Irrigation Flow Monitor and Control System, Version 1.7

By R. G. Sparber
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Conclusion

This package of hardware and software is able to stop water wasted due to irrigation leaks. Within one minute, it will detect and shut down any zone with a flow rate greater than 30% above normal. Besides sounding an audible alarm, it sends an email to the user[2].

I built this system for under $150. Approximately $80 of this was for commonly available parts. The challenge is to find an accurate flow meter at a reasonable cost. I used a modified second hand Badger Model 25 flow meter. This is fine for a hobbyist but not as part of a product.

My Goal

I want someone or some company to pick up this design and turn it into a product. Developing the hardware and software is 10% of the effort. Product development, packaging, marketing, distribution, and product support make up

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[2] Contact me for details. It uses IFTTT and an esp82666 board. Additional cost is under $10.

the other 90%. In exchange for this effort, they are free to keep all profits. I just want to see a significant reduction in wasted water.

Background

I own a very smart Irrigation Controller from RainBird. It is aware of the weather and adjust the run time of each of my 6 zones accordingly.

However, this controller is missing an important feature:

the ability to monitor and act on flow rates.

If a valve sticks closed or open it can't tell. If a pipe bursts, it can't tell. If a single "spaghetti line" blows its emitter, can't tell. Worse yet, I can't quickly shut off the water.

All of that changed with my Flow Monitor and Control (FMC) installed.

See https://www.youtube.com/watch?v=fuf6UD6G-A8&t=94s and https://www.youtube.com/watch?v=oRK1sAZ7rfI&t=73s for videos of the system in action.

Up until now, I have compensated for the lack of automatic flow control by manually recording my water usage on my city water meter. Since most of my usage is due to irrigation, this does at least tells me something is wrong. I must then sequence through all 6 zones and inspect the area of the property until I find the one with the problem.

In one case, I had a major leak that left no water on the surface. My monthly bill told me something was wrong when it indicated 20,000 gallons of unusual consumption. That $300 bill was a big motivator for finding an automatic method of dealing with flow problems.

RainBird does sell a flow monitoring system but it is targeted for the commercial market and is priced accordingly.

This article presents the design of my system including system block diagrams, schematics, flow charts, and software. It does ***not*** present the numerous dead ends and re-writes needed to get to what was finally built.

I have included sufficient detail so someone with some hardware background could build the system. Minimal software knowledge is needed since I have supplied my code. If requested, I can supply the binary file.

User's Manual

Under normal conditions, the user does nothing. If the beeper sounds, the screen will tell the user which zone has a problem and what is wrong.

If the Flow Monitor and Control was able to stop the flow of a faulted zone, the user should inspect the zone, correct the fault, and then clear the alarm.

If the flow cannot be stopped, the user should turn off the main water supply. The problem will be between the water meter's output and the valve's output. A broken pipe will be obvious. If a valve is unable to shut down you will see water flowing in the zone when the controller says it is off.

System Normal

When The Flow Monitor and Control is first powered up, it records the average water use for each zone. Here you see Zone 1 is active and the flow is 4.54 Gallons Per Minute (GPM). These measurements are saved as the first reference flow[3] when Zone 1 is turned off by the Irrigation Controller.

When a give zone is run again, its flow rate is compared to the reference. In this case, the current flow matches the flow the last time this zone ran.

When no zones are on, the flow is compared to a limit[4] of 0.06 GPM. Flow less than 0.06 GPM is considered acceptable.

[3] It is therefore essential that each zone is initially in proper working order. See page 9 for how to audit each zone.
[4] All readings are ± 0.03 GPM so this is the smallest limit we can have and not get false alarms.

Fault Situations

When no zones are on and the flow exceeds the limit of 0.06 GPM, we get an Overflow condition and a Major Alarm is sounded both day and night. It will sound for 0.1 seconds and be quiet for 0.1 seconds. The number in the lower right hand corner is the current flow. It is possible to see "Can't stop idle flow." with a current flow of 0. This means it ***was*** greater than 0.06 GPM but is ***now*** zero.

If the new flow is more than 30% higher than the reference, we get an Overflow condition. The system responds by turning off the valve and taking another flow measurement.

If the flow is stopped, the screen indicates the problem. If it is daytime, the Flow Monitor and Control sounds a Minor Alarm which is 0.3 seconds on and 2 seconds off. The flow that triggered the alarm is in the lower right corner.

In this case, other zones can run and they will be monitored. If the flow can't be stopped, a Major Alarm will sound. Any time an Overflowed zone with Minor Alarm runs, its flow will be stopped.

If the Flow Monitor and Control was unable to stop the flow[5], the screen tells the story and a Major Alarm is sounded. The current flow is in the lower right corner.

In this case, the Irrigation Controller can run other zones but they will be blocked as the Flow Monitor and Control continues to try and stop the leak. I have seen this fault when a valve was stuck open.

[5] 6.80 GPM is 9,800 gallons per day!

If the flow is more than 30% lower than the threshold, we get an Underflow condition. The second line shows the current flow and normal flow (ref). If during the day, a Minor Alarm is sounded.

If the underflowed zone is not active, the system will monitor and control the other zones while displaying the error message for the faulted zone.

Controlling Alarms

By pushing the "clear alarms" button, all alarms will be cleared. If the problem is still present, the alarm will come back after 70 seconds.

By pushing the PEST audible alarms button, any audible alarm will be silenced. It is a ***pest*** so this shuts it up. Alarms will return if the problem has not been resolved and cleared in time. For a Major alarm, expect it to sound again in 15 minutes. Minor alarms will sound again after 24 hours. Fault information will remain on the screen.

Maintenance Function

If the clear alarms button is held down before power up[6] and released after power up, all historical data will be erased. The system will then collect new data as the zones turn on and off.

If the PEST button is held down before power up and released after power up, you will see the current instantaneous[7] flow rate. Before any flow is detected, you get this screen. Press Clear Alarm at any time to return to this screen.

Once a non-zero flow rate is measured, the display will update every second. If the flow returns to 0, the last non-zero flow rate will remain on the screen. Press the PEST button to return to normal flow monitoring behavior.

Status Indicators

On most screens you will see one or two letters and one or two numbers. This is the status indicator. It is a sanity check to be sure all is working. The first letter can be **N** for nighttime with no audible alarms PESTed. If **n**, it is nighttime and a PEST is active. A **D** means daytime with no audible alarms PESTed. A **d** is daytime and PEST is active.

The next character will be a **T** when we are waiting for the flow to build up and stabilize. **[** means the flow meter has not indicated a unit of water[8] has passed. A **]** means the flow meter just saw a unit of water pass. The result is that you see **[** with the right side flickering into a rectangle when there is flow. The higher the flow rate, the closer you get to a constant rectangle.

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[6] This involves unplugging the power supply from the wall.
[7] Normally, flow is measured over one minute intervals so small variations are averaged out. This flow measurement is instant. That is good for seeing what the flow is doing every second.
[8] One unit of water is 3.6 ounces or 0.028 gallons.

The two numbers are a countdown until a new flow measurement is complete. If a zone just turned on, the count will go from 70 seconds down to 60 and the **T** will precede the count. At 60 you will see [and the count will decrement until it reaches 0. Then the flow information will update.

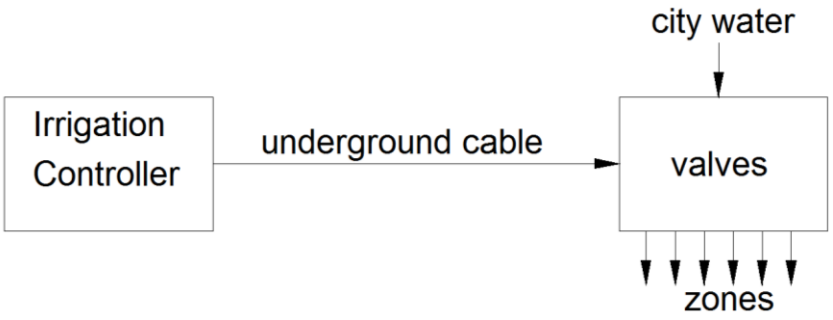
If the user chooses to manually operate more than one zone at the same time, the flow is not monitored.

There is an electromechanical relay inside the Flow Monitor And Control that can fail. As long as it is stuck in the open position, this message will display and a Minor alarm will sound. However, if the problem goes away, we will return to normal operation.

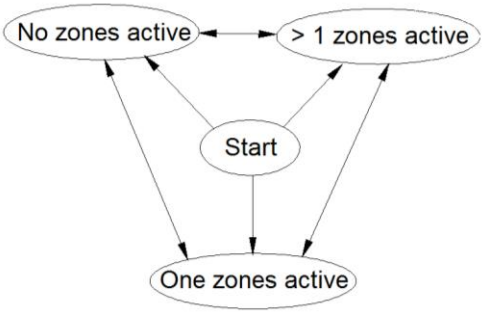
It is also possible that software errors will occur. This might be from real software bugs or could be due to electrical noise crashing the Flow Monitor And Control. If you get a software error message, please write it down. Then unplug power for 10 seconds and plug it back in. See if the problem returns. Any correlations with zones turning on or off would be helpful in debugging the problem.

Contents

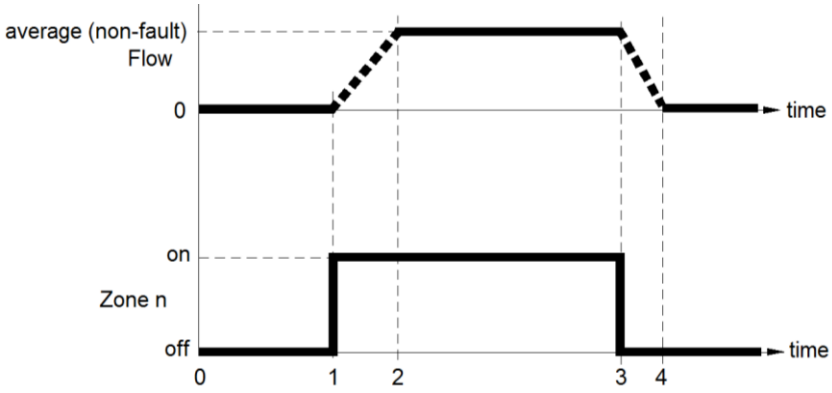
The Original Configuration



As intended by the manufacturer, the RainBird Irrigation Controller is connected to a number of electrically powered water valves via a cable. City water is applied to the input side of each valve. The controller applies power via the cable to one valve at a time to send water to the corresponding zone.



As viewed from a state diagram, the Irrigation Controller powers up in the "Start" state. From there we can move to one of three states. Either no zones are active, one zone is active, or more than one zone is active[9]. The irrigation controller can move between one zone active and no zones active as needed.

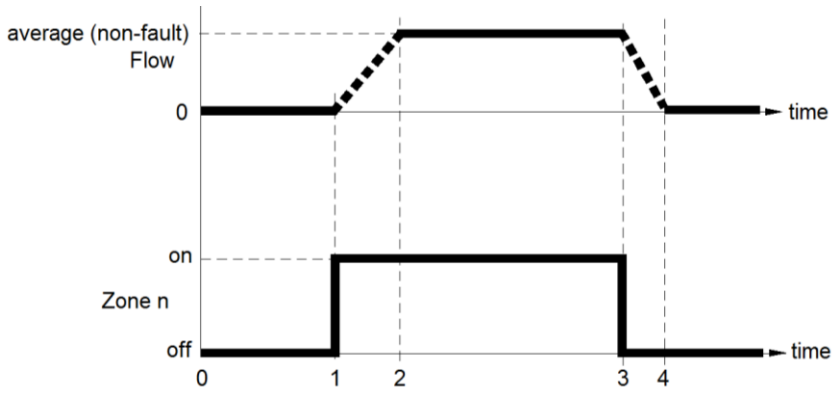


This behavior can be viewed on a time line. From start at time 0, we move to no zones active. Water flow is 0.

At time 1 Zone *n* turns on and flow starts to rise. It takes time for the pressure to build up in the pipes and for any pop up sprayers to rise. I call this the transient time and is less than 10 seconds for my small residential system.

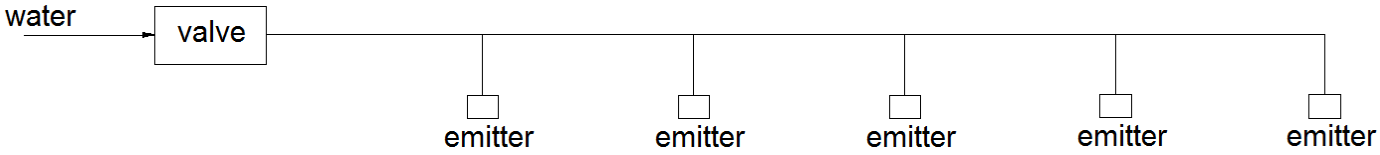
At time 2 the flow has stabilized and we are around the average flow rate. The rate could vary as a function of water pressure and sprinkler head variation but is expected to be within ±30% of the average. Between time 2 and 3 Zone *n* is running at full flow.

[9] This last state can only occur manually.



At time 3 the zone turns off and the flow starts to drop. At time 4 the flow is back to 0. This is the second transient time and is also less than 10 seconds. We just transitioned from one zone on to no zones on.

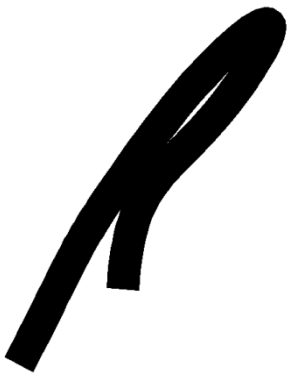
Auditing A Zone



The FMC assumes that the first time it watches a zone run, all is well. It is therefore essential that the user verifies there are no faults.

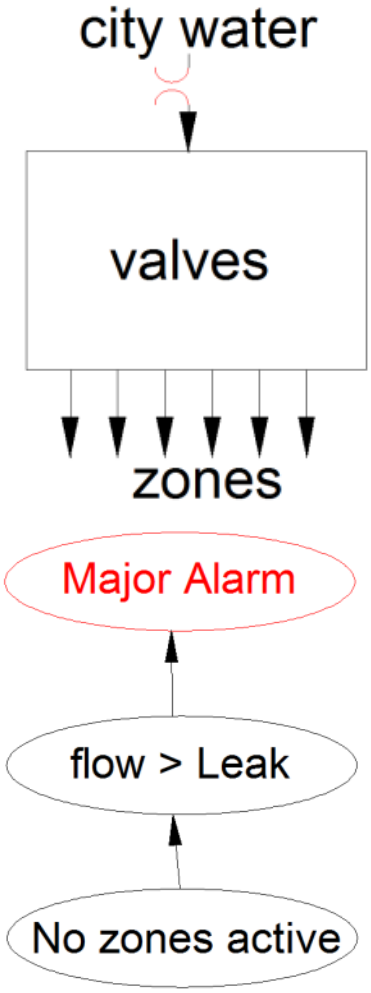
The FMC can be turned into a flow meter by holding down the PEST button when power is off, turning on power, and then releasing the button. Power cycle the FMC when done measuring flow.

Turn the zone on manually. Then walk along the zone. If an emitter or sprinkler head should be putting out water and is not, time to repair it.



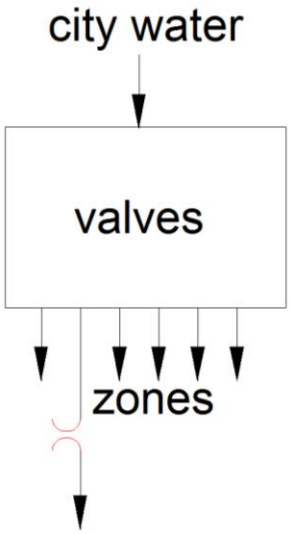
One way to detect leaks in a zone is to block all ¼ inch lines and see how much flow is left. This can be done by bending each ¼ inch line in half and securing it with a piece of wire or bag tie. No water should then come out of the emitter. With all ¼ inch lines blocked, the flow seen by the FMC will be from leaks.

Fault Scenarios

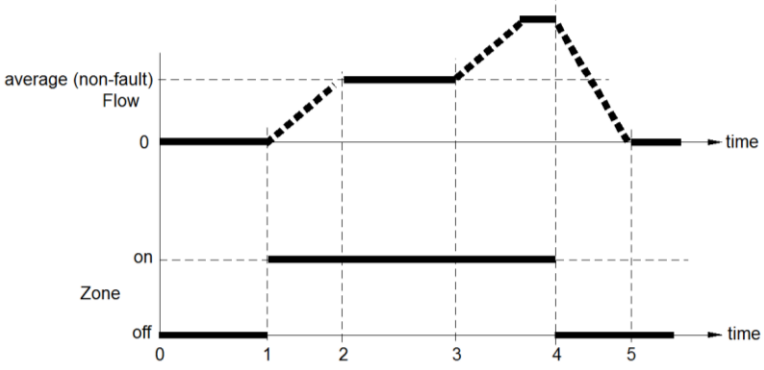


Of course, things do go wrong. A leak can develop between the city water supply and the valves. With no valve in the way, the leak cannot be stopped except by me turning off the city water.

We need to measure the flow, determine it is more than the Leakage limit, and sound a "Major Alarm". Of course, this assumes the leak occurs downstream of the flow measuring device.

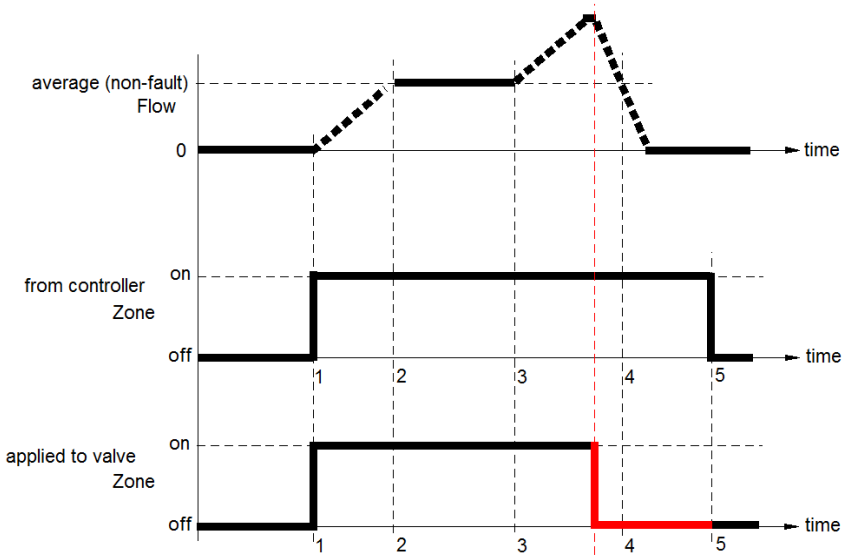


More likely is a leak in a zone downstream from the valve. As long as the zone is active, excess water will flow. But when we return to having all zones off, the leak stops.



In this time line we start out the same as the non-fault case. The zone is initially off and the flow is 0. At time 1 the zone turns on and the flow starts to build. At time 2 the flow is at the average. But at time 3 the flow builds up a second time. Maybe a pipe burst or a sprinkler head blew. We end up at a flow more than 30% above average. At time 4 the controller turns off the zone, not knowing that a fault has occurred. The flow then drops back to 0 at time 5.

Blocking the Faulted Flow



Now, what if we added a new function that was able to monitor the flow and the state of each zone. When it saw excessive flow, the new function would turn the zone off (red lines) and sound an alarm.

When the controller turned this zone off at time 5, the new function would stop interfering.

So what is "average (non-fault) flow"? In order to reduce the burden on the user, the system will assume that the first time a zone runs, it is normal. The software will record the average flow for this run and save it as normal flow. If the next time the zone runs it is within 30% of this historical data, all is fine. The new run becomes the historical data. If a fault is detected, the previous historical data is kept.

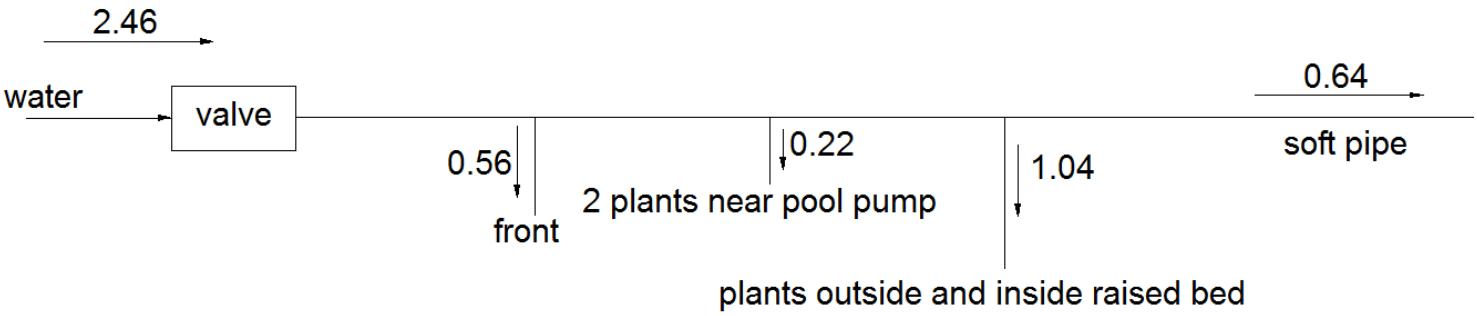
There is a blind spot here: if a zone is faulted while running for the first time, the flow will be assumed normal and become the historical data. The user can manually clear out all historical data so the system can learn anew.

Detecting A Fault

We do not want any false alarms but also do not want to miss faults. Experience has taught me that normal flow can vary ± 25%. To avoid false alarms, we want our limit to be greater than this variation. RainBird has their limit set at ±30% which is reasonable[10].

If a zone consists of sprinkler heads, the nominal flow will be much larger than with drip but a blown head will pass more water too. I don't have any problem detecting a blown head. However, a cracked riser could go undetected if it passes less than 30% of the total.

Here is a case study of a poorly designed zone.



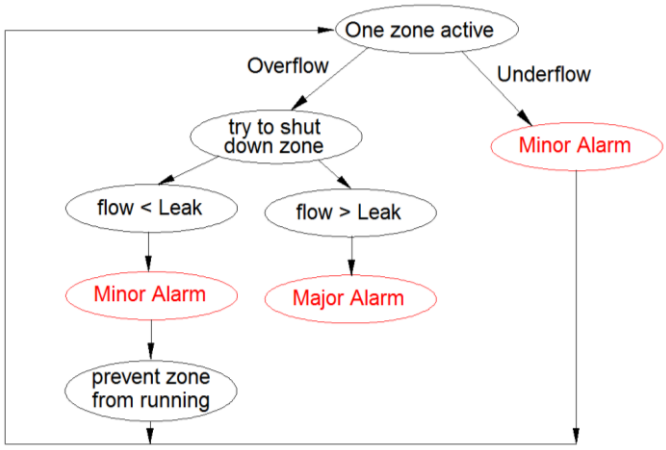
The FMC tells me this zone uses 2.46 GPM. I was able to sequentially close off flow and build this map. Additionally, I introduced two faults to see how the flow would change. Cutting a ¼ inch line near the raised bed caused an increase of 0.6 GPM. Far down the soft pipe run I only measured a 0.3 GPM rise due to a cut ¼ inch line.

30% of 2.46 GPM is 0.74 GPM. Therefore, neither fault will trigger an alarm. At the risk of causing a false alarm, I could reduce my alarm threshold to below $\frac{0.3\ GPM}{2.46\ GPM} \times 100\% = 12.2\%$. Alternately, I could just accept that this loss of detection is a consequence of an excessively large zone. Breaking this zone into thirds would solve the problem.

My really big leaks have come from split soft pipe that is buried deep enough in coarse crushed rock as to not show a puddle on the surface. Such a leak would likely increase flow more than 30% so would alarm. To directly address this failure mode, I replace all leaking soft pipe with ½ inch schedule 40 PVC.

[10] Any zone with an average flow rate of less than 0.04 GPM is given a larger limit.

Logic Overview



To address faults, we need to

1. monitor the flow on an active zone
2. determine if it is too much
3. try to shut down the valve
4. check the flow again
5. determine if it is now less than leakage
6. and sound an alarm

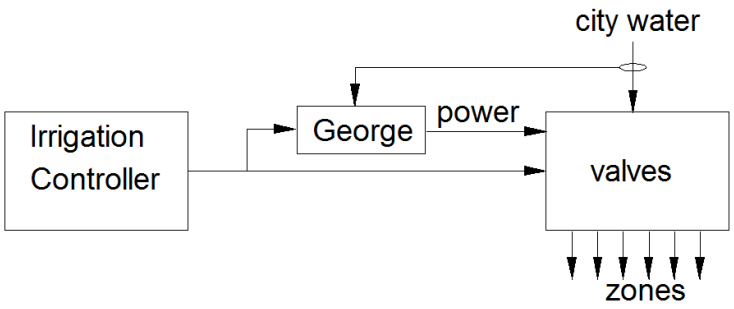
If closing the valve stopped the flow, we call it a Minor Alarm. Then we mark this zone so in the future it is prevented from running.

If, after we try to shut down the zone, the flow is more than leakage, we did not stop the flow. It is then marked as a Major Alarm.

If the flow is too small, we call it Underflow and declare a Minor Alarm. The plants are not getting enough water so shutting down the flow would only make matters worse.

System Overview

Flow Monitoring and Control is not a new invention. Companies like RainBird sell a similar function. They are used in application where a large amount of water normally flows and one leak can be costly. The price of such a system is over $1000 and I'm sure it pays for itself quickly. But in my little home irrigation system, this price tag is out of the question. Mine cost around $150.



I will call this new function "George". He sits between the Irrigation Controller and all of the valves.

George can see which valves have been operated by the Irrigation Controller and also how much water is flowing.

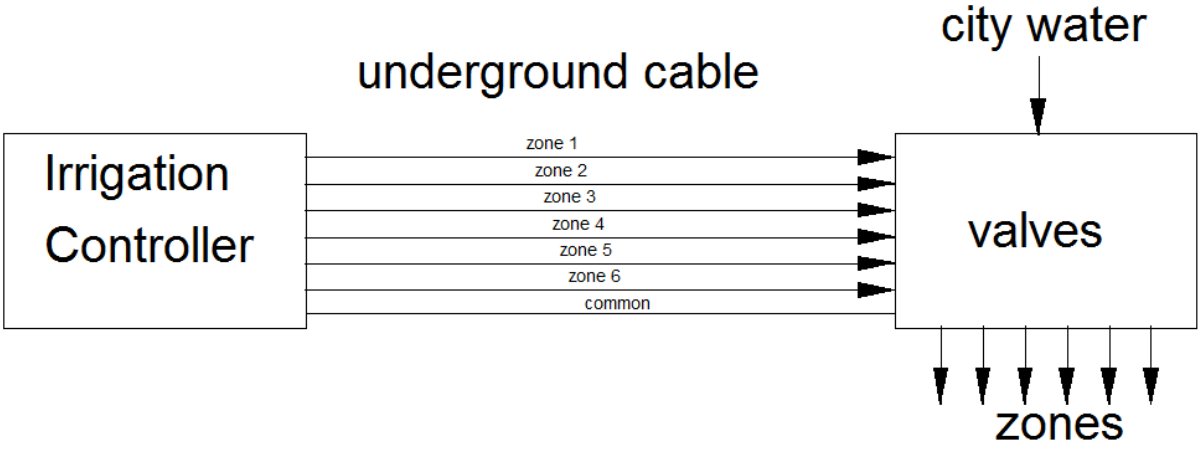
If the leak cannot be stopped, George must sound an alarm immediately. I must then manually turn off the city water.

If the leak is only flowing while zone ***n*** is active, George can turn off valve ***n*** every time the controller turns it on. Then he can sound an alarm during the day. No need to wake me up if it is night.

My RainBird Controller automatically turns on only one zone at a time. The user can manually turn on more than one zone. In this case, the user must deal with any excessive flow. Since George only looks at the total flow, he would not be able to figure out which zone was in trouble.

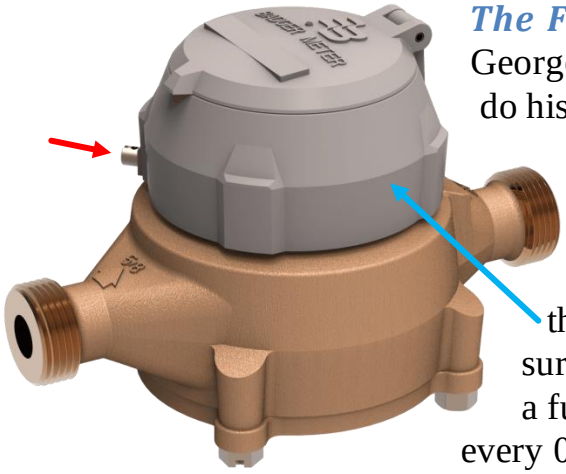
The user can also manually turn on a zone right on the valve. This will look like an uncontrolled leak and generate an Overflow Major Alarm. To avoid such excitement, it is best to manually turn on zones via the Irrigation Controller.

Details of the Existing System



A seven conductor cable carries control power from the controller to the valves. When the controller applies about 24 volts AC to a zone wire, the corresponding valve opens and water flows in the associated zone.

Introduction to the New Functionality

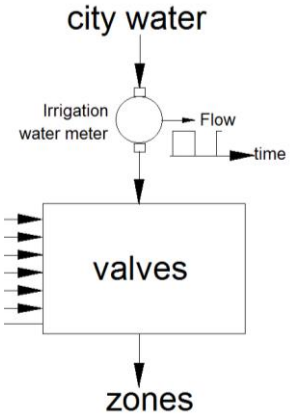


The Flow Measuring Device

George depends on knowing the precise flow rate in order to do his job. Therefore, the first thing I bought was a water meter. It was on eBay for $27 including shipping. This meter is a Badger model 25 with a plastic body[11].

By removing a screw (red arrow), the readout head comes off. This provides access to a surface with a spinning steel bar under it. The bar turns as a function of flow through the meter. I see one revolution every 0.028 gallons of flow[12].

I sense the steel bar with a magnet attached to an arm. The arm is supported by a ball bearing so is free to spin. A magnetic sensor suspended over the path of the magnet reports each revolution. It outputs pulses that are read by George.



By measuring the flow over 1 minute, George calculates the Gallons Per Minute (GPM). The meter connects between the city water inlet and my valves and will provide water usage for my irrigation system. This is necessary but not sufficient for knowing the water usage per zone.

Logic is needed to look at which zone is active and how much water is flowing.

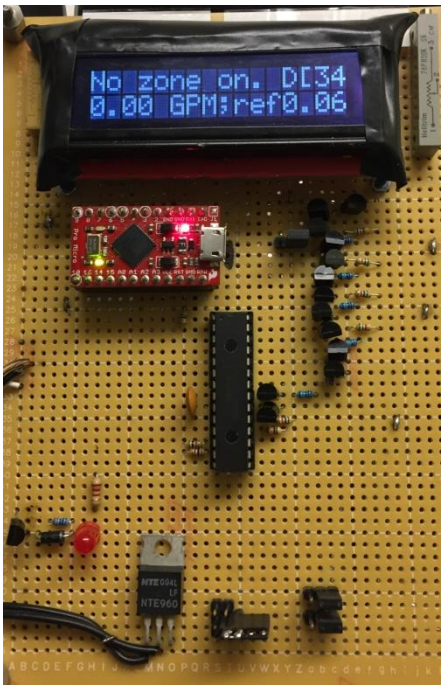
[11] The picture is of a bronze body meter. The plastic ones cost less and are black.
[12] I used the city's water meter while I counted revolutions to determine this conversion factor.

On 12/13/2019 I was searching for an off-the-shelf flow measuring device and came upon flows.com which is owned by Assured Automation. They are located in New Jersey. They sell the WM-PD-050 low volume flow measuring device. There is an option to add an electrical contact that closes each time 0.05 gallons passes through it. The price, including shipping/handling and tax is about $100.

This is a major find because it means that all components of the Irrigation Flow System can be bought, rather than fabricated.

The Flow Monitor and Control

The second piece of the puzzle is the Flow Monitor and Control that will read the flow signal from the water meter plus read and control the signals in the cable. This intelligence will have control of the valves including overriding the Irrigation Controller if a fault occurs in the valves or irrigation zones.



The FMC is built using discrete parts plus an Arduino system on a board. Since this is a prototype, I used a board much larger than ultimately needed. These things do have a tendency to grow over time.

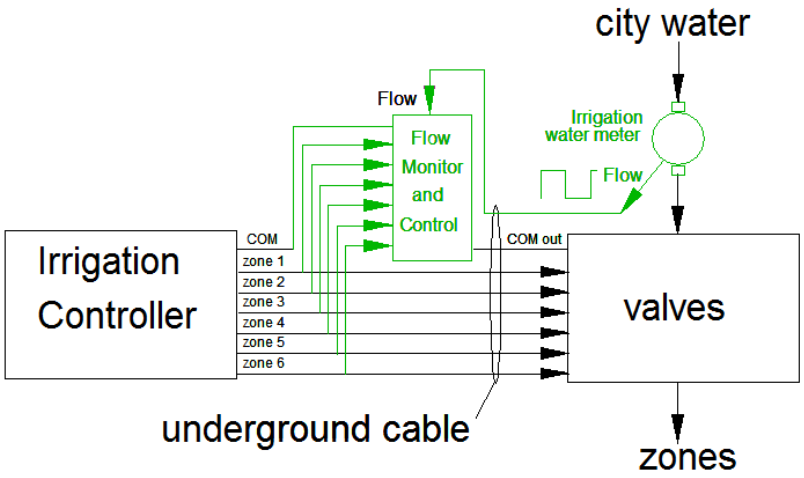
If turned into a real product, I expect the electronics to be all Surface Mount Technology. It likely could be slightly larger than the display.

Presenting the Design

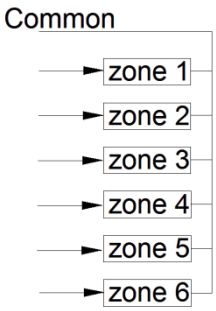
I have no interest boring you with ***how*** I arrived at the following design. Instead I will present the illusion that it was a simple task with no dead ends or false starts.

The hardware will be presented first starting with a high level view and ending with circuits. Then the software will be presented starting with a high level view and ending in code.

Level One System Block Diagram



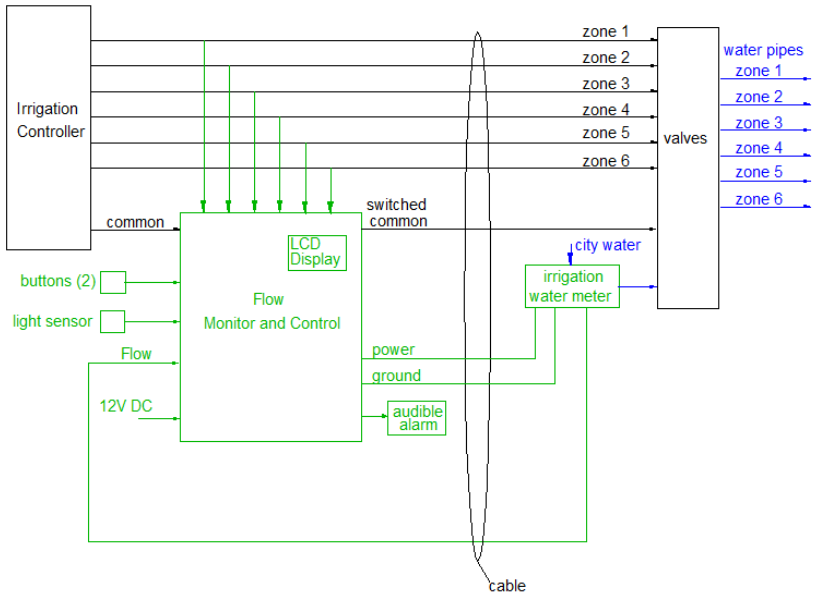
The Flow Monitor and Control taps into each zone output of the Irrigation Controller. It also connects to the Common (COM) wire. Under non-fault conditions, "Common out" (COM out) connects to COM.



All of the valves have two wires. One wire connects to a zone wire. The other wire is joined with all other valves into a single conductor called Common. Apply power between any zone wire and Common and that valves will operate.

The figure shows the flow signal connected to wires in the underground cable. In my case, the original cable had no spare wires so I had to run another cable.

Level Two System Block Diagram



The FMC's Human/Machine Interface consists of a display, two buttons, and a piezoelectric beeper. The beeper can be seen on the left side of the box (red arrow).

On many screens you will see "D[xx" where "xx" is a number between 0 and 70. This is a countdown timer that tells me how long until the next update. If during the day, you will see "D". At night, it will be "N". Remember that Minor Alarms sound only during the day. Major Alarms sound when they occur.

It is also common to see the flow rate on the second line. Here you have 4.54 GPM. It is being compared to the reference which is also 4.54. If there was no reference yet, you would have seen "ref-". After the zone has run once, the "-" is replaced by the reference flow.

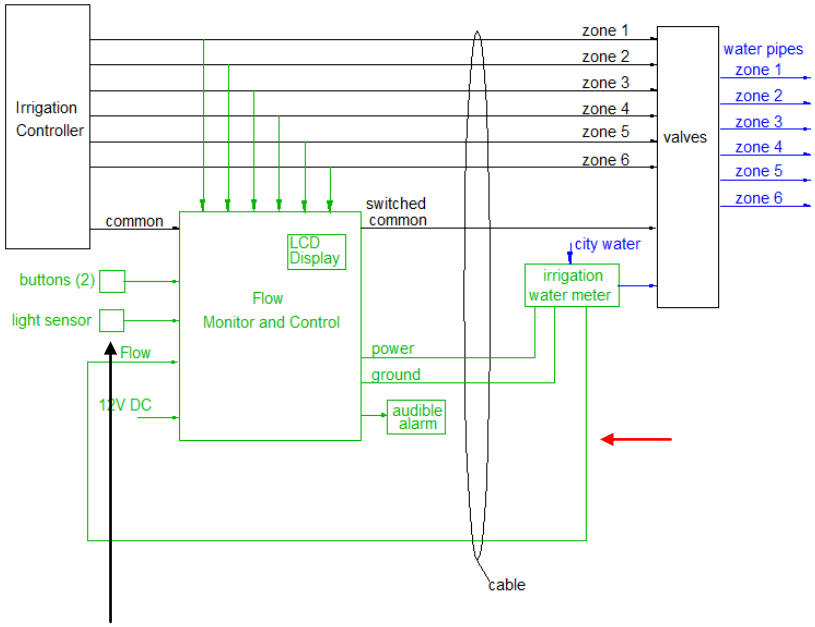
The top button clears all alarms. If the problem has not been corrected, the alarm will reappear after 70 seconds. The bottom button will temporarily silence the audible alarm. A Minor Alarm will stay quiet for 24 hours. A Major Alarm will return in 15 minutes.

The audible alarms emanate from the piezoelectric beeper. Intentionally, it is extremely annoying. A Minor Alarm will be on for 0.3 seconds and off for 2

seconds. A Major Alarm will be on for 0.1 seconds and off for 0.1 seconds. These patterns were chosen so they would not sound like a smoke alarm.

Flow Monitor and Control Inputs

The FMC will monitor all outputs of the Irrigation Controller so it knows what zone is supposed to be active. Under automatic control, there should be only one zone running at a time.



The FMC will also accept the common wire. This is the return path for all valves. If the FMC detects excessive flow through a valve, it will be able to disconnect the common wire and remove power to all valves.

The light sensor is located outside and outputs a logic 1 when the sun is out. It tells the system when there is daylight so safe to sound minor audible alarms.

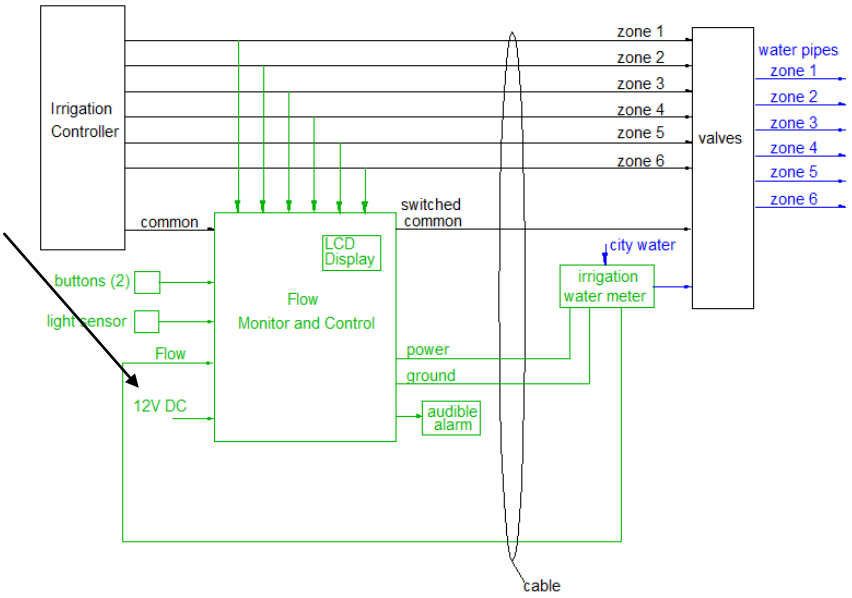
This approach lets me avoid the cost and complexity of including a real time clock. I do not need to know the exact time, just that it is a reasonable hour to sound a non-urgent alarm.

The irrigation water meter has a Hall Effect magnetic sensor attached to it. For every 0.028 gallons of water passed through the meter, the sensor will generate a pulse on the Flow line (red arrow). The FMC counts these pulses over time to determine flow rate. The maximum flow I have seen is 15 GPM. This means a pulse every

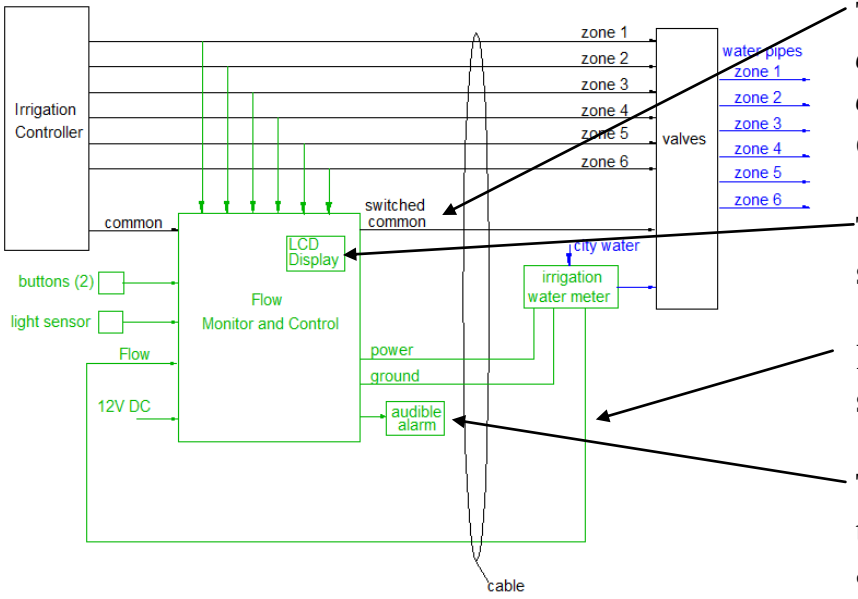
$$\frac{15\ Gallon}{minute} \times \frac{1\ pulse}{0.028\ gallons} = \frac{1\ pulse}{1.9\ milliseconds}.$$

The software has been designed to keep up with this pulse rate.

The FMC receives unregulated 12V DC.
It is used directly to run the relay that switches common and also to power the piezoelectric beeper. Most of this power feeds into a 5V regulator which supplies the rest of the board.



Flow Monitor and Control Outputs



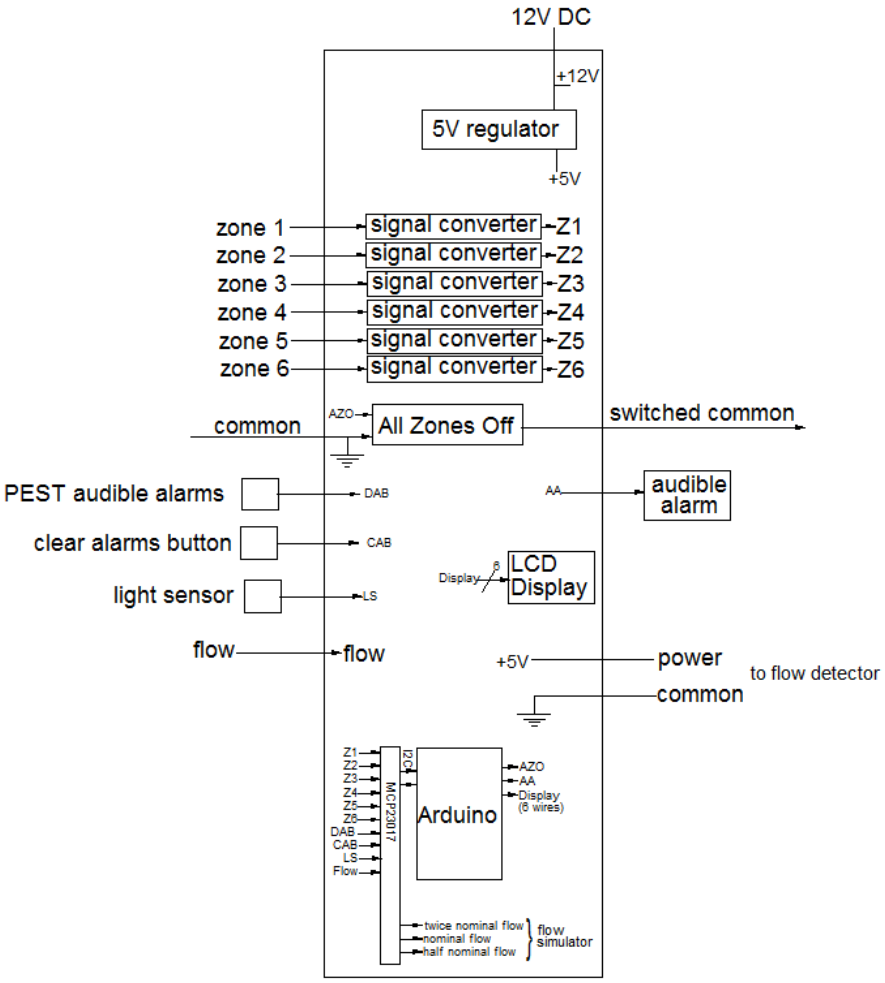
The FMC switches the ***switched common*** line between the ***common*** line at its input and an open circuit.

The LCD display tell the user status.

Power is supplied to the magnetic sensor on the water meter.

The audible alarm is sounded by the software to alert the user of any fault conditions.

Level Three System Block Diagram

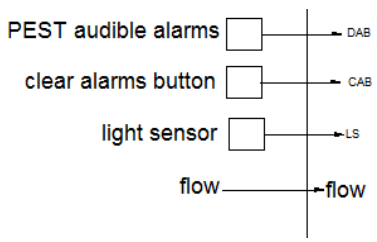


The FMC is controlled by an Arduino Pro Micro 5V/16 MHz. In runs on 5V and has a 16 MHz clock. The Arduino is paired with a MCP23017 port expander to provide sufficient digital input and output pins.

Starting at the top, we have unregulated 12V DC coming from a wall wart. This power supply can deliver up to 500 mA. The voltage is fed to the piezoelectric beeper and to the relay that switches the common wire. A 5V regulator brings the 12V down to a level used by the rest of the electronics.

Below the 5V regulator are our signal converters. They sense 24VAC on the zone leads and convert them to 5V logic levels.

Next we have the All Zones Off function. It contains a normally closed relay under software control. When no power is applied to this relay, the "common" wire is connected to the "switched common" wire. When needed, the Arduino will send an active AZO signal to the All Zones Off box which will energize the relay and disconnect the switched common from the common wire. This will cut power to all valves. Note that if the FMC loses power, it will become transparent to the RainBird Irrigation Controller.

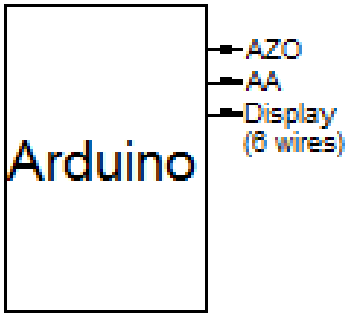


The PEST audible alarms and clear alarm buttons feed directly into the port expander which has been configured to connect 20K pull up resistors.

The light sensor generates a digital signal compatible with the port expander. The sensor was placed where it can detect daylight. If an irrigation fault is detected and controlled, the resulting alarm won't sound until the sun comes out. No need to wake me.

The flow signal from the irrigation water meter feeds directly into the port expander.

Software is used to remove any mechanical bounce in the buttons.



The Arduino has three outputs.

During an irrigation fault condition, it drives the AZO signal which cuts power to all valves and hopefully stops water flow.

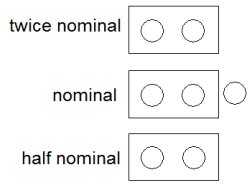
It drives an audible alarm, AA, to notify the user when a problem has been detected.

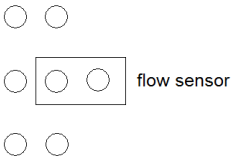
And finally, The Arduino feeds the Liquid Crystal Display to provide system status. While the other three outputs are single pins, the display takes 6.

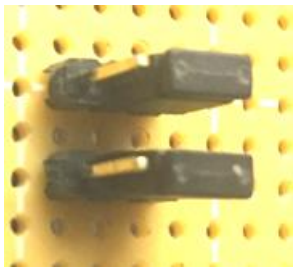
Built In Testing Features

In order to facilitate testing, a flow simulator has been built into the software and hardware. The port expander can output a pulse stream equivalent to a flow of 4.5 GPM. It can also output 9 GPM and 2.25 GPM. These signals are used to test nominal, Overflow, and Underflow states. By moving a jumper I can select the flow sensor or simulated flow. The jumper is shown in the flow sensor position.

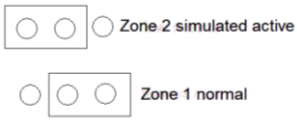
My jumper block is made from a length of connector to make it easier to grasp around all of those pins.







Not shown in the diagram are two jumpers that can simulate Zone 1 and Zone 2 being active. Here you see both jumpers set to normal operation.



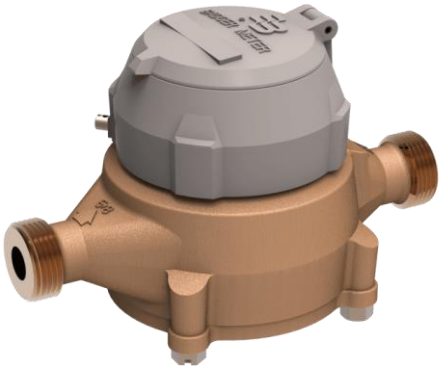
An LED with limiting resistor connects across the relay coils. This makes it easier to see when the software has disconnected the switched common wire from the common wire.

Additionally, there is a software switch called SpeedUp. When turned on, the software only measures flow for 10 seconds rather than a full minute. It also shortens the PEST intervals to 100 seconds. This makes testing the software quicker.

Level Four System Block Diagram

At this level of detail, each functional block is described.

Flow Sensor Mechanism



I started with a Badger model 25 flow meter. The readout mechanism was lifted off

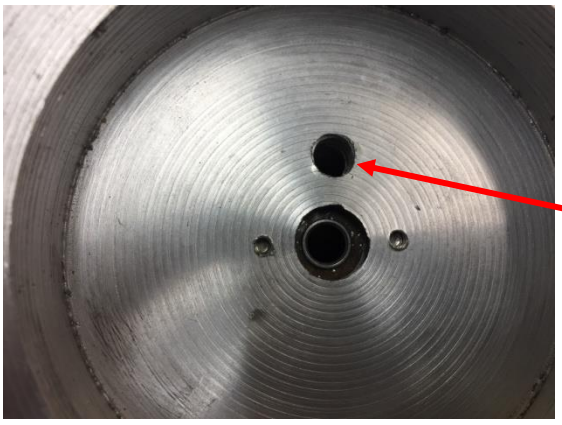
and my interface hardware dropped in place.

The interface hardware was an unfortunate addition. Originally I thought that there was a spinning magnet inside the water meter. This could be directly sensed by a Hall Effect device. But upon investigation, I discovered that a steel bar was in there. The interface hardware senses the bar and generates a spinning magnetic field. Then my Hall Effect device can do its job and convert revolutions to pulses. By using the City's water meter as my reference, I found that one revolution equals 0.028 gallons of flow.

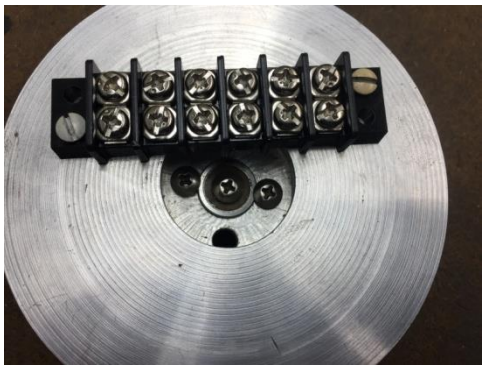
The bar has a spigot on the back that is a close fit to the ID of a ball bearing. The bar has a ¼ inch diameter hole in it that accepts a neodymium magnet 1/8 inch thick.

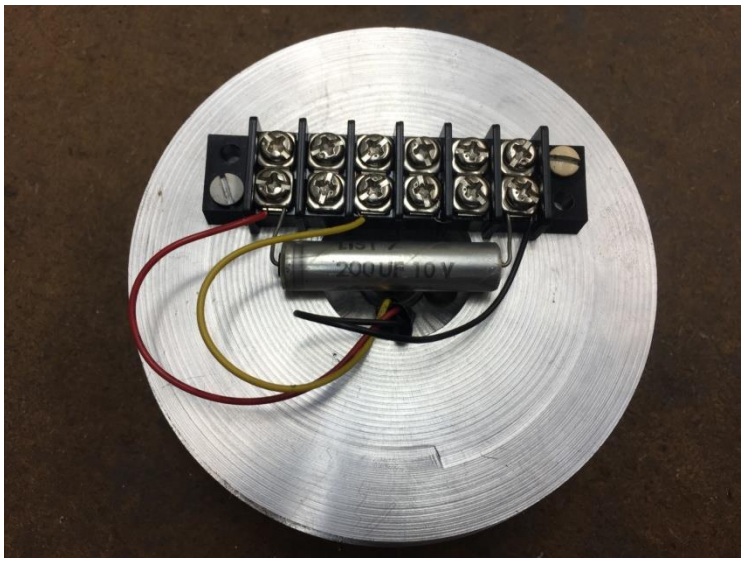
I locked it in place with 3 punch marks. At first I had two magnets but found that this prevented movement.

I later found that I needed to move the bar closer to the top of the meter in order to insure reliable coupling. Placing a 3/8 inch diameter by 1/8 inch thick magnet on top did the trick.



Looking at the underside of the enclosure, you can see the ball bearing's inside diameter. The spigot slides through and is secured with a screw on the other side.
This hole accepts the Hall Effect sensor.





With the Hall Effect sensor installed, the power, ground, and output leads are routed to a terminal block. The electrolytic capacitor completes the assembly.

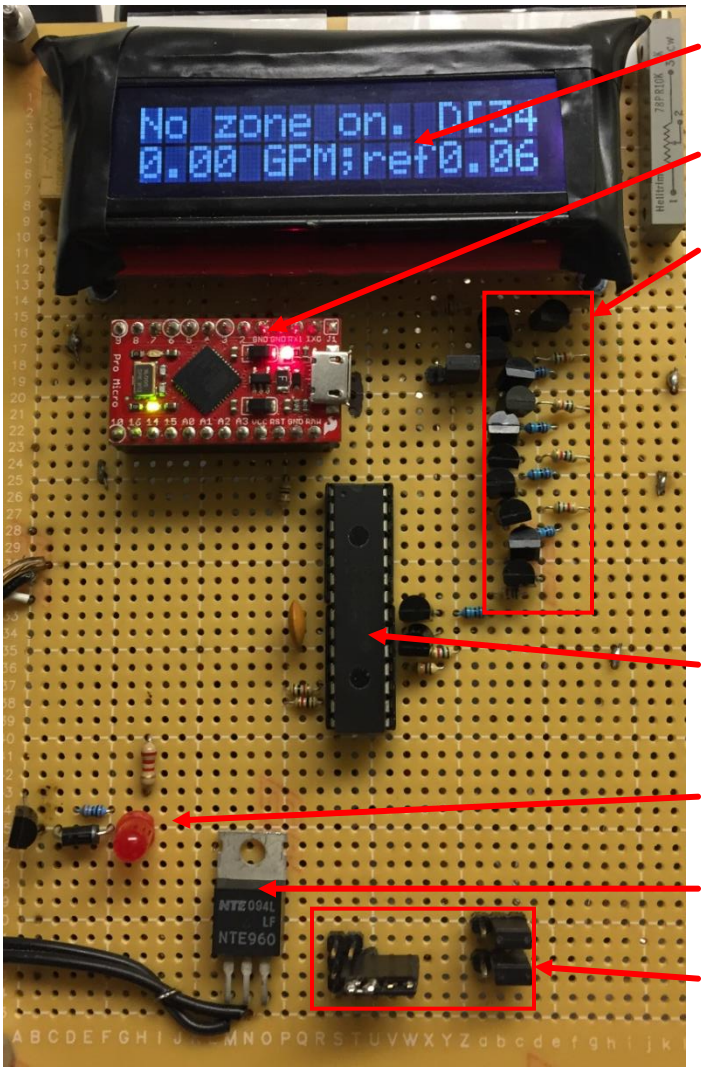
A 4 inch diameter PVC pipe end is used as a weather tight enclosure. The cable running back to the FMC passes through this cover and terminates on the terminal block.

The resulting assembly came out nice but in the future I hope to be able to simplify the interface hardware and go with a proximity switch that can sense the spinning steel bar. The proximity switch I tried did not work.

I did spend a lot of time sitting with the installed flow meter trying to get it to work. This was not without excitement. That is a Western Diamond Back rattlesnake. My wrist was about one inch from its head when I realized it was there. Fortunately, it was early morning and cold out. The snake did not perceive me to be a threat and was also rather slow. I was able to convince it to move on by filling the pit with some water. I watched as it went back through a hole in the block wall. Closing that hole worked. No more company while I work in the valve pit. Yes, I do look carefully before climbing in.

Flow Monitor and Control

Here is an overview of the subsystems on the perf board.



2 row by 16 character LCD

Arduino Pro Mini

Signal Converter Subsystem

Port expander

Relay driver and status LED

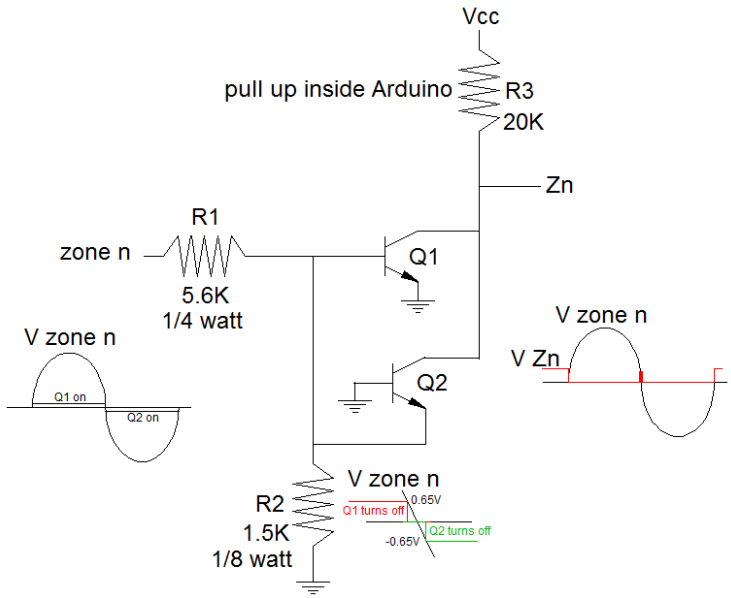
5V regulator

Testing jumpers

The relay is mounted on the back side.

Signal Converter Subsystem

The zone wires will either have about 24V RMS on them or be open circuits. The signal converter circuit monitors this AC voltage and puts the state in a format readable by the Arduino.



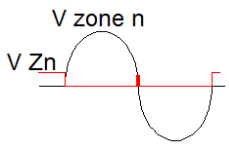
The signal converter circuit consists of 2 resistors and 2 NPN transistors. The input is the voltage $V_{zone\ n}$ and the output is V_{Zn}.

When $V_{zone\ n}$ is above about 2V, Q_1 turns on. This pulls down on the Z_n node and presents a logic 0 to the port expander.

While Q_1 is on, Q_2 has about -0.65V across its base emitter junction. This keeps Q_2 off but does no damage.

When $V_{zone\ n}$ is below about -2V, Q_2 turns on. This pulls down on the Z_n node and presents a logic 0 to the port expander.

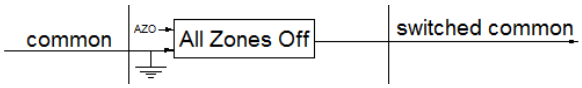
When $V_{zone\ n}$ is less than 0.6V but greater than -0.6V, both transistors will be off. The output then gets pulled up to V_{cc} (+5V) by internal pull up resistor R_3.



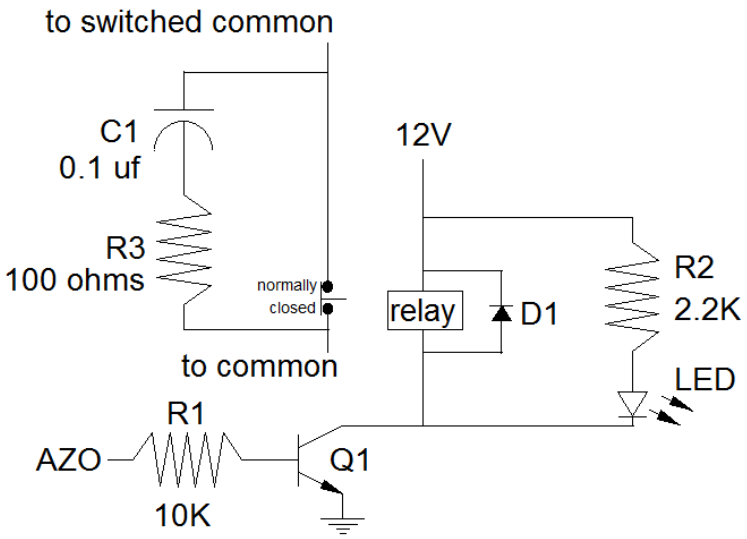
Note the red vertical line on the V_{Zn} trace as $V_{zone\ n}$ changes from positive to negative. This results from $V_{zone\ n}$ being less than 2V in magnitude. The spike is treated the same as bounce on a mechanical switch.

See Appendix 1 on page 69 for details on this narrow pulse which is about 320 microseconds wide.

All Zones Off

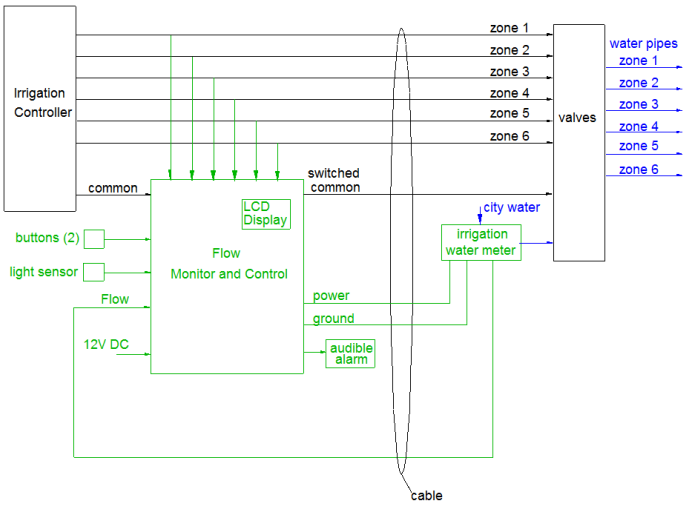


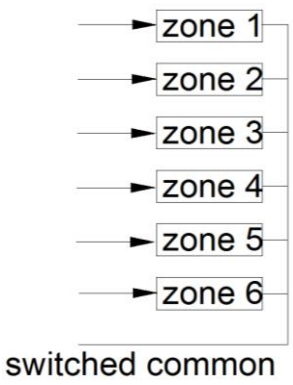
This functional block is an electromagnetic relay with contacts that are closed when power is removed. When the FMC loses power or when all is idle, AZO is near 0 volts. This turns off Q_1 and no power is sent to the relay. The common wire is therefore connected to the switched common wire.



When AZO becomes active (around 5V), Q1 turns on. The relay powers up along with the optional indicator LED next to it.

When the relay is operated, the normally closed contacts open. The current being broken is AC and passes through the valves which are inductive. This means that arcing can occur on these contacts. The snubber circuit, C1 and R3, provide an alternate path for the transient current. This minimizes the arcing which can erode the contacts and cause the Arduino to go off the rails.





When the relay is operated, the switched common lead is disconnected from common. This means the signal converters will be connected to a long cable that floats at the far end. Electrical noise can be picked up and cause zones to randomly look active when they are not.

Even worse, if one zone is active so 24V AC is applied to one zone wire and the switched common lead is floating, all zones will be at this voltage. This say they are all active.

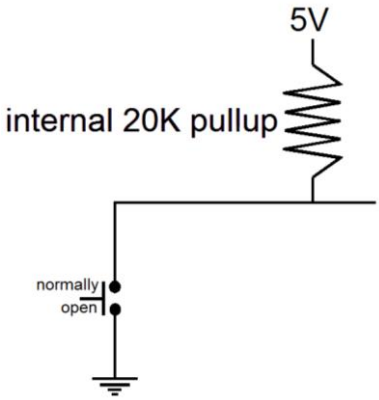
The problem is solved in software. When at least one zone is active and the relay is then operated, we just wait for all zones to turn off. That will occur when the one zone goes inactive. When all zones turn off, we again monitor zone states.

If the contacts on the relay fail to conduct due to built up oxides caused by arcing, the software will see all 6 zones turn on when any one of them turns on.

Any time all 6 zones are seen in the on state while the relay is not operated, we assume the relay is the problem. By turning the relay on and off quickly 20 times, we attempt to break up the oxide layer. If that works, we return to normal operation. If we still see all 6 zones on, we monitor the state and only return to normal operation if the fault goes away. The display will say "hardware failure" as long as the fault is detected or until the clear all alarms button is pushed.

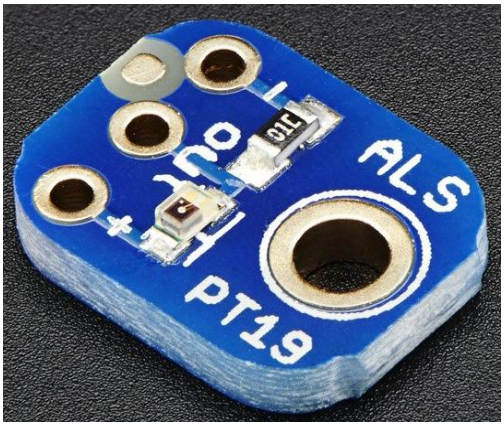
Pushbuttons

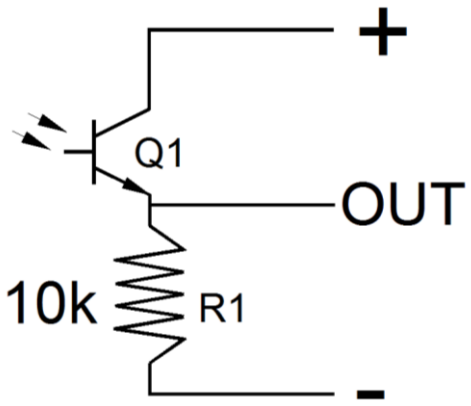
When either of the pushbuttons is depressed, a contact closes and the port expander sees a logic 0. When released, the internal pull up resistor generates a logic 1.



This closing action may cause the contacts to bounce. Software is used to filter that out. We take 10 readings and average the result. If it is less than ½, we call a zero. Greater than or equal to ½ is a one.

Light Sensor

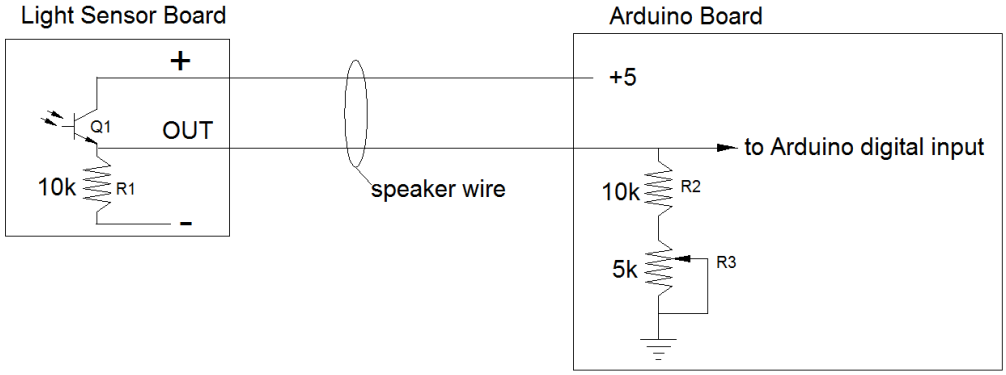




I am using an ALS-PT19 light sensor from Adafruit Industries. When light shines on the sensor, the phototransistor, Q1 conducts. This moves the output voltage towards the voltage on the positive terminal. Without light, Q1 is off and the output voltage moves towards the voltage on the negative terminal.

My light sensor is mounted inside a glass bottle that is a tight fit into a PVC 45° coupler. I happen to have two wire speaker cable. Since the ALS-PT19 has three terminals, I would need to run two of these speaker cables and have half of one cable unused.

Instead, I chose to not use R1. Then I was able to use a single cable between sensor and Arduino board. Over at the Arduino I duplicated R1 plus put a 5K variable resistor, R3, from the output signal to ground. It was then possible to adjust the variable resistor so daytime generated a logic 1 and nighttime produced a logic 0.



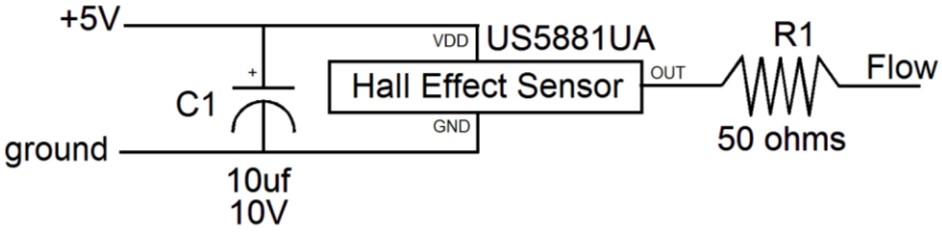
This scheme lets me avoid the cost and complexity of having a battery backed up real time clock.

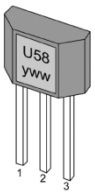
Flow Interface

The Hall Effect Sensor pulls the Flow lead down to ground very quickly to generate a logic 0. With a logic 1 it just lets go. Rise time is defined by the capacitance of the cable[13] and a pull up resistor. This means that the fall time is extremely small compared to the rise time. Both are much smaller than the minimum period of the pulse stream.

The fast fall time is not a good thing. It causes undershoot at the port expander that is greater than what the device can safely handle. I see about -0.8V which is beyond the -0.5V spec.

By placing a 50 ohm resistor in series with the Hall Effect device's output, I was able to slow the fall time and therefore reduce undershoot. Now the undershoot is about -0.2V so all is well. It still takes only about 200 ns to go from +5V down to near 0.

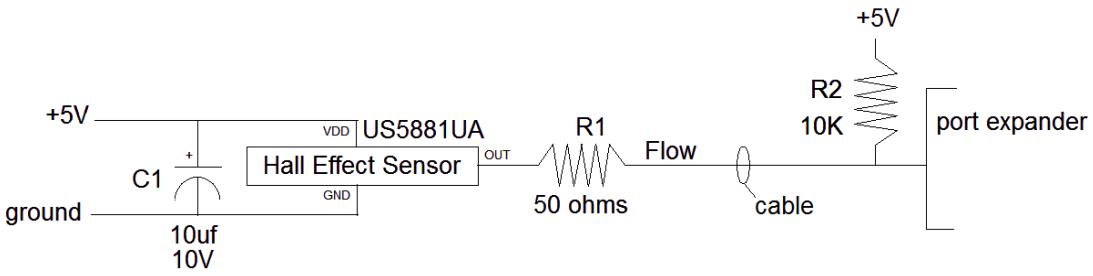


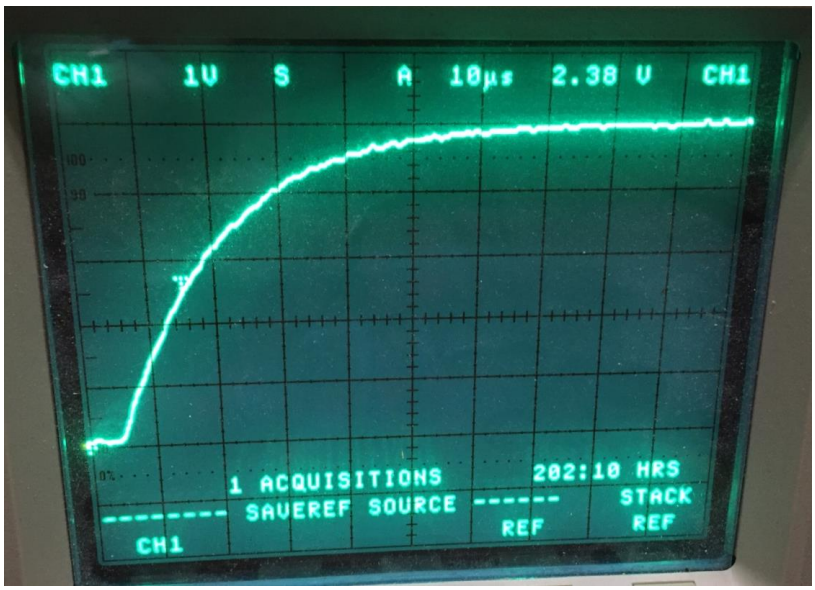


UA package

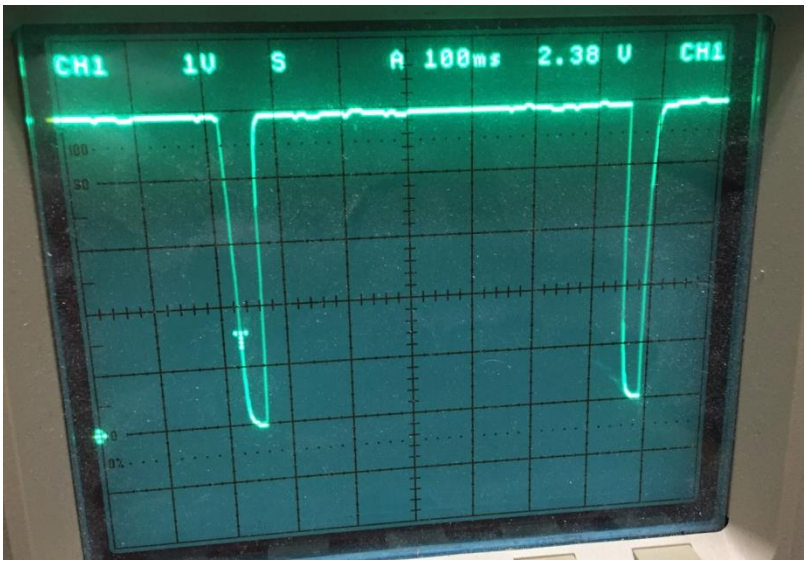
UA Pin №	Name	Type	Function
1	VDD	Supply	Supply Voltage pin
3	OUT	Output	Open Drain Output pin
2	GND	Ground	Ground pin

[13] My cable is 50 feet long.





There is a 10K pull up resistor at the port expander which assists the internal "weak" pull up. The result is a rise time of about 40 µs which is fine given that the minimum period for Flow pulses is 2 ms.



Each time the water meter's nutating disk[14] moves, my spinning magnet[15] follows it. The Hall effect sensor sees this magnetic field and pulls low. The software responds to this high to low transition. To be consistent with other inputs, I use the debounce software to read the Flow signal. Here you see a period of 640 ms.

[14] Here is a good explanation: https://www.youtube.com/watch?v=hxuFuT-RQyI
[15] Refer back to page 25.

Give a period of 640 ms we can verify the conversion process works. Each pulse represents 0.028 gallons. Therefore

$$\frac{1\ pulse}{640\ ms} \times \frac{60{,}000\ ms}{1\ minute} \times \frac{0.028\ gallons}{pulses} = 2.63\ GPM$$

The display showed 2.69 GPM which is a difference of 0.03 GPM or 1 pulse. All readings are ±1 pulse so this is reasonable.

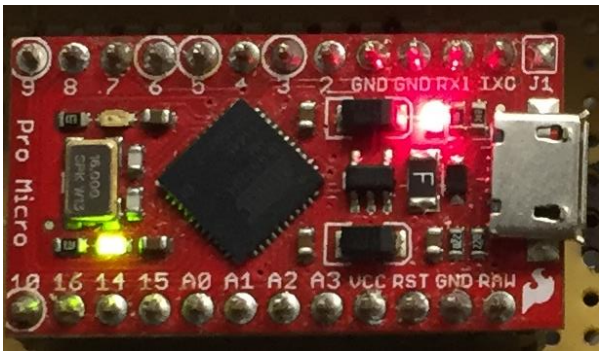
The maximum flow rate that I have directly measured is around 15 GPM. The software can handle up to 63 GPM.

Power

A wall wart supplies unregulated 12V DC at up to 500 mA. It is used directly to power the relay and the piezoelectric beeper. It also feeds a 3 terminal regulator that supplies 5V to the rest of the FMC.

The Arduino

I am using a Pro Micro 16 MHz 5 volt device from Sparkfun.com. For about $20 (2017 price), you get an insane amount of functionality. This device is far more than just a computer. Much has been written about it so I won't duplicate that effort.

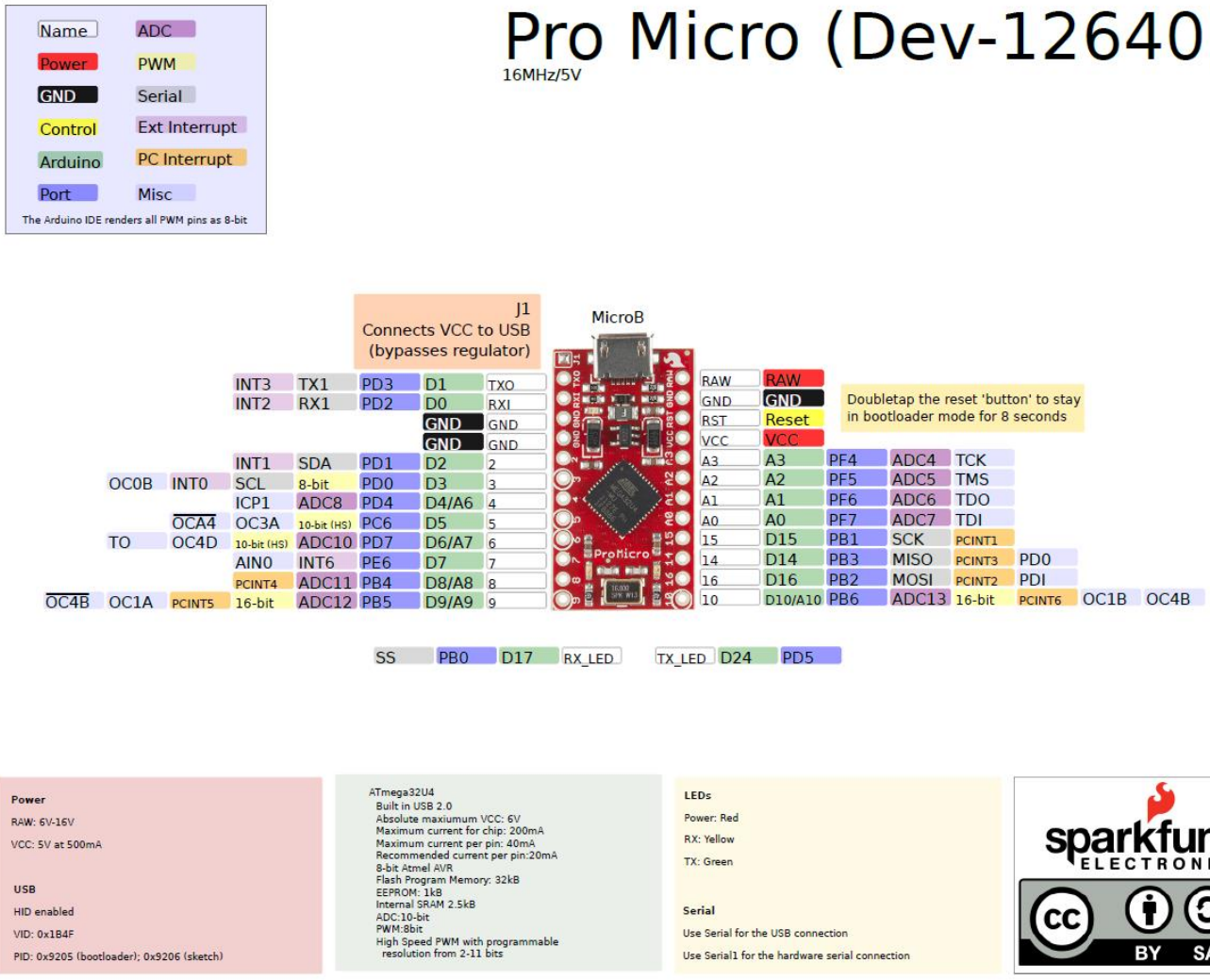


It is important to understand the two basic ways a pin is named: physically and logically.

Physical: its physical location. When looking at the socket that will accept the Pro Micro, pin are numbered starting at 1 and sequentially numbered in a counter clockwise fashion when looking down on the socket from the top. Pin 1 is in the upper right corner.

Logical: the logical names of the pins. Some of these names are letters, some are numbers, and the rest are a mix of letters and numbers. For example, physical pin 1 has the logical name TXO. It can get rather confusing at times. Consider physical pin 5 which is logical pin 2. On top of this, you can configure each of these logical pins to be any one of a number of types. This further changes the name. For example, logical pin 2 can be configured to be a Serial Data port (SDA) or to be Interrupt 1 (INT1).

You really need a score card to keep it all straight! Fortunately, Sparkfun has done a masterful job of providing such a card as can be seen on the next page.

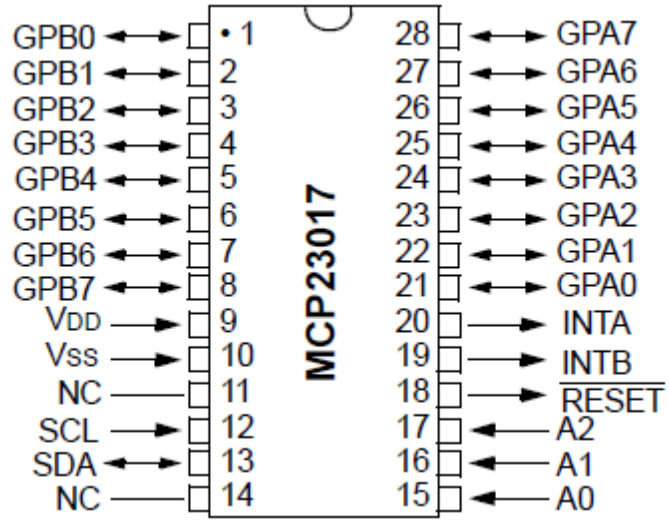


The D# values are the logical pins recognized by the software. The physical pins are shown in the above color graphic. I^2C uses pin 3 for Serial Clock so we can't use D3. Serial Data is on pin 2 so we can't use D2. There is also a 10K pull up on RESET.

Arduino D# Outputs	**Signal Destination**
0	AZO
4	AA
5-10	Display[16]

[16] See page 37 for details.

One limitation of the Pro Micro is the number of input/output pins. This is easily solved by adding a MCP23017 Port Expander. The device is controlled via I^2C using the **S**erial **CL**ock and **S**erial **DA**ta pins.

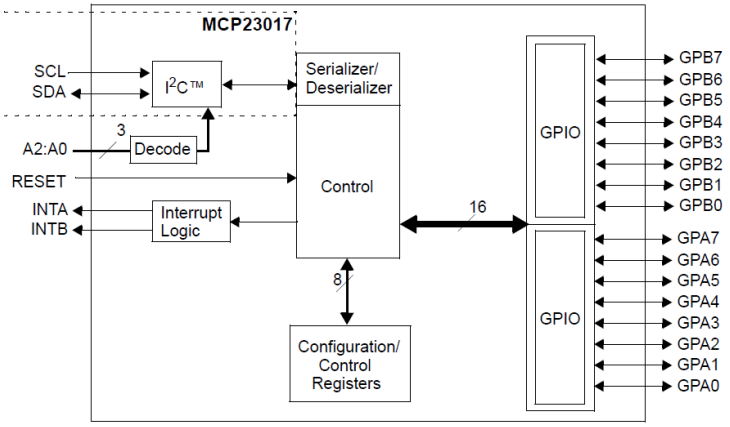


Connect pin #12 (SCL) of the expander to the Arduino SCL pin plus add a 1K pull-up resistor to 5V.
Connect pin #13 (SDA) of the expander to Arduino SDA pin plus add a 1K pull-up resistor to 5V.
Connect pins #15, 16 and 17 of the expander to ground (address selection).
Connect pin #9 (V_{DD}) of the expander to 5V.
Connect pin #10 (V_{ss}) of the expander to ground.
Connect pin #18 (RESET) through a 10K ohm resistor to 5V (reset pin, active low).

From Adafruit: https://cdn-shop.adafruit.com/datasheets/mcp23017.pdf

GPA0-7 and GPB0-7 give a total of 16 input/output pins.

An example of how to use this device can be found at https://github.com/adafruit/Adafruit-MCP23017-Arduino-Library/blob/master/examples/button/button.ino#L1



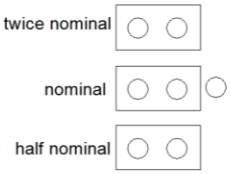
We must include two header files available from Adafruit: wire.h and Adafruit_MCP23017.h. The file "wires.h" sets up the I^2C interface.

Port Expander Input Name	Virtual pin#	Physical pin #	Signal Source
GPA0	0	21	Zone 1
GPA1	1	22	Zone 2
GPA2	2	23	Zone 3
GPA3	3	24	Zone 4
GPA4	4	25	Zone 5
GPA5	5	26	Zone 6
GPA6	6	27	PAB
GPA7	7	28	CAB
GPB0	8	1	LS
GPB1	9	2	Flow

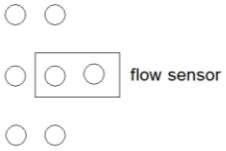
This leaves 6 spare virtual I/O pins (10 - 15) on the port expander. I use three of them as outputs of a flow simulator:

Port Expander Input Name	Virtual pin#	Physical pin #	Description
GPB2	10	3	Half of nominal
GPB3	11	4	nominal
GPB4	12	5	Twice nominal

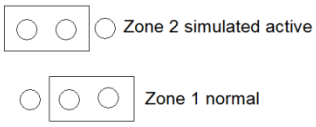
This flow simulator will generate a square wave of 50% duty cycle and output the above 3 signals as long as the program is running. The cycle rate of the loop is divided by the FlowSimulatorDivider value. Additionally, jumpers exist that can pull Zone 1's and/or Zone 2's input to ground to simulate it/them going active.



The rectangles represent the position of the jumper blocks. I can select twice nominal flow, nominal, or half.



When not testing, the jumper connect to the flow sensor.

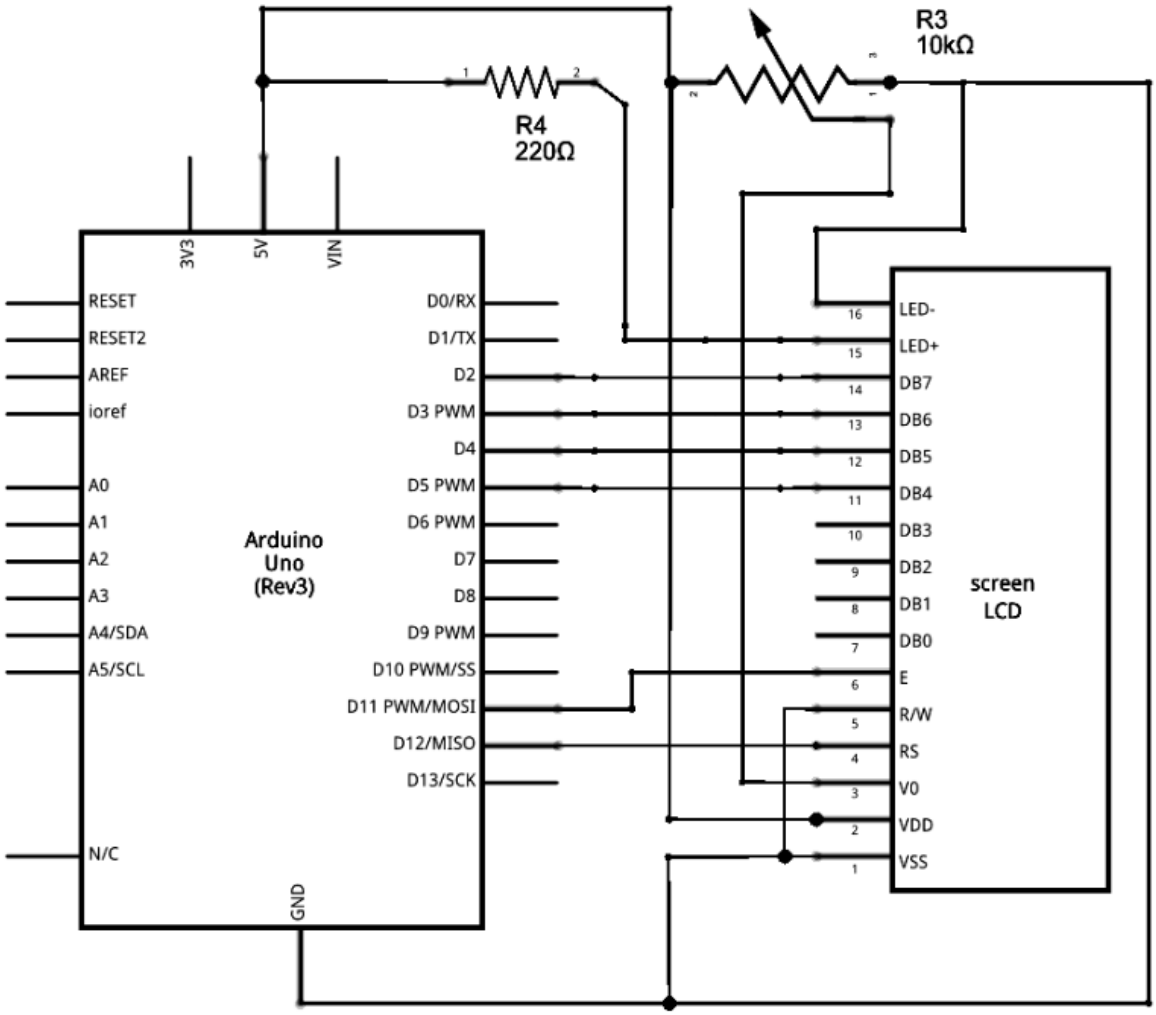


I can also switch between simulate active and normal for zones 1 and 2. As shown, zone 1 is in normal operational mode while zone 2 is simulated active.

This simulation subsystem was invaluable for debugging the code.

The Liquid Crystal Display

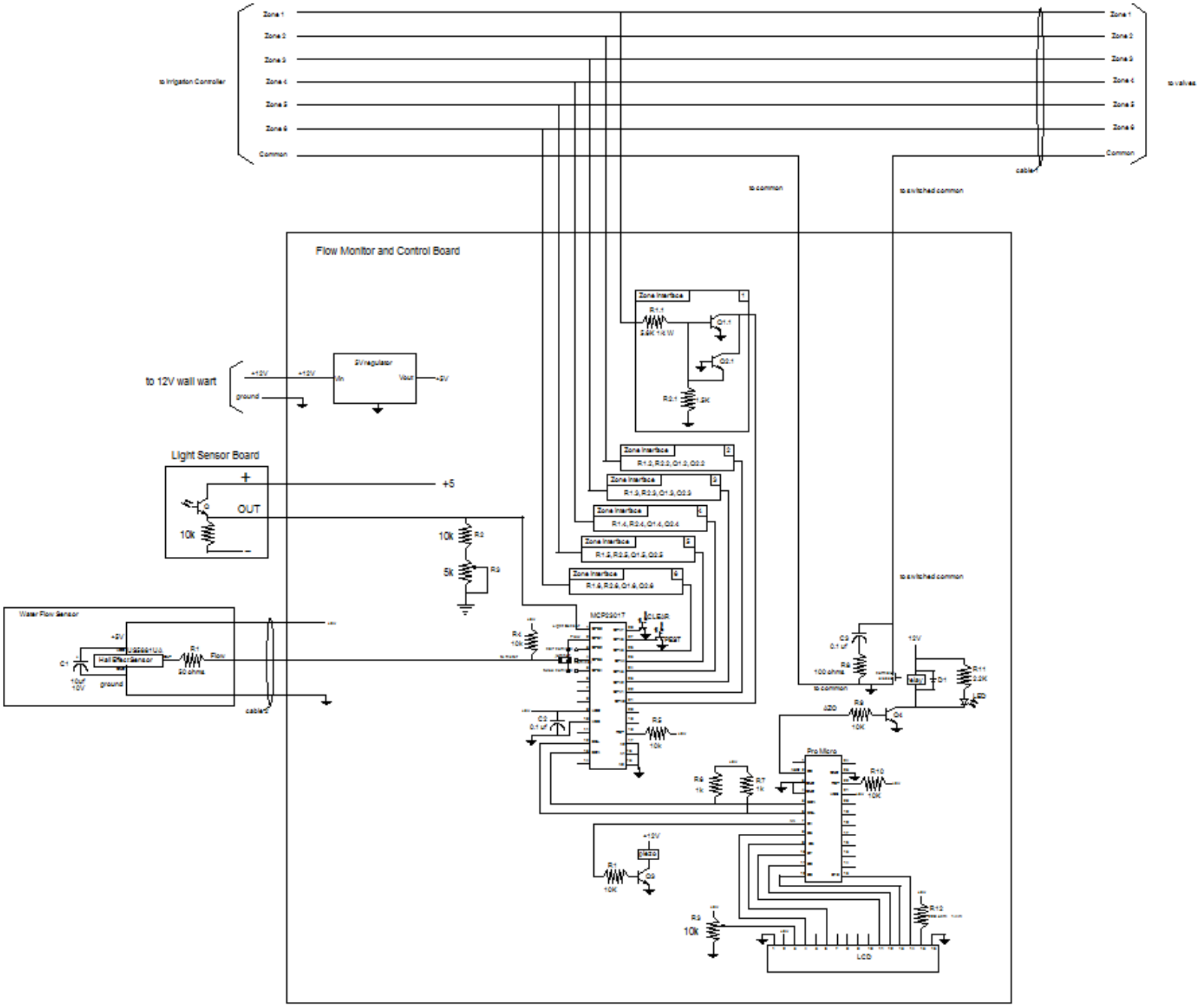
I am using a Sparkfun Basic 16x2 Character LCD - Black on Green 5V for $14. It can be controlled with 6 pins as shown in https://www.arduino.cc/en/Tutorial/HelloWorld?from=Tutorial.LiquidCrystal
Support circuits include a 10K ohm contrast control potentiometer and 220 ohm backlight power resistor:
https://www.arduino.cc/en/uploads/Tutorial/LCD_Base_bb_Schem.png

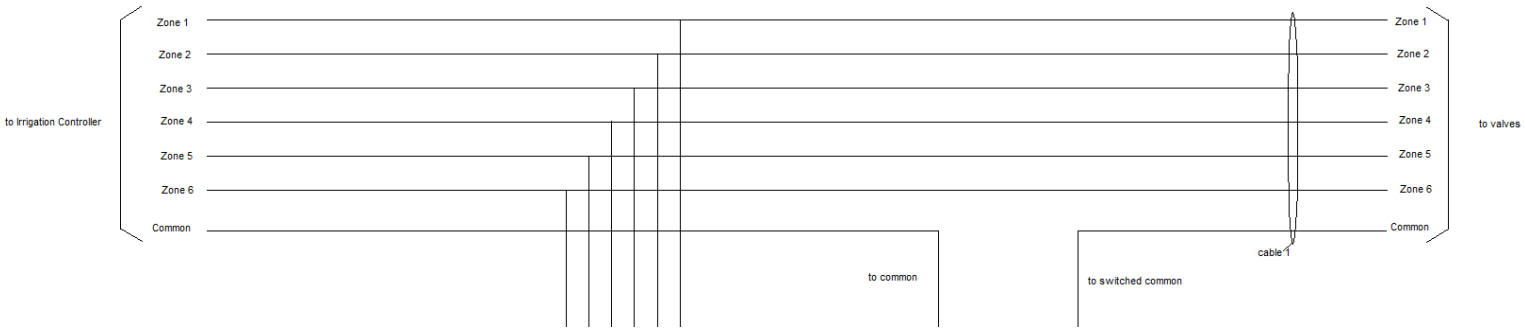


LCD Inputs	LCD pin	Pro Micro Outputs, D#
RS	4	5
EN	6	6
DB4	11	7
DB5	12	8
DB6	13	9
DB7	14	10

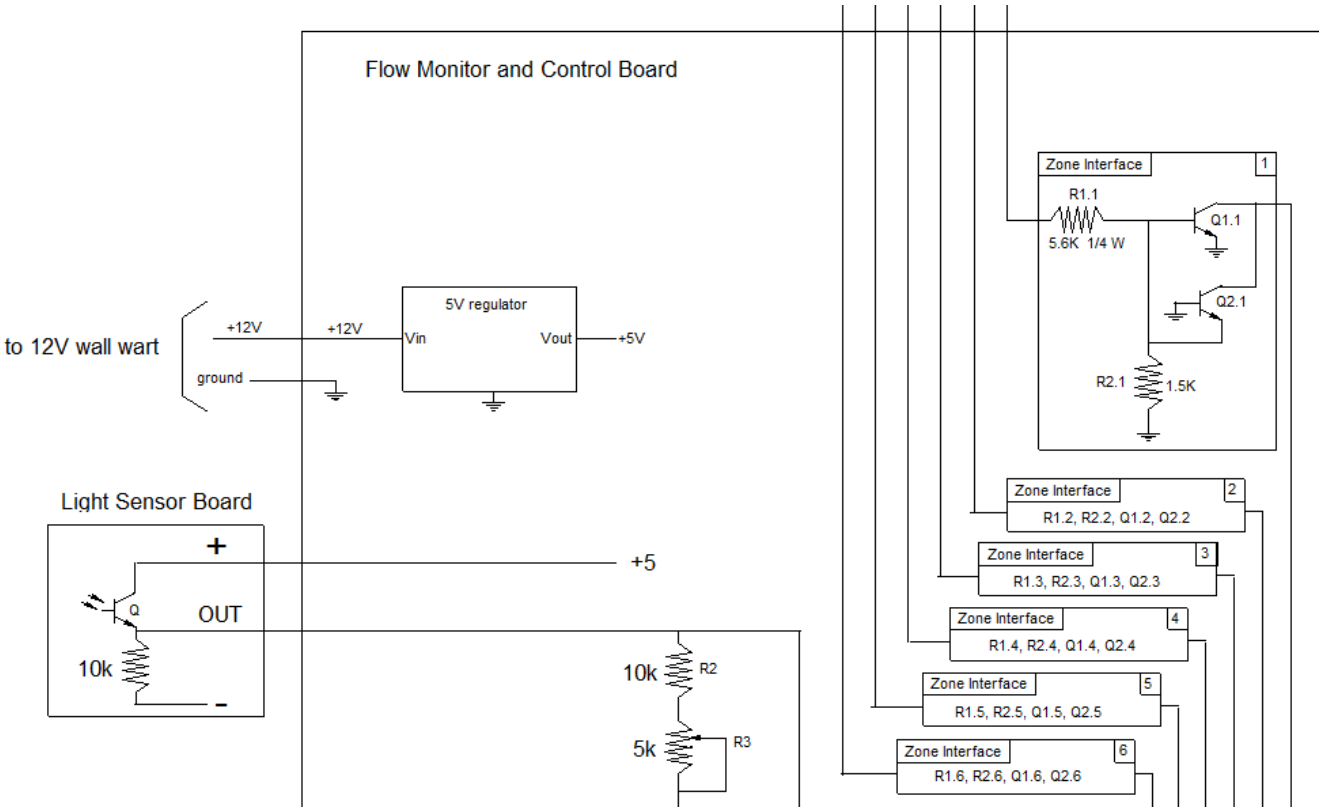
The Full Schematic

Here is an overview.





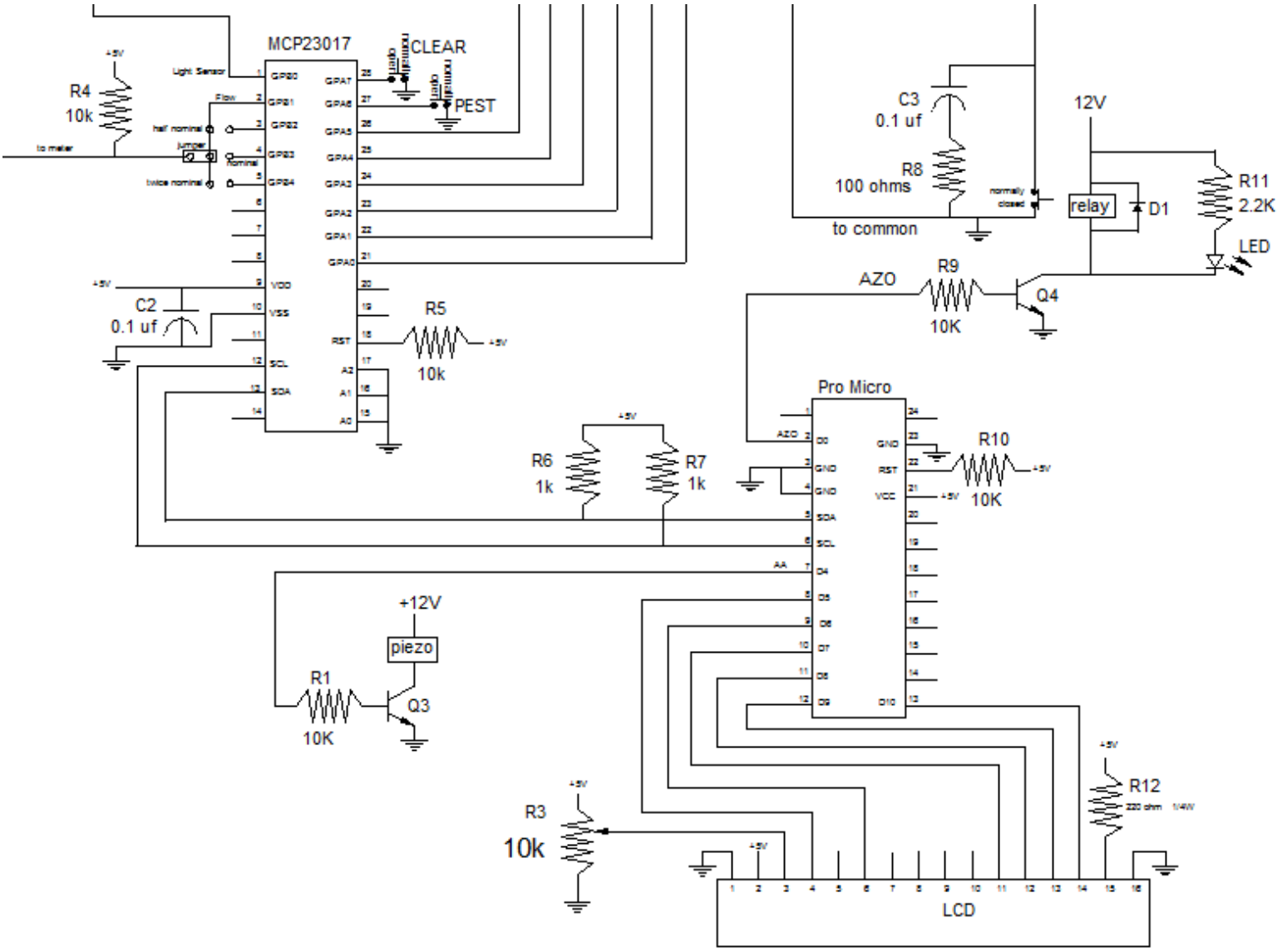
The zone wires from the Irrigation Controller pass through but are monitored. The Common wire goes into the FMC and back out. All of these wires go into Cable 1 that runs out to the zone valves.



Power from the wall wart feeds the 5 volt regulator along with the relay and piezoelectric beeper, not shown here.

The Light Senor runs through a two conductor cable a short distance to where it can see daylight.

The six zone interface circuits are identical. Note that zone interface 1 shows all detail and the rest are identical except for the names of the components. When 24 VAC is seen on a zone line, the interface sends a logic 0 to the port expander.



The port expander, MCP23017, outputs test flow signals that are selectable via optional jumpers. It accepts inputs from the clear all alarms and PEST audible alarms buttons.

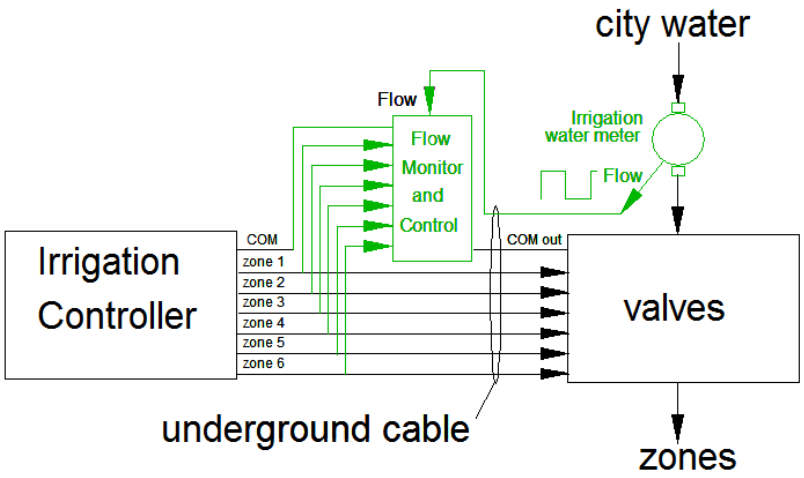
The Pro Micro Arduino controls the port expander via the I^2C which consists of the Serial Data (SDA) and Serial Clock (SCL) lines. It drives the piezoelectric beeper via R1 and Q3 plus the relay via R9 and Q4. And finally, it drives the Liquid Crystal Display.

Bill Of Materials

Estimated cost is $80 plus the cost of the Badger flow meter, cable, and enclosure.

Name	Quantity	Description	Notes
R1	1	50 ohms 1/8W	Mouser.com
R1.1 - R1.6	6	5.6K 1/4W	Mouser.com
R2.1 - R2.6	6	1.5K 1/8W	Mouser.com
R3	1	10K 1/8W pot	Mouser.com
R4, R5, R9, R10, R12	5	10K 1/8W	Mouser.com
R6, R7	2	1K 1/8W	Mouser.com
R13	1	220 ohms	Mouser.com
R8	1	100 ohms 1/4W	Mouser.com
R11	1	2.2K 1/8W	Optional
R14	1	5K 1/8W pot	Mouser.com
C1	1	10 uf 10V electrolytic	Mouser.com
C2, C3	2	0.1 uf	Mouser.com
Q1.1 - Q1.6, Q2.1 - Q2.6, Q3, Q4	14	BC550B or any general purpose NPN	Mouser.com
D1	1	any general purpose diode	Mouser.com
LED	1	any general purpose LED	optional
RELAY	1	OUAZ-SS112D,900	Mouser.com
LIGHT SENSOR	1	ALS-PT19	Adafruit.com
HALL EFFECT DEVICE	1	US5881UA	Mouser.com
PRO MICRO	1	Arduino	Sparkfun.com
PORT EXPANDER	1	MCP23017	Adafruit.com
PIEZO	1	254-20C6-ROX	Mouser.com
LCD	1	LCD 00709	Sparkfun.com
PUSH BUTTON 1 AND 2	2	any general purpose low power	
PERFERATED CIRCUIT BOARD	2	As needed	
CABLE 1, CABLE 2		As needed	
FLOW METER	1	BADGER MODEL 25	eBay.com
FLOW SENSOR ENCLOSURE	1	See page 32	
FLOW MONITOR AND CONTROL ENCLOSURE	1	Your choice	
5V Regulator	1	833-MC7805CT-BP	Mouser.com
12VDC at 500 mA unregulated power supply	1	Your choice	
jumper	3	Two terminal blocks	optional

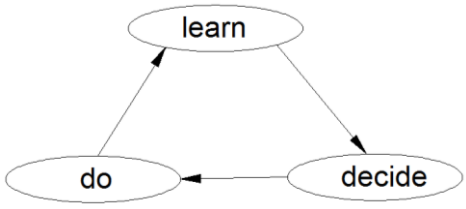
Software



We have 6 zones. Normally no more than one zone is on at a time. Any zone can have a flow that is too low or too high. Depending on the fault, we might be able to stop excessive flow. At any time there can be a change in active zone or in fault state.

The result is similar to a pinball machine with many possible states. For example, zone 1 might be running normally while zone 4 is in underflow and zone 5 is in overflow but controlled. The software must deal with all of these situations. Appendix 5 contains a list of my test cases. All of these cases passed but that does not mean the software is free of bugs.

Overall Software Strategy

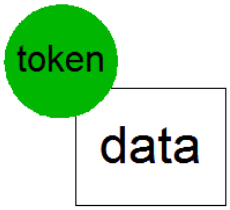


Control constantly circulates between learning what is going on, determining what to do, and acting. This is a "polling" strategy which I prefer over an interrupt driven scheme. With polling, the software's behavior is known at all times. This makes debugging easier.

An essential requirement is that each cycle through the loop take place faster than the time variant inputs change. Otherwise the real world's behavior will be missed by the software.

You have seen a bowl of cooked spaghetti. The strands are easily identified but not the ends. Of course, there is no "logic" to it. As my software was evolving, it was starting to look like spaghetti. Debugging and even comprehension quickly became too difficult for me.

Life got better when I re-architected the code into functions. For example, Timer Control contains all timers. If another function wants to start, stop, or read a timer, it must send a flag. In this way, I always know to look at Timer Control if there is a problem with timing.



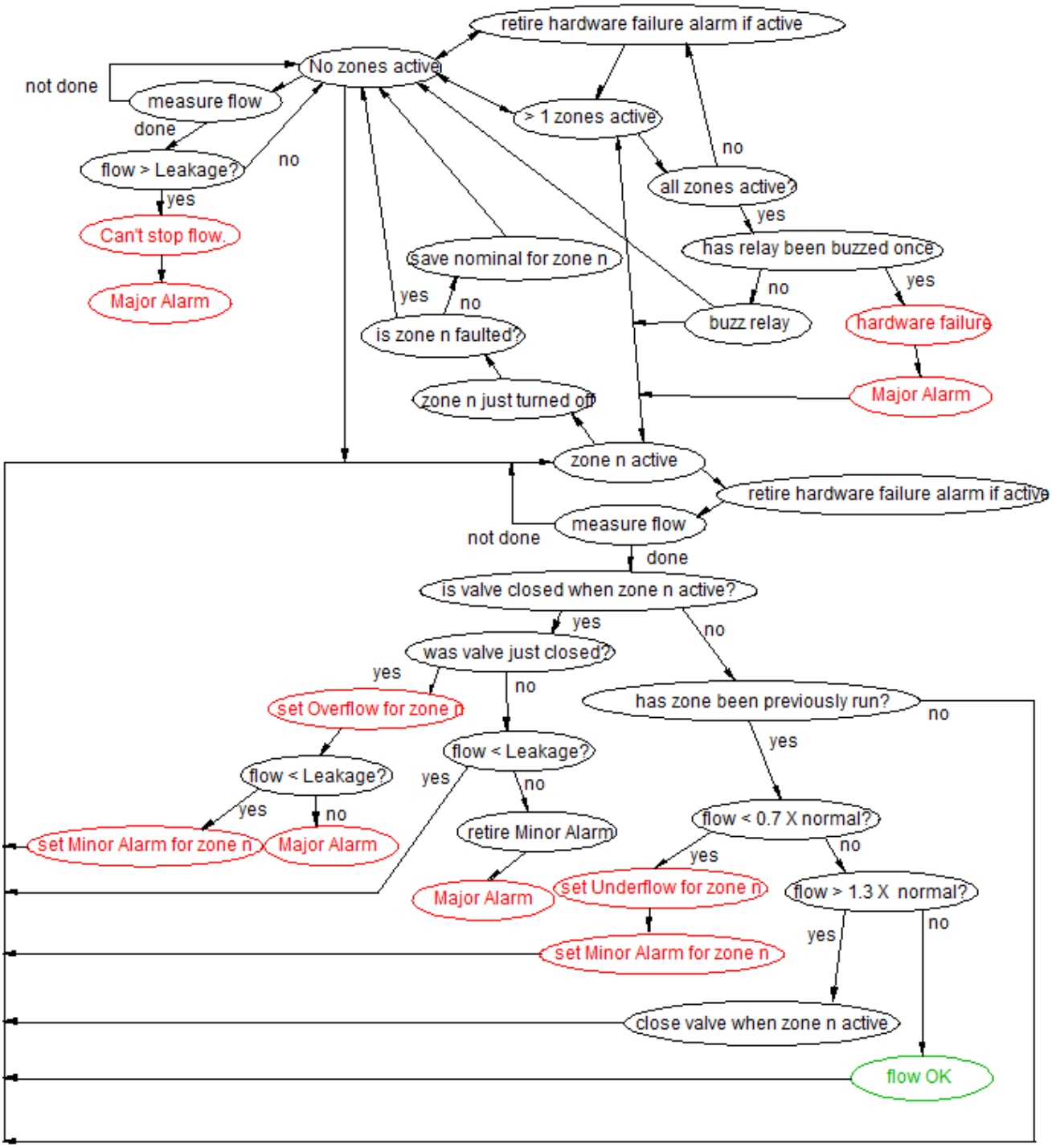
When a flow measurement is taken, I define a "token". This token says the measurement is valid. If the token is used to inform the user via the LCD, it is still valid. But when the data is used to make a state change, the token becomes invalid and the data is ignored. This scheme prevents old data from being reevaluated while we collect new data.

Many timers are used. In some cases I just need to know that a given timer is running. In other cases I need to know when it starts and when it ends. Flags are defined in the Timer Control subroutine and used by the rest of the code.

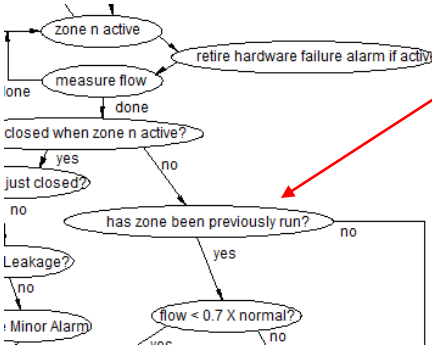
If you make it all the way down to the code, you will see that I have taken full advantage of variables and subroutine naming freedom. These tags have been selected to help me remember what is going on. For example, The subroutine used to get zones states is called GetZoneStates( ). My flag that tells me I just set the inhibit flag active is called JustSetInhibitActive. These long names are removed during compilation so do not take up space in the Arduino's memory. By using copy and paste, I avoid typing them more than once.

Level 1 Flowchart

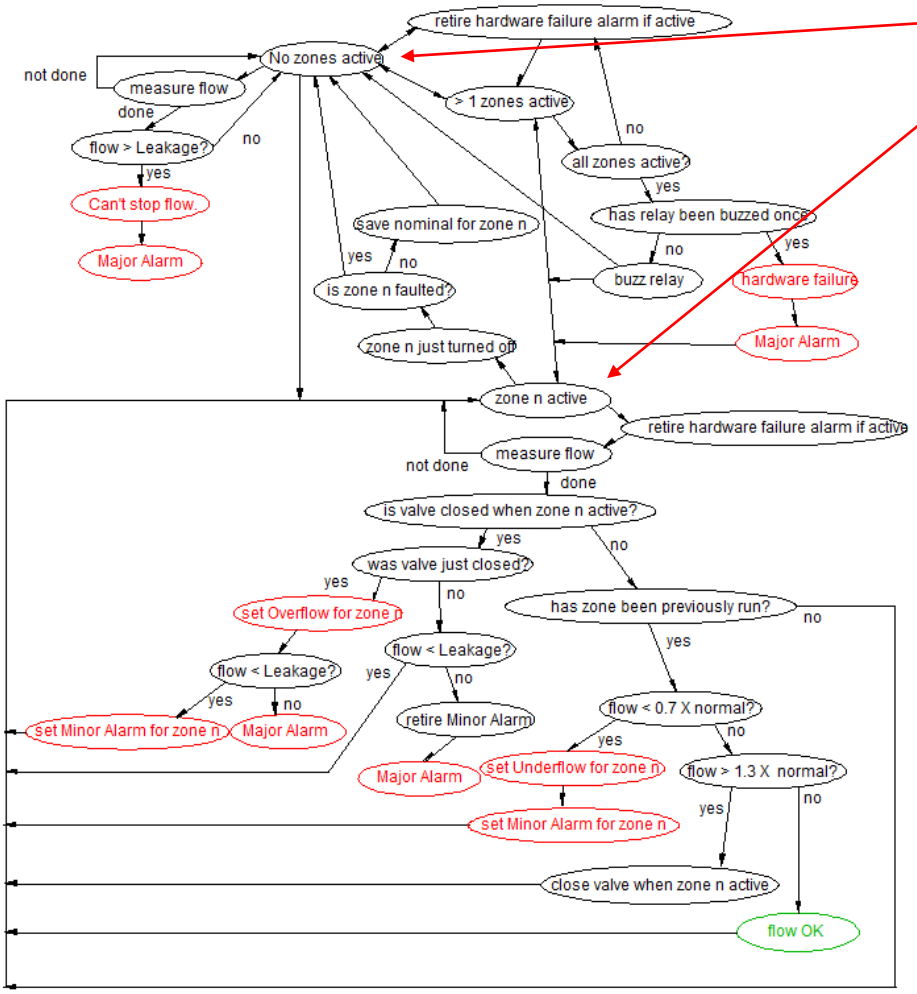
When viewed for the first time, I'm sure there is an urge to just turn the page. If you just want to run the code, there is no need to go further. But if you want to understand the code, here is the first step.



Not shown is display, and audible alarm logic.



When the program starts for the first time, it has no flow data on each zone. After it has run each zone, that data exists.



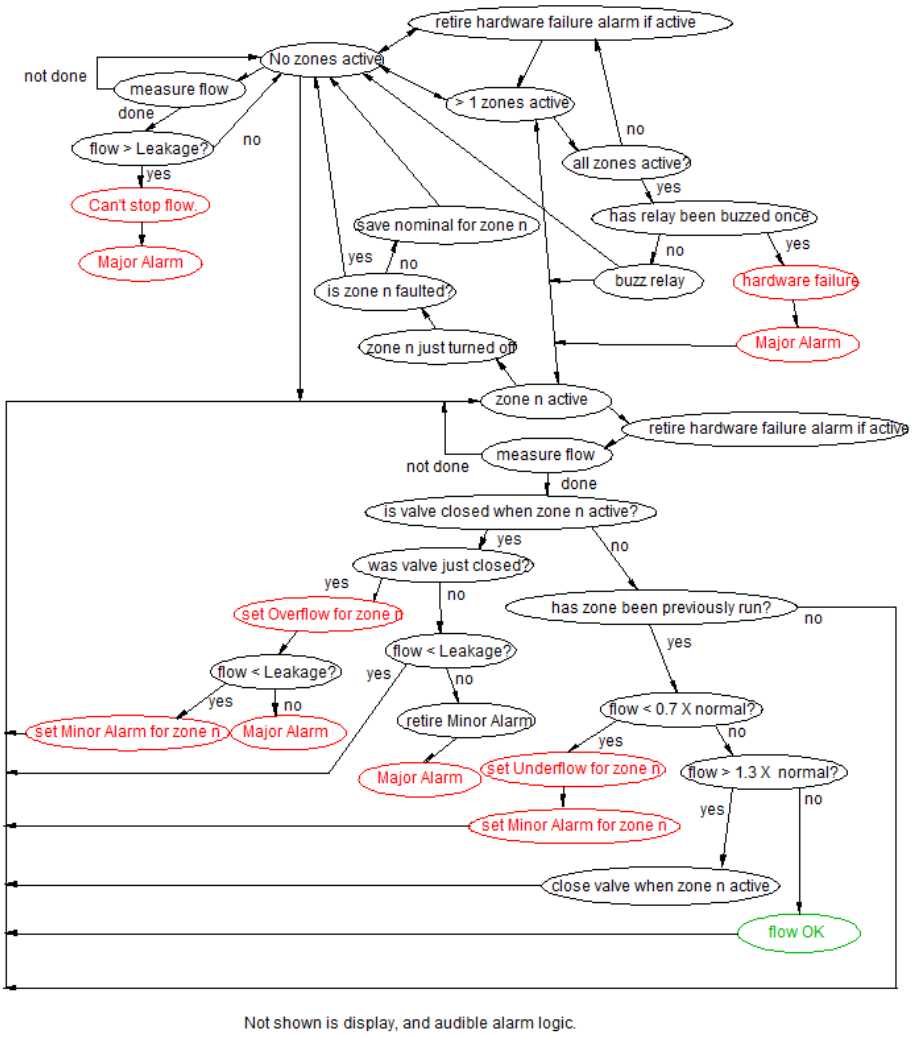
Not shown is display, and audible alarm logic.

Starting at "No zones active", we go to "zone n active". The flow is measured for 60 seconds. When done, we see if the zone's valve was closed due to a previous fault. If it was not, we see if this zone has ever run before. If this is the first time, we have no historical flow data so cannot judge if there is a problem. If it has run before, we know what "nominal[17]" means so start judging the flow. If the flow is below 70% of nominal, we have Underflow and set Minor Alarm for this zone. Then we start the cycle over.

If Above nominal by more than 30%, we close the valve every time this zone is active. Then we start the cycle over.

If the flow is within 30% of nominal, it is ok and we start the cycle over.

[17] "nominal" uses too many characters on my LCD so I use "ref" there.



Not shown is display, and audible alarm logic.

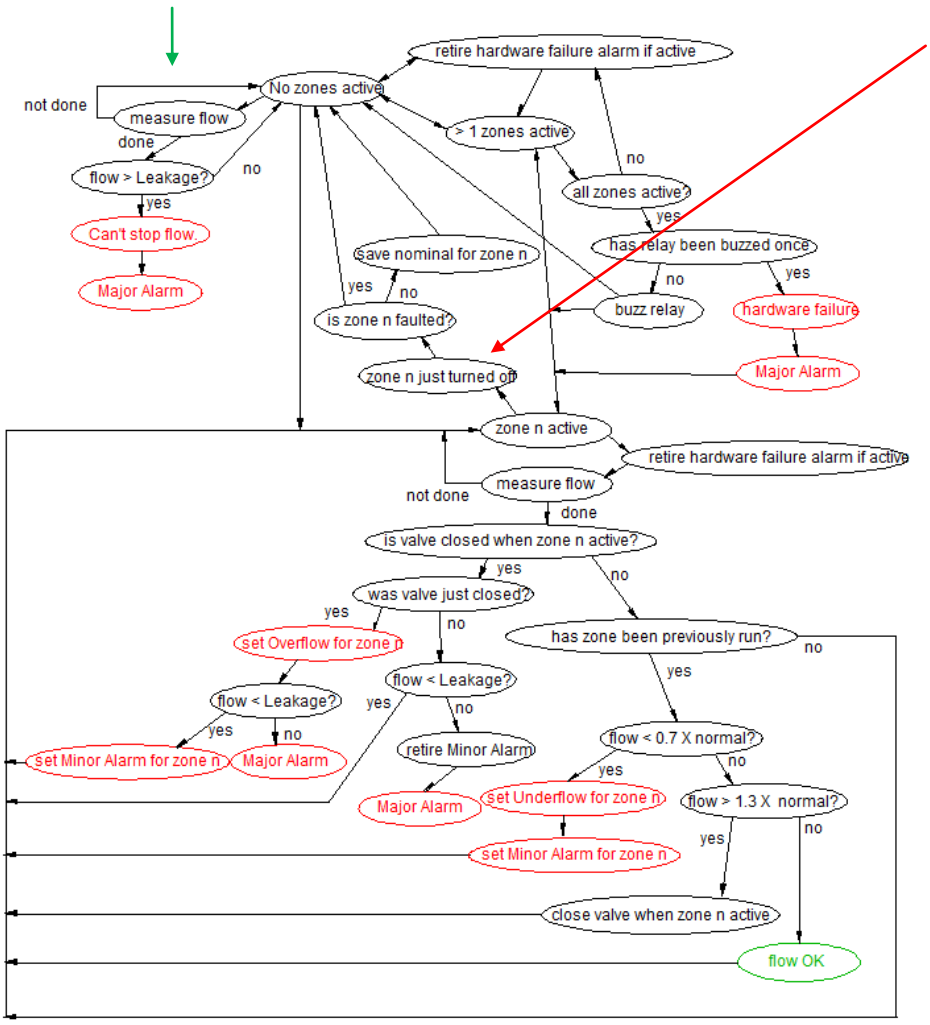
If the valve has been closed when this zone is active, we check if it was just closed. If it was, we say the zone is in Overflow and then see if the flow is below the leakage limit.

If closing the valve did not turn off the flow, we go to Major Alarm and wait for human intervention. We have an uncontrolled flow.

If closing the valve turned off the flow, we call out a Minor Alarm for this zone. As we repeat the cycle, this zone is defined as in Overflow with Minor Alarm.

On the next pass, we again measure the flow and see that the valve has been closed. But now we see that the valve has not ***just*** been closed. If the flow is still less than Leakage, the cycle repeats. If the flow is now greater than Leakage, we retire the Minor Alarm and escalate to a Major Alarm and wait for help to arrive.

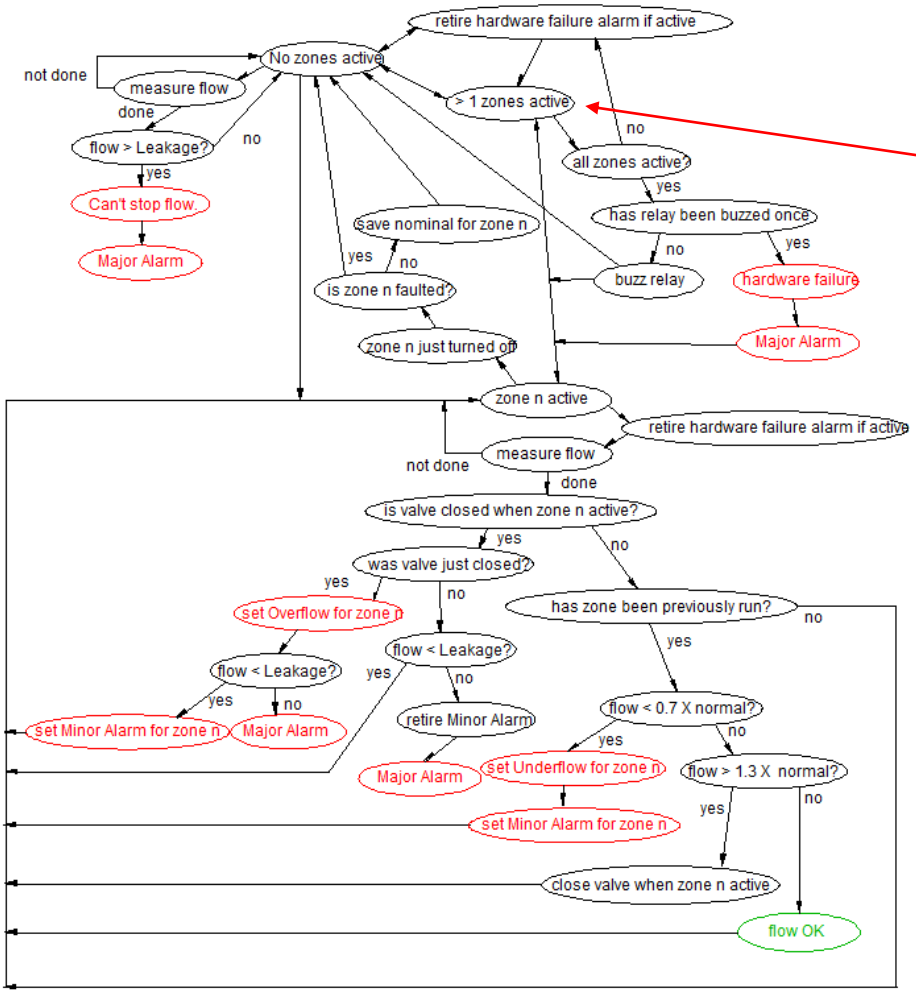
If a zone is in Overflow Minor alarm, every time it runs the FMC blocks the flow.



Not shown is display, and audible alarm logic.

When a zone turns off, we first check if it is in an alarm state. If not, we save the flow data collected while it was running and store that as the new nominal for this zone. If there is an alarm state for this zone, we do not save the flow data.

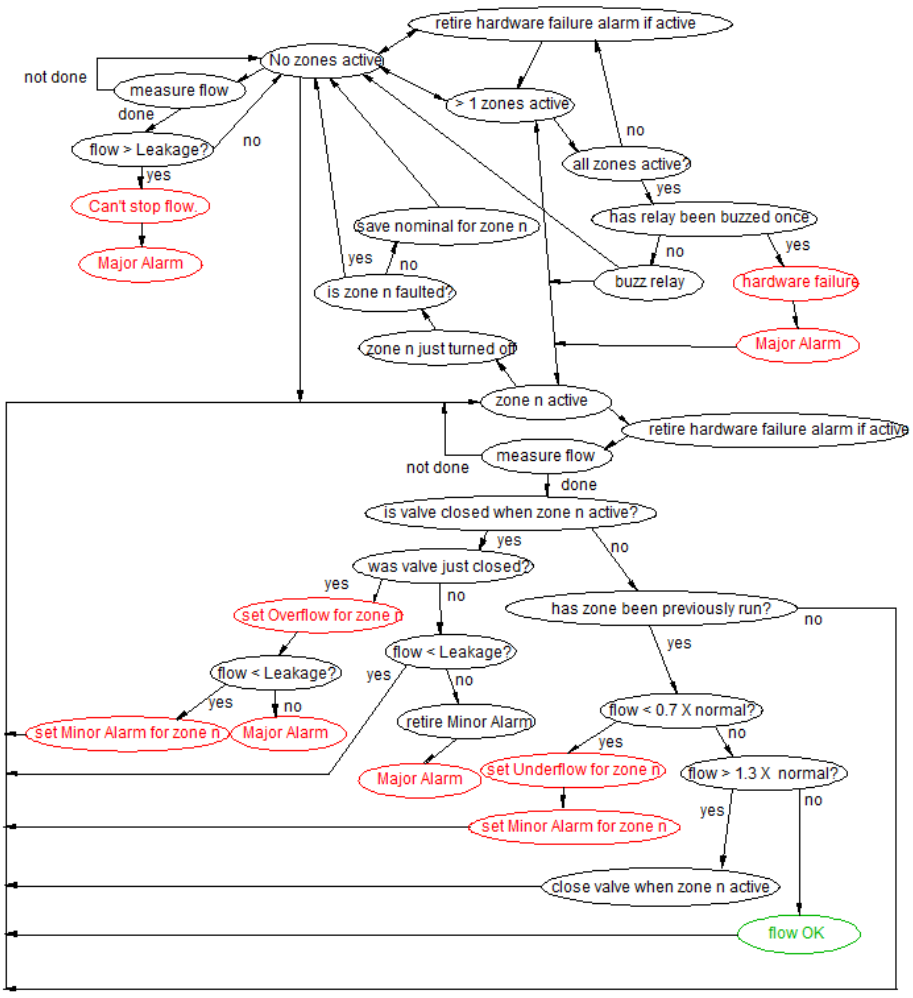
When no zones are active, we constantly check that the flow is less than the leakage limit (green arrow). If excessive leakage is detected, we go to Major Alarm and wait for help.



Not shown is display, and audible alarm logic.

The automatic operation of the RainBird Irrigation Controller only turns on one zone at a time. However, it is possible for a user to turn on more than one zone. In this case, which I call MultiZone, we just wait until less than two zones are on.

If all zones are active at the same time, we probably have a problem with our relay. If so, we turn it on and off quickly 20 times and check again. If we are then seeing less than all zones active, we return to normal scanning. If we still see all zones active, we go to hardware fault Major Alarm. Then we return to scanning just in case the relay corrects itself. If so, the hardware fault Major Alarm is retired.



Not shown is display, and audible alarm logic.

Four secondary functions are not shown in this flowchart.

The first is the display function. See the User's Manual, starting on page 12 for what is shows. See also Appendix 4 which explains how I prevent flickering of the display.

The second secondary function is audible alarms. A Minor Audible alarm sounds for 0.3 seconds and is off for 2 seconds. A Major Audible alarm sounds for 0.1 seconds and is off for 0.1 seconds. At any time, the user can push the PEST audible alarms button and it will bring silence.

The third secondary function clears all alarms. All variables are initialized except for historical flow data. If a fault condition still exists, it will return in 70 seconds.

The forth secondary function clears all alarms and historical flow data. This would be used if a change was made to the flow rate that was more than 30% from nominal. The FMC is powered down, the clear alarm button held down, and power is brought back up. Then the clear alarm button is released.

Major Subroutines

Here you see the main subroutines that are in the loop and the subroutines called from them.

- GetZoneStates()
  - InitializeZone()
  - PopulateZones()
  - FindActiveZone()
- ZonePower()
- TimerControl()
  - TransientTimeElapseTimer ()
  - OneMinuteElapseTimer ()
  - MinorPestElapseTimer ()
  - MajorPestElapseTimer ()
  - MinorCadence()
  - MajorCadence()
  - AntiFlickerCadence()
- ZoneTransitionQ()
  - SaveOldZoneFlowMeasurement()
  - PrepareForNewZone()
- ProcessFlowInfo()
  - GetFlowRate()
  - DisplayFlowRate()
    - SuspectRelay
    - MoreThanOne()
    - PossibleFault()
    - NoZoneOnAndNoDataYet()
    - NoZoneOnWithData()
    - ActiveZoneNoDataYet()
    - ZoneActive()
  - JudgeFlowRate()
    - MajorAlarm
    - MultiZoneQ
    - NoFlowDataQ()
    - NoHistoryQ()
    - SmallFlowQ()
    - UnderflowQ()
    - OverflowBeforeInhibitQ()
    - ImmediatelyAfterInhibitFaultQ()
    - AfterInhibitStableFaultQ()
    - LeakageNoZonesActiveQ()
  - RelayErrorControl()
  - AlarmControl()
    - CleanUpPrematureAlarmExitQ()
    - DisplayFaultDetails()
      - RelayErrorQ()
      - CABpressed()
      - SoftwareError()
      - CannotStop()
      - Trying()
      - HaveMinor()
    - ManuallyClearAlarmQ()
    - PestActiveAlarmQ()
    - AudibleAlarmProcessing()

GetZoneStates() looks at all of the zones and reports back which ones are active. To do this it calls three subroutines:

InitializeZone()
PopulateZones()
FindActiveZone()

ZonePower() turns the relay on and off under the control of an array of Inhibit flags. If the Inhibit flag for the active zone is true, then the relay is powered up and power is removed from this zone's valve.

TimerControl() handles all timers including the transient timer, the one minute timer, PEST timers, and audible alarm cadence timers. Timers that only run when needed are initiated by telling them to start. When they start, the clear the start flag and raise a running flag. When timed out, the running flag is lowered.

ZoneTransitionQ() looks at the previous active zone and the current active zone to see if there has been a zone transition. If so, it looks to see if the previous active zone had a fault. If not, it saves the flow data as the new historical flow. If there was a fault, it does not save the flow data. Then it prepares for the new zone being active.

ProcessFlowInfo() performs three major tasks. First it measures the flow rate, then it displays the flow rate, and finally, it judges the flow rate to see if it is normal or faulted. The subroutine SmallFlowQ() checks the historical flow for the active zone in order to prevent a division by 0.

RelayErrorControl() displays a message if the relay is stuck.

AlarmControl() handles all alarms associated with flow. This includes displaying fault details, responding to a manual clear alarms request, responding to a PEST audible alarm request, and controlling the audible alarm.

Software Structure

Although it is possible to have multiple files that together hold the Arduino software, I have chosen to put it all in one file to minimize confusion and error. Separate files must be loaded is a specific order to link correctly.

The following is an outline of how I ordered the segments of the program. Note that variables and constants defined outside of functions are accessible by all functions which is why you see so much going on before we reach Setup. See Appendix 6 on page 77 for the code.

- Program name and version number - they are displayed at start up on the LCD
- #include - pulls in libraries that define hardware. In my case I have EEPROM, an LCD display, and a port expander chip that uses I^2C.
- Constants and variables
    - MCP23017 port expander inputs
    - Arduino Outputs
    - States of the hardware and software
    - Timers
    - Rate of change of flow parameters
    - Flow level parameters
    - Input states like "Day" versus night and a button being pushed or not
    - Faults that are recorded and processed
    - Software error descriptions
    - LCD flicker reduction parameters
    - Diagnostic and built in simulator parameters
- Hardware Initialization - port expander and LCD
- Void Setup - this is where code is placed that only executes once. All of the input and output pins in the hardware are defined here. We also look at the pushbuttons to determine if the user wants all historical data erased or if they want flow measuring mode enabled

- Void Loop - a collection of high level subroutines that hold the major functional blocks resides here. These subroutines are made up of lower level subroutines defined next.
- Lower level subroutines - these are built from subroutines that are at the lowest level.
- Lowest level subroutines - narrowly defined functions that act as my custom made program language.
- End of file

An important fine point:

Looking at the code, you may spot something odd in my print commands to the LCD. The standard command would be

```
lcd.print ("All alarms");
```

but I wrote

```
lcd.print (F("All alarms"));
```

You are looking at the F() subroutine which I found on an Adafruit forum[18]. F() tells the Arduino compiler to keep the string "All alarms" in program store rather than duplicating it in Static Random Access Memory (SRAM). Without this subroutine, the program runs out of memory used to store variables and strange things happen.

For example, I was checking a small block of code because it did not seem to execute correctly. A series of Serial.println statements told me what was going on. I could see command 1 being reached followed by command 2. But rather than command 3 I saw that a subroutine was called. That code did not call this subroutine. It was corrupted memory caused by the SRAM being corrupted.

[18] First try the URL: https://learn.adafruit.com/memories-of-an-arduino/optimizing-sram but if this link is broken, search using " Adafruit managing sram F()"

Acknowledgements

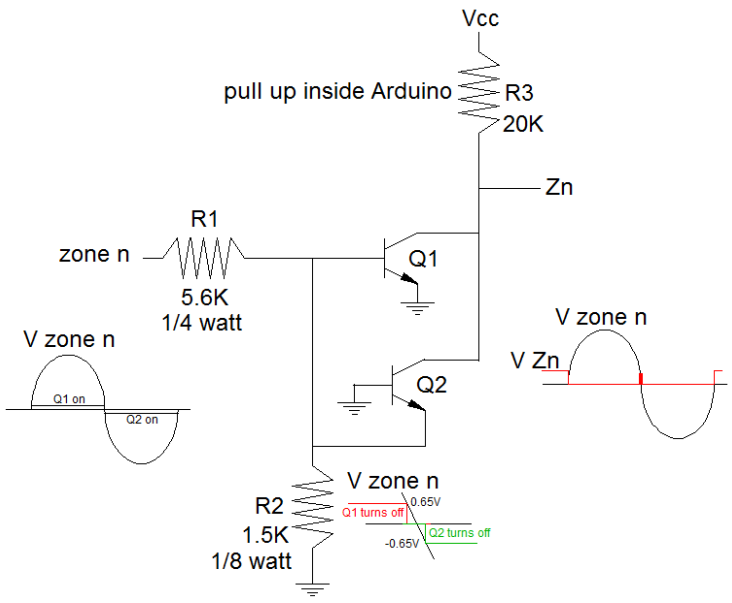
Very special thanks go to my wife, Donna, for putting up with me constantly at my computer writing and debugging the software.

I welcome your comments and questions.

If you wish to be contacted each time I publish an article, email me with just "Article Alias" in the subject line.

Rick Sparber
Rgsparber.ha@gmail.com
Rick.Sparber.org

Appendix 1: Zero Crossing Pulse Width



The input voltage is specified at 24V RMS but I measured 27V RMS. Assuming 24V RMS, that is a peak of $\sqrt{2} \times 24V\ RMS = 34V_{peak}$. This means that $V_{zone\ n} = 34 \sin \omega t$ where $\omega = 2\pi f = 2 \times 3.14 \times 60\ Hz = 377 \frac{radians}{second}$. Assuming Q_1 turns on when $V_{zone\ n}$ is more than 2V, we can solve for t and see the width of the spike. Be sure your calculator is set to radians and not degrees for the following calculations.

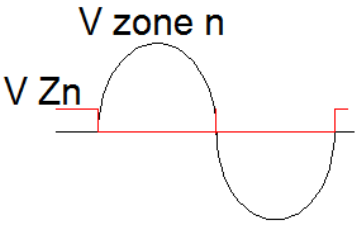
$$2V = 34V \sin 377t$$

$$\frac{2}{34} = 0.06 = \sin 377t$$

$$377t = \sin^{-1} 0.06$$

$$377t = .06$$

t = 160 microseconds.



AT t = 0, $V_{zone\ n} = 0$. At t = 160 microseconds, it is at +2V and Q_1 turns on.

The 60 Hz sine wave has a period of 16.67 milliseconds. This means it goes through half of its cycle in 8.33 milliseconds. 160 microseconds before 8.33 milliseconds, Q_1 has turned off. Then 160 microseconds after 8.33 milliseconds Q_2 turns on. This says I will have both transistors off for about (2×160 =) 320 microseconds every 8.33 milliseconds. With both transistors off, the digital output goes high. So if the software sees a logic 1, it just has to wait more than 320 microseconds and take another reading to be sure it didn't hit this crossover zone.

Appendix 2: EEPROM Map

The Electrically Erasable Programmable Read-Only Memory (EEPROM) present inside the Arduino device will hold two seven member arrays of data.

The first array is ZoneNeverRun. It is initialized to all elements true. As each zone is run for the first time and historical flow data collected, that element will be set to false. Each element is defined as boolean so takes one byte.

We have:

ZoneNeverRun[i] with i equal any integer from 0 to 6. It occupies EEPROM at memory locations 0 through 6.

To write to this array, we will use the subroutine WriteZoneNeverRun( ). To read this array, we will use the subroutine ReadZoneNeverRun( ).

The second array is HistoricalFlow[i]. It is not initialized. Instead, we only look at a given element when ZoneNeverRun[i] says HistoricalFlow[i] has valid data. As each zone is successfully run, the measured data is written into this array. Each element is defined as float so takes four bytes.

We have:

HistoricalFlow[i] with i equal any integer from 0 to 6. It will occupy EEPROM at memory locations 7 through 28.

To write to this array, we will use the subroutine WriteHistoricalFlow( ). To read this array, we will use the subroutine ReadHistoricalFlow( ).

Appendix 3: Arduino Compilation Error Experiences

It has been a while since I programmed an Arduino so ran into many "newbie" problems. The most confusing were the error messages when my code was not in the sketch book folder. I saw many errors due to files I just included and even one I didn't include. They went away once I moved my code to the sketch book folder.

After working through way too many typos in my program, I ran into two compilation errors related to code supplied by Sparkfun and Adafruit.

The first error was

"main.cpp:43 undefined reference to 'setup'
Collect2.exe: error: ld returned
1 exit status

A search of the web turned up others with this problem plus a solution that worked for them. Going to the file main.cpp line 43 I found

```
setup( );
```

I was instructed to add "void"

```
void setup( );
```

After switching to Administrator mode, I was able to save the change.

The second error was

EEPROM.h:43:30: warning: type qualifiers ignored on function return type [-Wignored-qualifiers]
operator const uint8_t( ) const { return **this; }

I learned that EEPROM.h had two bugs in it. On line 43 was

```
operator const uint8_t( )
```

The expert said to remove "const".

I then was instructed to go to line 92

operator const int( ) const

and remove the first "const". The modified file was then saved. The compilation was then error free.

Appendix 4: Anti-flicker

The software is constantly running in a loop. If a given LCD screen is written, it will be re-written on each pass. This is both bad and good. It is bad because doing many updates each second causes the LCD to flicker annoyingly. However, it is good because any corruption of the LCD's displayed data is quickly corrected. The trick is to do updates often, but not too often. I have found that an LCD refresh every 10 seconds is about right.

The strategy I chose was to maintain a unique name for each LCD screen plus have a global flag that presents the opportunity to do an update only every 10 seconds. This flag is part of the TimerControl() subroutine.

We have two types of LCD screens. The simpler one is just text. I can describe it with a constant. For example:

const int TryingToClose = 25;

TryingToClose has been assigned an arbitrary but unique value of 25.

I also have screens that display text that doesn't change mixed with numbers that do change. In these cases, I assign them an arbitrary but unique value that has the changing number added to it. For example, NoZoneOnWithGPMConstant is assigned a unique number to represent the No Zone On screen. I generate the complete screen name by adding the displayed GPM with the result saved as NoZoneOnWithGPMC.

I keep track of the current LCD screen with the variable lcdNowDisplaying.

When the software is about to print a screen, it checks if the new screen differs from the old screen or if it is time for an update. If either is true, the LCD screen is refreshed. The one exception is when the software has closed the valve and is waiting to see if the flow is now near 0. While displaying the "Trying to close valve" screen, I block all non-alarm screens. Otherwise, I would get alternating screens which is unreadable.

Appendix 5: Test Cases

The following Cases are designed to fully test the software so are detailed. There were developed in parallel with creating the flow charts and thinking about how my irrigation runs and fails.

"Start" means all variables have been initialized. This is done by powering off, holding down the clear alarms button, powering on, and then releasing the button.

When a zone is first turned on, the software waits 10 seconds for the flow to stabilize. It then takes 60 seconds to measure the flow. I am using the built in flow simulator which generates half nominal, nominal, and twice nominal flow rates.

In all cases, m does not equal n.

Non-fault Cases

1. Start to no zones on for 65 seconds.
2. Start to zone n on
3. Zone n on with nominal flow. Zone n off. Zone n on with nominal flow. See that nominal flow becomes reference. Turn off power. Hold down Clear all alarms button. Power up. See that historical data removed. Zone n on with nominal flow and see that ref is - .
4. Zone n on. Nominal flow for 1.5 minutes. Zone n off. Zone m on. Nominal flow for 1.5 minutes. Zone m off. Zone n on for 75 seconds. Zone n off. Zone m on for 75 seconds. Zone m off.
5. MultiZone (more than one zone on)
    a. Before Start have zones n and m on. Start.
    b. Zone n on. Zone m on. Zone m off.
    c. Zone n on. Zone m on. Zone n off.
6. No zones on to more than one zone on
7. No zones on to zone n on for first time with nominal flow. See that ref is - .
8. No zones on to zone n on not first time. See that ref has nominal after it.

Fault Cases

A. Single fault
   1. No zones on and then flow > leakage so go to "Can't stop flow." Major. Press Clear All Alarms.
   2. Zone n on with underflow. Then pest.
   3. Zone n on with underflow. Zone m on normal flow.
   4. overflow
      a. Zone n on with overflow minor .Then pest. Zone n off. Zone n.
      b. Zone n on with overflow minor .Then pest. Zone m on with nominal flow for 75 seconds. Zone m off. Zone n on.
      c. Zone n on with overflow major. Then pest. Zone m on. Zone m off.

B. Sequential Double fault on same zone
   a. underflow
      1. Zone n on with underflow. Then pest. Then overflow minor and should hear minor audible alarm. Then pest. Then clear all alarms.
      2. Zone n on with underflow. Hear minor. Then pest. Then overflow major. Hear major audible alarm. Then pest. Then clear all alarms.
      3. Zone n in underflow. Hear minor. Then pest. Then zone n off; zone m runs normally.
      4. Zone n in underflow. Hear minor. Then pest. Then zone n off; zone m goes into underflow. Hear minor. Then pest.
   b. Zone n on with overflow minor. Hear Minor audible alarm. Then pest. Then overflow major. Hear major audible alarm. Then pest.

C. First zone faults and then turns off. Second zone on and faults.
   1. Underflow
      a. Zone n in underflow and then zone n off; zone m goes into overflow minor
      b. Zone n in underflow and then zone n off; zone m goes into overflow major
   2. Overflow
      a. Zone n in overflow minor and then zone n off; zone m runs normally
      b. Zone n in overflow minor and then zone n off; zone m goes into underflow
      c. Zone n in overflow minor and then zone n off; zone m goes into overflow minor
      d. Zone n in overflow minor and then zone n off; zone m goes into overflow Major

e. Zone n in Overflow Major. Turn off zone n. Turn on zone m nominal flow. Wait 1.5 minutes. Zone m off. Should stay in Overflow Major.

3. Interrupted flow measurement
    a. Zone n on. Flow < 0.7 X nominal. While measuring flow, turn on zone m. Then turn zone m off. Zone n should return to start of measuring.
    b. Zone n on. Flow = nominal. While measuring, turn on zone m. Then turn zone m off. Zone n should return to start of measuring.
    c. Zone n on. Flow > 1.3 X nominal. While measuring, turn on zone m. Then turn zone m off. Zone n should return to start of measuring.
4. Interrupted Inhibit processing
    a. Zone n on. Flow > 1.3 X nominal. When valve first closed, zone n off. Flow = nominal. Zone m on.
    b. Zone n on. Flow > 1.3 X nominal. When valve first closed, Zone m on. Zone m off. Zone n should go to Overflow Minor.

Appendix 6: The Code

This code must be in a folder with the same name. If you forget, the Software Development Environment will ask you if it is ok to create this folder and put your code into it.

Before compiling, the following libraries must be present in the system library:

EEPROM.h
LiquidCrystal.h
Wire.h

The following must be in the user's library
Adafruit_MCP23017.h

In all cases an associated .c or .cpp file must also be in place. If not, the compiler will tell you what is missing.

Use the software development tools to place the header files in the system library. The header for the user's library is just placed there.

The driver for the MCP23017 was developed by Adafruit. Please support Adafruit by buying your device from them. See https://github.com/adafruit/Adafruit-MCP23017-Arduino-Library for details.

```
///Flow Monitor and Control
String version = "V1.3";  //put version number here so it ends up on the welcome screen

//#define SpeedUp //comment out to set One minute back to 60 seconds. If defined, One Minute is 10 seconds

// include the library drivers:
#include <EEPROM.h> //hardware built into Arduino
#include <LiquidCrystal.h>
#include <Wire.h> //supports I2C used by port expander
#include "Adafruit_MCP23017.h" //supports port expander

//boolean SerialPrintEnable = false; //if true, all diagnostic Serial.prints that are not commented out are active
//Constants and Variables

//MCP23017 port expander inputs
const int Zone1Pin = 0;
const int Zone2Pin = 1;
const int Zone3Pin = 2;
const int Zone4Pin = 3;
const int Zone5Pin = 4;
const int Zone6Pin = 5;
const int PestAlarmButtonPin = 6; //Pest Alarm button
const int ClearAlarmButtonPin = 7; //Clear Alarm button
const int LightSensorPiin = 8;  //Light Sensor
const int FlowPin = 9; //Flow signal from water meter

//Arduino Outputs
const int AllZonesOffPin = 0;
const int AudibleAlarmPin = 4; //Audible Alarm
const int RS = 5; //name on LCD assigned to D number on Pro Micro
const int EN = 6;
const int DB4 = 7;
const int DB5 = 8;
const int DB6 = 9;
const int DB7 = 10;
const int OnBoardYellowLED = 17; //on board yellow LED pin
```

```
//States
const int Active = 0; //when a zone is active, pin will be 0; see also ActiveFlag
const int Inactive = 1; //when a zone is inactive, pin will be 1
const int Enable = 0; //when a relay or sound gets power, pin will be 0
const int Disable = 1; //when a relay or sound has power removed, pin will be 1
const int Closed = 0; //when AZO must be closed, output a 0 because relay is NC
const int Open = 1; //to open the AZO contacts, power up relay by outputting a 1
const int Sound = 1; //turns on piezoelectric beeper
const int Quiet = 0; //turns piezoelectric beeper off
const int None = 0; //when ActiveZone = 0, it means there is no active zone
const int MultiZone = 99; //when ActiveZone = 99, more than one zone is active
const int All = 6;//total number of zones
int Zones[7] = {1,1,1,1,1,1,1};//will hold on/off state of all zones but first element
not used. 0 means active
int ActiveZone = 0;
int PreviousZone = 0;
int NumberActiveZones = 0;

//Timer
boolean TransientTimerStart = true; //if true, transient timer starts from 0 & clears
this flag
boolean TransientTimerRunning = false; //if true, transient timer is running
boolean OneMinuteTimerStart = false;//if true, One Minute Timer starts from 0 &
clears this flag
boolean OneMinuteTimerRunning = false; //if true, One Minute Timer is running
boolean MinorAlarmPestTimerStart = false;//if true, Minor alarm Pest Timer starts
from 0 & clears this flag
boolean MinorAlarmPestTimerRunning = false; //if true, Minor alarm Pest Timer
is running
boolean MajorAlarmPestTimerStart = false;//if true, Major alarm Pest Timer starts
from 0 & clears this flag
boolean MajorAlarmPestTimerRunning = false; //if true, Major alarm Pest Timer is
running
boolean MinorAudibleAlarmCadence = true; //Minor Audible alarm Cadence.
Toggles between true & false continuously
boolean MajorAudibleAlarmCadence = true; //Major Audible alarm Cadence.
Toggles between true & false continuously
boolean EndOfMinute = false;
boolean StartOfTransientTimer = false; //used to indicate a zone transition
```

```
boolean LastMinuteFlowMeasurementValid  = false; //is set true when flow data updated and set false when flow data is used to change a state. It is not set false if we just print to screen.
boolean NoTimerRunning = false; //summary flag over both transient and one minute timers
const unsigned long  TransientTimerInterval  = 10000; //10000 TransienT Timer 10 seconds

#ifdef SpeedUp
const unsigned long  MinorAudibleAlarmPestTimerInterval  = 100000;
const unsigned long  MajorAudibleAlarmPestTimerInterval  = 100000;
#else
const unsigned long  MinorAudibleAlarmPestTimerInterval  = 86400000; //change to 10 seconds for testing 86400000 Minor Alarm Pest Timer  24 hrs
const unsigned long  MajorAudibleAlarmPestTimerInterval  = 900000;  //change to 10 seconds for testing 900000 Major Alarm Pest Timer 15 minutes
#endif

const unsigned long  MinorAlarmOnTime = 300; //used by cadence function
const unsigned long  MinorAlarmOffTime = 2000;
const unsigned long  MajorAlarmOnTime = 100;
const unsigned long  MajorAlarmOffTime = 100;
unsigned long  TransientTimerFirstReading  = millis(); //Transient Timer
unsigned long  OneMinuteTimerFirstReading  = millis(); //One Minute Timer
unsigned long  MinorAudibleAlarmPestTimerFirstReading  = millis(); //Minor Alarm Pest timer
unsigned long  MajorAudibleAlarmPestTimerFirstReading  = millis(); //Major Alarm Pest timer
unsigned long  MinorAudibleAlarmCadenceTimerFirstReading  = millis(); //Minor Alarm Cadence first reading
unsigned long  MajorAudibleAlarmCadenceTimerFirstReading  = millis(); //Major Alarm Cadence first reading
boolean AntiFlickerWriteOK = true;
unsigned long AntiFlickerFirstReading  = millis();
unsigned long AntiFlickerUpdateTime  = 10000;//LCD updates every 10 seconds


#ifdef SpeedUp
const unsigned long OneMinuteTimerInterval = 10000;
int CountDownSeconds = 20;
```

```
const int CountDownFromSeconds = 20;//Transient time plus 10 seconds; used in display to tell user when state will change. made an int because I only want 2 digits
#else
const unsigned long OneMinuteTimerInterval = 60000;
int CountDownSeconds = 70; //variable used by Countdown timer that displays on screen
const int CountDownFromSeconds = 70;//Transient time plus 60 seconds; used in display to tell user when state will change. made an int because I only want 2 digits
#endif

//Flow Rate Symbol
boolean NewTick = false; //signals that Flow changed from high to low during this cycle.
boolean NewTickForTopDisplay = false; //set with NewTick and cleared by top display. It is used to control Flow indictator on LCD.
boolean NewTickForBottomDisplay = false; //set with NewTick and cleared by bottom display. It is used to control Flow indictator on LCD.

//Flow Meter
float FlowTickTime = 0; //used by Flow Meter
float InstantaneousFlowReading = 0;//used by Flow Meter
boolean JustMeasureFlow = false;//used by Flow Meter
float OldMeasureFlowStartTime = millis();//used by Flow Meter
boolean HighLevel = true;
boolean LowLevel = false;
float JustFlowTimer = millis(); //used by Flow Meter

//Flow Level
boolean FlowState = false; //state of Flow bit
boolean LastFlowStateHigh = false; //holds flow meter's previous output state
boolean LastFlowState = false; //holds flow meter's previous output state
boolean StartCollectFlowAfterInhibit = false;
boolean CollectFlowAfterInhibit = false;
const float MinFlowFraction[7] = {0,0.7,0.7,0.7,0.7,0.7,0.7}; //underflow is when flow count plus 1 is more than 30% below reference
const float MaxFlowFraction[7] = {0,1.3,1.3,1.3,1.3,1.3,1.3}; //overflow is when flow count minus 1 is more than 30% above reference
const float LeakagePPM = 2; //must be > 0 or causes software error. Assume 2 pulses per minute; threshold for flow when all valves off. if the flow is equal to or
```

```
greater than this threshold, I flag Major Alarm. A leakage of 0.06 GPM is 87
gallons per day! At least display will show it although not alarm
float LastMinuteFlowPPM = 0;
float LastMinuteFlowGPM = 0;
float FlowCountPulse = 0;
float FlowRatePPM = 0;
float TotalFlowCount  = 0; //running total of flow count while a zone is active
float TotalRunTime = 0; //running total of minutes zone is active after transient
time
float HistoricalDataPPM;  //used when writing to EEPROM
const float GallonsPerPulse = 0.0280 ;//based on measurements with city meter.

//Input states
const boolean Day = true; //when light sensor output is true, it means daytime
because detector pulls up to Vcc
const boolean ActiveFlag = false; //when a zone is active, debounced read will
return false in response to seeing 0. See also Active which is an const integer and
equals 0
const boolean Pushed = false; //used by debouncedRead() of buttons
const boolean Released = true; //used by debouncedRead() of buttons

//Faults
boolean Fault = false; //fault summary flag
boolean MajorAlarm = false;
boolean AllAlarmsCleared = false;//set when CAB pushed and cleared when
display shows action.
boolean MinorAlarm[7] = {false, false, false, false, false, false, false}; //this lets
me handle multiple Minor alarms at same time although only first one is display
and available to clear. Pest blocks all of them.
boolean ZoneUnderflow[7] = {false, false, false, false, false, false, false};
boolean ZoneOverflow[7] = {false, false, false, false, false, false, false};
boolean Inhibit[7] = {false, false, false, false, false, false, false}; //when true, it
requests that zone power be removed from the active zone. ZonePower() makes the
change
boolean PESTrescindRequest = false;//if Judge Flow Rate() sees an escalation of
alarm state, it requests that Alarm Control() rescind all PESTs
boolean RelayMayBeOnSoDontLook = false; //if Alarm Control sees a manual
clear alarm, we must blind Get Zone States until relay releases
boolean SuspectRelay = false;//if the normally closed contacts on the relay are
open when the relay is off, we will get all zones on
```

```
boolean StuckRelay = false; //if, after cycling relay many times, it is still open, call it a hardware failure
boolean TriedToUnstickRelay = false; //set true after trying and to false if it worked or via clear all alarms
boolean RequestOverflowMinorAlarmOnPreviousZone = false;//set by ZoneTransitionQ() and cleared by Alarm Control

//Errors
boolean EEPROM_ReadZoneNeverRunRangeError = false;
boolean EEPROM_WriteZoneNeverRun_RangeError = false;
boolean EEPROM_ReadHistoricalFlow_RangeError = false;
boolean EEPROM_WriteHistoricalFlow_RangeError = false;

//LCD flicker reduction screen names
const int TryingToClose = 25;
const int NoZoneOnNoDataYet = 26;
const int ZoneButNoDataYet = 27;
const int MutiZoneDisplayed = 28;
int lcdNowDisplaying = 0;//what was last written to LCD
const int NoZoneOnWithPPMConstant = 1000; //add PPM value to get name of this screen
const int ZoneOnWithPPMConstant = 2000; //add PPM value to get name of this screen
const int lcdUnderflowPlusZoneConstant = 3000; //add PPM value to get name of this screen
const int lcdOverflowPlusZoneConstant = 4000; //add PPM value to get name of this screen
int NoZoneOnWithPPM = 0; //complete name includes constant plus PPM
int ZoneOnWithPPM = 0; //complete name includes constant plus PPM
int lcdUnderflowPlusZone = 0; //complete name includes constant plus PPM
int lcdOverflowPlusZone = 0; //complete name includes constant plus PPM

//Scratch and index
long DiagCurrentTime = 0; //scratch variable
long DiagStartTime = 0; //scratch variable
int i = 0; //index used in while loops
float HistoricalGPM;//used in displaying historical flow data
int HaveMinorIndex = 0;

//Diagnostic
```

```
boolean DiagOn = false; //set true to enable all instances of the Diag() tool
const int Pause = 1; //used by Diag()
const int Wait = 2; //used by Diag()
int qaz = 999; //local scratch used to calculate Diag data

//Built in Flow Simulator
boolean FastestFlow = false; //used in Flow Simulator
boolean NominalFlow = false; //used in Flow Simulator
boolean LowestFlow = false; //used in Flow Simulator
const int FlowSimulatorDivider = 1;//used by the Flow Simulator to generate rates
of 0.5, 1, and 1.5
int FlowSimulatorCount = 0; //used by the Flow Simulator to generate rates of 0.5,
1, and 1.5

//Hardware Initialization
Adafruit_MCP23017 mcp; //port expander that ties to Pro Micro via I2C
LiquidCrystal lcd(RS, EN, DB4, DB5, DB6, DB7);

void setup(){
lcd.begin(16, 2);    // set up the LCD's number of columns and rows

//define each output on Arduino
pinMode(AllZonesOffPin, OUTPUT); //0 turns off relay and makes connection
pinMode(AudibleAlarmPin, OUTPUT); //1 turn on audible alarm through an NPN
pinMode(OnBoardYellowLED, OUTPUT);  //on board LED for debug
digitalWrite(OnBoardYellowLED, HIGH); //turns off on board yellow LED

//Port Expander: define each input with pull ups
mcp.begin(); //using default address of 0
mcp.pinMode(0,INPUT); //define port 0 as an input
mcp.pullUp(0,HIGH); //enables 100K pull up on input
mcp.pinMode(1,INPUT);
mcp.pullUp(1,HIGH);
mcp.pinMode(2,INPUT);
mcp.pullUp(2,HIGH);
mcp.pinMode(3,INPUT);
mcp.pullUp(3,HIGH);
mcp.pinMode(4,INPUT);
mcp.pullUp(4,HIGH);
mcp.pinMode(5,INPUT);
```

```
mcp.pullUp(5,HIGH);
mcp.pinMode(6,INPUT); //PAB
mcp.pullUp(6,HIGH);
mcp.pinMode(7,INPUT); //CAB
mcp.pullUp(7,HIGH);
mcp.pinMode(8,INPUT); //Light Sensor
//I do not want the pull up resistor for the light sensor.
mcp.pinMode(9,INPUT); //Flow
mcp.pullUp(9,HIGH);

//used by Flow simulator
mcp.pinMode(10,OUTPUT);
mcp.pinMode(11,OUTPUT);
mcp.pinMode(12,OUTPUT);

/*
mcp.digitalRead(n)) returns the state of virtual pin #n.
Signal  Virtual Pin#
Zone 1   0
Zone 2   1
Zone 3   2
Zone 4   3
Zone 5   4
Zone 6   5
PAB      6  (Pest Audible Alarm Button)
CAB      7  (Clear All Alarms Button)
LS    8     (Light Sensor)
Flow     9
spare    10-15


EEPROM memory map
addresses       used by      init value meaning
   0-6    ZoneNeverRun flag array  1    true
   7-34    historical flow data array    n/a
*/

//Note that the user can push either button
//Initialize EEPROM if clear alarms button is held down at power up.
```

```
if (debouncedRead(ClearAlarmButtonPin) == Pushed){ //clear EEPROM and tells
user
    i=0;
  while(i<7){
  EEPROM.write(i,1);
   i = i+1;
   }
  lcd.clear();
  lcd.print (F("Historical"));
  lcd.setCursor(0,1); //print next line on second row
  lcd.print (F("data cleared."));
  }
WaitUntilClearButtonReleased:
if (debouncedRead(ClearAlarmButtonPin) == Pushed) goto
WaitUntilClearButtonReleased;

//Enable Flow Meter if Pest button was held down at power up. Default is
FlowMeter() off
if (debouncedRead(PestAlarmButtonPin) == Pushed){
    JustMeasureFlow = true;
    lcd.print (F("Will just"));
    lcd.setCursor(0,1); //print next line on second row
    lcd.print (F("measure flow."));
   }
WaitUntilPestButtonReleased:
if (debouncedRead(PestAlarmButtonPin) == Pushed) goto
WaitUntilPestButtonReleased;

Serial.begin(9600); //This pipes text to the PC's //Serial monitor

//Welcome screen at power up
lcd.clear();
lcd.print(F("Flow Monitor"));//the F() function prevents alphanumeric string from
be stored in scratch memory
lcd.setCursor(0,1); //print next line on second row
lcd.print (F("& Control "));
lcd.print (version);
delay(3000);

OldMeasureFlowStartTime = millis();//set starting time. Used by flow meter mode
```

```
digitalWrite(AudibleAlarmPin, Quiet);   //initialize Audible Alarm to off which is low
}//**End of setup()

void loop(){ //TOL
JustMeasureFlowQ(); //if user just wants to measure flow, we do not return. Cancel option with power cycle
  Simulator(); //generate test Flow pulses on each pass through the loop. Selectable via jumper plugs on board
  SecondaryFlowScan();//runs often to catch narrow Flow pulses
GetZoneStates(); //returns Previous Zone and Active Zone
  SecondaryFlowScan();//runs often to catch narrow Flow pulses
ZonePower(); //responds to Inhibit[] and controls zone power
  SecondaryFlowScan();//runs often to catch narrow Flow pulses
TimerControl(); //all timers turned on and run from here
  SecondaryFlowScan();//runs often to catch narrow Flow pulses
ZoneTransitionQ(); //Zone Transition? If so, prepare for it
  SecondaryFlowScan();//runs often to catch narrow Flow pulses
ProcessFlowInfo(); // gets flow rate, displays it, and judges if flow rate is OK
  SecondaryFlowScan();//runs often to catch narrow Flow pulses
RelayErrorControl();//if relay contacts fail, try to clean them
AlarmControl();//display fault details, accept manual clear of alarms, accept pesting of active alarms, and generate audible alarms as necessary
}
//end of loop()

void GetZoneStates(){
/* GZS
Inputs: zone control lines, ActiveZone from last pass through loop, RelayMayBeOnSoDontLook
Outputs: PreviousZone and new ActiveZone
*/
PreviousZone = ActiveZone; //save last zone state before recording new one
InitializeZone(); //set all of Zones[] to Inactive which means ones

//if Alarm Control was instructed to clear all alarms and related flags
//plus release relay, it can't be done until Zone Power so just don't look at zones this time. Pass
//back no zones on.
```

```
if (RelayMayBeOnSoDontLook == true){
goto FAZ;
}
PopulateZones(); //read zone pins and fill the Zones[] array
FAZ:
FindActiveZone(); //returns ActiveZone
}
//End of GetZoneStates()


void ZonePower(){ //ZP()
/*
Input: Inhibit[]
Output: control of All Zones Off relay
*/

if (Inhibit[ActiveZone] == true) {
    digitalWrite(AllZonesOffPin, Open);//turn All Zones Off by operating the relay
  }else{
//otherwise, ActiveZone should not be inhibited so insure it by write
digitalWrite(AllZonesOffPin, Closed);//let any zone be on by releasing the relay
(remove power from it)
  }
if (RelayMayBeOnSoDontLook == true){ //I must wait after releasing the relay so
//GetZoneStates() doesn't see multizone due to floating COMMON OUT
delay(200);//wait 200 mS for relay to release but only in this special case
RelayMayBeOnSoDontLook = false; //clear flag because all is back to normal now
}
  return;
}
//** End of ZonePower()

void TimerControl(){ //TC()
/*
if valve power removed due to Under or Over flow detected, wait 10 seconds for
Inhibit's effect on flow to stabilize.
*/
if ((ActiveZone != PreviousZone)&&(ActiveZone != MultiZone)){
  TransientTimerStart = true; //so we have a zone transition to a single zone state or
just set Inhibit on a zone so start transient timer
```

```
  DiagStartTime = millis();//reset starting time to when TT starts. Then 10 sec for
TT followed by 1
  }
if(StartCollectFlowAfterInhibit == true){
  StartCollectFlowAfterInhibit = false;
  TransientTimerStart = true;
  DiagStartTime = millis();//reset starting time to when TT starts. Then 10 sec for
TT followed by 1 minute timer
  }

TransientTimeElapseTimer();//Transient Timer
//if transient timer was just started or is running and the one minute timer was just
about to start or is running, we must Early Terminate the one minute timer

if((TransientTimerRunning == true)|| (TransientTimerStart == true)){
  OneMinuteTimerStart = false;
  OneMinuteTimerRunning = false;
  }
/*TT starts out running. When TT done, start OM timer unless we are in
MultiZone.
 */
if ((TransientTimerRunning == false) && (OneMinuteTimerRunning == false)
&& (ActiveZone != MultiZone))OneMinuteTimerStart = true;
OneMinuteElapseTimer();//One Minute Timer
MinorPestElapseTimer();//Minor alarm Pest Timer
MajorPestElapseTimer();//Major alarm Pest Timer
MinorCadence();//Minor Alarm Cadence generator toggles
MinorAudibleAlarmCadence flag true/false
MajorCadence();//Major Alarm Cadence generator toggles
MajorAudibleAlarmCadence flag true/false
AntiFlickerCadence(); //sets the AntiFlickerWriteOK flag true every
AntiFlickerUpdateTime seconds
}
//**End of TimerControl

void ZoneTransitionQ(){//Zone Transition? ZT()
if (ActiveZone != PreviousZone){//if true, we have a zone transition
    TestingNewInhibitInterruptedQ();//if inhibit was active but subsequent flow
measurement interrupted by zone change, ask for minor alarm on previous zone
    SaveOldZoneFlowMeasurement(); //only does save if collected data valid
```

```
    PrepareForNewZone(); //initilizes variables
    CollectFlowAfterInhibit = false;//if zone transition was during measurement
right after Inhibit invoked, we need to clean up flags
    LastMinuteFlowMeasurementValid = false;

  }
if (TransientTimerRunning == true){ //this signals a zone has been inhibited and
we must measure the resulting flow so reset flow variables
  PrepareForNewZone(); //initilizes variables used to count flow
}
}
//End of ZoneTransitionQ()


void GetFlowRate(){
//one minute and running counts are done here
/* GFR()
Inputs: timers, Zones()
Outputs: if FlowMeasurementValid is true, LastMinuteFlowPPM is valid. Clear
this flag when data is part of a decision that comes out positive to prevent double
counting it. Flow rate while zone active is TotalFlowCount/TotalRunTime
*/
if ((ZoneOverflow[ActiveZone] == true) && (MinorAlarm[ActiveZone] ==
true)){//if we are in overflow and minor alarm has been set, stop collecting flow
data after inhibit because we are done
CollectFlowAfterInhibit = false; //clearing this flag lets Display Fault Details show
Overflow
}
FlowState = debouncedRead(FlowPin); //single read of Flow bit which is used here
and to update LCD flow symbols
digitalWrite(OnBoardYellowLED, FlowState);//echo Flow state to on board
yellow LED
if((TransientTimerStart == true) || (TransientTimerRunning == true)) return; //flow
not stable so don't measure it
if (OneMinuteTimerRunning == true){//within one minute flow sampling interval
if ((LastFlowStateHigh == true) && (FlowState == false)){
  LastFlowStateHigh = false; //record that Flow is now low
  FlowCountPulse = FlowCountPulse + 1;//then Flow went from high to low so
count it
  FlowTickTime = millis(); //record time falling edge occurred
```

```
  NewTick = true; //set flag that a new falling edge has arrived on Flow
  NewTickForTopDisplay = true; //used for top status display to show Flow activity
  NewTickForBottomDisplay = true; //used for bottom status display to show Flow
activity
  goto EndOfMinuteQ;
      }
    if ((LastFlowStateHigh == false) && (FlowState == true)){
      LastFlowStateHigh = true; //record that Flow is now high
      goto EndOfMinuteQ;
      }
     //Flow didn't change state
      }
EndOfMinuteQ:
if (EndOfMinute == true){ //one minute just ended so calc flow
   LastMinuteFlowPPM = FlowCountPulse;
   LastMinuteFlowMeasurementValid  = true;//used by Process Flow Info() and set
false after it is used to make a state change other than an LCD print
   TotalFlowCount = FlowCountPulse + TotalFlowCount;//running total while zone
active
   TotalRunTime = TotalRunTime + 1;//running total while zone active
   FlowCountPulse = 0;//clear count for next 1 minute interval
   }
return;
}
//**End of GetFlowRate()

void SecondaryFlowScan(){
//this runs multiple times in the loop to catch Flow pulses that are too narrow to be
caught
//if scanned once per cycle. Program cycle is approx 60 ms and min pulse est at
around 5 ms.
/* SRS()
Inputs: timers, Zones()
Outputs: just update flow count
*/
FlowState = debouncedRead(FlowPin);//do single read of Flow and then process it
plus I use it to toggle LCD flow status symbols
digitalWrite(OnBoardYellowLED,FlowState);//echo  Flow state to on board yellow
LED
```

```
if((TransientTimerStart == true) || (TransientTimerRunning == true)) return; //flow not stable so don't measure it

if (OneMinuteTimerRunning == true){//within one minute flow sampling interval

  if ((LastFlowStateHigh == true) && (FlowState == false)){
    LastFlowStateHigh = false; //record that Flow is now low
    FlowCountPulse = FlowCountPulse + 1;//then Flow went from high to low so count it
    FlowTickTime = millis(); //record time falling edge occurred
    NewTick = true; //set flag that a new falling edge has arrived on Flow
    NewTickForTopDisplay = true;
    NewTickForBottomDisplay = true;
    }
  if ((LastFlowStateHigh == false) && (FlowState == true)){

    LastFlowStateHigh = true; //record that Flow is now high
    }
     //Flow didn't change state
  }
return;
}
// ** End of SecondaryFlowScan()


void DisplayFlowRate(){  //DFR()
//display the flow rate. Note that this is only sunny day. Rainy day displays done in Alarm Control()
LastMinuteFlowGPM = LastMinuteFlowPPM*GallonsPerPulse;
if (SuspectRelay == true)return; //block all non fault messages if relay contacts seem to be faulted
if (MoreThanOne() == true)return;
if (PossibleFault() == true)return;//if we have a fault or have just invoked Inhibit, we don't want alarm message erased by nonfault flow info
if (NoZoneOnAndNoDataYet() == true)return;
if (NoZoneOnWithData() == true)return;
if (ActiveZoneNoDataYet() == true)return;
if (ZoneActive() == true)return;
}
//** End of DisplayFlowRate()
```

```
void JudgeFlowRate(){ //JFR()
/*
Inputs: LastMinuteFlowPPM and flow references
Outputs: MinorAlarm[ActiveZone], Major Alarm, Fault flag.
ZoneUnderflow(ActiveZone), ZoneOverflow(ActiveZone). Major Alarm is not
tied to any zone. Fault is tied to current ActiveZone

Judge Flow Rate looks at LastMinuteFlowPPM only if
LastMinuteFlowMeasurementValid is true to determine if in spec. Once
LastMinuteFlowPPM is used to make a state change
(not just to print to LCD), LastMinuteFlowMeasurementValid is set to false so I
don't use the reading again. If LastMinuteFlowPPM is not within range, it sets
Inhibit[ActiveZone] to true. On the next pass through, it evaluates the flow to see if
the inhibit worked.
*/
if(MajorAlarm == true)return; //Once we reach Major Alarm, no flow judging is
done.
if(MultiZoneQ == true) return;
if (NoFlowDataQ() == true)return;
if(NoHistoryQ() == true)return;
if(SmallFlowQ() == true)return;//if flow is small, include uncertainty of readings to
determine if normal or Overflow. Return if normal or overflow set.
if(UnderflowQ() == true)return;
if(OverflowBeforeInhibitQ() == true)return;
if(ImmediatelyAfterInhibitFaultQ() == true)return;//if Inhibit was just invoked and
first flow data taken, set Minor Alarm if it held. If it didn't hold, set Major Alarm.
if (AfterInhibitStableFaultQ() == true)return;// if true, Inhibit not holding anymore,
we have Overflow Major
if(LeakageNoZonesActiveQ() == true)return;
/*
To get here, flow must be within normal range. Note that once a zone has been
inhibited, it can only be cleared manually. Otherwise, I would
have to turn on the suspect zone periodically and see if the problem
still there. Since manual intervention needed to fix the problem,
makes sense to just make alarm clear manual.
*/
}
//**End of JudgeFlowRate()
```

```
void TransientTimeElapseTimer(){//**  TTE()
   if (ActiveZone == MultiZone){  //stop TT timer if MultiZone active
     DiagStartTime = millis();//reset  starting time to when TT starts. Then 10 sec
for TT followed by 1
     TransientTimerStart = false;
     TransientTimerRunning = false;
     return;
     }
   NoTimerRunning =((TransientTimerStart == false) &&
(TransientTimerRunning == false) && (OneMinuteTimerStart == false) &&
(OneMinuteTimerRunning == false));
   if ((PreviousZone == MultiZone) && (NoTimerRunning == true)){
    TransientTimerStart = true; //while in MultiZone, all timers were stopped but
now that we have left, start the TT
    DiagStartTime = millis();//reset  starting time to when TT starts. Then 10 sec for
TT followed by 1
   }
   if (TransientTimerStart == true){
     LastMinuteFlowMeasurementValid = false; //will be true after first minute
passes and the first Flow data has been generated
     StartOfTransientTimer = true;//used to indicate a zone transition NOT USED
     TransientTimerStart = false;
     DiagStartTime = millis();//reset  starting time to when TT starts. Then 10 sec
for TT followed by 1
     TransientTimerFirstReading = millis();
     TransientTimerRunning = true;
     CountDownSeconds = CountDownFromSeconds; //since this is the start of
transient interval, initialize countdown
     return;
   }
 //When TT done, clear TransientTimerRunning flag
 if (TransientTimerRunning == true){
   CountDownSeconds = CountDownFromSeconds - (millis() -
TransientTimerFirstReading)/1000;  //start at CountDownFrom and count down to
60. Then OM takes over
   if ((millis() - TransientTimerFirstReading) >= TransientTimerInterval){  //so
transient interval is over
     TransientTimerRunning = false;
```

```
    CountDownSeconds = OneMinuteTimerInterval/1000; // count down during
transient is done so prepare for one minute count down
    return;
    }
  }
}
//** end of TransientTimeElapseTimer()

void OneMinuteElapseTimer(){//**one minute timer OME()
if (ActiveZone == MultiZone){//stop OM timer if MultiZone active
  OneMinuteTimerStart = false;
  OneMinuteTimerRunning = false;
  EndOfMinute = false;
  return;
  }
if (OneMinuteTimerStart == true){
  EndOfMinute = false;
  OneMinuteTimerStart = false;
  OneMinuteTimerFirstReading = millis();
  OneMinuteTimerRunning = true;
  CountDownSeconds = OneMinuteTimerInterval/1000;
  return;
  }

if (OneMinuteTimerRunning == true){
  CountDownSeconds = OneMinuteTimerInterval/1000. - (millis() -
OneMinuteTimerFirstReading)/1000; //CountDown timer used on screen when
flow being displayed.
  if ((millis() - OneMinuteTimerFirstReading) >= OneMinuteTimerInterval){ //if
timer done
    OneMinuteTimerRunning = false;
    EndOfMinute = true;
    return;
    }
}
}
//**end of OneMinuteElapseTimer()

void MinorPestElapseTimer(){//**Minor alarm Pest Timer  MIPE()
if (MinorAlarmPestTimerStart == true){
```

```
  digitalWrite(AudibleAlarmPin, Quiet);   //turns sound off
  MinorAlarmPestTimerStart = false;
  MinorAudibleAlarmPestTimerFirstReading = millis();
  MinorAlarmPestTimerRunning = true;
  return;
  }
if ((MinorAlarmPestTimerRunning == true) && ((millis() -
MinorAudibleAlarmPestTimerFirstReading) >=
MinorAudibleAlarmPestTimerInterval))MinorAlarmPestTimerRunning = false;
return;
}
//**end of MinorPestElapseTimer()


void MajorPestElapseTimer(){//**Major alarm Pest Timer MAPE()
if (MajorAlarmPestTimerStart == true){
  digitalWrite(AudibleAlarmPin, Quiet);   // be sure sound is off
  MajorAlarmPestTimerStart = false;
  MajorAudibleAlarmPestTimerFirstReading = millis();
  MajorAlarmPestTimerRunning = true;
  return;
  }
if ((MajorAlarmPestTimerRunning == true) && ((millis() -
MajorAudibleAlarmPestTimerFirstReading) >=
MajorAudibleAlarmPestTimerInterval))MajorAlarmPestTimerRunning = false;
return;
}
//**end of MajorPestElapseTimer()


void MinorCadence(){ //**Minor Cadence Timer Subroutine MiC()
if (MinorAudibleAlarmCadence == true){
  if ((millis() - MinorAudibleAlarmCadenceTimerFirstReading) <
MinorAlarmOnTime)return;
  MinorAudibleAlarmCadence = false; //change timer from true to false
  MinorAudibleAlarmCadenceTimerFirstReading = millis();//reset timer for use by
MIACC being false
  }else{
  if ((millis() - MinorAudibleAlarmCadenceTimerFirstReading) <
MinorAlarmOffTime)return;
```

```
  MinorAudibleAlarmCadence = true; //change timer from false to true
  MinorAudibleAlarmCadenceTimerFirstReading = millis();//reset timer for use by
MIACC being true
  }
return;
}
//**End of MinorCadence()


void MajorCadence(){ //**Major Cadence Timer Subroutine
  if (MajorAudibleAlarmCadence == true){
    if ((millis() - MajorAudibleAlarmCadenceTimerFirstReading) <
MajorAlarmOnTime)return;
    MajorAudibleAlarmCadence = false; //change timer from true to false
    MajorAudibleAlarmCadenceTimerFirstReading = millis(); //reset timer for use
by MAACC being false

    AntiFlickerWriteOK = true;//UNRELATED TO ALARM CADENCE: once
every MajorAlarmOnTime interval we will update the LCD to reduce flicker

  }else{
    if ((millis() - MajorAudibleAlarmCadenceTimerFirstReading) <
MajorAlarmOffTime)return;
    MajorAudibleAlarmCadence = true;//change timer from false to true
    MajorAudibleAlarmCadenceTimerFirstReading = millis();//reset timer for use
by MAACC being true
  }
return;
}
//**End of MajorCadence()

void AntiFlickerCadence(){ //generates a flag that is set true every
AntiFlickerUpdateTime seconds. It is cleared when any screen is updated
if ((millis() - AntiFlickerFirstReading) < AntiFlickerUpdateTime)return;//if not
time to set AntiFlickerWriteOK flag, just return
AntiFlickerWriteOK = true; //time to set the flag true
AntiFlickerFirstReading = millis(); //reset timer for use by AntiFlickerWriteOK
being set true
return;
}
```

```
//**End of AntiFlickerCadence()

void ProcessFlowInfo(){ //flow is in pulses per minutes except when being
displayed
GetFlowRate();
DisplayFlowRate();
JudgeFlowRate();
}
//** End of ProcessFlowInfo()

void AlarmControl(){ //** AC()
/*
Inputs: alarm states, Inhibit(), pushbuttons
Outputs: audible alarms, LCD display text, cleared error arrays
*/
CleanUpPrematureAlarmExit();//if zone change occurred during flow
measurement immediately after Inhibit true, force MinorAlarm on the zone as best
guess
DisplayFaultDetails(); //if there is a software fault, stop the program; otherwise
display and return
ManuallyClearAlarmQ();
PestActiveAlarmQ();
AudibleAlarmProcessing();
}
//**End of AlarmControl()

void SaveOldZoneFlowMeasurement(){ //SOZFM()
//only save historical flow data that is not from faulted zone or Multizone and is
from at least one minute of measuring flow

if ((TotalRunTime == 0) || (Inhibit[PreviousZone] == true) ||
(MinorAlarm[PreviousZone] == true) || (MajorAlarm == true) || (PreviousZone ==
MultiZone))return;
//no save if past flow data not valid. However, when CAB pushed, all of these are
cleared so should cause return.
//otherwise, save the past flow data
HistoricalDataPPM = TotalFlowCount/TotalRunTime; //the new historical data in
PPM is the average rate over the full time the zone was just running
WriteHistoricalFlow(PreviousZone, HistoricalDataPPM);
WriteZoneNeverRun(PreviousZone, false); //this zone's historical data is now valid
```

```
}
//end of SaveOldZoneFlowMeasurement()


void PrepareForNewZone(){ //PFNZ()
FlowCountPulse = 0;//initialize  since new zone active
TotalFlowCount = 0;//initialize  since new zone active
TotalRunTime = 0;//initialize  since new zone active
}
//end of PrepareForNewZone()

void InitializeZone(){  //IZ()
/*
Inputs: none
Outputs: Zones[]
Desc: sets all elements of Zones[] to Inactive
*/
i=0;
while(i<7){
  Zones[i]=Inactive;
  i=i+1;
  }
}
//**End of InitializeZone()


void PopulateZones(){ //read zone pins and fill the Zones() array
//if COM disconnected but one zone active, all zones will appear active
if (debouncedRead(Zone1Pin) == ActiveFlag)Zones[1] = Active;
if (debouncedRead(Zone2Pin) == ActiveFlag)Zones[2] = Active;
if (debouncedRead(Zone3Pin) == ActiveFlag)Zones[3] = Active;
if (debouncedRead(Zone4Pin) == ActiveFlag)Zones[4] = Active;
if (debouncedRead(Zone5Pin) == ActiveFlag)Zones[5] = Active;
if (debouncedRead(Zone6Pin) == ActiveFlag)Zones[6] = Active;
}
//**End of PopulateZones()


void FindActiveZone(){
i = 1;
```

```
NumberActiveZones = 0;//initialize count of active zones
while(i<7){ //count number of active zones
  if (Zones[i] == Active)NumberActiveZones = NumberActiveZones + 1;
  i=i+1;
  }
if (NumberActiveZones == 0){//no zones are active
//with no zones active, we can't tell if relay not stuck so if SusprectRelay was true,
leave it there
  ActiveZone = None;
  return;
  }
if (NumberActiveZones == 1){//identify the one active zone
SuspectRelay = false;//with only 1 active zone, relay can't be stuck
  i = 1;
  while(i<7){
    if (Zones[i] == Active){
      ActiveZone = i;
      return; //found the active zone so stop looking
    }
    i=i+1;
  }
}
//otherwise, more than 1 zone is active or relay is active
//if Inhibit is active, COM has been disconnected and the ActiveZone backfeeds
the zones that are off
//to cause them all to look active. Therefore, just return so the previous ActiveZone
value persists.
if (Inhibit[ActiveZone] == true){
return;
}
//if all zones are active but Inhibit not true, it is likely that the relay contacts have
oxides on them which prevents them closing when the relay is released
if (NumberActiveZones == All){
SuspectRelay = true; //relay contacts may not have closed but also call it
MultiZone
}
//Since Inhibit not active, assume NumberActiveZones > 1 due to user action so
have Multizone
ActiveZone = MultiZone;
return;
```

```
}
//** End of FindActiveZone()

void DisplayFaultDetails(){//DFD()
if (RelayErrorQ()==true) return;
if(CABpressed()==true)return;
if (SoftwareError() == true)return;
if(CannotStop() == true)return;
if (Trying() == true)return;
if(HaveMinor() == true)return;
}
//** end of DisplayFaultDetails()


void ManuallyClearAlarmQ(){//manually  clear alarm?
if (debouncedRead(ClearAlarmButtonPin) == Pushed){
//clears Major or all Minor alarms; put all flags back to init state except a few
    AllAlarmsCleared = true; //used to control display managed by Alarm Control()
    TransientTimerStart = true;//start timing sequence the same as a zone change
    TransientTimerRunning = false;
    TotalRunTime = 0; //this prevents bad flow data from being saved in historical
    OneMinuteTimerStart = false;
    OneMinuteTimerRunning = false;
    MinorAlarmPestTimerStart = false;
    MajorAlarmPestTimerStart = false;
    EndOfMinute = false;
    StartOfTransientTimer = false;
    LastMinuteFlowMeasurementValid = false;
    NoTimerRunning = false;
    FlowState = false;
    EEPROM_ReadZoneNeverRunRangeError = false;
    EEPROM_WriteZoneNeverRun_RangeError = false;
    EEPROM_ReadHistoricalFlow_RangeError = false;
    EEPROM_WriteHistoricalFlow_RangeError = false;
    SuspectRelay = false;
    CollectFlowAfterInhibit = false;//Inhibit[] cleared below but must also clear this
flag
    StartCollectFlowAfterInhibit = false;
    MajorAlarm = false;
    Fault = false;
```

```
    MajorAlarmPestTimerRunning = false; //in case Major Pest timer running, turn
it off
    i = 0;
    while(i<7){
      MinorAlarm[i] = false;
      Inhibit[i] = false;
      RelayMayBeOnSoDontLook = true; //tells Get Zone States to not look because
if relay is operated it will see multizone
      ZoneUnderflow[i] = false;
      ZoneOverflow[i] = false;
      MinorAlarmPestTimerRunning = false; //in case Minor Pest timer running,
turn it off
      i=i+1;
     }
   //this is a violation of the architecture because it is a display function not done in
a display subroutine. Must do it here because we stay in a tight loop until CAB
released and need positive feedback to user.
   lcd.clear();
   lcd.print (F("Cleared"));
   lcd.setCursor(0,1); //print starting at col 0 row 1
   lcd.print (F("all alarms."));
WaitForClearButtonRelease:
if (debouncedRead(ClearAlarmButtonPin) == Pushed)goto
WaitForClearButtonRelease;  //user will hear audible alarm go away so wait until
they let go of clear button
   lcd.clear();
}
} //end of ManuallyClearAlarmQ()


void PestActiveAlarmQ(){
if(PESTrescindRequest == true){
//Judge Flow Rate() has requested that Major and Minor Alarm PEST be rescinded
because new alarm has arrived
MinorAlarmPestTimerStart = false;//stops Minor alarm Pest Timer
MinorAlarmPestTimerRunning = false; //stops Minor alarm Pest Timer
MajorAlarmPestTimerStart = false;//stops Major alarm Pest Timer
MajorAlarmPestTimerRunning = false; //stops Major alarm Pest Timer
PESTrescindRequest = false;//clear rescind flag
return;
```

```
}
if (debouncedRead(PestAlarmButtonPin) == Pushed){
lcd.clear();//after pesting alarms, acknowledge button pushed
lcd.print (F("Silenced"));
lcd.setCursor(0,1); //print starting at col 0 row 1
lcd.print (F("audible alarms."));
 //pest any audible alarms
  if(MajorAlarm == true){
    MajorAlarmPestTimerStart = true; //starts the Major Alarm Pest timer
    }
  //if any zone has MinorAlarm, start Minor Alarm Pest timer
  i = 1;
    while(i<7){
      if (MinorAlarm[i] == true){
        MinorAlarmPestTimerStart = true; //start the Minor alarm pest timer
        goto WaitForPestButtonRelease;
        }
      i=i+1;
      }
WaitForPestButtonRelease:
if (debouncedRead(PestAlarmButtonPin) == Released){
  lcd.clear();
  return;
  }else{
  goto WaitForPestButtonRelease;  //user will stop hearing audible alarm when they
let go of Pest button
  }
}
}
// end of PestActiveAlarmQ()


void AudibleAlarmProcessing(){
if(MajorAlarmPestTimerRunning == true)return; //Major audible alarm Pested so
just leave audible alarm generation
if (MajorAlarm == true){
     if(MajorAudibleAlarmCadence == true){ //if cadence says time to beep, do it
       digitalWrite(AudibleAlarmPin, Sound);   //turn on sound
      }else{
       digitalWrite(AudibleAlarmPin, Quiet);   //turns sound off
```

```
      }
     return; //by leaving audible alarm generation now, we prevent having both a
Major and Minor alarm at the same time. Only the Major will sound.
  }

//there is no Major Alarm but there might be a Minor
if (MinorAlarmsActiveQ() == false){//no Minor Alarms so be sure piezo is quiet
and return
    digitalWrite(AudibleAlarmPin, Quiet);
    return;
  }//otherwise we have a Minor Alarm
if(MinorAlarmPestTimerRunning == true){ //Minor audible alarm Pested so return
    digitalWrite(AudibleAlarmPin, Quiet);
    return;
  }//have at least one Minor Alarm that is not pested
if (debouncedRead(LightSensorPiin) == Day){
//it is daytime so sound it
     if(MinorAudibleAlarmCadence == true){ //if cadence says time to beep, do it
        digitalWrite(AudibleAlarmPin, Sound);
      }else{
        digitalWrite(AudibleAlarmPin, Quiet);   //turns sound off
      }
  }else{
  digitalWrite(AudibleAlarmPin, Quiet); //be sure audible alarm is off at night
  }
  return; // then it is night so do not sound Minor audible alarm even if active
}
// **end of AudibleAlarmProcessing()


boolean ReadZoneNeverRun(byte zone){
/*
EEPROM memory map
addresses       used by      init value meaning
    0-6    ZoneNeverRun flag array  1    true
    7-34    historical flow data array    n/a
*/
boolean flag;
if (zone > 6){
  EEPROM_ReadZoneNeverRunRangeError = true;
```

```
  return true;
  }
if (zone == None) return false; //since we use Leakage limit for No zones on, we always have historical data so can say it has always run before
flag = EEPROM.read(zone);
return flag;
} //end of ReadZoneNeverRun()


void WriteZoneNeverRun(int zone, boolean data){
/*
EEPROM memory map
addresses       used by      init value meaning
   0-6    ZoneNeverRun flag array  1    true
   7-34    historical flow data array    n/a
*/
if (zone > 6){
    EEPROM_WriteZoneNeverRun_RangeError = true;
    return;
  }
if (zone == None) return;//no need to write because we use Leakage as historical so it is as if we have always previously run for this case
EEPROM.write(zone, data);
} //end of WriteZoneNeverRun()


float ReadHistoricalFlowPPM(int zone){
/*
EEPROM memory map
addresses       used by      init value meaning
   0-6    ZoneNeverRun flag array  1    true
   7-34    historical flow data array    n/a
*/
int address;
float data;
if (zone == None)return LeakagePPM;//when no zones on, we use Leakage as our historical
if (zone > 6){
    EEPROM_ReadHistoricalFlow_RangeError = true;
    return 0;
```

```
  }
address = (zone * 4) + 7; //points to lowest byte in float variable
EEPROM.get(address,data);
return data;
} //end of ReadHistoricalFlow


void WriteHistoricalFlow(int  zone,float data){
/*
EEPROM memory map
addresses       used by      init value meaning
   0-6    ZoneNeverRun flag array  1    true
   7-34    historical  flow data array     n/a
*/
int address;
if (zone == None) return; //nothing to write because we use Leakage
if (zone > 6){
    EEPROM_WriteHistoricalFlow_RangeError  = true;
    return;
  }
address = (zone * 4) + 7;
EEPROM.put(address,data);
} //end of WriteHistoricalFlow


void SoftwareFaultBeep(){  //0.1 second on and 10 seconds off
SFB:
digitalWrite(AudibleAlarmPin,  Sound);
delay (100);
digitalWrite(AudibleAlarmPin,  Quiet);
delay (10000);
goto SFB;
} // end of SoftwareFaultBeep


void Diag(int marker, int data, int control){ //diagnostic tool; control can be Pause
or Wait. Pause is for 5 seconds. Wait is until Pest pushed and released

if (DiagOn == false) return; //default is all instances of this diagnostic tool off.
Turn them on by holding down only the Pest button at power up.
```

```
/*
Inputs:
marker - identify of this instance of Diag()
data - an integer to be displayed
control - what to do when data is displayed
    * Pause - delay 3 seconds and then return
    * Wait - wait until the Pest button is pushed and then return
*/
delay (3000); //give time for last LCD message to be seen.
lcd.clear();
lcd.print (F("ID "));
lcd.print(marker);
lcd.setCursor(0,1); //print starting at col 0 row 1
lcd.print (F("Data "));
lcd.print (data);

if (control == Pause){
  delay(3000); //wait 3 seconds
  lcd.clear(); //clean up display
  return;
    }

if (control == Wait){
ScanPestButton:
if(debouncedRead(PestAlarmButtonPin) == Pushed){
  //clean up display; next wait for Pest to be pushed and then wait for it to be
released
  lcd.clear(); //when Pest is pushed, clear the display
  if (debouncedRead(PestAlarmButtonPin) != Pushed)return; //when Pest is then
released, return
  }
  goto ScanPestButton; //keep scanning for Pest to be pushed and released
}
//control is not Pause or Wait so tell user they didn't specify a valid Control type,
wait 5 seconds, clean up, and return
lcd.clear();
lcd.print (F("ID "));
lcd.print(marker);
lcd.setCursor(0,1); //print next line on second row
lcd.print (F("Control?")); //was Control
```

```
delay(5000); //wait 5 seconds
lcd.clear();
return;
} // **end of Diag()


boolean MinorAlarmsActiveQ(){ //return true if we have at least one Minor
Alarms
if(StuckRelay == true)return true;//a stuck relay is a minor alarm
i = 1;
while(i<7){
  if(MinorAlarm[i] == true)return true;
  i=i+1;
  }
return false; //no Minor Alarms exist
} // end of MinorAlarmsActiveQ


//Debounced Read of an input on the MCP23017
boolean debouncedRead(int Pin){//this is the only place a local variable is used and
passed back as the value of a subroutine
float debounce = 0;
float reading;
i = 0;
while (i<10){//read pin 10 times and take average rounded to nearest int
  //note that read is from port expander and not from Arduino pin
  reading = float(mcp.digitalRead(Pin));
  debounce = reading + debounce;
  i = i+1;
  }
debounce = round((debounce/10));//take average and round to nearest integer but
debounce is still float
if (debounce <= 0.5)return false;
// fall through to signal must be > 0.5 so true
return true;
}
//**End of port expander Debounced Read.

void PrintStatusTop(){//puts day/night, flow activity, and countdown timer in top
right corner
```

```
lcd.setCursor(12,0); //column, row
if (debouncedRead(LightSensorPiin) == Day){
  if((MajorAlarmPestTimerRunning  == false)&&(MinorAlarmPestTimerRunning
== false)){
  lcd.print (F("D"));//daytime with no active pests
  }else{
  lcd.print (F("d"));//daytime with an active pest
  }
  }else{//is night
  if(MajorAlarmPestTimerRunning  == false){
  lcd.print (F("N"));//nighttime with no active pests
  }else{
  lcd.print (F("n"));//nighttime with an active pest
  }
  }
if (TransientTimerRunning == true){//we are in the transient interval so ignoring
flow
  lcd.print (F("T"));
}else{//we are measuring flow for 1 minute so show flow activity
  if (NewTickForTopDisplay == true){ //when a falling edge detected on this cycle,
show a "]".
    lcd.print (F("]"));
    NewTickForTopDisplay = false; //clear Flow edge flag in preparation for next
falling edge
    }else{ //when there has not been a falling edge, show a "[".
    lcd.print(F("["));
    }
    }
if(CountDownSeconds < 10)lcd.print(F(" ")); //going from 2 digits to 1 digit so
shift count over 1 space
lcd.print(CountDownSeconds);
}
//** end of PrintStatusTop()


void PrintStatusBottom(){//puts countdown timer in bottom right corner along with
flow indicator. It does not show day/night or pest status.
lcd.setCursor(13,1); //so 3 character positions left on second line
if (TransientTimerRunning == true){//we are in the transient interval so ignoring
flow
```

```
  lcd.print (F("T"));
}else{//we are measuring flow for 1 minute so show flow activity
if (NewTickForBottomDisplay == true){ //when a falling edge detected on this
cycle, show a "]".
  lcd.print (F("]"));
  NewTickForBottomDisplay = false;
  }else{ //when there has not been a falling edge, show a "[".
  lcd.print (F("["));
  }
  }
if(CountDownSeconds < 10)lcd.print(F(" "));//going from 2 digits to 1 digit so
shift count over 1 space
lcd.print (CountDownSeconds);
}
//**end of PrintStatusBottom()


//Flow Simulator executes on each pass of the loop but only increments its count
every "FlowSimulatorDivider" times.
void Simulator(){
if (FlowSimulatorCount < 1){
  FlowSimulatorCount = FlowSimulatorDivider;//reset the count
  //ripple counter to divide down fastest rate
  if (FastestFlow == false){//it toggles each time we have count down to 0
    //FastestFlow falling edge
    FastestFlow = true;
    mcp.digitalWrite(12,HIGH);
    if (NominalFlow == false){ //each time the fastest flow rises, toggle the nominal
rate
      //Nominal Flow rising edge
      NominalFlow = true;
      mcp.digitalWrite(11,HIGH);
      if (LowestFlow == false){
        LowestFlow = true;
        mcp.digitalWrite(10,HIGH);
        //digitalWrite(OnBoardYellowLED, HIGH); //drive yellow LED on the board
too
        }else{
        LowestFlow = false;
        mcp.digitalWrite(10,LOW);
```

```
      //digitalWrite(OnBoardYellowLED, LOW);//drive yellow LED on the board
too
       }
     }else{
     NominalFlow = false;
     mcp.digitalWrite(11,LOW);
     }
   }else{
   FastestFlow = false;
   mcp.digitalWrite(12,LOW);
   }
  }
 -- FlowSimulatorCount; //decrement Flow Simulator Counter
}
//end of Simulator()

void PrintLastMinuteFlowGPM(){  //does rounding based on size of number so it
fits into 4 character positions
   if (LastMinuteFlowGPM >= 10.) {// xx.x
      lcd.print (LastMinuteFlowGPM,1); //print looks at the variable and sees it is a
float so rounds to 1 place
      }
   if (LastMinuteFlowGPM < 10.){//x.xx or 0.xx
      lcd.print (LastMinuteFlowGPM,2);//print looks at the variable and sees it is a
float so rounds to 2 place
      }
}

boolean MultiZoneQ(){
if (ActiveZone == MultiZone){//don't judge flow if in Multi Zone
  return true;
  }else{
  return false;
  }
}


boolean NoFlowDataQ(){//see if we have no flow data yet for what appears to be a
healthy ActiveZone.
if ((TotalRunTime == 0) && (Inhibit[ActiveZone] == false)){//Assume no fault.
```

```
return true; //We have no historical flow data to use as reference. No zone active has Leakage limit so can proceed. Assume no fault.
}else{
return false;
}
}

boolean NoHistoryQ(){//see if we have no historical flow data to use as reference. No zone active has Leakage limit so can proceed.
if (ReadZoneNeverRun(ActiveZone) == true){//Assume no fault.
  return true;
  }else{
  return false;
  }
}

boolean ImmediatelyAfterInhibitFaultQ(){

if((CollectFlowAfterInhibit == false) || (LastMinuteFlowMeasurementValid == false))return false; //if we are not waiting for flow data
//right after Inhibit enabled or new measured data not available yet, return false.
//zone has just been inhibited and data good, see if flow has been controlled
  LastMinuteFlowMeasurementValid  = false;//we are about to use LastMinuteFlowPPM so it is no longer valid.
  //we know flow isn't right because Inhibit just invoked but do not know the new alarm state yet. Therefore
  //leave old alarm state in place along with state of PEST
  Fault = true;//since we do know a new alarm state will be found soon, set fault summary flag true
  CollectFlowAfterInhibit = false; //finally can retire this flag because collected data after inhibit was used to set an alarm. Data's value now used up
  PESTrescindRequest = true; //we are reaching a new alarm state so be sure PEST rescinded
  ZoneOverflow[ActiveZone] = true;//since Inhibit was set active, we know Overflow exists. Must next determine if Minor or Major
  if(LastMinuteFlowPPM < LeakagePPM){
    //inhibit did work so we have just arrived at Overflow Minor Alarm
    MinorAlarm[ActiveZone] = true;
   }else{//the LastMinuteFlowPPM >= LeakagePPM //inhibit did not work so we have just arrived at Overflow Major Alarm
```

```
  MajorAlarm = true; //zone inhibited and it did not work so Overflow Major
Alarm
  }
  return true; //return true because an alarm always results from Inhibit first going
active
}
// ** End of ImmediatelyAfterInhibitFaultQ()


boolean AfterInhibitStableFaultQ(){
if((Inhibit[ActiveZone] == false) || (CollectFlowAfterInhibit == true) ||
(LastMinuteFlowMeasurementValid == false))return false;
//We are already at Overflow Minor. Monitor flow to be sure blocked flow persists.
if(LastMinuteFlowPPM >= LeakagePPM){
  //inhibit was working but has now failed so we have moved from Overflow Minor
to Overflow Major Alarm
  //I will be coming back here when Inhibit true in the minor alarm case. We just
escalated to major.
  MinorAlarm[ActiveZone] = false; //we keep fault type at Overflow but retire
Minor.
  MajorAlarm = true; //set new alarm level
  PESTrescindRequest = true; //we are changing alarms so be sure PEST rescinded
  return true; //have new alarm state
  }else{ //LastMinuteFlowPPM is < LeakagePPM so are holding at Overflow
Minor
  return false; //no new alarm state
  }
}
// ** End of AfterInhibitStableFaultQ()


boolean SmallFlowQ(){//if small flow, guard against 0/0 and do best to determine
if normal or overflow
//note that historical flow, i.e, ref, is an average so can be fractional. Flow is a
count so is an integer
if((ZoneUnderflow[ActiveZone] == true) || (ZoneOverflow[ActiveZone] == true) ||
(LastMinuteFlowMeasurementValid == false))return false;//no valid data to
evaluate
if(ReadHistoricalFlowPPM(ActiveZone) < 1.43){
```

```
//given a ref of less than 1.43, can't have underflow. (flow+1)/ref = 0.7 so at flow of 0, ref = 1.43
if (LastMinuteFlowPPM <= 3){ //0, 1, 2, or 3 is normal flow
goto CallItNormal;
}else{ //4 or higher is overflow. (flow-1)/ref = 1.3 so at ref of 1.43, flow = 2.86. Therefore, 3 +/- 1 is overflow
goto CallItOverflow;
}
}else{
return false; //there was no small flow so can use the regular logic to determine underflow, normal, and overflow
}
CallItNormal:
LastMinuteFlowMeasurementValid = false;//I used LastMinuteFlowMeasurementValid to make a state change so has now been used up
return true;
CallItOverflow:
PESTrescindRequest = true;//we are about to arrived at a new alarm state so request that any PESTed audible alarms be rescinded
ZoneOverflow[ActiveZone] = true;//have Overflow so next try Inhibit() and go around loop again.
ZoneUnderflow[ActiveZone] = false;//if we were in Underflow, retire that flag since we just went to Overflow
Inhibit[ActiveZone] = true;
CollectFlowAfterInhibit = true;
LastMinuteFlowMeasurementValid = false;//I used LastMinuteFlowMeasurementValid to make a state change so has now been used up
StartCollectFlowAfterInhibit = true; //tells Timer Control() to set TransientTimerStart true and that starts new flow measurement. It then clears this flag so we don't continuously restart TT.
//Fault summary flag not set yet because we don't know if Minor or Major
return true;
}

boolean UnderflowQ(){
if (ActiveZone == None){
  return false; //there can't be underflow when no zones active
  }
```

```
if ((Inhibit[ActiveZone] == false) && (ZoneOverflow[ActiveZone] == false)
&&(LastMinuteFlowMeasurementValid == true) &&((LastMinuteFlowPPM +
1)/ReadHistoricalFlowPPM(ActiveZone)) < MinFlowFraction[ActiveZone]){
//we have Underflow.
  MinorAlarm[ActiveZone] = true; //no retesting of flow needed so just declare
Minor Alarm
  Fault = true; // no retesting of flow needed so just declare Fault
  ZoneUnderflow[ActiveZone] = true; //set Underflow flag for this zone
  LastMinuteFlowMeasurementValid = false;//we used LastMinuteFlowPPM so it
is no longer valid
  return true;
  }else{
  return false;
  }
}

boolean LeakageNoZonesActiveQ(){
//all flow measurements are +/- 1 pulse. When LastMinuteFlowPPM is only a few
pulses per minute, +/- 1 pulse is a large percentage.
//Therefore I will decrease LastMinuteFlowPPM by 1 for Overflow
//see if we have excessive flow when no zones are active
if ((ActiveZone == None) && (LastMinuteFlowPPM > LeakagePPM)){//if flow is
greater than leakage, set Major Alarm now because Inhibit won't help
  PESTrescindRequest = true;//we are about to arrived at a new alarm state so
request that any PESTed audible alarms be rescinded
  MajorAlarm = true;//a Major alarm takes priority over Minor alarms so no need to
deal with state of any Minor alarms
  Fault = true; //fault summary flag set
  return true;
  }else{
  return false;
  }
}

boolean OverflowBeforeInhibitQ(){
//see if we have Overflow before Inhibit when a zone is running
if ((Inhibit[ActiveZone] == false) && (LastMinuteFlowMeasurementValid ==
true) &&((LastMinuteFlowPPM - 1)/ReadHistoricalFlowPPM(ActiveZone)) >
MaxFlowFraction[ActiveZone]){
//have Overflow so try to Inhibit
```

```
  Inhibit[ActiveZone] = true;
  ZoneUnderflow[ActiveZone] = false;//in case we came from Underflow, retire this alarm to make way for new alarm
  MinorAlarm[ActiveZone] = false;//retire the current alarm since we are about to determine a new one after affects of inhibit are known.
  CollectFlowAfterInhibit = true;
  LastMinuteFlowMeasurementValid  = false;//I used LastMinuteFlowMeasurementValid to make a state change so has now been used up
  StartCollectFlowAfterInhibit = true; //tells Timer Control() to set TransientTimerStart true and that starts new flow measurement. It then clears this flag so we don't continuously restart TT.
  //Fault summary flag not set yet because we don't know if Minor or Major
  return true;
  }else{
  return false;
  }
}

boolean NoZoneOnAndNoDataYet(){
if ((TotalRunTime < 1) && (ActiveZone == None)){ //if we do not have one full minute of data yet for the No zones on case
  if ((lcdNowDisplaying != NoZoneOnNoDataYet) || (AntiFlickerWriteOK == true)){ //if update to LCD isn't needed, just update status and return.
  AntiFlickerWriteOK = false; //clear flag that lets us update screen every few seconds to reduce flicker
  lcdNowDisplaying = NoZoneOnNoDataYet; //used to prevent flicker
  lcd.clear();
  lcd.print (F("No zone on."));
  PrintStatusTop();
  lcd.setCursor(0,1); //print next line on second row
  lcd.print (F("No data yet."));
    }else{
    PrintStatusTop(); //just update one minute countdown in top right corner on each cycle
    }
return true;
}else{
return false;
}
```

```
}

boolean NoZoneOnWithData(){
if ((TotalRunTime >= 1) && (ActiveZone == None)){//if we have at least one full minute of data for the No zones on case, print this screen
  if ((lcdNowDisplaying != NoZoneOnWithPPM) || (AntiFlickerWriteOK == true)){ //if this is a new screen or it is time for a refresh
    AntiFlickerWriteOK = false; //clear flag that lets us update screens
    NoZoneOnWithPPM = NoZoneOnWithPPMConstant + LastMinuteFlowPPM;//the constant means "No zone on." and LastMinuteFlowPPM is rest of display screen. Update every few seconds to reduce flicker
    lcdNowDisplaying = NoZoneOnWithPPM;
    lcd.clear();
    lcd.print (F("No zone on."));
    PrintStatusTop();
    lcd.setCursor(0,1); //print next line on second row. column, row counting from 0
    PrintLastMinuteFlowGPM();  //does rounding based on size of number so it fits into 4 character positions
    lcd.setCursor(4,1); //leave 4 characters for LastMinuteFlowGPM which includes decimal point
    lcd.print (F(" GPM;ref"));//leave 4 characters for historical data including decimal point
    HistoricalGPM =LeakagePPM*GallonsPerPulse;//when no zone on, we check measured flow against leakage
    lcd.print(HistoricalGPM,2);//the variable is rounded to 2 places
    }else{//this is an old screen that does not need full refresh
    PrintStatusTop(); //just update one minute countdown in top right corner.
    }
    return true;
    }else{
    return false;
    }
  }

boolean ActiveZoneNoDataYet(){
if((TotalRunTime < 1) && (ActiveZone > 0) && (ActiveZone < 7)){
  PrintStatusTop(); //places one minute countdown in top right corner
  if ((lcdNowDisplaying != ZoneButNoDataYet) || (AntiFlickerWriteOK == true)){ //if update to LCD isn't needed, just return.
```

```
   AntiFlickerWriteOK = false; //clear flag that lets us update screen every few
seconds to reduce flicker
   lcdNowDisplaying = ZoneButNoDataYet; //used to prevent flicker  lcd.clear();
   lcd.clear();
   lcd.print (F("Zone "));
   lcd.print(ActiveZone);
   PrintStatusTop();
   lcd.setCursor(0,1); //print next line on second row
   lcd.print (F("No data yet."));
  }
  return true;
  }else{
  return false;
  }
}

boolean ZoneActive(){
//we only get here if all other possible screens don't apply
if ((LastMinuteFlowMeasurementValid  == true) && (ActiveZone > 0) &&
(ActiveZone < 7)){
  //I check to see that flow data is valid but since I'm just updating the LCD, do not
set LastMinuteFlowMeasurementValid  false
  //if any other screen written, lcdNowDisplaying will not equal ZoneOnWithPPM
so will write it now
  if ((lcdNowDisplaying != ZoneOnWithPPM) || (AntiFlickerWriteOK == true)){
//if new display or time for update, print new screen
  AntiFlickerWriteOK = false; //clear flag that lets us update screen every few
seconds to reduce flicker
  ZoneOnWithPPM = ZoneOnWithPPMConstant + LastMinuteFlowPPM;//the
constant means "zone on." and LastMinuteFlowPPM is rest of screen name which
completely represents what is on the LCD
  lcdNowDisplaying = ZoneOnWithPPM; //update variable that says what is on the
LCD now
  //refresh the screen
  lcd.clear();
  lcd.print (F("Zone "));
  lcd.print (ActiveZone);
  PrintStatusTop();
  lcd.setCursor(0,1); //print next line on second row
  PrintLastMinuteFlowGPM();//xx.x  or x.xx
```

```
  lcd.setCursor(4,1); //leave 3 characters for LastMinuteFlowGPM which includes
decimal point
  lcd.print (F(" GPM;ref"));
  if (ReadZoneNeverRun(ActiveZone) == true){
    lcd.print (F("-"));
    }else{
    HistoricalGPM = ReadHistoricalFlowPPM(ActiveZone)*GallonsPerPulse;//put
historical flow data next to measured data
    lcd.print (HistoricalGPM);
    }
  }
return true;
}else{
PrintStatusTop(); //places one minute countdown in top right corner even though
rest of screen not updated
return false;
}
}

boolean MoreThanOne(){
if (ActiveZone == MultiZone){
  if ((lcdNowDisplaying != MutiZoneDisplayed) || (AntiFlickerWriteOK == true)){
//if new display or time for update, print new screen
    AntiFlickerWriteOK = false; //clear flag that lets us update screen every few
seconds to reduce flicker
    lcdNowDisplaying = MutiZoneDisplayed;
    lcd.clear();
    lcd.print(F("More than one"));
    lcd.setCursor(0,1); //print next line on second row
    lcd.print (F("zone active."));
    }
  return true;
  }else{
  return false;
  }
  }

boolean PossibleFault(){
if ((Fault == true) || (CollectFlowAfterInhibit == true)){
```

```
  return true; //if we have a fault or have just invoked Inhibit, we don't want alarm message erased by nonfault flow info
  }else{
  return false;
  }
}

boolean CABpressed(){
//if CAB pressed, display fact.
if (AllAlarmsCleared == true){//one time display so no flicker problem
  lcd.clear();
  lcd.print (F("All alarms"));
  lcd.setCursor(0,1);
  lcd.print (F("were cleared."));
  delay(5000); //needed a little bit longer to see it. I didn't do clear so message will stay up until new message and avoid blank screen.
  AllAlarmsCleared = false; //clear flag since this is its only use
  return true;
  }else{
  return false;
  }
}

boolean SoftwareError(){
//if any software errors, display and stop
if(EEPROM_ReadZoneNeverRunRangeError == true){//one time display so no flicker problem
  lcd.clear();
  lcd.print (F("EEPROM read"));
  lcd.setCursor(0,1); //print next line on second row
  lcd.print (F("range error."));
  SoftwareFaultBeep(); //0.1 second on and 10 seconds off and never come back
  return true;
  }

if(EEPROM_WriteZoneNeverRun_RangeError == true){//one time display so no flicker problem
  lcd.clear();
  lcd.print (F("EEPROM write"));
  lcd.setCursor(0,1); //print next line on second row
```

```
  lcd.print (F("range error."));
  SoftwareFaultBeep(); //0.1 second on and 10 seconds off and never come back
  return true;
  }

if(EEPROM_ReadHistoricalFlow_RangeError == true){//one time display so no
flicker problem
  lcd.clear();
  lcd.print (F("Historical read"));
  lcd.setCursor(0,1); //print next line on second row
  lcd.print (F("range error."));
  SoftwareFaultBeep(); //0.1 second on and 10 seconds off and never come back
  return true;
  }

if(EEPROM_WriteHistoricalFlow_RangeError == true){//one time display so no
flicker problem
  lcd.clear();
  lcd.print (F("Historical write"));
  lcd.setCursor(0,1); //print next line on second row
  lcd.print (F("range error"));
  SoftwareFaultBeep(); //0.1 second on and 10 seconds off and never come back
  return true;
  }
  return false;
}

boolean CannotStop(){
if (MajorAlarm == true){//one time display so no flicker problem
  lcd.clear();
  lcd.print (F("Can't stop"));
  PrintStatusTop();
  lcd.setCursor(0,1); //print first column second row
  if (ActiveZone == None){
    lcd.print (F("idle flow.  "));
    PrintLastMinuteFlowGPM();
    }else{
    lcd.print (F("Zone "));
    lcd.print(ActiveZone);
    lcd.print (F(".     "));
```

```
    PrintLastMinuteFlowGPM();
    }
  return true;
  }else{
  return false;
  }
}

boolean Trying(){
if(CollectFlowAfterInhibit == true){ //only true while flow is being collected immediately after Inhibit set so this message will show for 60 seconds
//and does supersede all other error messages
  if ((lcdNowDisplaying != TryingToClose) || (AntiFlickerWriteOK == true)){ //if this is the first time this screen has printed or if it is time for a refresh, print screen
  AntiFlickerWriteOK = false; //clear flag that lets us update screen every few seconds to reduce flicker
  lcdNowDisplaying = TryingToClose; //update what is now displayed
  lcd.clear();
  lcd.print (F("Valve off."));
  lcd.setCursor(0,1); //print next line on second row
  lcd.print (F("Measuring flow."));
  PrintStatusTop(); //updates only on full screen update
  }else{
  PrintStatusTop(); //just update status
  }
return true;
}else{
return false;
}
}


boolean HaveMinor(){
//display first zone with Minor Alarm but Overflow checked before Underflow. Clear alarm will remove all minor alarms.
HaveMinorIndex = 1;
while(HaveMinorIndex<7){
if (MinorAlarm[HaveMinorIndex] == true){
  if (ZoneOverflow[HaveMinorIndex] == true){
```

```
   //for overflow Minor Alarm, the flow has been stopped so we do not display
flow rate.
     if ((lcdNowDisplaying != lcdOverflowPlusZone) || (AntiFlickerWriteOK ==
true)){
     AntiFlickerWriteOK = false; //clear flag since screen about to be updated
     lcdOverflowPlusZone = lcdOverflowPlusZoneConstant + HaveMinorIndex;
     lcdNowDisplaying = lcdOverflowPlusZone; //update screen variable to reflect
LCD
     lcd.clear();
     lcd.print (F("Overflow"));
     PrintStatusTop();
     lcd.setCursor(0,1); //print next line on second row
     lcd.print (F("in Zone "));
     lcd.print(HaveMinorIndex);
     lcd.print (F(".  "));
     PrintLastMinuteFlowGPM();
     return true;
     }else{
     PrintStatusTop();
     return true;
     }
   }
   if (ZoneUnderflow[HaveMinorIndex] == true){//for underflow there is still flow
so we will display it
     if((lcdNowDisplaying != lcdUnderflowPlusZone) || (AntiFlickerWriteOK ==
true)){ //if new screen or time to refresh it
       AntiFlickerWriteOK = false; //clear flag since screen about to be updated
       lcdUnderflowPlusZone =  lcdUnderflowPlusZoneConstant +
HaveMinorIndex;
       lcdNowDisplaying = lcdUnderflowPlusZone;
       lcd.clear();
       lcd.print (F("Underflow Zone "));
       lcd.print(HaveMinorIndex);
       lcd.setCursor(0,1); //print next line on second row starting at first column
       if (HaveMinorIndex == ActiveZone){//if faulted zone is active, display flow
information
         PrintLastMinuteFlowGPM();//xx.x or x.xx
         //note that if zone was in underflow and then goes into overflow, I won't
change alarm but will show higher flow
```

```
        lcd.setCursor(4,1); //leave 4 characters for LastMinuteFlowGPM which
includes decimal point
        lcd.print (F(" GPM;ref"));
        HistoricalGPM =
ReadHistoricalFlowPPM(HaveMinorIndex)*GallonsPerPulse;//put historical flow
data next to measured data
        lcd.print (HistoricalGPM);
        }else{//faulted zone is not currently active
        lcd.print(F("but not active."));
        }
       }
       return true;
     }
   }
  HaveMinorIndex=HaveMinorIndex+1;
  }
return false;
}
// ** End of HaveMinor()


void RelayErrorControl(){
if((SuspectRelay == false) && (TriedToUnstickRelay == false)) return; //no fault
present
if((SuspectRelay == false) && (TriedToUnstickRelay == true)){
TriedToUnstickRelay = false;//unstick worked for leave fault state
Fault = false; //clear Fault flag so system can get back to looking for irrigation
faults
StuckRelay = false;
return;
}
if((SuspectRelay == true) && (TriedToUnstickRelay == false)){
i = 1;
while(i<21){ //try to break through any oxides on contact by cycling relay 20 times
digitalWrite(AllZonesOffPin, Open); //this powers up relay
delay(10);//give a little time for the contacts to open
digitalWrite(AllZonesOffPin, Closed); //this powers down relay
delay(10);//give a little time for the contacts to close
i = i+1;
}
```

```
delay(100);//give time for relay to settle
TriedToUnstickRelay = true;
return;
}
if((SuspectRelay == true) && (TriedToUnstickRelay == true)){//gave up on relay so alarm
Fault = true;
StuckRelay = true;
return;
}
}

boolean RelayErrorQ(){
if (StuckRelay == true){
lcd.clear();
lcd.print (F("Hardware failure."));
return true;
}else{
return false;
}
}

void TestingNewInhibitInterruptedQ(){//see if zone change occurred immediately after Inhibit invoked so no alarm set
if ((Inhibit[PreviousZone] == true) && (CollectFlowAfterInhibit == true) && MinorAlarm[PreviousZone] == false){
//Inhibit was set on last zone and was in the middle of measuring flow when zone change occurred.
//Assuming Minor Alarm on that zone. If it really is Major, the next zone or no zone will get the alarm.
RequestOverflowMinorAlarmOnPreviousZone = true;//ask Alarm Control to set MinorAlarm[PreviousZone] to true
}
}

void CleanUpPrematureAlarmExit(){
if (RequestOverflowMinorAlarmOnPreviousZone == true){
MinorAlarm[PreviousZone] = true;
ZoneOverflow[PreviousZone] = true;
Fault = true;
```

```
RequestOverflowMinorAlarmOnPreviousZone = false;
}
}

void JustMeasureFlowQ(){
if (JustMeasureFlow == false)return;
JustMeasureFlow = false;//user held down PEST button at power up
//to indicate they want to just measure flow. Now clear flag.
OldMeasureFlowStartTime = millis();
lcd.clear();
lcd.print (F("Ready for flow."));
lcd.setCursor(0,1); //print next line on second row
lcd.print (F("Exit? Press PEST"));
JustFlowTimer = millis() - 1000;//start timer at present minus 1 second so screen
prints right away
JustFlow:
if (debouncedRead(PestAlarmButtonPin) == Pushed){//does user want to exit
measurement mode?
  lcd.clear();
  lcd.print (F("Exit flow"));
  lcd.setCursor(0,1); //print next line on second row
  lcd.print (F("measurements."));
WaitUntilPestButtonReleasedToEndFlowMeasurements:
if (debouncedRead(PestAlarmButtonPin) == Pushed) goto
WaitUntilPestButtonReleasedToEndFlowMeasurements;
return;//when PEST released, start normal FMC operation
}
FlowState = debouncedRead(FlowPin); //look at Flow signal
  if ((LastFlowState == HighLevel) && (FlowState == LowLevel)){
  //have a falling edge
    LastFlowState = LowLevel; //record that Flow is now low
    FlowTickTime = millis(); //record time falling edge occurred
    goto ShowLiveFlow;
  }
  if ((LastFlowState == LowLevel) && (FlowState == HighLevel)){ //see if there
is a rising edge
    LastFlowState = HighLevel; //record that Flow is now high
  }
  goto JustFlow;//no falling edge so keep looking
```

```
ShowLiveFlow: //calculate  period and convert to flow
  if((millis() - JustFlowTimer) > 1000){ //only update display once per second to
prevent flickering at high flow rates // 20 -(-9990) SO TRUE
    lcd.clear();
    if((FlowTickTime - OldMeasureFlowStartTime)  == 0)goto JustFlow;//divide by
0 protection //15 - 0 = 15
    InstantaneousFlowReading = 1680./(FlowTickTime -
OldMeasureFlowStartTime);  //convert period of flow pulses to
GPMlcd.setCursor(0,0); //start on first column and first line
    lcd.setCursor(0,1); //print on second row
    lcd.print (F("Exit? Press PEST"));
    lcd.setCursor(0,0); //go back to first line for update
    if (InstantaneousFlowReading < 10){ //so x.xx
      lcd.print (F("    "));
      lcd.print(InstantaneousFlowReading,2);//display  flow with 2 place accuracy
past decimal
      lcd.print (F(" GPM "));
    }else{  //so xx.xx
      lcd.print (F("   "));//shortened fill by 1 to make room for extra digit
      lcd.print(InstantaneousFlowReading,2);//display  flow with 2 place accuracy
past decimal
      lcd.print (F(" GPM "));
    }
  JustFlowTimer = millis();//set  new current time
  }
OldMeasureFlowStartTime  = FlowTickTime;  //record new last falling edge time
goto JustFlow;
}

//end of file. Be sure the next line has a number but no code follows.
```