**
    - Most efficient first
    - Based on load
    - Optimizes fuel usage

Control Parameters:

```
Stage 1 ON: 20% load
Stage 2 ON: 40% load
Stage 3 ON: 60% load
Stage 4 ON: 80% load

Stage delays: 10 minutes
Stage differential: 10°F
Rotation: Weekly
```

Advanced Features:

Outdoor Reset Integration:

- Common outdoor sensor
- Coordinated supply temps
- System optimization

Warm Weather Shutdown:

- Boilers off above 65°F

- DHW priority
- Summer/winter modes

Parallel Positioning:

- All boilers modulate together
- Equal loading
- Maximum efficiency
- Complex control

Fault Management:

- Automatic isolation
- Backup activation
- Alarm notification
- Runtime balancing

Building Automation Basics

BAS Overview: Building Automation Systems integrate HVAC, lighting, security, and other systems.

System Architecture:

1. **Field Level**
    - Sensors
    - Actuators
    - VAV boxes
    - Local controllers
2. **Automation Level**
    - DDC controllers
    - Equipment controllers
    - Network controllers
3. **Management Level**
    - Supervisory computers
    - Servers
    - User interfaces
    - Graphics

Benefits:

- Energy optimization
- Central monitoring
- Scheduling
- Trending
- Alarming

- Remote access

Common Functions:

Scheduling:

```
Occupied: 6:00 AM - 6:00 PM
Unoccupied: 6:00 PM - 6:00 AM
Weekend: Unoccupied
Holidays: Programmed
Override: 2-hour timer
```

Optimal Start:

- Calculates start time
- Based on outdoor temp
- And indoor temp
- Reaches setpoint on time

Demand Limiting:

- Monitors power usage
- Sheds loads at peak
- Prevents demand charges
- Priority-based shedding

Trending:

- Records data over time
- Temperature trends
- Energy usage
- Equipment runtime
- Troubleshooting tool

Communication Protocols

BACnet (Building Automation and Control Network):

Overview:

- ASHRAE standard
- Open protocol
- Multi-vendor compatible
- Most common in commercial

BACnet/IP:

- Ethernet based
- High speed
- IT infrastructure
- Remote access capable

BACnet MS/TP:

- Master-Slave/Token-Passing
- RS-485 wiring
- Lower cost
- 2-wire communication

Objects and Properties:

- Analog Input (temperature)
- Analog Output (valve position)
- Binary Input (status)
- Binary Output (start/stop)

Modbus:

Overview:

- Industrial protocol
- Simple and robust
- Master/slave architecture
- Wide equipment support

Modbus RTU:

- Serial communication
- Binary protocol
- RS-485 typical
- 2-wire or 4-wire

Modbus TCP/IP:

- Ethernet based
- Higher speed
- Network integration
- Modern systems

Register Types:

- Coils (binary outputs)
- Discrete inputs

- Input registers (analog)
- Holding registers

LON (Local Operating Network):

- Echelon protocol
- Peer-to-peer
- Free topology wiring
- Self-healing

Integration Gateways:

- Protocol converters
- Multi-protocol support
- Web interfaces
- Cloud connectivity

Wireless Protocols:

Wi-Fi:

- Standard 802.11
- High bandwidth
- Existing infrastructure
- Security concerns

Zigbee:

- Low power
- Mesh network
- Self-healing
- Short range

EnOcean:

- Energy harvesting
- No batteries
- Self-powered sensors
- Green technology

15.6 Troubleshooting Control Systems

Systematic Approach

Troubleshooting Methodology:

1. **Information Gathering**
   - Customer complaint
   - System history
   - Recent changes
   - Operating conditions
2. **Visual Inspection**
   - Obvious problems
   - Burnt components
   - Loose connections
   - Physical damage
3. **System Understanding**
   - Review sequence
   - Identify components
   - Understand normal operation
   - Check documentation
4. **Problem Isolation**
   - Which circuit?
   - Which component?
   - Intermittent or constant?
   - Single or multiple issues?
5. **Testing and Verification**
   - Systematic testing
   - Document readings
   - Compare to specifications
   - Verify each component
6. **Repair and Retest**
   - Replace failed parts
   - Verify operation
   - Check related components
   - Complete system test

Documentation:

```
Service Record:
Date: ___________
Complaint: No heat Zone 2
Found: Open damper motor
Action: Replaced motor
Test: All zones operational
Tech: ___________
```

Using Wiring Diagrams

Diagram Types for Troubleshooting:

Ladder Diagrams:

- Best for circuit tracing
- Shows electrical path
- Easy voltage tracking
- Clear component relationships

Schematic Diagrams:

- Component connections
- Not physical layout
- Good for understanding
- Complex system overview

Pictorial Diagrams:

- Physical representation
- Component locations
- Wire routing
- Field reference

Connection Diagrams:

- Terminal connections
- Wire colors/numbers
- Board layouts
- Quick reference

Effective Diagram Use:

1. **Obtain Correct Diagram**
    - Model number match
    - Serial number range
    - Revision level
    - Field modifications
2. **Mark Test Points**
    - Expected voltages
    - Key connections
    - Problem areas
    - Test sequence
3. **Trace Circuits**
    - Power source
    - Through controls
    - To loads
    - Return path
4. **Document Findings**
    - Actual voltages
    - Open circuits

- Failed components
- Unusual readings

Voltage Tracing Techniques

Half-Split Method: Efficiently locates open circuits.

```
Procedure:
1. Verify voltage at source
2. Check voltage at load (none)
3. Check midpoint of circuit
4. If voltage: problem in second half
5. If no voltage: problem in first half
6. Continue splitting to isolate
```

Step-by-Step Tracing: Check voltage at each component.

```
Example - No Heat Call:
1. 24V at transformer secondary? Yes
2. 24V at thermostat R? Yes
3. 24V at thermostat W (calling)? No
4. Problem: Thermostat contacts
```

Common Voltage Checks:

24V Control Circuit:

```
Test Points:
R to C: 24-28VAC (no load)
W to C: 24VAC (heat call)
Y to C: 24VAC (cool call)
G to C: 24VAC (fan call)
```

Line Voltage:

```
Test Points:
L1 to L2: 208/230VAC
L1 to Ground: 120VAC
L2 to Ground: 120VAC
L1 to Neutral: 120VAC
```

Safety Practices:

1. Use proper meter (CAT III)
2. Test meter first
3. One hand when possible
4. Stand to side
5. Proper PPE

Component Verification

Systematic Component Testing:

Transformers:

Tests:
1. Primary voltage (115V)
2. Secondary voltage (24V)
3. Secondary current (<VA/24)
4. Temperature (<140°F)

Pass: All readings normal
Fail: Replace transformer

Relays/Contactors:

Tests:
1. Coil resistance (10-50Ω)
2. Coil voltage when energized
3. Contact continuity (closed)
4. Contact resistance (<1Ω)

Pass: Contacts switch properly
Fail: Replace relay

Pressure Switches:

Tests:
1. Continuity at rest
2. Tube connections tight
3. Actual pressure vs. setpoint
4. Diaphragm integrity

Pass: Makes at rated pressure
Fail: Adjust or replace

Thermostats:

Tests:
1. Power at R terminal
2. Output on call (W,Y,G)
3. Actual vs. displayed temp
4. Calibration check

Pass: Switches at setpoint
Fail: Recalibrate or replace

Motors:

Tests:
1. Winding resistance
2. Current draw
3. Capacitor value
4. Bearing condition
5. Insulation resistance

Pass: Within specifications
Fail: Repair or replace

Sequence Verification

Heating Sequence Verification:

```
Expected Sequence:
0s: Thermostat call (W)
1s: Inducer starts
15s: Pressure switch makes
16s: Igniter energizes
45s: Gas valve opens
48s: Flame proven
49s: Igniter off
50s: Blower on delay
80s: Blower starts

Actual Observations:
0s: W signal present ✓
1s: Inducer runs ✓
15s: Pressure switch ✗
Result: No ignition attempt

Diagnosis: Pressure switch issue
```

Cooling Sequence Verification:

```
Expected:
0s: Thermostat call (Y)
0s: Blower starts (high)
5s: Compressor starts
Continuous operation

Actual:
0s: Y signal present ✓
0s: Blower runs ✓
5s: No compressor ✗

Check:
- Contactor coil voltage
- Contactor operation
- Compressor voltage
- Overload protection
```

Common Failure Modes

Control Board Failures:

Symptoms:

- No response to calls
- Erratic operation
- Wrong sequences

- No diagnostic lights

Causes:

- Power surge
- Moisture damage
- Component failure
- Overheating

Diagnosis:

1. Check input power
2. Check fuse
3. Verify inputs
4. Check outputs
5. Replace if faulty

Thermostat Issues:

No Display:

- Dead batteries
- No C wire power
- Blown fuse
- Failed thermostat

Wrong Temperature:

- Poor location
- Needs calibration
- Anticipator setting
- Defective sensor

Short Cycling:

- Anticipator wrong
- Location issues
- Loose connections
- Differential too narrow

Sensor Failures:

Temperature Sensors:

- Drift over time
- Opens/shorts

- Corrosion
- Poor contact

Testing:

- Resistance vs. temperature
- Compare to chart
- Check connections

Flame Sensors:

- Carbon buildup
- Cracked insulator
- Poor ground
- Positioning

Testing:

- Clean with steel wool
- Check microamps
- Verify ground
- Check position

Communication Failures:

Symptoms:

- Lost communication
- Intermittent drops
- Wrong data
- No response

Causes:

- Wiring issues
- Termination resistors
- Addressing conflicts
- Noise interference

Solutions:

- Check wiring
- Verify terminations
- Check addresses
- Add isolation

Chapter Review

Key Concepts Summary

1. **Control Logic Types**
   - On-off: Simple, reliable, some temperature swing
   - Staged: Better comfort, improved efficiency
   - Modulating: Precise control, maximum efficiency
   - Proper differential prevents short cycling
   - Anticipation reduces overshoot
2. **Safety Sequences**
   - CSA B149.1 requirements mandatory
   - Ignition trial times limited
   - Continuous flame supervision required
   - Lockout on repeated failure
   - Manual reset for critical faults
3. **System Integration**
   - Heating/cooling interlock required
   - Proper staging improves efficiency
   - Changeover control prevents conflicts
   - Emergency heat provides backup
   - Dual-fuel optimizes cost/comfort
4. **Zone Control Benefits**
   - Individual comfort control
   - Energy savings potential
   - Reduced equipment cycling
   - Better load matching
   - Bypass prevents problems
5. **Advanced Features**
   - Outdoor reset saves energy
   - Building automation enables optimization
   - Communication protocols allow integration
   - Predictive control improves comfort
   - Remote monitoring reduces downtime

Sequence of Operation Exercises

Exercise 1: Single-Stage Furnace Write the complete sequence for a standard furnace with HSI:

```
Answer:
1. Thermostat calls for heat (R-W)
2. Control board receives W signal
3. Inducer motor starts
4. Pressure switch proves (15-30s)
```

```
5. Hot surface igniter energizes
6. Igniter reaches temperature (30-45s)
7. Gas valve opens
8. Flame sensor proves flame (5s)
9. Igniter de-energizes
10. Blower starts after delay (30-60s)
11. Continuous operation
12. Thermostat satisfied (W off)
13. Gas valve closes
14. Inducer post-purge (15-30s)
15. Blower off delay (90-180s)
```

Exercise 2: Two-Stage Cooling Describe staging sequence for 2-stage AC:

```
Answer:
1. Small temperature rise: Y1 only
2. Compressor stage 1 operates
3. Larger rise or time: Y2 energizes
4. Both compressor stages run
5. Temperature drops
6. Y2 de-energizes first
7. Y1 continues alone
8. Setpoint reached
9. Y1 de-energizes
10. System off
```

Control System Design Scenarios

Scenario 1: Three-Zone Residence Design zone control for 2000 sq.ft. home:

```
Solution:
Equipment: 3-ton AC, 80,000 BTU furnace
Zones:
- Zone 1: Bedrooms (600 CFM)
- Zone 2: Living areas (800 CFM)
- Zone 3: Basement (400 CFM)
Total: 1800 CFM

Bypass required: 1200 CFM capacity
Damper sizes: 12", 14", 10" respectively
Control: 3-zone panel with priority
```

Scenario 2: Dual-Fuel System Select balance point for heat pump/gas:

```
Given:
- Heat loss: 45,000 BTU at 0°F
- Heat pump capacity: 36,000 at 30°F
- Gas cost: $1.00/therm
- Electric: $0.12/kWh

Calculate:
- Balance point: 25°F (thermal)
- Economic balance: 30°F
- Recommendation: 30°F switchover
```

Troubleshooting Case Studies

Case 1: No Heat Zone 2

```
Symptom: Zone 2 won't heat, others OK
Found: Zone 2 damper not opening
Tests: 24V at motor, motor doesn't run
Diagnosis: Failed damper motor
Solution: Replace motor, verify operation
```

Case 2: Short Cycling

```
Symptom: Furnace cycles every 2 minutes
Found: Rapid limit switch cycling
Tests: High temperature at limit
Diagnosis: Restricted airflow
Solution: Replace dirty filter, check registers
```

Case 3: Intermittent Lockout

```
Symptom: Random lockouts, code 3
Found: Pressure switch fault
Tests: Marginal pressure readings
Diagnosis: Partially blocked intake
Solution: Clear intake, clean inducer
```

Case 4: No Cooling

```
Symptom: Thermostat calls, no cooling
Found: Y signal present, contactor not pulling
Tests: No 24V at contactor coil
Diagnosis: Open wire in condensate switch
Solution: Clear condensate, repair switch
```

Case 5: Wrong Temperature

```
Symptom: 5°F difference from setpoint
Found: Thermostat reading incorrect
Tests: Actual temp vs. display
Diagnosis: Poor thermostat location
Solution: Relocate thermostat
```

Case 6: Erratic Zone Operation

```
Symptom: Random zones opening/closing
Found: Intermittent control signals
Tests: Voltage fluctuations at panel
Diagnosis: Failing transformer
Solution: Replace transformer
```

Case 7: Boiler Short Cycling

```
Symptom: Boiler fires for 30 seconds
Found: Quick temperature rise
Tests: Flow rate low
Diagnosis: Air in system
Solution: Purge air, check pressure
```

Case 8: Communication Loss

```
Symptom: BAS can't see equipment
Found: No response from controller
Tests: Communication wiring
Diagnosis: Missing termination resistor
Solution: Install 120Ω resistor
```

Case 9: Outdoor Reset Not Working

```
Symptom: Constant supply temperature
Found: Outdoor sensor reading -40°F
Tests: Sensor resistance incorrect
Diagnosis: Broken sensor wire
Solution: Repair wire connection
```

Case 10: Heat Pump Won't Switch

```
Symptom: Stays in heat mode
Found: O terminal no voltage
Tests: Thermostat output OK
Diagnosis: Broken wire to reversing valve
Solution: Repair wire, verify operation
```

Wiring Problem Diagnosis

Problem 1: Crossed Wires

```
Symptom: Heat runs in cool mode
Investigation: Y and W reversed at furnace
Solution: Correct wire connections
```

Problem 2: Floating Common

```
Symptom: Erratic operation
Investigation: C wire not connected
Solution: Connect common properly
```

Problem 3: Induced Voltage

```
Symptom: Ghost voltages
Investigation: Control parallel to power
Solution: Separate wire runs
```

Problem 4: Multiple Transformers

```
Symptom: Blown fuses
Investigation: Two transformers fighting
Solution: Use single transformer
```

Professional Reminders

1. **Safety First**
    - Never bypass safety controls
    - Verify sequences before leaving
    - Test all safety devices
    - Document all changes
2. **System Understanding**
    - Know normal operation
    - Understand sequences
    - Read documentation
    - Ask when unsure
3. **Diagnostic Skills**
    - Be systematic
    - Document findings
    - Use proper tools
    - Verify repairs
4. **Customer Service**
    - Explain problems clearly
    - Provide options
    - Educate on maintenance
    - Set proper expectations

Conclusion

Control systems orchestrate the complex operation of modern HVAC equipment. From basic on-off control to sophisticated building automation, understanding control theory and sequences enables proper installation, optimal performance, and effective troubleshooting.

Key principles:

- Safety sequences protect equipment and occupants
- Proper integration ensures efficient operation
- Zone control improves comfort and efficiency
- Advanced controls optimize performance
- Systematic troubleshooting solves problems
- Documentation and standards ensure consistency

As control technology continues evolving with IoT, AI, and predictive analytics, gas technicians must maintain current knowledge while mastering fundamental principles that remain constant. The ability to understand, implement, and troubleshoot control systems distinguishes professional technicians in the modern HVAC industry.