Sichuan University - Pittsburgh Institute

ME 1042

Dynamics/Controls Lab

Programmable Logic Controllers

Revised
September 2021

Mechanical Engineering Department

Goal: To investigate the fundamentals of programmable logic controllers (PLCs) and their operation as it relates to fluid transport and liquid level.

Equipment Needed:
CE111 PLC Process
CE123 PLC Trainer
PC with GX Developer software

1 Introduction and Basic Theory

Programmable logic controllers, also called programmable controllers or PLCs, are solid-state computers that use integrated circuits instead of electro-mechanical devices to implement control functions. The primary function of a PLC is to perform sequential operations that are usually triggered by a received input. They are capable of storing instructions, such as sequencing, timing, counting, arithmetic and data manipulation to control industrial machines and processes, such as the opening/closing of a valve. Figure 1 illustrates a conceptual diagram of a PLC application. PLCs can be thought of as industrial computers with specifically designed hardware to protect against the rigors of the industrial environment. Their development replaced the typical relay controlled system, which was expensive and inflexible.

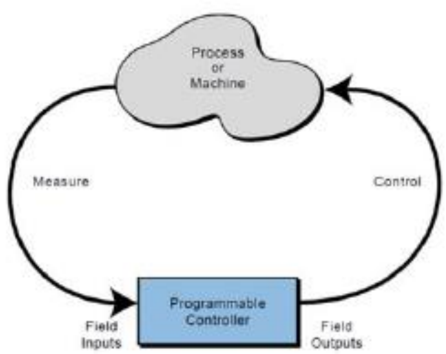


Figure 1: PLC conceptual design.

1.1 *Principles of Operation*

The operation of a PLC is relatively simple. The input/output (I/O) system is physically connected to field devices, such as motor starters, valves, sensors, limit-switches etc. The I/O interface provides the connection between the central processor and the information providers (inputs) and controllable devices (outputs) as seen Figure 2.

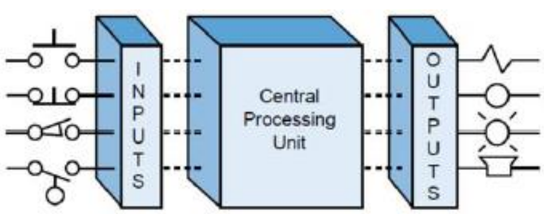


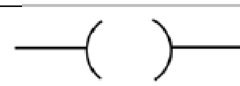
Figure 2: PLC block diagram.

The inputs monitor process conditions and are usually connected to devices such as switches (limit, push-button etc.). The activation of a switch by some means, a limit switch for instance, changes the logic level, either HIGH (1) or LOW (0), on the input channel to which it is connected. The processor monitors the status of the input channels and sets the output channels according to the logical operations defined in the control program. The output channels of the CE123 are digital, as are most PLCs. Therefore the output signal can also be either HIGH (1) or LOW (0). The outputs are connected to the device that requires control, such as solenoid valves and motor starters, and are activated (or de-activated) depending on the HIGH or LOW status. The logical operations performed by the processor are written and stored as a program in an external user interface such as a personal computer. The program can be written in various formats depending on software. The type of programming explored here and widely used is called Ladder Logic.

1.2 Introduction to Ladder Logic

Ladder logic is very closely associated to basic relay logic. There are both ***contacts*** and ***coils*** that can be loaded and driven in different configurations that make up a ladder diagram. There are two types of contacts, normally open (NO) and normally closed (NC) which can be seen below in Table 1. Coils drive the outputs and are usually represented with a set of parenthesis:

Table 1: Ladder diagram symbols.

Instruction	Symbol
Contact (Normally Open)	
Contact (Normally Closed)	
Coil	

The contact and coil symbols described in Table 1.1 represent devices in the PLC. These devices are actuated by or act upon variables associated with the PLC hardware. These variables are outlined in Table 2. All the variables are logical, and take values either OFF (Logical '0') or ON (Logical '1').

Table 2: Variables used in hardware.

X	This is used to represent the physical inputs to the PLC. There are 8 physical inputs to the CE123 addressed as X0 — X7
Y	This represents the physical outputs of the PLC. There are 6 physical outputs to the CE123 addressed as Y0 – Y5
T	This represents a timing device in the PLC. There are 64 timers in the CE123 addressed as T0 to T63. The CE123 timers are set in units of 0.1 seconds but can be reprogrammed. Timers and counters will be further discussed below
C	This represents a counting device in the PLC. There are 32 counters in the CE123 addressed as C0-C31
M	These are used to represent internal operational flags in the PLC. There are 512 M flags.

Programmable Logic Controllers

A simple introduction to ladder logic is given by the following example: Figure 3 shows a schematic of an electrically powered pump activated by an ON/OFF switch and dependent upon the condition of a float switch and overload relay.

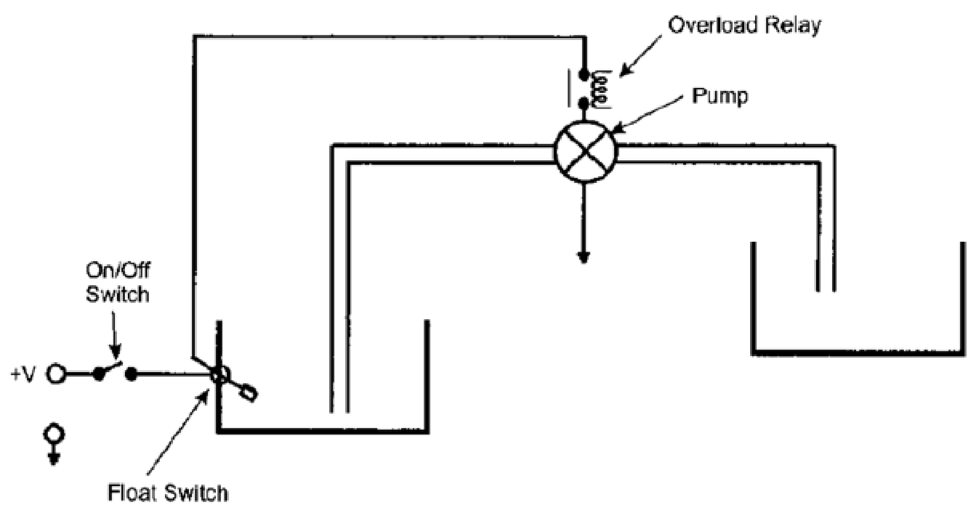


Figure 3: Pump schematic.

The pump will run if the switch is activated, there is enough fluid in the tank and the overload switch is set and will keep running if all these conditions continue to be met.
This system can be represented as components connected in series between two power rails shown in Figure 4.

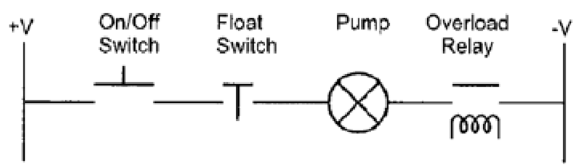


Figure 4: Pump circuit connected in series.

By replacing the component symbols with contact/coil symbols, the system can be further reduced and represented as a ladder diagram, shown in Figure 5.

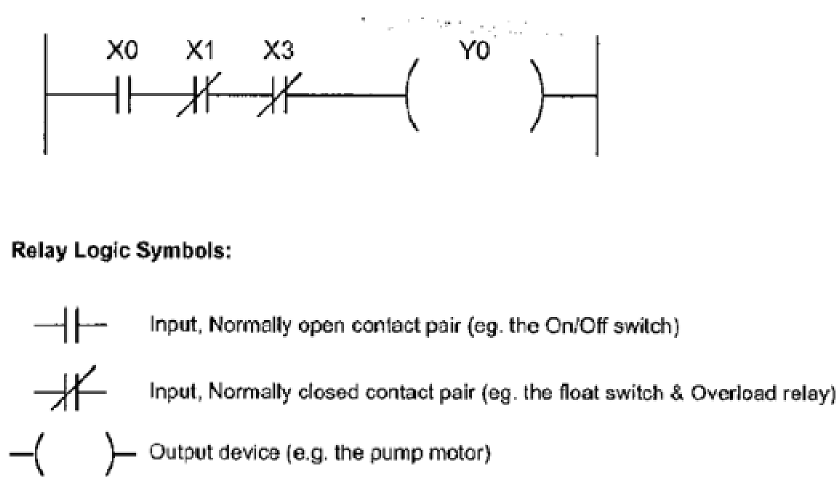


Figure 5: Ladder diagram of pump circuit.

As seen in Figure 5, the output Y0 (pump motor) will not activate unless the ON/OFF switch is closed and the float switch and overload relay are closed. If, for instance, the tank empties, the float switch will open and the motor will turn off regardless of the status of the ON/OFF switch and overload relay.

Ladder diagrams can be used to represent logic control systems and can become more complex as the complexity of the system increases. Figure 6 shows three examples of ladder diagrams which should indicate the inherent simplicity of ladder logic diagram representation:

(a) Represents a system comprised of a motor, Y0, which will only operate if switch X2 (normally open) has been closed and switch X1 (normally closed) has not been triggered.

(b) Represents a system comprised of an output device, Y0, which will operate if either of two normally open switches, X6 or X7, are closed.

(c) Shows a more complex diagram: output Y2 will be turned on if the contact, X1, is closed. Output Y1 is controlled by the state of witches X0 and X2, only being activated if X0 is closed and X2 is not opened. Outputs Y0 and Y3 will both be activated if either switch, X3 or X4 are closed.

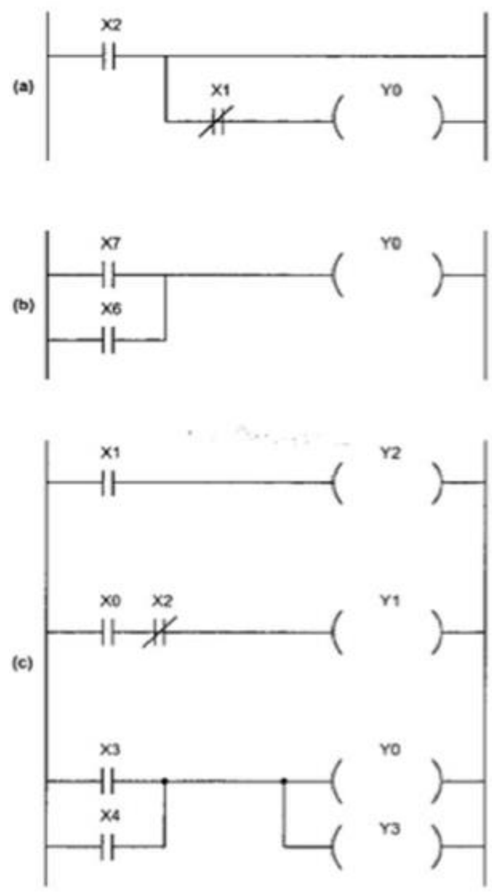


Figure 6: Ladder diagram examples.

1.3 Timers and Flags

Timers and flags can be used in both a coil or contact configuration. That is, they can be used to drive an output (coil) or they can be used to trigger an input (contact). The section below shows how each variable can be used.

Timers
When configuring a coil (output) for use as a timer, a constant must also be entered. This constant, identified by the letter "K", tells the program how long that timer will run. The value of the constant K and the duration of the data hold is dependent on the type of PLC used. As previously noted, the CE123 operates on a 100msec increments (0.1s). Therefore, the number associated with K will be multiplied by 100 msec. For example, if you enter K8 for a timer constant, the duration data will be held for 800 ms (8 x 100ms) or 0.8 seconds. Figure 7 shows a simple ladder diagram that will help understand timer functionality.

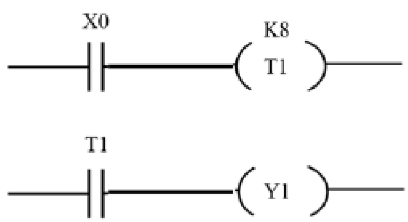


Figure 7: Timer example.

When input X0 is opened, T1 is initiated and holds for 0.8 seconds before executing (opening). After 0.8 seconds, output Y1 is triggered. Timers can be used for both NO (normally open) and NC (normally closed) contacts as well as for coils.

Flags
Flags are used internally to store an event. They are entirely internal to the system, therefore, no direct external input is needed and they do not directly drive an output. We use the letter 'M' and a number from 0-511 to identify a flag. The number next to the M is used only as identification. Flags are useful if you use chunks of logic, repeatedly throughout your program. Instead of writing the same code (which may be many lines long) you can store that line as a flag and call it when needed.

1.4 GX Developer Software

The menu driven software package supplied with the CE123 allows you to:

- Create and edit ladder diagrams
- Download and upload ladder diagrams to and from the PLC
- Load and save ladder diagrams to and from disk
- Add comments to aid ladder diagram clarity
- Monitor ladder diagrams in the PLC
- Print ladder diagrams and comments

Operation of the GX developer software will be investigated in the Pre-Lab Assignment.

1.5 CE 111 and Water Tower Fluid Dynamics

The CE111 water tower apparatus is a bench mounted modular instrument comprised of a reservoir pump and two tanks as seen in Figure 8. The apparatus is equipped with solenoid valves to control the filling and emptying of the two tanks. Used in conjunction with the CE123 PLC Trainer, the CE111 can be automatically controlled via ladder logic and GX developer software, or manually controlled by switching logic buttons on the CE123 front panel.

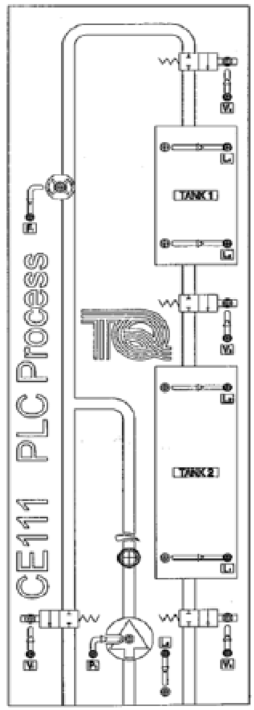


Figure 8: C111 front panel.

Introduction to Fluid Dynamics: Mass conservation

In this lab, we will examine the time it takes to drain tank 1 to a specific level and program this into a ladder diagram for automated level control. First, we must understand the fluid dynamics of a tank draining under force of gravity using the conservation of mass. Figure 9 shows the water tower, with a fluid height, *h(t).*

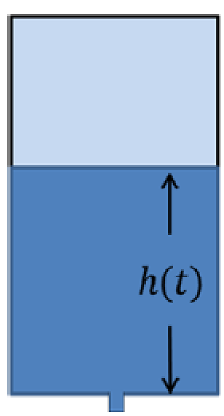


Figure 9: Cylindrical water tank.

According to Torricelli's theorem, the velocity of a fluid, with height, h, draining from a hole in a tank is governed by equation:

$$V = \sqrt{2gh}$$

Using the water in the tank as a control volume mass, m_{cv} and applying conservation of mass

$$\frac{\delta m_{cv}}{\delta t} + \dot{m}_{out} = 0$$

Where, ▯▯▯▯▯▯ is the rate of change of the control volume mass and $\frac{\delta m_{cv}}{\delta t}$ is the mass flow rate at the exit hole. Mass flow rate is defined by:

$$\dot{m} = \rho V A$$

Where ρ is the density of the fluid, V is the velocity of the fluid and A is the area of the outlet. The control volume mass is changing with respect to time, due to changing height, *h(t).*

2 Experimental Procedure

2.1 Intro to the CE 111 PLC Process

The CE111 consists of two water tanks, a reservoir pump, and solenoid valves. Tank 1 is filled directly by the pump and a flow control knob. Tank 2 is filled by draining tank 1. Tank 2 is drained back in to the reservoir. All valves are controlled by solenoids and each tank has a low and high indicator. The reservoir also has a low-level float switch to indicate whether there is enough fluid in the system. The inputs/outputs on the apparatus are summarized in Table 3.

Table 3: Connection of inputs and outputs between CE 111 and CE 123.

CE111	CE123	Function
L1	X1	Tank 2 LOW level Float Switch
L2	X2	Tank 2 HIGH level Float Switch
L3	X3	Tank 1 LOW level Float Switch
L4	X4	Tank 1 HIGH level Float Switch
L5	X5	Reservoir LOW level Float Switch
V1	Y1	Pump to Reservoir Valve (by-pass)
V2	Y2	Tank 1 Feed Valve
V3	Y3	Tank 1 Drain Valve
V4	Y4	Tank 2 Drain Valve
P1	Y0	Pump ON/OFF
F1	X0	Flow meter, pulse related to flow rate

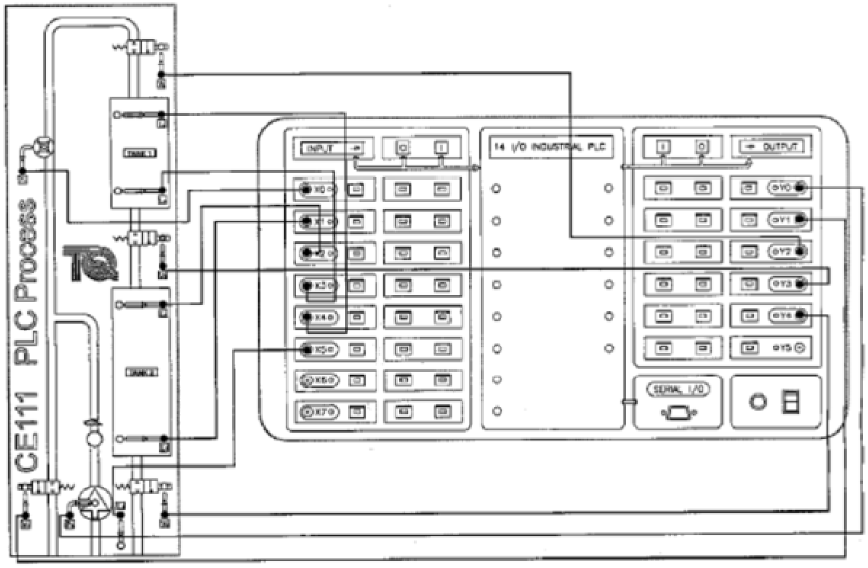


Figure 10: Wiring connections between CE 111 and CE 123.

1. Make sure the CE123 is off and make sure the run switch is in the “OFF” position.
2. With help from the Lab Engineer, connect the leads from the CE123 to the CE111.
3. Turn on the CE123. Use the manual selectors to set all outputs to logic 0 (LOW). The CE111 should now be inactive, except for the reservoir float switch (X5/L5) and possibly the flow meter (X0/F1), which may or may not be illuminated. ENSURE L5/X5 IS LIT. IF NOT, TOP THE RESEVOIR FLUID.
4. The valves are OPEN if set HIGH (logic 1) and CLOSED when LOW (logic 0). Open and close each of the valves in turn and an audible click should be heard as they operate and corresponding indicator light should illuminate.
5. SET: Y1 ON – This opens the return to reservoir valve, V1 SET: Y0 ON – This starts pump P1. Set the speed control knob to maximum.

   NOTE: Do not run the pump with both the bypass valve V1 and the feed valve to tank 1 (V2) closed as it will damage the pump. Close the valve V1 after valve V2 is open, otherwise the fluid will pump water back to the reservoir tank.

6. The noise of the pump and the water going back into the reservoir tank should be audible. Open valves V2, V3, V4 (set CE123 outputs Y2, Y3, Y4 HIGH) and close by-pass valve V1 (set Y1 LOW). The water will not flow through tanks 1 and 2 and back to the reservoir.

   NOTE: the CE111 is equipped with fluid overflow pipes to prevent water spilling over edge of tanks.

7. Turn off the pump P1 (set Y0 to LOW).
8. Work on manually filling the tanks and emptying them back into the reservoir. Open valves V1, V2, V3, V3 (If not already open).
9. Start the pump and close valve V1. Set the speed control to mid-way.
10. Close valve V4
11. When level indicator L2 lights up, close valve V3.
12. When level indicator L4 lights up, stop the pump (set Y0 LOW).
13. Drain the tank by opening valves V3 and V4.

2.2 Tank Draining Exercise

In this exercise you will open an already existing program and examine its function. The task that the program executes is to repeatedly fill Tank 1, and when full, it drains for a specific time into Tank 2 and the reservoir. There is a timer delay in the program that controls how long the tank drains. Follow the steps below:

1. Hit the open project icon.
2. Navigate to D:\ME MS2\ PLC Training project and open it.
3. Check the transfer set-up to be sure the PLC is reading from the correct port (COM3).
4. Write the program to the PLC. Make sure the CE123 is in STOP mode. Hit ONLINE → Write to PLC. Select MAIN and then hit Execute.
5. Review the program, as seen in Figure 11. The function of each rung is outlined below:
    a. Rung 1 starts the pump when X6 is HIGH and, if the reservoir level is high, it also opens the by-pass valve if the feed to Tank1 is closed. This is a safety feature to not damage the pump.
    b. Rung 2 opens Tank 2 drain valve to allow water to flow back into the reservoir, if there is water in Tank 2 (Tank 2 low level, X1, is HIGH).
    c. Rung 3 initiates a timer, if Tank 1 is not full and the ON/OFF switch is turned on. ***This is the timer that will determine how long Tank 1 drains.***
    d. Rung 3 when the timer opens, Tank 1 feed is opened and Tank 1 begins to fill.
    e. Rung 4 & 5 use internal memory flag, M1, to open the drain to Tank 1, if Tank 1 level is HIGH.

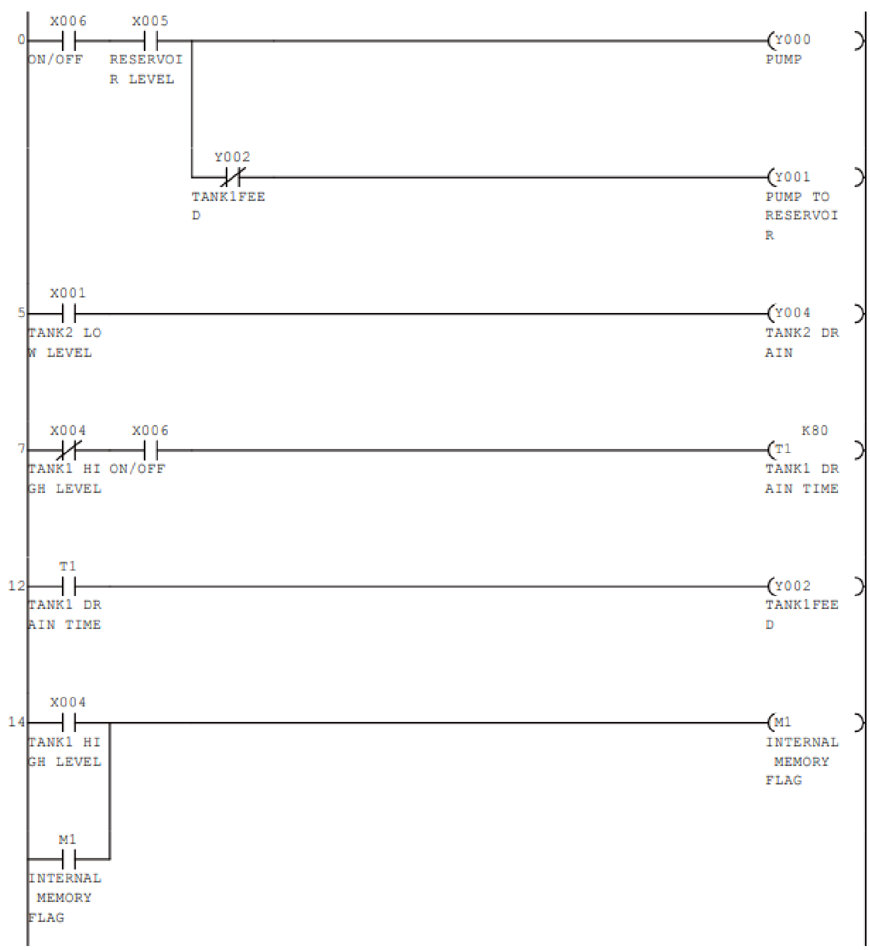


Figure 11: Tank 1 draining example.

6. Turn the run switch to RUN.
7. Initiate the program by clicking X6 to '1'. Examine the control cycle behavior. The Tank 1 Drain Timer (T1) constant is initially set to 20 (K20), therefore, the program will delay 2 sec (20x100mec) to allow the tank to drain.
8. Change the value of T1 constant to 50. Double click the timer in the program to edit, as seen in Figure 12. Now, the tank will drain for 5 seconds before it refills.

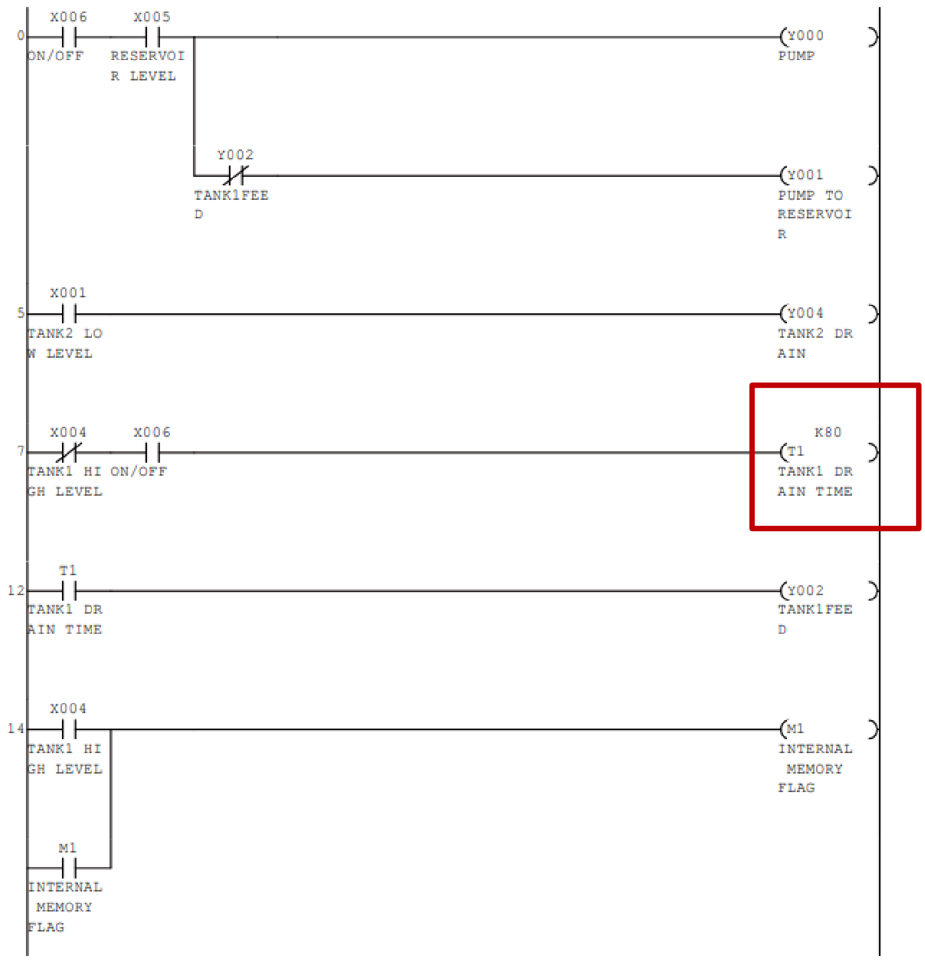


Figure 12: Edit timer constant.

9. Convert the program and write to the PLC. Make sure the run switch is in STOP position.
10. Check the operation by turning the run switch to RUN and setting X6 to '1'.
11. Adjust the timer constant to try and get the tank to drain half way before refilling. Follow steps 8-10 to edit the constant and check operation. **Note in your lab manual the timer constant that drains the tank to half height.**
12. Repeat the draining process for a 25% drain, 75% drain and a 100% drain.

This concludes the Lab. Make sure all the tanks are drained back to the reservoir and the CE123 control panel is turned off.

3 For the Report

You work in a chemical refinery and your boss has asked you to update an old relay system for automated fluid level control using PLCs. The task that needs solved is outlined below.

a) Tank 1 is filled with chemical A.
b) A portion of tank 1 is drained into tank 2 and the reservoir (i.e. 50%, 25%, 75% or 100%).

*** NOTE: you only have high and low level indicators on the tanks. To drain tank 1 to half level, you must use your knowledge of fluid dynamics discussed earlier to come up with how much time it will take to drain tank 1 half way.

1) Solve the conservation of mass equation (equation 1.2) to determine how much time is needed to drain to the intended height**.** Plot height of the fluid in the tank as a function of time, ***h(t)* =** ??. Plot time (x-axis) vs. height of fluid in cylinder (y-axis) and indicate on your plot the time to reach the draining level (i.e. y = 65mm, x=??? seconds).

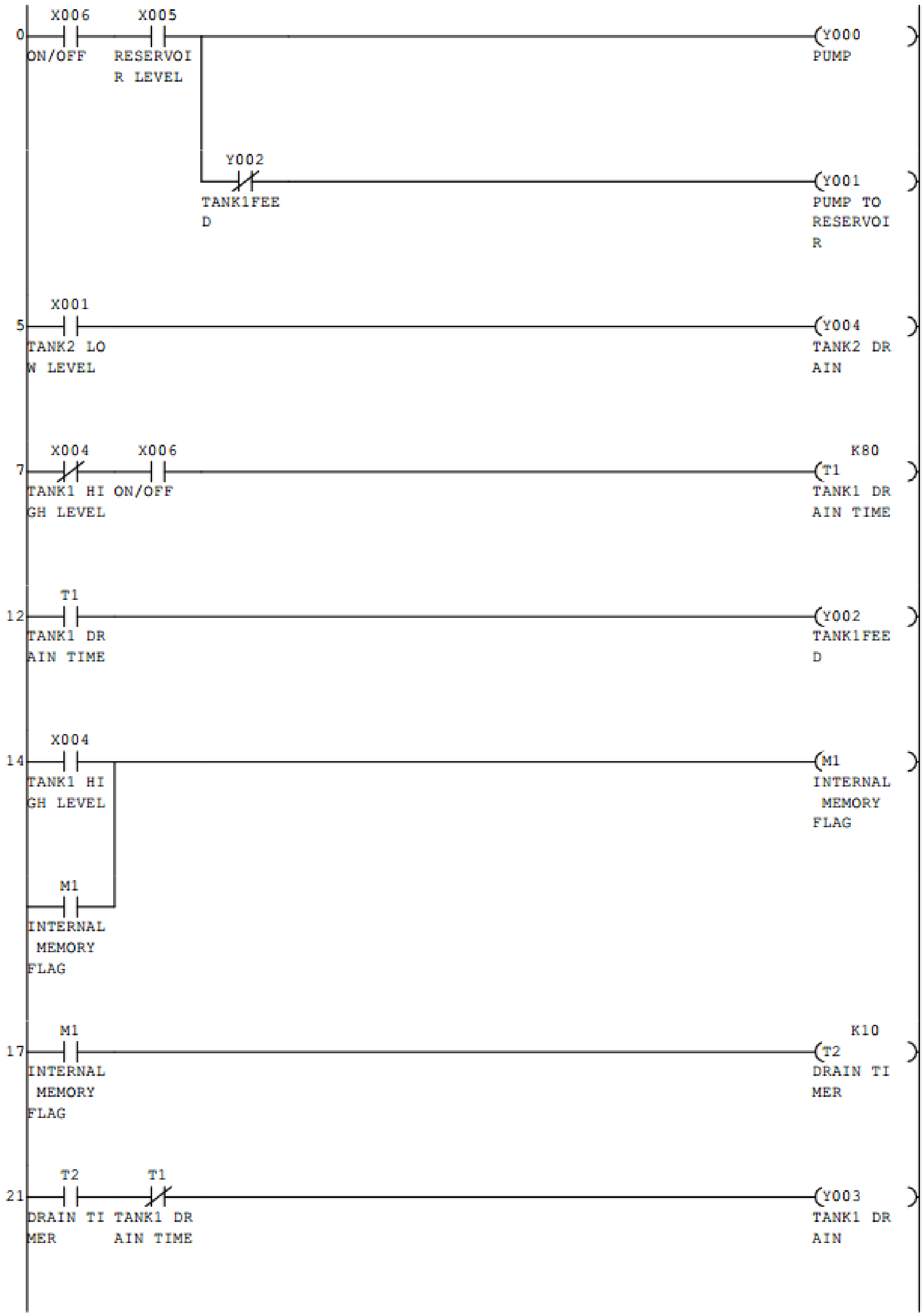
The dimensions of tank 1 and the outlet drain are summarized below:
Tank Diameter: 90mm
Outlet Diameter: 7mm
Tank Height (Max Fluid Height): 130mm
Use 1 gram/cm^3 as density of the fluid.

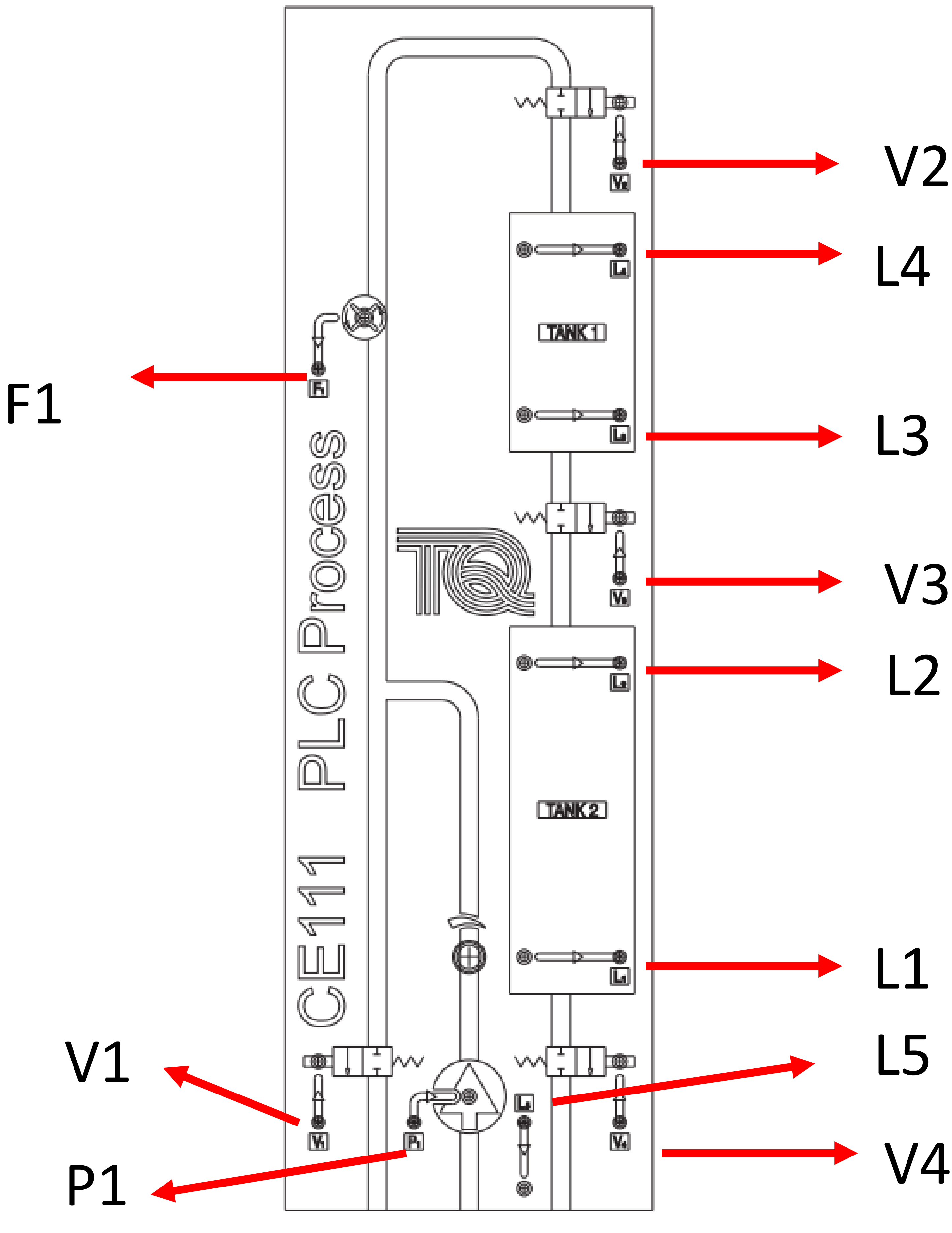
2) Write a memo to your boss explaining why the use of PLCs is an effective way to handle the tasks outlined above. In your memo, outline how you will use the inputs and outputs available on the CE123 and CE111 to simulate this. You can summarize with words, make a flow chart, or sketch a ladder diagram to illustrate how this problem can be solved. Be sure to include the logic learned in lab, such as AND/OR, NAND/NOR and Timers. Include the following:

   a. Attach the Plots from (1).

   b. How close does your timer constant you obtained through trial and error in the lab match the time you solved for? Why don't they match? What assumptions were used in solving the drain problem? Are they valid?

Appendix I PLC Ladder Program



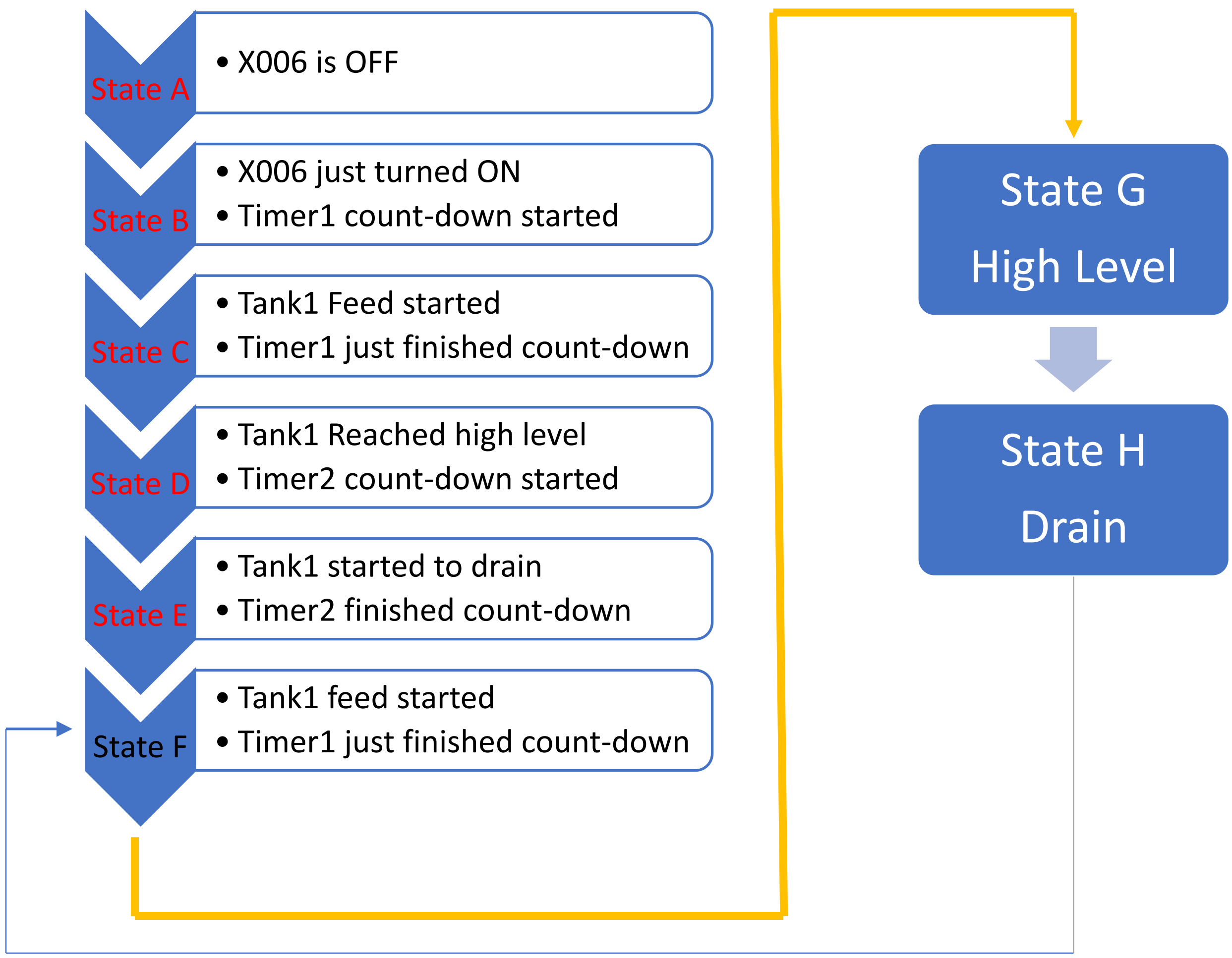


V2
L4
TANK 1
F1
L3
CE111 PLC Process
V3
L2
TANK 2
L1
V1
L5
P1
V4

Socket Label	I/O	Function
L1	Output	Tank 2 LOW level Switch
L2	Output	Tank 2 HIGH level Switch
L3	Output	Tank 1 LOW level Switch
L4	Output	Tank 1 HIGH level Switch
L5	Output	Reservoir LOW level Float Switch
V1	Input	Pump to Reservoir Valve (by-pass)
V2	Input	Tank 1 Feed Valve
V3	Input	Tank 1 Drain Valve
V4	Input	Tank 2 Drain Valve
P1	Input	Pump ON/OFF
F1	Output	Flow meter, pulse related to flow rate

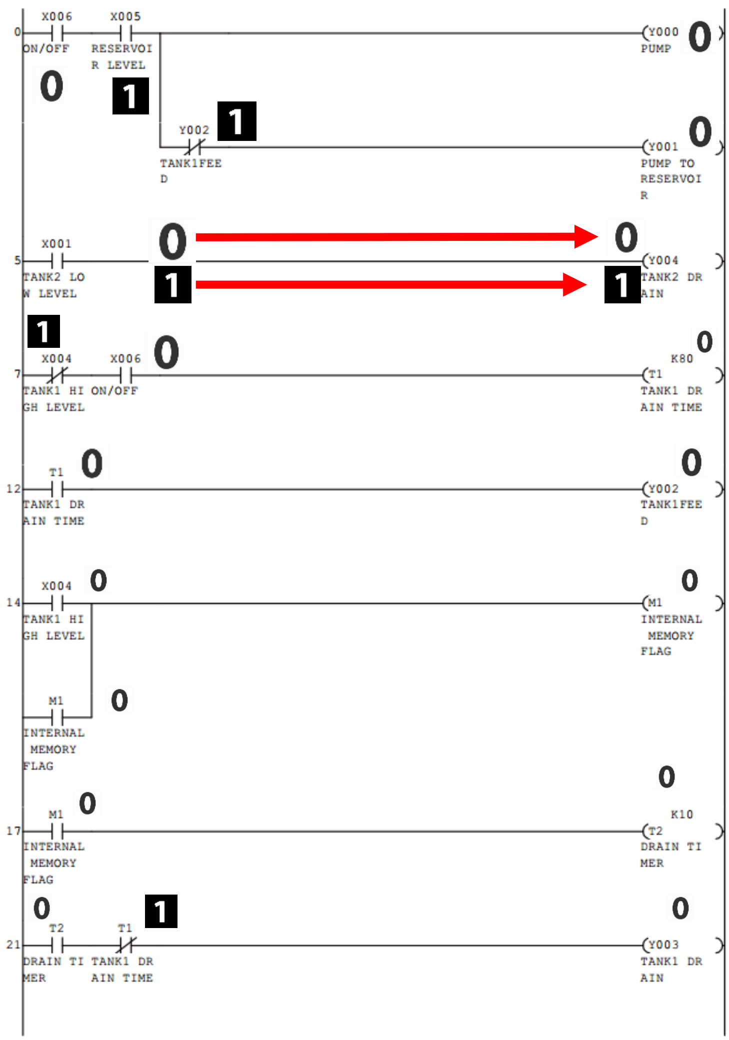
Table 2.1: Connection of Inputs/Outputs between CE111 and CE123

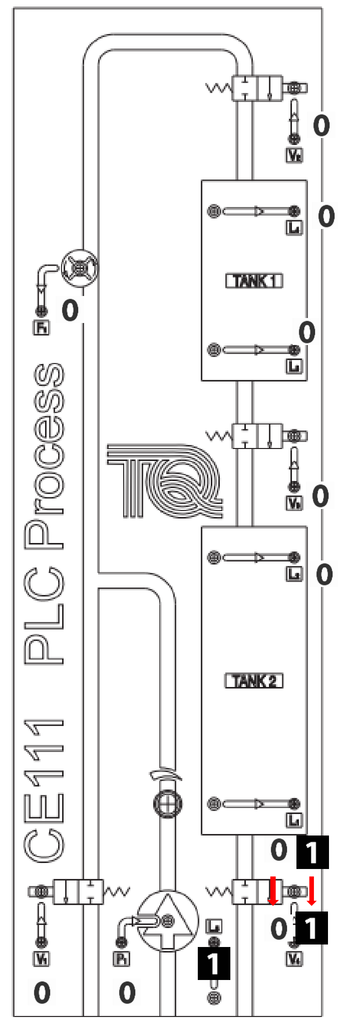
CE111	CE123	Function
L1	X1	Tank 2 LOW level Float Switch
L2	X2	Tank 2 HIGH level Float Switch
L3	X3	Tank 1 LOW level Float Switch
L4	X4	Tank 1 HIGH level Float Switch
L5	X5	Reservoir LOW level Float Switch
V1	Y1	Pump to Reservoir Valve (by-pass)
V2	Y2	Tank 1 Feed Valve
V3	Y3	Tank 1 Drain Valve
V4	Y4	Tank 2 Drain Valve
P1	Y0	Pump ON/OFF
F1	X0	Flow meter, pulse related to flow rate



State A
• X006 is OFF
State B
• X006 just turned ON
• Timer1 count-down started
State C
• Tank1 Feed started
• Timer1 just finished count-down
State D
• Tank1 Reached high level
• Timer2 count-down started
State E
• Tank1 started to drain
• Timer2 finished count-down
State F
• Tank1 feed started
• Timer1 just finished count-down
State G
High Level
State H
Drain

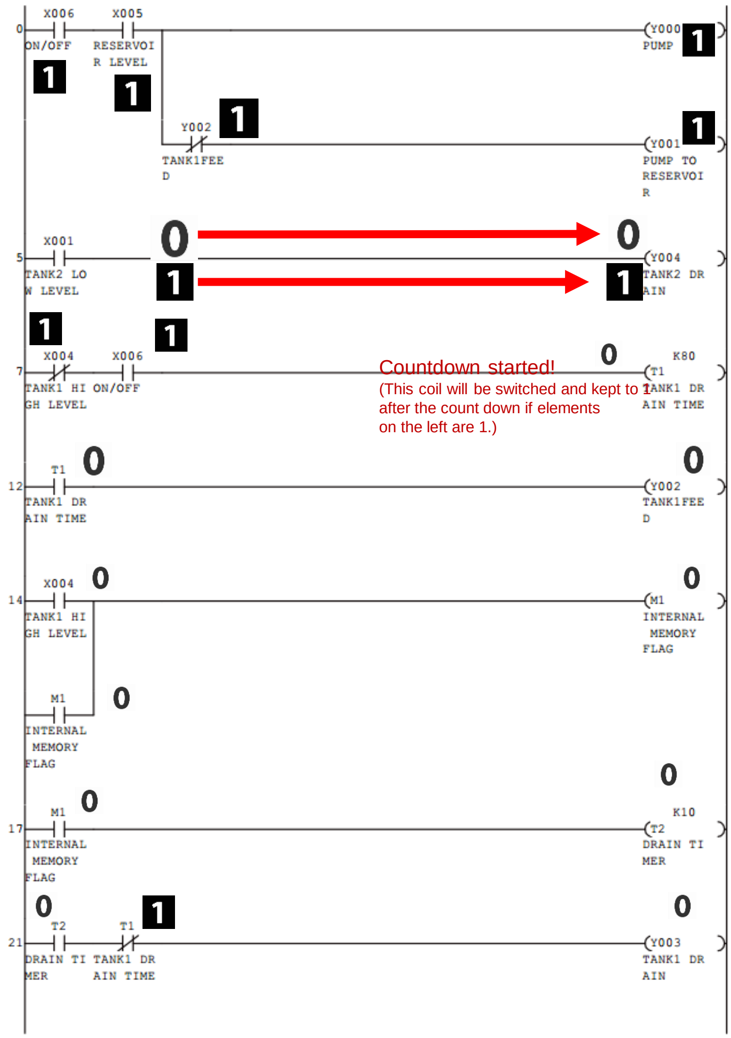
State A:
X006 was OFF
- Assume that there is no water in either tank.

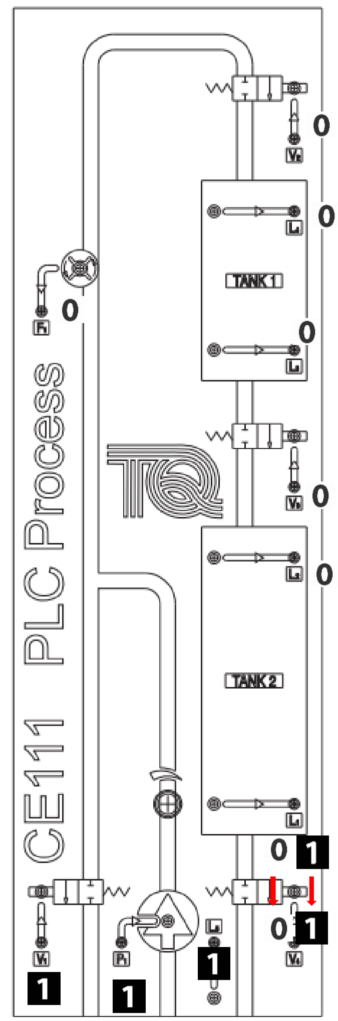




State B:
X006 was just turned ON and T1 started the count-down process

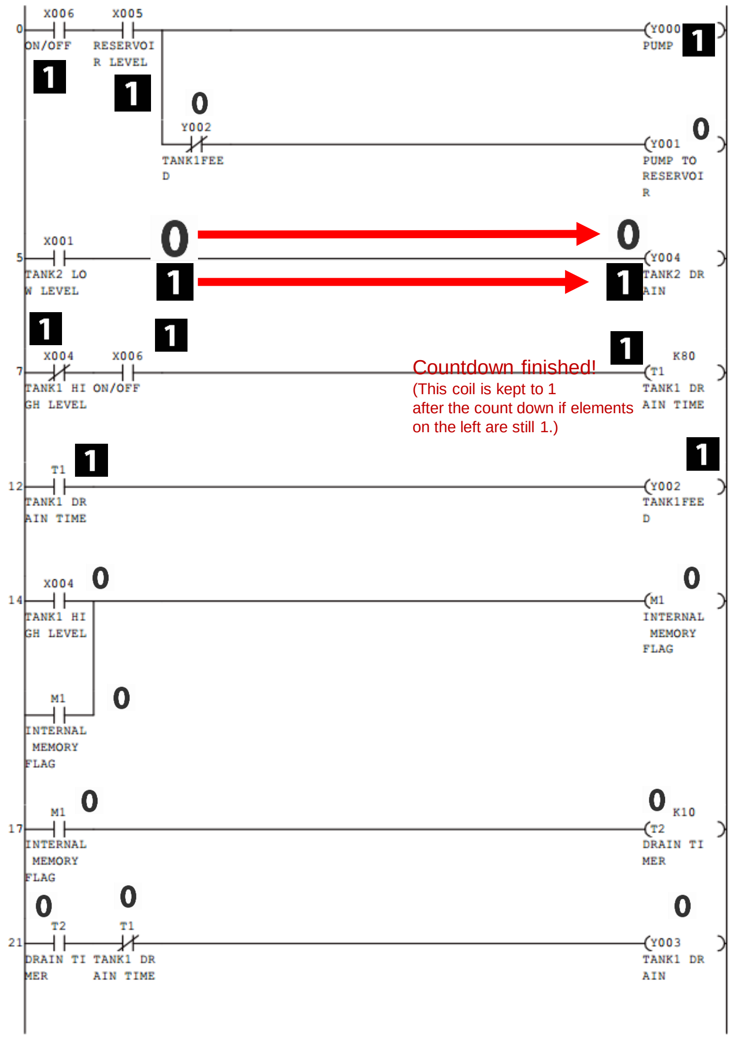
- Assume that there is no water in either tank.

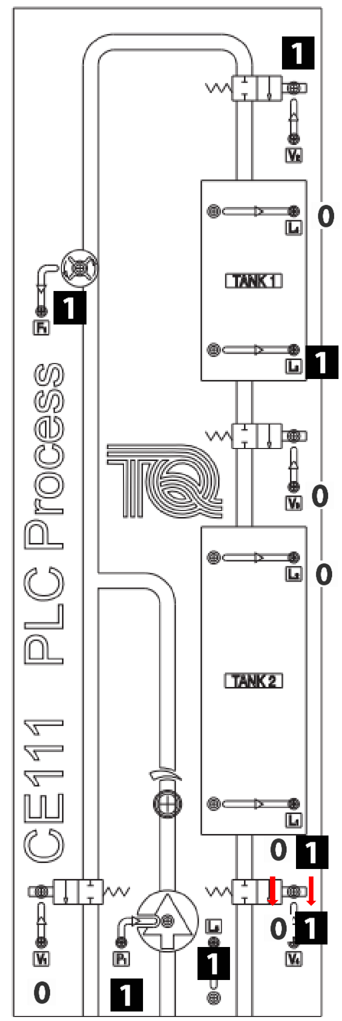




State C:
T1 just finished the count-down process and entered the feeding tank1 process

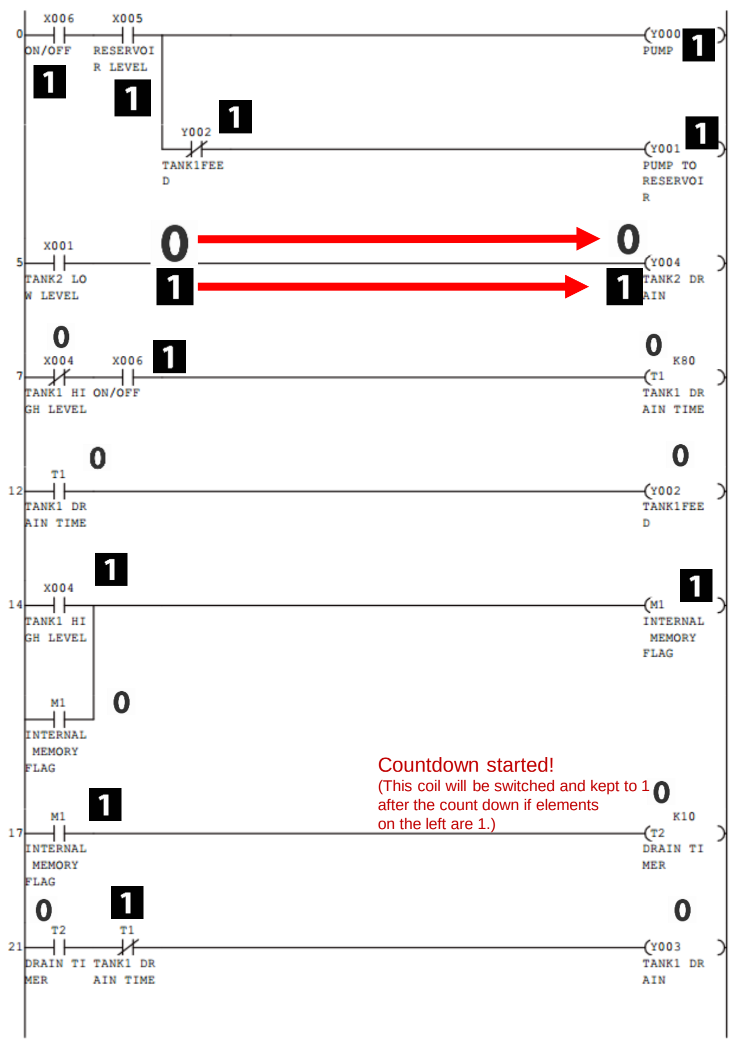
- Tank 1 is not full yet
- X006 keeps in ON mode

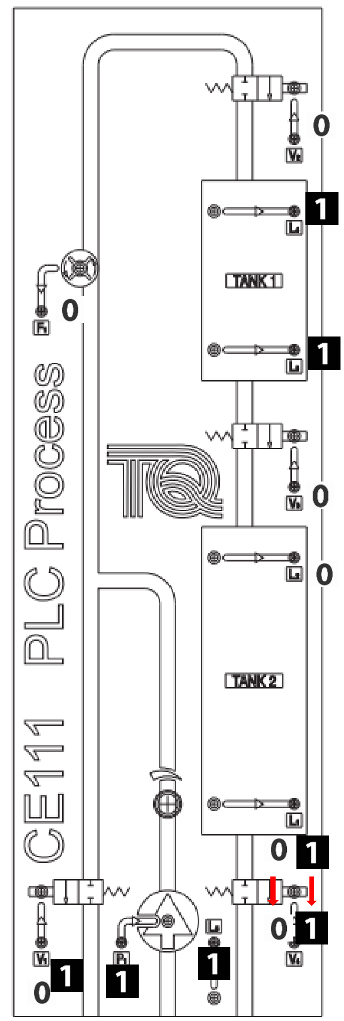




State D:
Water in Tank 1 had just reached the high level

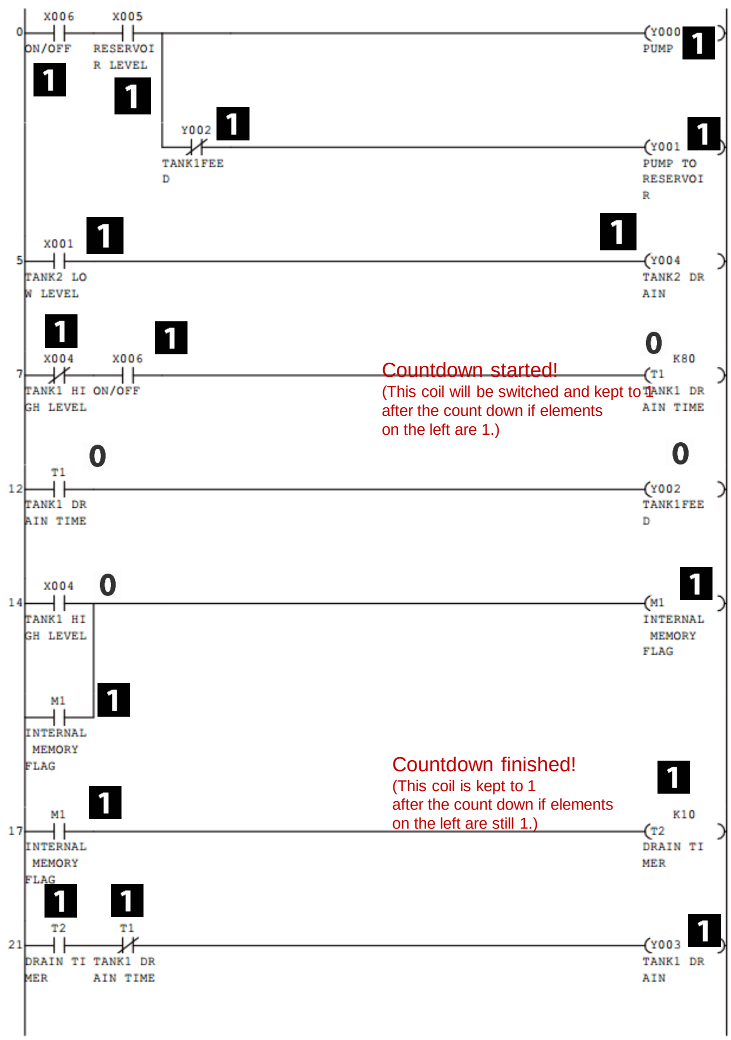
- The feed stopped immediately
- T2 enters count-down process

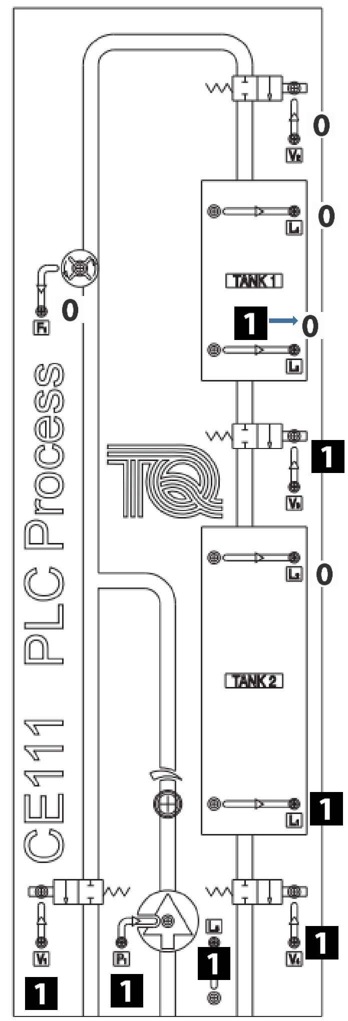




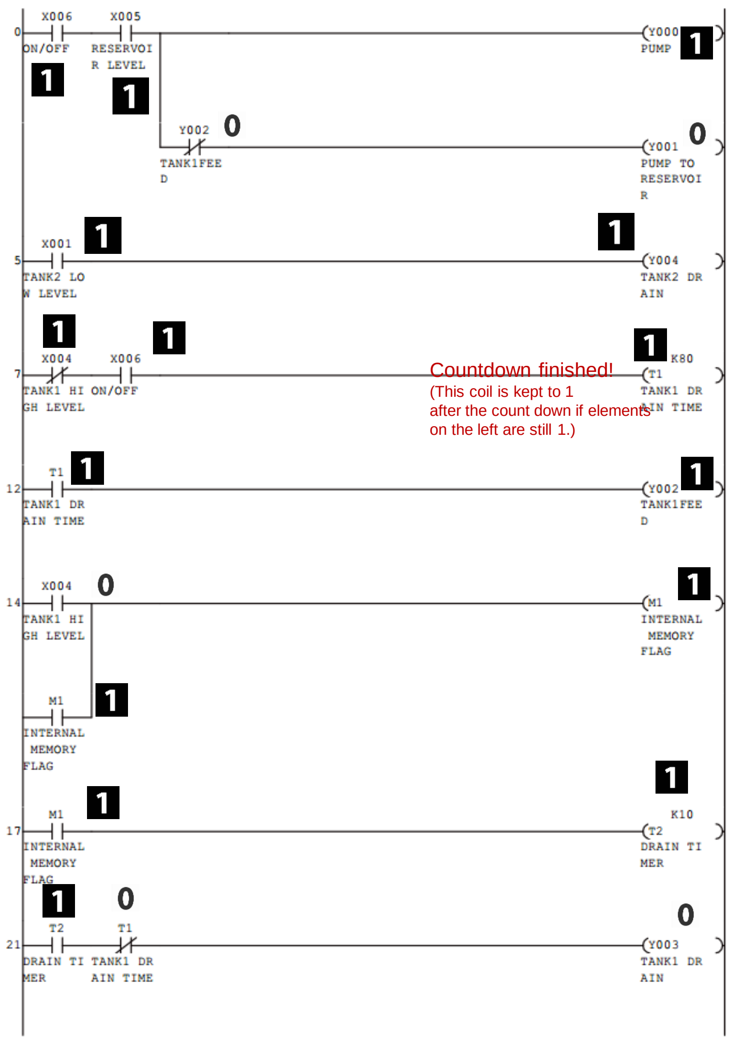
State E:
T2 finished count-down and Tank 1 started to drain

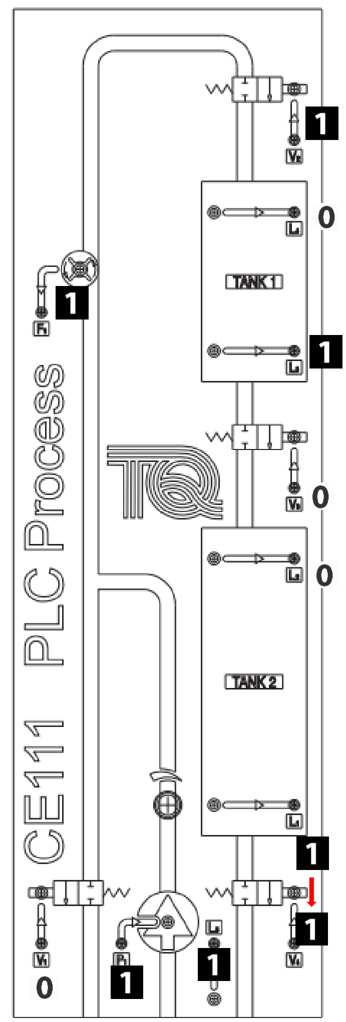
- Water in Tank 1 dropped lower than high level
- T1 entered count-down process





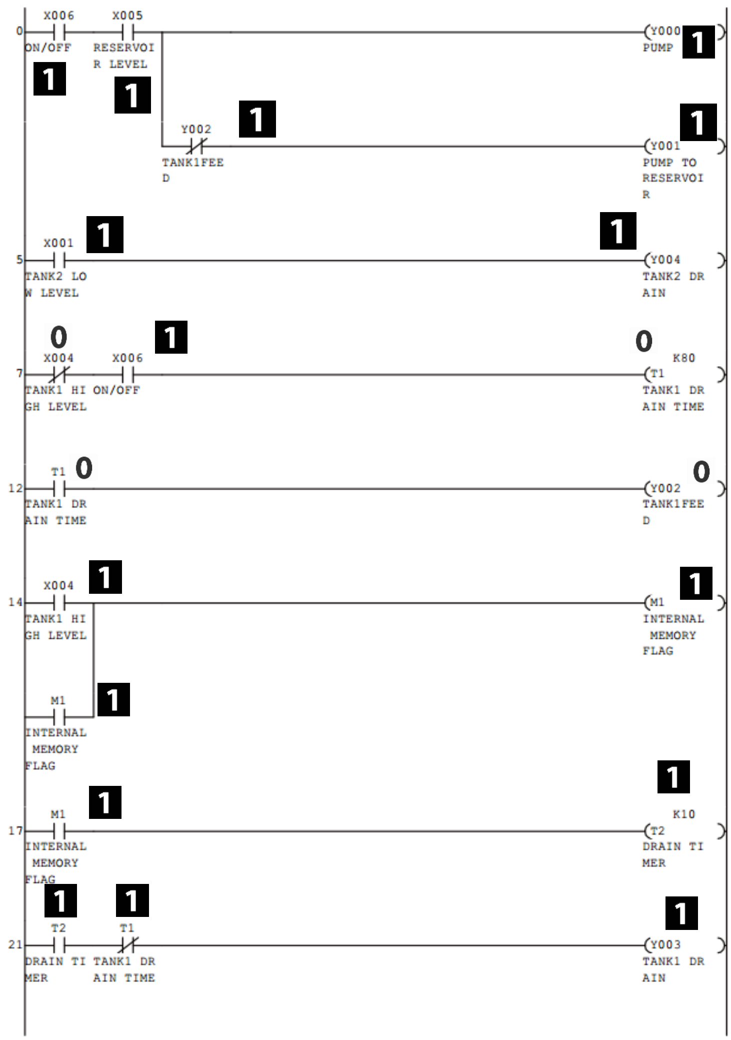
State F:
T1 finished count-down, drain stopped, and started to feed Tank 1

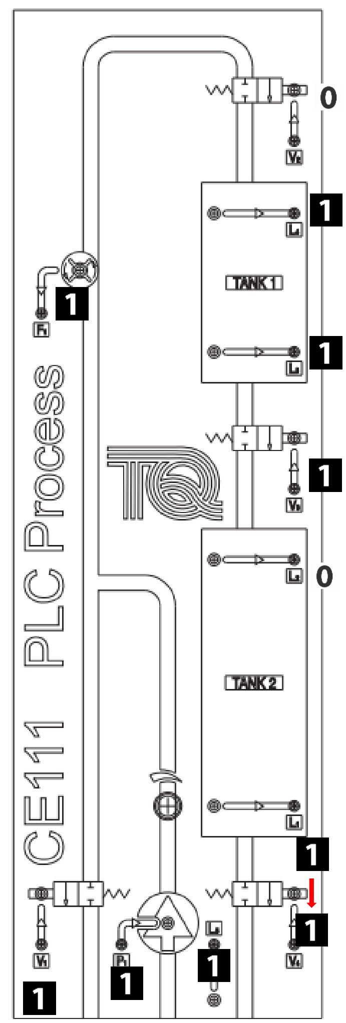




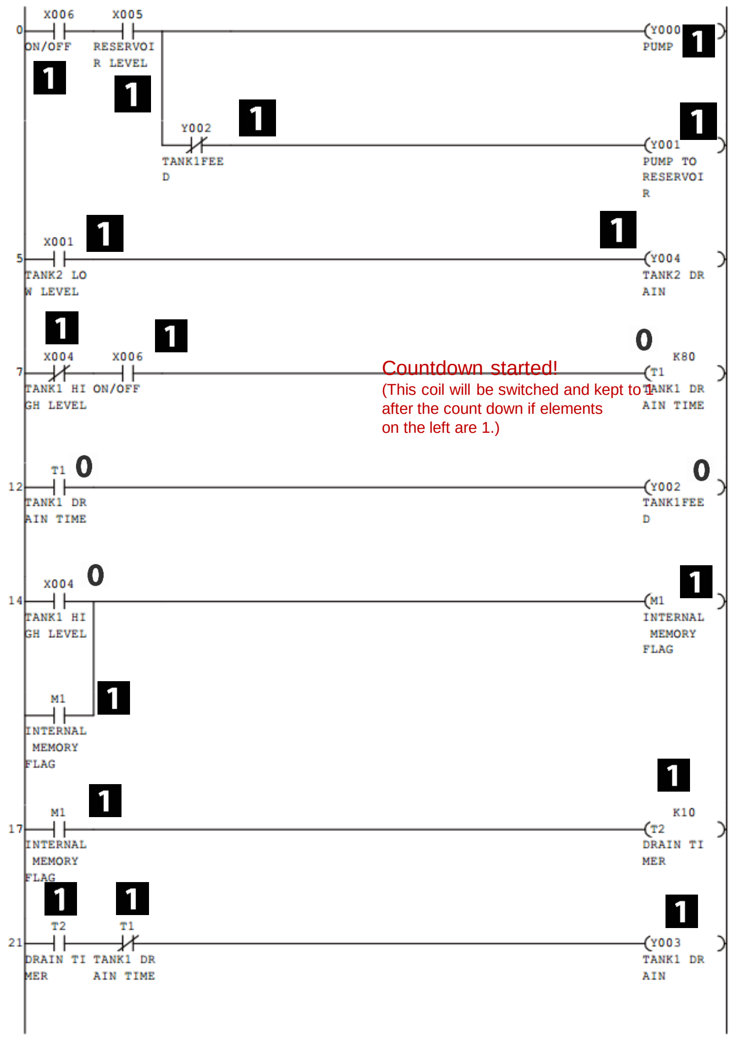
State G:
Water in Tank 1 had just reached the high level

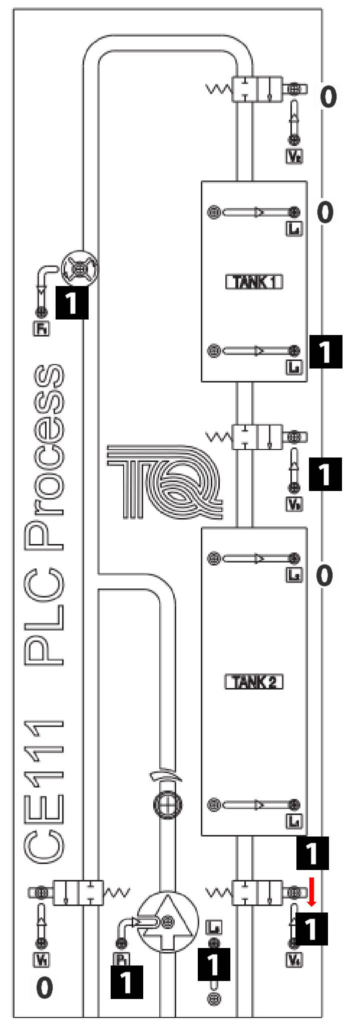
- The feed stopped immediately
- Timer1 reset to zero
- Tank1 Drain just started



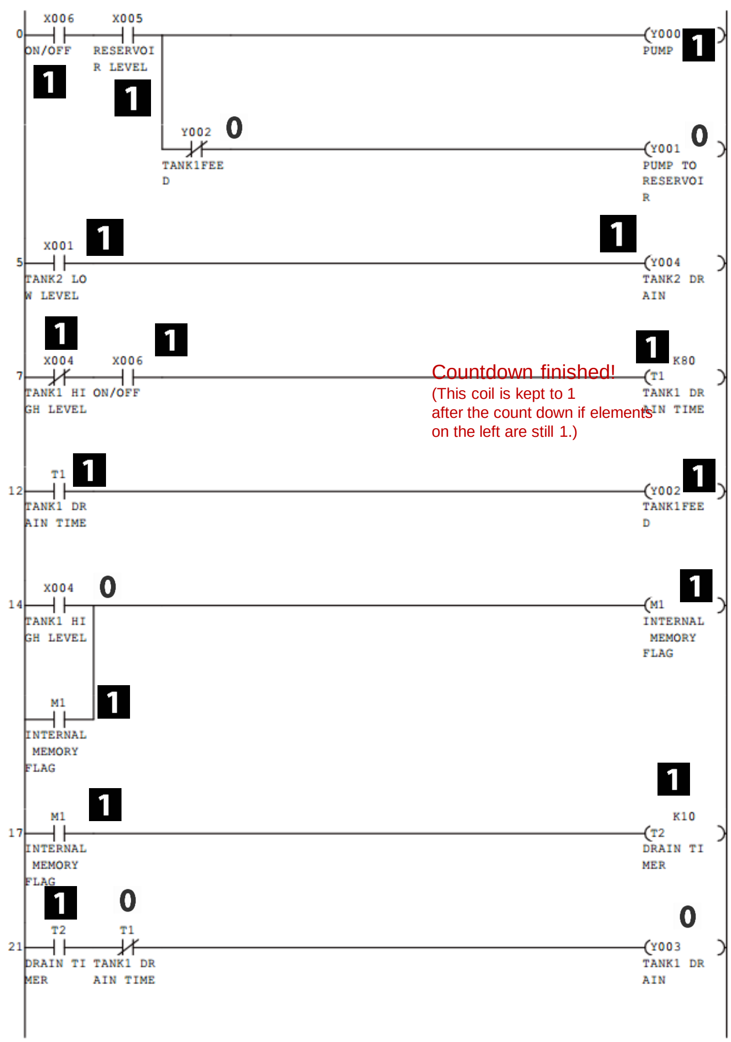


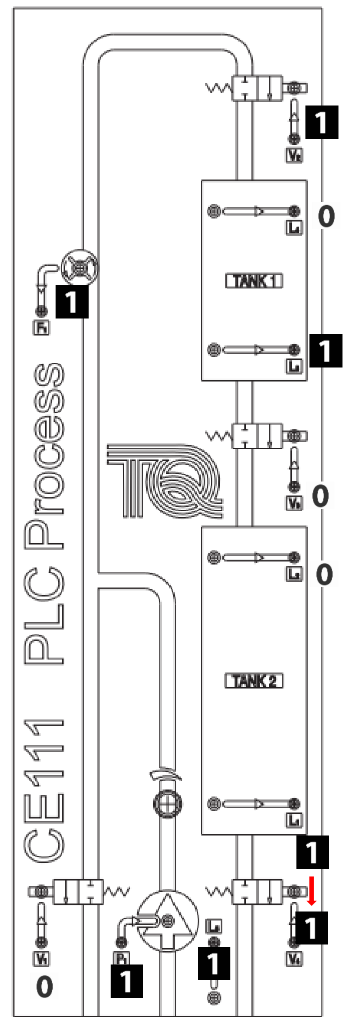
State H:
Water in Tank 1 was draining from high level





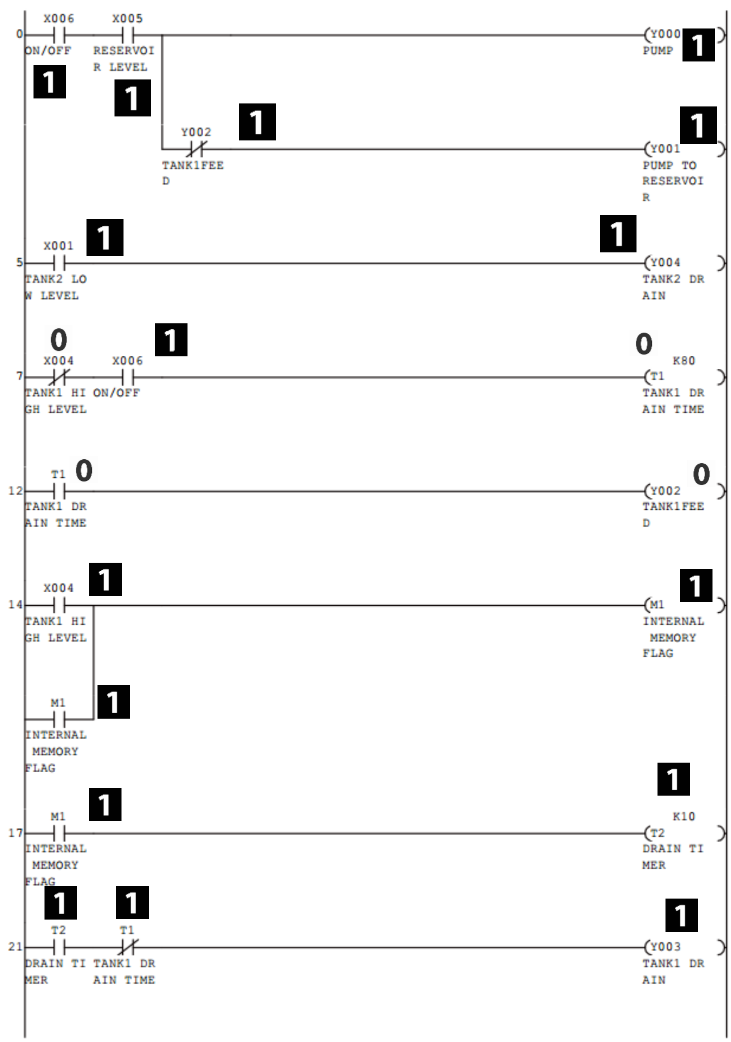
State F:
T1 finished count-down, drain stopped, and started to feed Tank 1

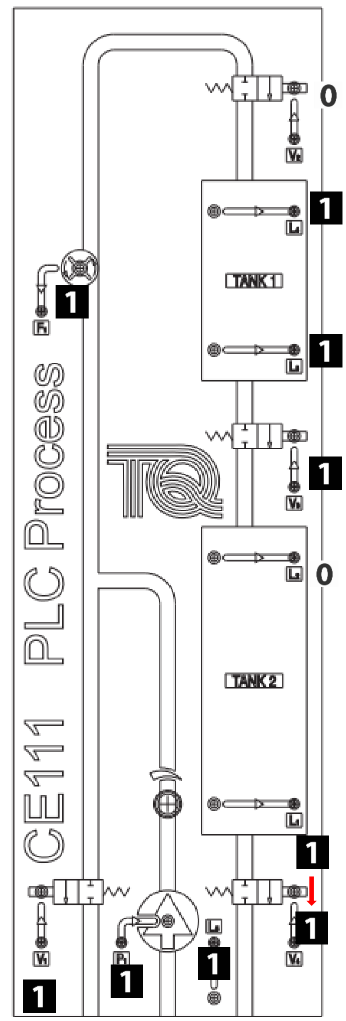




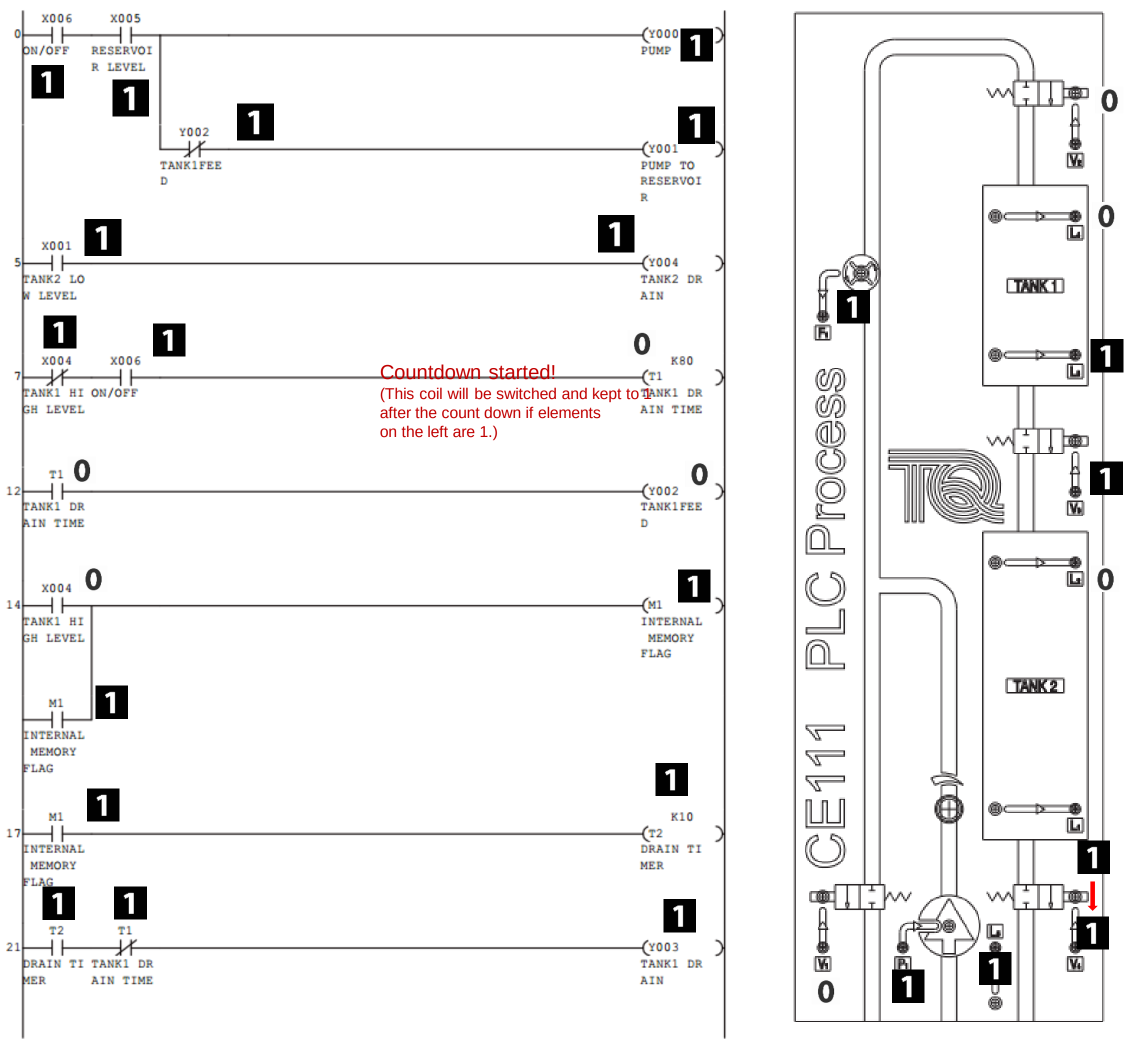
State G:
Water in Tank 1 had just reached the high level

- The feed stopped immediately
- Timer1 reset to zero
- Tank1 Drain just started

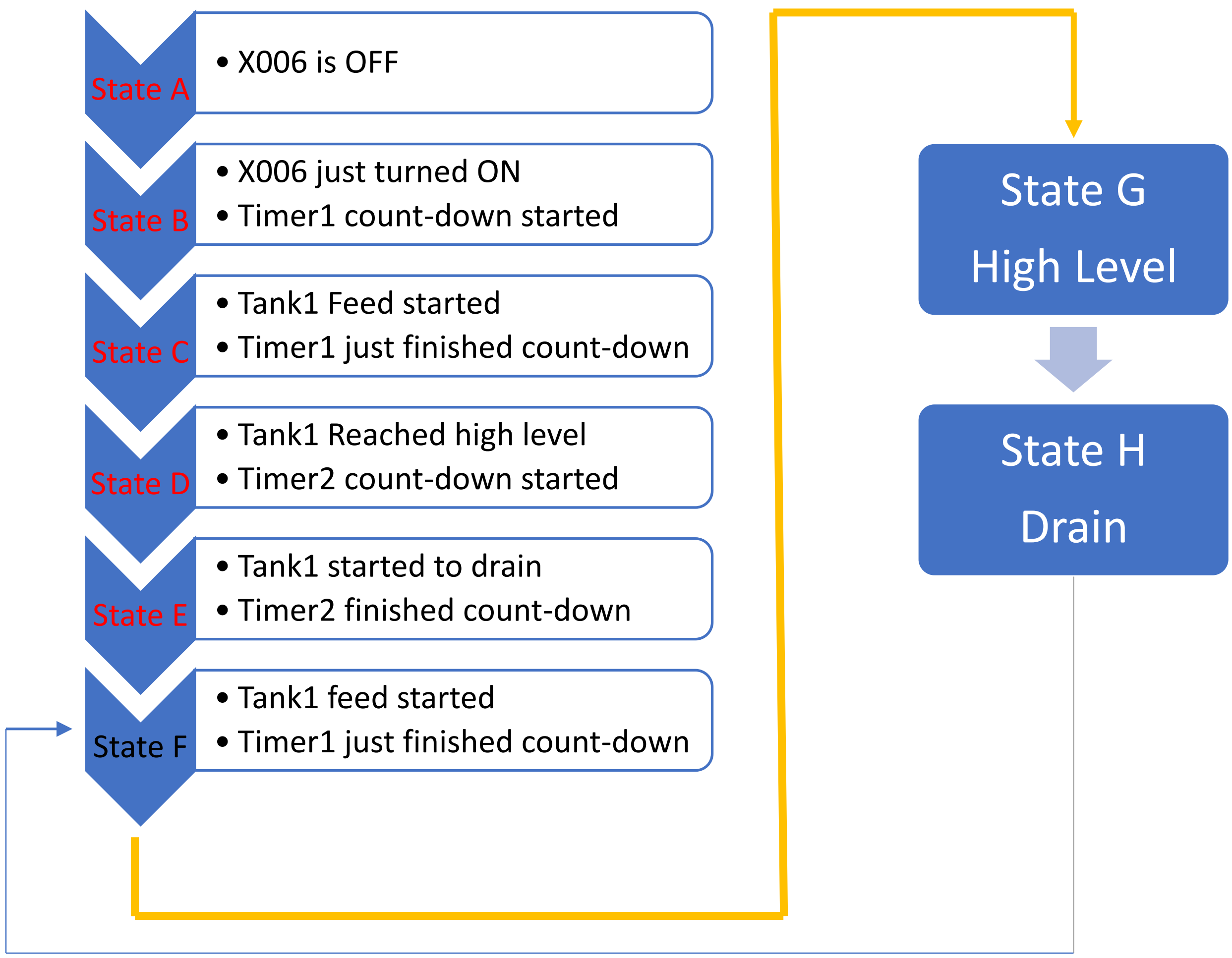




State H:
Water in Tank 1 was draining from high level



Keep looping in states of F G H


State A
• X006 is OFF
State B
• X006 just turned ON
• Timer1 count-down started
State C
• Tank1 Feed started
• Timer1 just finished count-down
State D
• Tank1 Reached high level
• Timer2 count-down started
State E
• Tank1 started to drain
• Timer2 finished count-down
State F
• Tank1 feed started
• Timer1 just finished count-down
State G
High Level
State H
Drain