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Design, Build and Validation of a Small-Scale Combustion Chamber Testing Facility

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DESIGN, BUILD AND VALIDATION OF A SMALL SCALE COMBUSTION CHAMBER TESTING FACILITY

THESIS

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AFIT/GAE/ENY/06-M06

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THESIS

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Eric R. Dittman

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Abstract

This study investigated the design parameters necessary for the construction and use of a testing facility built to evaluate advanced combustor designs for future gas turbine engines. User inputs were acquired by interview and by evaluating facilities at other organizations and used in the decisions made in the accuracy, capability, safety and flexibility of pieces of machinery and how different systems were to interact. All systems and measurements are designed to be compliant with the guidance set forth in SAE ARP 1256. Safeguard systems were also designed into the facility to maintain a safe work environment for the user. These safeguards include automatic fuel shut-offs, heater shut-offs, and general system power downs. While the system is designed to evaluate the testing of a planar 2-D section of the UCC, the labs now have the capability to analyze many systems. The facility, now built, has the ability to supply up to 260 SCFM of air in two legs with 200 SCFM and 60 SCFM splits. These air lines can be independently heated up to 500 °F. The testing area can flow both liquid and gaseous fuels, with a maximum flow rate of 340 mL/min for liquid fuels and 200 SLPM for gaseous fuels. The air flow and fuel flows combine to allow equivalence ratios up to 4 for JP-8 fuels. The facility is also capable of testing systems requiring combustion analysis following SAE ARP 1256 for testing of emissions, a system that requires heated air or fuel, a system that requires an exhaust system to pull gasses out of the testing area, or a system that needs open flame. These additional capabilities allow further research to be conducted on site with an ability to report standardized results.

DESIGN, BUILD AND VALIDATION OF A SMALL SCALE COMBUSTION CHAMBER TESTING FACILITY

I. Introduction

Background

In the never-ending pursuit of more thrust and better efficiency, the gas turbine engine is constantly being improved. More thrust, better efficiency, and more thorough combustion are always being pursued with advancements in technology and new innovations. The concept of a constant temperature (CT) cycle gas turbine engine has been proposed as a way to increase specific thrust (ST) with equal or reduced thrust specific fuel consumption (TSFC). While highly desirable, this would require burning in the turbine rotor, which may place the cost too high for initial production. A proposed alternative is a discrete inter-stage turbine burner (ITB). This concept would burn fuel in the turning vanes leading into the rotor. While this idea has shown improvements in ST by 50%, a conventional combustor is much too large to fit between the stages of a turbine (Liu and others, 2000:1).

In order to reduce the size penalties of a conventional combustor, an Ultra Compact Combustor (UCC) has been proposed. The UCC makes use of centripetal acceleration in an outer cavity to increase the speed of the combustion thereby allowing for a shorter combustor length. Another benefit of the UCC is that efficiencies of 99+% are achievable with multiple fuels. Anthenien et al. found that the flame length of the UCC is 50% the size of a conventional combustor section, which also opens up the possibility of using the UCC as the main combustor in a gas turbine engine to reduce engine length and weight since it is 66% shorter than a conventional burner (Anthenien and others, 2001:2). While these studies are encouraging, further studies are needed to improve upon the design and make the turning vanes more efficient. Non-intrusive measurements of the cavity-vane interaction are needed to accurately assess and improve upon the UCC design. To make this possible, it was decided that a new testing facility would be built at AFIT to test a 2D planar section of the UCC with optical access to the cavity-vane area. This is used to investigate the flow from the outer cavity down into the vane.

Objectives

In order for the further testing of the cavity-vane interaction, a facility would need to be built. The Air Force Institute of Technology currently does not have a facility that could control and measure combustion processes with the ability for visual measurements. The objective of the current research is to design, lay-out, build and begin the validation process of a small scale combustion chamber testing facility. Room 258 in Building 640 was already chosen for the laboratory; however no equipment was in place to run a combustion testing facility. The objective of the current thesis is to design and build a combustion testing facility with the ability for visual measurements and the flexibility for other types of future research. The laboratory will need to have access to a constant supply of heated air in order to reach flow velocities of 0.1 to 0.3 Mach in the test section. It will also need the ability to supply enough fuel to the test section for equivalence ratios up to 4 and down to 0.2 in the cavity to replicate previous work

(Anthenien and others, 2001:3). As with all research facilities, the ability to record and replicate the work done is a must. Also, safety is needed to protect the users of the laboratory and the equipment in the room. The efficiency of the combustion will also need to be analyzed. For this, samples of the emission gasses need to be taken and analyzed for the different concentrations of gasses in the emission. Finally, the entire system will need to be monitored from a computer station and the results compiled there.

Method

In order to accomplish the previously stated objective, the entire lab set-up needed to be designed. The following steps were used to design the testing facility:

1) What are the user requirements with the testing facility?
2) What are the minimal requirements to create a testing facility that can report valid results?
3) What future uses could the facility serve and how can they be planned for?
4) What is needed to create a safe work area?
5) How can the systems run in a manageable and repeatable way?

This thesis is organized to allow the reader to understand the design challenges and the reasons for why the facility is organized and designed as it is. The theory chapter outlines the basics of how the sub-systems work and why this affects the facility. The methodology chapter explains what is used in the testing facility, why and how it was installed. It will also outline the safety features included in the design of the room, give an overview of the accuracy of the system and how the data is recorded and test results are able to be replicated. The results chapter gives the reader an overview of the completed facility and how it runs along with the capabilities found therein. Finally, the conclusions and recommendations chapter gives ideas and suggestions for improving and using the facility. It also details what further work needs to be done.

II. Theory

Combustion

In a simple view, combustion is the process of turning oxygen and a hydrocarbon into water and carbon dioxide and releasing heat in the process. In a stoichiometric and complete combustion process, all of the hydrocarbons combine with oxygen molecules to form only water and carbon dioxide. This does not happen very often in real world situations. Air that is used in combustion does not consist of only oxygen. Air is composed of approximately 79% nitrogen and 21% oxygen (Warnatz and others, 1996:5-6). The nitrogen available in the combustion process along with incomplete combustion produce other gasses. One combustion performance parameter is to measure the concentration of these gasses (CO, CO_2, NO, NO_2, O_2, hydrocarbons) and use the combustion efficiency equation defined in SAE ARP1533.

SAE ARP 1533 defines a variable, the emission index, as the mass rate of production of a product divided by the mass rate of fuel flow, all multiplied by 1000 as seen in Equation 1 Emission Index.

$$EI_Z = \frac{\text{Moles of Pollutant}}{\text{Moles of Fuel}} \frac{\text{Molecular weight of Pollutant}}{\text{Molecular weight of fuel}} (1000)$$

Equation 1 Emission Index

The equations for the different emission indexes are defined in the Methodology section. These emission indexes need the concentrations of the different gasses found in the emission of the combustion.

While it is expected that a pressure drop should occur across the combustor, it is desired that this pressure drop be as small as possible. The measurement of the pressure across that combustor allows the user to gain insight about the performance of the combustor. The change in temperature is also important since heat is the main reason for combustion.

Before all of these performance parameters can be measured, fuel needs to be introduced to the combustion process. As stated before, the stoichiometric combustion occurs when all the hydrocarbons are combined with oxygen molecule to form only carbon dioxide and water. An example is seen in Equation 2 Example Stoichiometric Combustion. However, if less fuel is introduced to the combustion process and excess

$$2H_2 + O_2 \rightarrow 2H_2O$$

Equation 2 Example Stoichiometric Combustion

oxygen is introduced, this process is called a lean burn. If more fuel is added, then carbon monoxide is formed and un-burnt hydrocarbons can be produced. The ratio of fuel added to the stoichiometric amount of fuel is called the equivalence ratio. An

$$\Phi = \frac{(\text{Mole fraction fuel/Mole fraction air})_{\text{Actual}}}{(\text{Mole fraction fuel/Mole fraction air})_{\text{Stoichiometric}}}$$

Equation 3 Fuel Equivalnce Ratio

equivalence ratio less than one indicates a lean burn, and a ratio greater than one is a rich burn (Warnatz and others, 1996:5-6).

Emission Detectors

The detection of hydro-carbons in the emissions gasses is accomplished by a Flame Ionization Detector (FID). The California Analytical Instruments (CAI) Model

300-HFID works by maintaining a flame in a heated oven using controlled jets of pure hydrogen and oxygen. This flame becomes the negative electrode of a high precision power supply. Another electrode, called the collector, is placed opposite the flame and is connected to a high impedance, low noise electronic amplifier. These two electrodes create an electrostatic field in the oven. As the emissions gasses are passed through the flame, the hydro-carbons are ionized in the flame and then move to the respective electrodes in the oven. This movement of ions creates a small current which is measured by the amplifier. The current produced by the ionization of the hydro-carbons is directly proportional to the amount of hydro-carbons in the emission gasses (Model 300 HFID Manual, 2001:26).

Since the current is directly proportional to the total number of hydro-carbons, calibration of the instruments is needed. This is accomplished by passing gasses of known concentrations of hydro-carbons into the flame. The analyzer is calibrated using these known concentrations (Model 300 HFID Manual, 2001:23-24).

Oxides of nitrogen are another byproduct of combustion and determining the amount in emissions is important to predicting pollutant emission. Concentrations of nitric oxide (NO) and nitrogen dioxide (NO_2) are determined by passing the emissions through a heated chemiluminescent detector (HCLD). The CAI Model 400-HCLD works by utilizing the chemiluminescent reaction between ozone and NO. The reaction between NO and ozone yields NO_2 and oxygen (O_2). Approximately 10% of the NO_2 from this reaction is in an excited state and as it changes back to a normal state produces light. This light is proportional to the mass flow of the NO_2 in the reaction chamber. A photodiode tube measures the light and the signal is then amplified. This measures only the NO in the emission gas, in order to measure the total concentration of the gasses, the sample is first passed through an internal NO_2 to NO converter. Then the gas analyzed as before (Model 400 HCLD Manual, 2003:23).

The level of Carbon Monoxide (CO) and Carbon Dioxide (CO_2) in the emission gasses is measured by using the principle that each type of gas demonstrates a unique absorption of infrared light. The analyzer used in the lab uses a setup found in Figure 1 CAI Model 300-NDIR Analyzer.

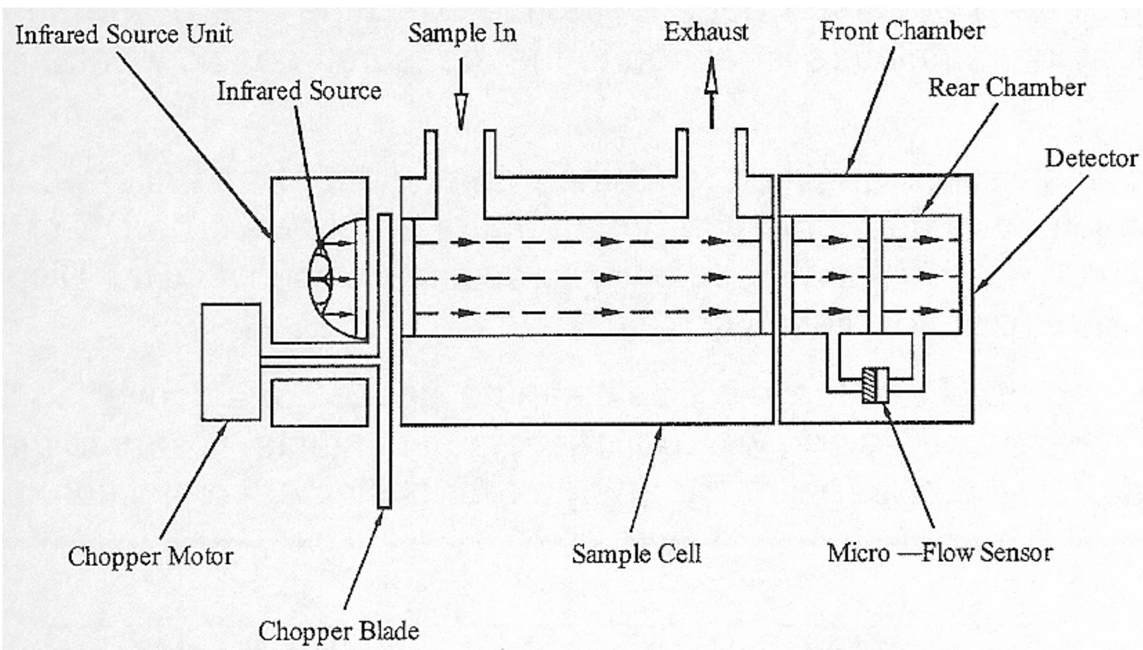

Figure 1 CAI Model 300-NDIR Analyzer

Using a curved reflecting surface, all of the light from an infrared source is directed into a chamber where the sample gas is passed. Before it enters the chamber, the light passes through a chopper wheel so the light can be modulated at a regular frequency. Once in the chamber, the light is partially absorbed by the emission gasses. After leaving the sample chamber, the light passes into a front chamber, and then onto a rear chamber, both holding the gas that is to be measured. The light is further absorbed by the gas in the front chamber and then the residual light is absorbed by the gas in the rear chamber. The absorbed light causes the pressures in these chambers to rise, however the pressure in one chamber will rise more than the pressure in the other. This pressure differential is measured by a micro flow sensor positioned between the two chambers. The sensor creates a small AC signal, which is then transformed into a DC voltage. The amplitude of the DC voltage decreases as the concentration of the measured gas increases, as seen in Figure 2 Signal Versus Concentration of Gas.

The absorption of infrared light by other gasses present can cause interference in the signal produced. The two chamber system in the current setup minimizes the contribution by interference gasses. The differential pressure system of the CAI Model 300-NDIR reduces the effect of the extra absorption by the interference gasses through the different rises in pressure of the front and rear chambers (Model 300 Infrared Manual, Sec 2. 8-10).

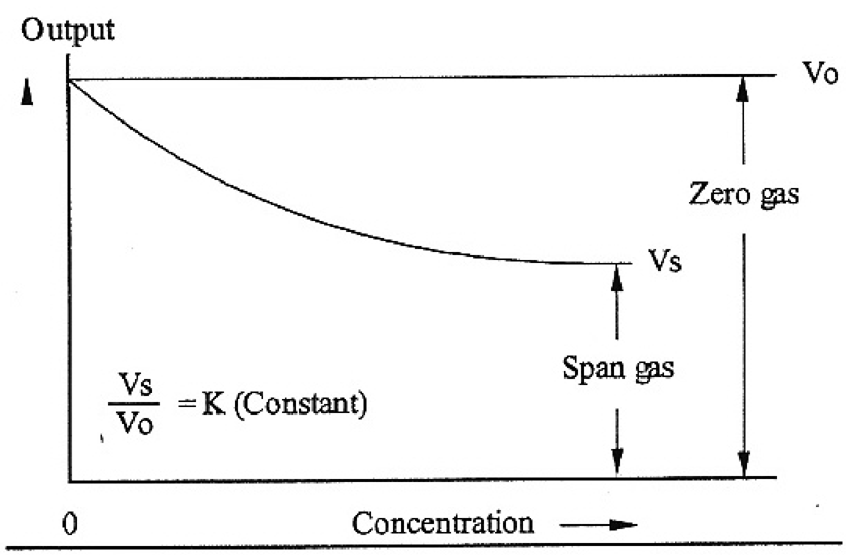

Figure 2 Signal Versus Concentration of Gas

Measurement of oxygen levels is accomplished by means of a paramagnetic oxygen detector. This detector works on the attraction of oxygen molecules to a magnetic field. Oxygen is much more strongly attracted to a magnetic field than other common gasses, while some common gasses such as nitrogen are diamagnetic, or are repelled by a magnetic field. This phenomena is seen in Figure 3 Magnetic Susceptibility of Gases.

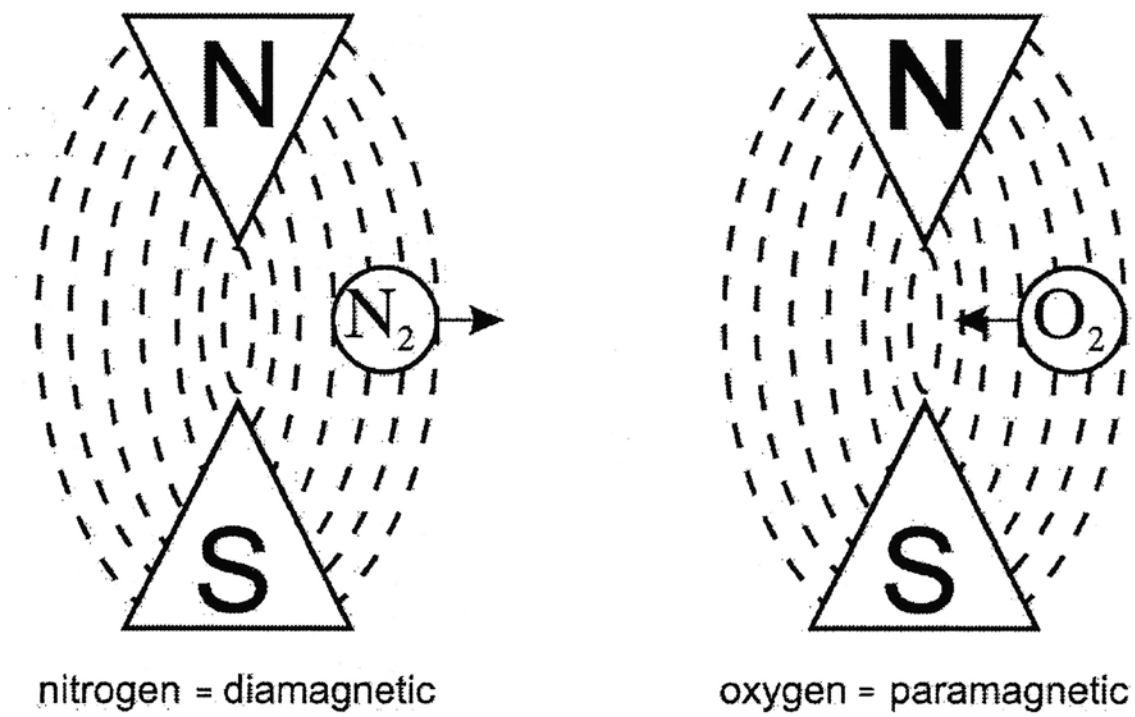

Figure 3 Magnetic Susceptibility of Gases

Using this principle, the CAI Model 300-Paramagnetic Oxygen Sensor can accurately measure the concentration of oxygen in the emission gas. The sensor consists of two nitrogen filled spheres arranged in a dumbbell shape. A single turn of platinum is placed around the dumbbell as shown in Figure 4 The Measuring Cell in Theory. The dumbbell is then suspended in a symmetrical non-uniform magnetic field. As the sample gas passes

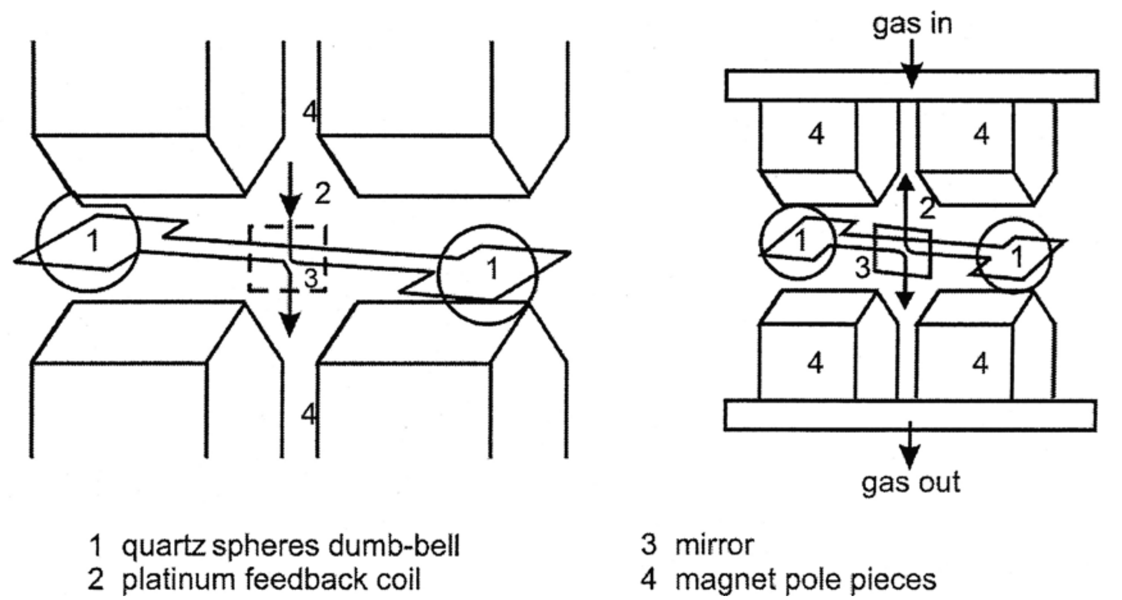

Figure 4 The Measuring Cell in Theory

through the magnetic field, the nitrogen spheres are displaced by the change in the field caused by the presence of oxygen. The torque acting on the dumbbell is proportional to the paramagnetism of the surrounding gas, and therefore can be used to measure the oxygen concentration of the gas.

A further refinement of the measurement is done with a mirror attached to the dumbbell. A light is transmitted to the mirror and reflected back to two photocells.

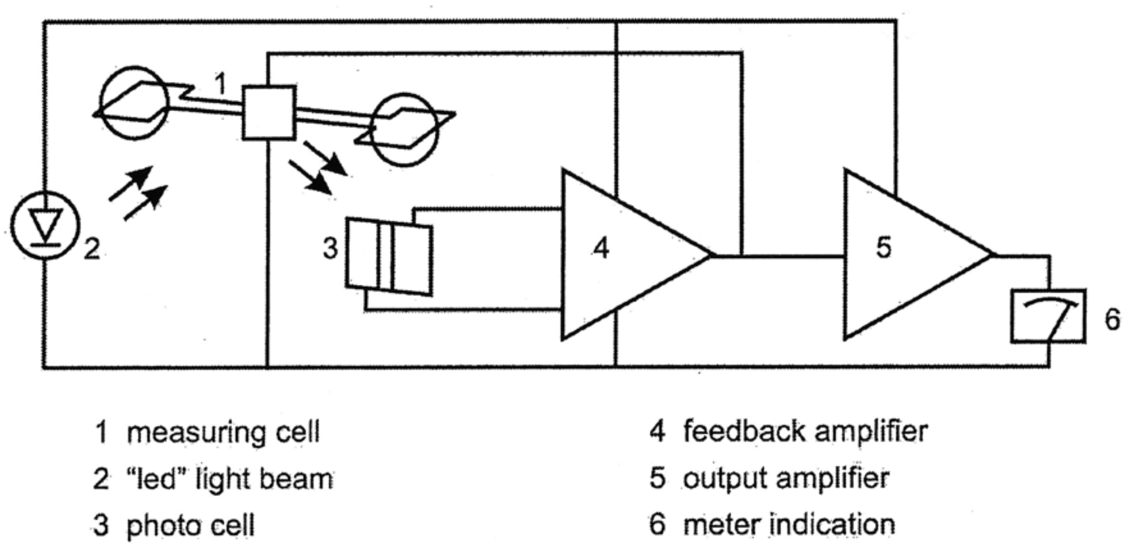

Figure 5 Principle of Operation

When both photocells measure the same intensity of light, the oxygen concentration is zero. As the dumbbell twists, the photocells will measure different intensities, which is again proportional to the oxygen content of the sample gas. This signal is also sent to the feed back coil. As the oxygen content of the gas changes, the signal produces a magnetic field in the feedback coil, opposing the force of the moving dumbbell, causing it to return to its original position.

Lastly on the paramagnetic oxygen detector, the paramagnetic properties of oxygen are inversely proportional to the temperature of the gas. To compensate for this, a temperature sensitive element is in contact with the measuring assembly. This provide a small correction in the feedback current loop (Supplemental Oxygen Manual, Sec. 6, 17-19).

Measurement and Control Devices

Mass Flow Meter

One of the measurement and control devices used in the laboratory is a Fox Thermal Instruments Model FT2 flow meter. By using two heated elements the device measures the flow of the line in cubic feet per second. One heated element is positioned in the stream of passing air. The second element is isolated and held at a constant temperature. As the air passes by the first element, the element is cooled through convective heat loss. The sensor increases the amount of energy in the element to maintain the element at the same temperature as the isolated element. The difference in the amount of energy used between the two elements is directly proportional to the mass of the flow. By setting a standard for the gas at a predetermined temperature, the mass flow rate of the fluid can be accurately measured (Fox Thermal Instruments, Rev. E, 1).

Figure 6 Fox Thermal Instruments FT2 Flow Meter

Heated Sample System

When the emission sample is taken just after the test section, the gas needs to be held a temperature outlined in SAE ARP 1256. This temperature is 320 °F ±20 °F. The reason that the gas needs to be held at this temperature is to insure that any moisture in the gas remains in a gas state and does not condense. Any moisture collection on the previously mentioned detectors can drastically affect their accuracy and life. To maintain the emission gasses at 320 °F, a heat transfer system is used. A large heater and pumping unit keeps a heat transfer fluid at a temperature high enough to maintain the emission gasses in the desired temperature range.

III. Methodology

To better study the UCC, it is desired that a visual method of measuring the cavity-vane interaction be available. There are facilities at Wright-Patterson Air Force Base (WPAFB) that allow the testing of axi-symmetric combustors; however it is very difficult to obtain optical off-axis measurements in an axi-symmetric combustor. The axi-symmetric combustor has a large main flow of air that runs parallel to the axis of the test

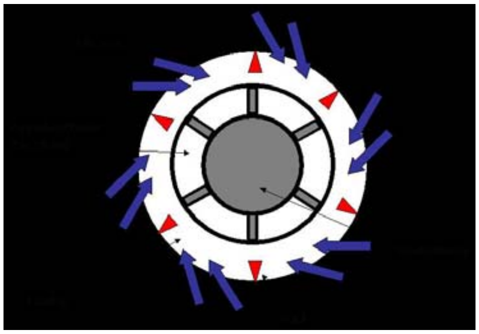

Figure 7 Diagram of the UCC

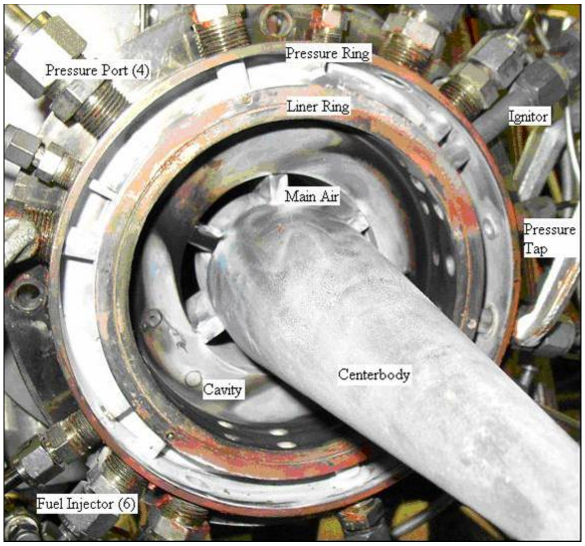

Figure 8 Rear View of UCC

section. The cavity runs around the main flow creating a ring around the axis. In this ring, the air and fuel mix and ignite the air and fuel. This ring makes it very difficult to access the cavity-vane area with optical instruments. To facilitate the use of laser Doppler velocimeters, PIV, PLIF and other measuring tools, the cavity-vane section of the combustor needs to be simplified into a two dimensional configuration with optical access to the cavity and vanes. This is accomplished by taking a small section of the axi-symmetric test section. The main flow is still modeled the same, by running a large amount of air in a straight line. The cavity and the spinning air are modeled differently. Instead of running the air all the way around the main flow, a small piece of the cavity is used and the air is run perpendicular to the main flow. Since the planar section is a small piece of the larger axi-symmetric section, the perpendicular model can closely model the original. The main loss occurs in the acceleration loading that occurs in the axi-symmetric model. By changing the combustor to a two dimensional problem, it is possible to use have off axis optical access in the test section of the combustor. It was decided to build a facility at the Air Force Institute of Technology (AFIT) for this purpose after discussing the options with AFPL/PRTC at WPAFB.

Room 258 in Building 640 was chosen for the combustion lab. The room started out as a bare room with no support systems in the room. The layout of the pieces of the facility was chosen by the author using input from future users of the facility. The room was then built using the author’s designs by the author and a lab technician. All parts of the facility were chosen and purchased in coordination with the author’s advisor to insure correct use of funding. Software for the facility was written by the author unless otherwise noted. The only piece of hardware previously purchased prior to the thesis was the analyzer rack. The thesis will include the choice of the analyzer rack; however these decisions were made prior to the author's current study.

Air Lines

The main limiting factor in designing a testing facility at AFIT is the air supply. While AFIT does have a blow-down system that allows for large quantities of air to pass through a testing area, the nature of combustion experiments and the need to achieve thermal equilibrium between test points require a long sustained supply of air. The air compressors at AFIT are able to supply 260 standard cubic feet per minute (SCFM) at 200 psig on a sustained basis. Previous experiments were able to take advantage of facilities that could supply around 575 SCFM through three independent lines. Without this large of a supply of air, the facility at AFIT needs to change certain parameters of the combustor in order to still meet critical experimental parameters.

One of the important experimental parameters that need to be met is the velocity of the air through the test section. In previous UCC experiments the velocities tested in the main flow were between 0.1 and 0.3 Mach and cavity velocities of 10 to 50 m/s (Anthenien and others, 2001:3). In order to reach these velocities with the 260 SCFM that AFIT can supply, a 1/6 slice of the axi-symmetric UCC was used. The sizes of the inlets are 0.672 square inches and 1.204 square inches. At this size, the 260 SCFM total will provide enough continuous air to run the test section at a maximum speed of 0.3 Mach at sea level through the main inlet. To provide for the proper split of air, only 168 SCFM are needed for the main section, but to allow for greater flexibility, 200 SCFM run through the main air line and the remaining 60 are in the secondary air line. The 60 SCFM will provide sufficient air to achieve the 10 to 50 m/s in the cavity.

Control valves are needed in both air lines to regulate the flow of air and decrease the flow when slower velocities are desired. A needle valve is placed in each air line to restrict the flow of air continuing down the line. Needle valves are excellent for controlling the flow due to the ability to fine tune the amount the needle constricts the flow.

The needle valve needs to be controlled automatically in order to make the system work. Changing combustor conditions can change heat released and the back pressure in the line. A process controller is needed for this purpose. A process controller is used to automate the control of a feedback system. In this case, the process controller will be used to control the needle valve, and consequently the flow of the line. The process controller receives a setpoint from the user through a computer to establish the desired valve to be controlled, i.e. the flow of the air line. The process controller also receives the actual flow of the pipe from the aforementioned flow meter stationed upstream of the needle valve. The flow meter sends the process controller the actual flow of the air line and the process controller then compares this to the setpoint. The process controller then calculates what the new position of the needle valve to correct the flow to the setpoint. The needle valve is pneumatically actuated. The process controller sends the correction signal to a current to pressure transmitter. This device takes the process controller signal and changes it to the proper pressure level for the needle valve.

While needle valves are excellent for fine control of an air flow, they have difficulty at the ends of their ranges. Needle valves have a tendency to snap open or shut when the come close to the end of their range, making control of the flow extremely difficult at these points. A pressure regulating valve is used upstream of the flow meter and needle valve to regulate the pressure of the flow in the pipes. The AFIT compressor can achieve 200 psi. The pressure regulating valve takes and reduces the line pressure to a user set value. By decreasing the pressure in the line, a greater range of flow rates are achievable. This also allows the needle valve to only work in a range where it is most accurate and not near the edges of its range.

Pressure transducers and thermocouples have been placed in both air lines to monitor and record conditions in the line. The locations and numbers of these measurement devices can be seen in Figure 10 Air Lines. The flow meter also sends the computer a temperature signal. These values give the user a better picture of the conditions of the flow and how the user needs to adjust controls to create the test condition that are desired.

Since the combustion tests use JP-8 as a fuel, the air lines connected to the test section need to be heated. The heated air is required due to the high flashpoint of the fuel. The heaters used on both air lines are large electric resistance element type heaters. These heaters are capable of heating the air up to 1000 °F if needed. However, these temperatures will not be reached due to the temperature limitations of the composite hoses used at the combustor rig.

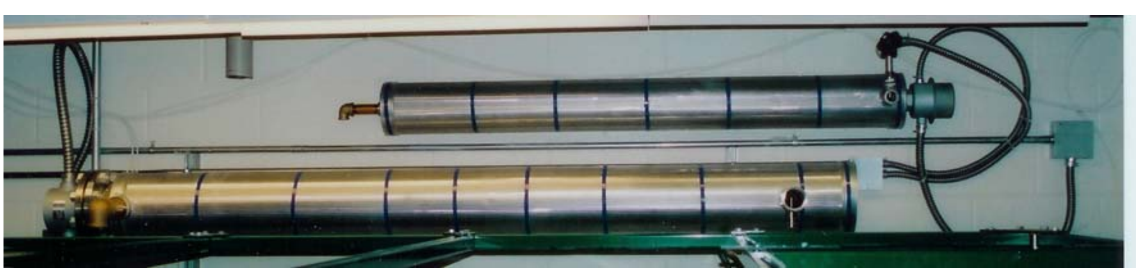

Figure 9 Air Heaters

The heaters have process controllers located inside the power box. These process controllers can be controlled manually or remotely just like the previous ones. The large power boxes were chosen since they allow for the user to restrict access to the power on functions and to allow the computer to run the heater setpoint remotely.

Insulated stainless steel pipes take the heated air to the test section. Composite hoses take the heated air the remaining six feet to the combustor. As stated before, these hoses restrict the maximum temperature of the heated air to 500 degree F. The hoses are used to allow the test section to have a range of motion for easier data collection. Rather than having to move a large and cumbersome laser table to the proper measuring location, the hoses allow the user to move the test section to the proper location. See Figure 10 Air Lines for a drawing of the air lines.

Fuel Lines

Now that the air lines are designed to match previous experimental numbers, the fuel system needs to match as well. Using previous UCC experiments as a basis, the fuel system would need to match the range of equivalence ratios that the other facility used, or ratios of 0.5 to 4. In order for the fuel system at AFIT to match the ratios, the fuel system needs to deliver 281.5 mL of JP-8 per minute. For this reason, the ISCO 1000D series pump was chosen to deliver the fuel. Each pump can flow 340 ml/min of liquid at a

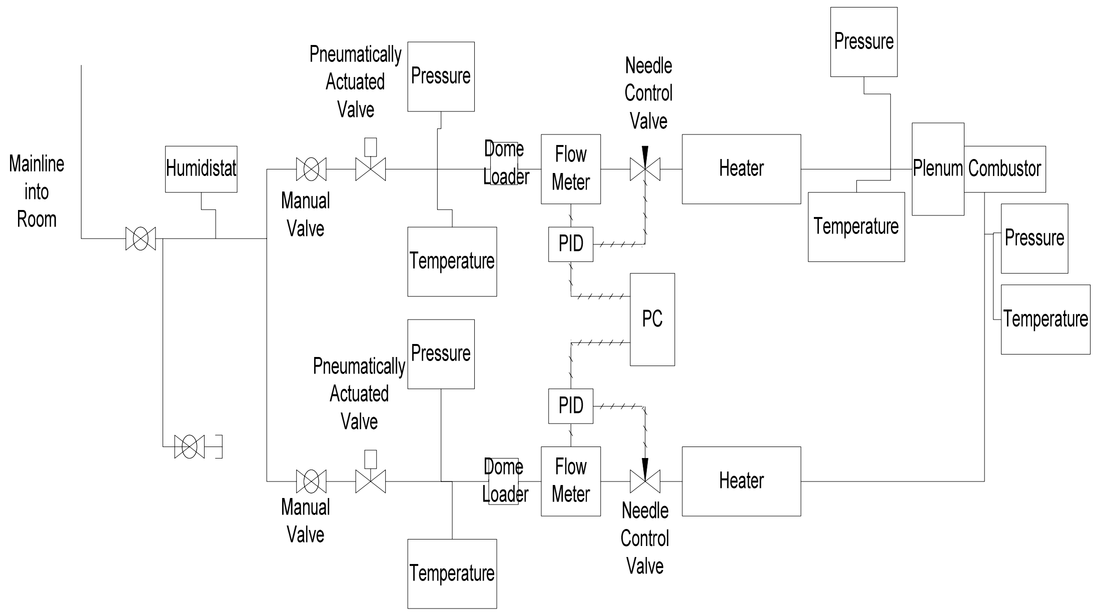

Figure 10 Air Lines

pressure of 137.9 bar and can flow up to 408 mL/min at reduced pressures. This flow rate allows the system to run at the same equivalence ratios that the previous experiments did. The ISCO Model 1000D pump is a syringe type pump and has a high degree of accuracy, accurate to 25.38 nL, which insures accurate and measured fuel delivery, however an individual pump needs to stop the flow to refill.

To further improve the fuel delivery system, a dual pump system was incorporated. The two pumps allow the system to continuously deliver fuel to the test section until the reserve canisters run out. This is accomplished by a switching system set-up between the two pumps. Pneumatically actuated, the control box for the pumps signals for one pump to turn on as the other stop delivering fuel. The empty pump then refills and awaits use after the second pump finishes.

Other features in the fuel line include safety valves. A manual quarter turn valve sits between the fuel pumps and the fuel canisters. A pneumatically actuated ball valve sits after the fuel pumps to shut off the fuel in an emergency. Finally, the fuel passes through a filter before an injector sends it into the combustor. Figure 11 Fuel Line is a drawing of the fuel line.

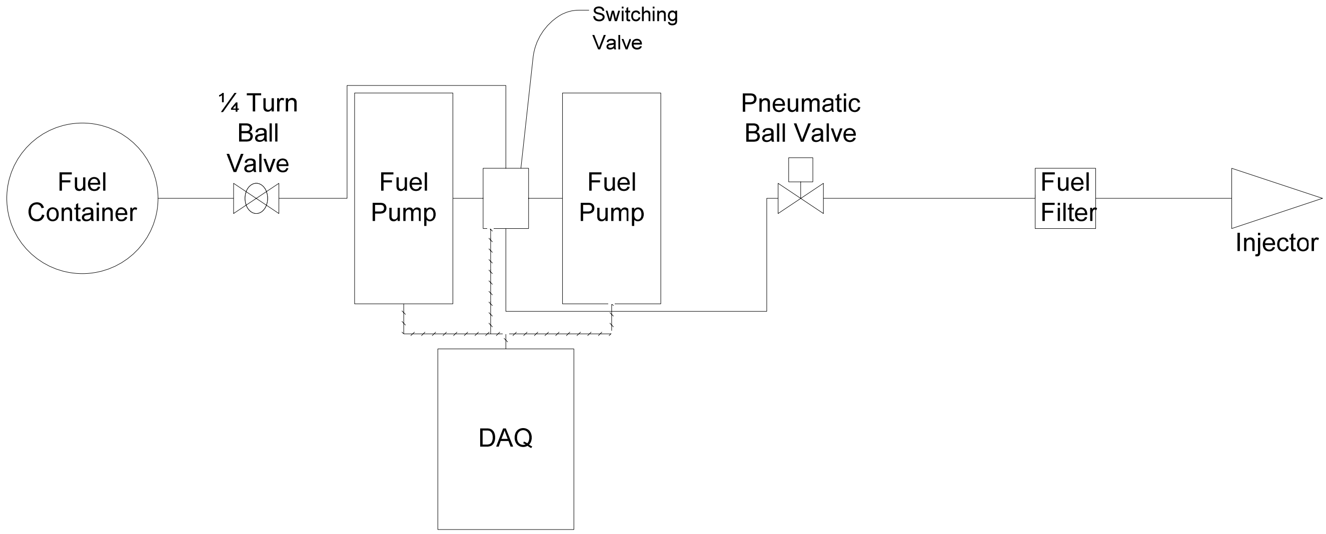

Figure 11 Fuel Line

Combustion Measurements

With the air and fuel lines in place, combustion can occur. However, proper reporting of combustion efficiencies or products cannot happen yet. To properly report combustion efficiencies, the concentrations of certain combustion products must be known. The efficiency equation for combustion appears in Equation 4 Combustion Efficiency in SI units.

$$\eta_b = \left[1.00 - 10109\frac{EI_{CO}}{H_C} - \frac{EI_{C_xH_y}}{1000}\right](100)$$

Equation 4 Combustion Efficiency in SI units

Where EI_{CO} and $EI_{C_xH_y}$ are defined as follows:

$$EI_{CO} = \left[\frac{[CO]}{[CO]+[CO_2]+[C_xH_y]} \right] \left[\frac{10^3 M_{CO}}{M_C + \alpha M_H} \right] [1 + T(X/m)]$$

Equation 5 Emission Index for CO

$$EI_{C_xH_y} = \left[\frac{[C_xH_y]}{[CO]+[CO_2]+[C_xH_y]} \right] \left[\frac{10^3 M_{C_xH_y}}{M_C + \alpha M_H} \right] [1 + T(X/m)]$$

Equation 6 Emission Index for CH

Where [CH], [CO], and [CO_2] are the mole fraction concentrations of the respective gasses and $M_{C_xH_y}$, M_C, and M_H are the molecular weights of the molecules. α is y/x which is the ratio of hydrogen atoms to carbon atoms of the fuel and T is defined as the molecular fraction of carbon dioxide in the air and has an accepted value of 0.00033. Further definitions are as follows:

$$\left[\frac{X}{m} \right] = \frac{2Z - \alpha}{4(1 + h - (TZ/2))}$$

Equation 7

$$Z = \frac{2 - [CO] - \left[\frac{2}{x} - \frac{y}{2x} \right] [C_xH_y] + [NO_2]}{[CO]+[CO_2]+[C_xH_y]}$$

Equation 8

Where h is the humidity of the air, which is found by placing a humidistat at the beginning of the air line.

As seen in the previous equations, the concentration of gasses in the combustion emissions needs to be known. Therefore, a proper emissions analyzer is needed. The Society of Automotive Engineers has established standards for the collection of emission products. ARP 1256 outlines the minimums that are needed by different analyzers for proper reporting of these concentrations. These minimums are found in Table 1 Required Performance Minimums (SAE ARP 1256).

Table 1 Required Performance Minimums (SAE ARP 1256)

Analyzer Type	Performance Specs	Zero Drift	Span Drift	Noise	Precision
CO and CO2 analyzer	Nondispersive infrared analyzer	Less than ±1% full scale in 1h	Less than ±1% full scale in 1h	Less than ±1% full scale	Better than ±1% full scale
Total Hydrocarbon Analyzer	Flame Ionization Detector	Less than ±1% full scale in 1h	Less than ±1% full scale in 1h	Less than ±1% full scale	Better than ±1% full scale
Oxides of Nitrogen Analyzer	Chemiluminescence Analyzer	Less than ±1% full scale in 1h	Less than ±1% full scale in 1h	Less than ±1% full scale	Better than ±1% full scale

Using these minimums as a baseline in searching for analyzers, California Analytical Instruments (CAI) was chosen as a supplier for the analyzers. The Model 300-HFID, Model 400-HCLD, Model 300-NDIR, and Model 300-paramagnetic oxygen detector analyzers from CAI met or exceeded the minimums set forth by SAE for reporting combustion results. The performance of the analyzers in the lab can be seen in Table 2 CAI Analyzer Standards. Insurance of minimum standards allows other researchers to take results from the facility and replicate the same experiments for further validation. While the ARP 1256 does not specify an oxygen analyzer or the minimums that this analyzer must meet, the knowledge of oxygen levels is useful in evaluating combustor performance.

Table 2 CAI Analyzer Standards

Analyzer Type	Performance Specs	Zero Drift	Span Drift	Noise	Precision
CO and CO2 Analyzer	Non-dispersive Infrared Detector	Less than ±1% full scale in 24 h	Less than ±1% full scale in 24 h	Less than ±1% full scale	Better than ±1% full scale
Total Hydrocarbon Analyzer	Heated Flame Ionization Detector	Less than ±1% full scale in 24 h	Less than ±1% full scale in 24 h	Less than ±0.5% full scale	Better than ±0.5% full scale
Oxides of Nitrogen Analyzer	Chemiluminescence Detector	Less than ±1% full scale in 24 h	Less than ±1% full scale in 24 h	Less than ±0.5% full scale	Better than ±1% full scale
Oxygen Analyzer	Paramagnetic Detector	Less than ±1% full scale in 24 h	Less than ±1% full scale in 24 h	Less than ±1% full scale	Better than ±1% full scale

Oil System

Another important aspect of testing procedure outlined in ARP 1256 is maintaining the emission sample at 320 ºF ± 27 ºF until it reaches the analyzers. To accomplish this, heat transfer fluid will be pumped at a predetermined temperature by the MOKON Model H22103AJ Heated Thermal Fluid System to the location of the emission sampling probe and back to the analyzer to insure the proper temperature is maintained. The heated fluid is pumped to the probe through tubes and sets of valves seen in Figure 12 Oil Line. These valves allow the user to open and close parts of the tubing preventing overpressure during warm-up.

Other Measurements

Another way to measure combustion performance is with pressure transducers and thermocouples. Part of determining combustion efficiency is reading the pressure drop across the test section and determining the change in temperature. Differential pressure transducers, Dwyer Model 655-5s, and thermocouples are placed before and after the test section to measure these changes. Other pressure transducers are placed in the air lines to gain an understanding of the air flow before it reaches the test section and to allow the user to changes these parameters to best suit the experiments. Thermocouples also give a better picture into the conditions of the air flow. There are also pressure transducers on the gaseous fuel line to help set the fuel flow. All of the locations and numbers of these devices can be seen in Figure 10 Air Lines and Figure 11 Fuel Line.

Shop Air

With the needle valves, safety valves, and fuel switching valve using pneumatics for power, a separate air system is needed. This second shop line also prevents disturbances in the research air line. This air is brought into the room from an external compressor and settled in a 50 gallon tank at a pressure of 150 psi. From the storage tank this air is passed through an oil-water separator and a 3 micron air filter.

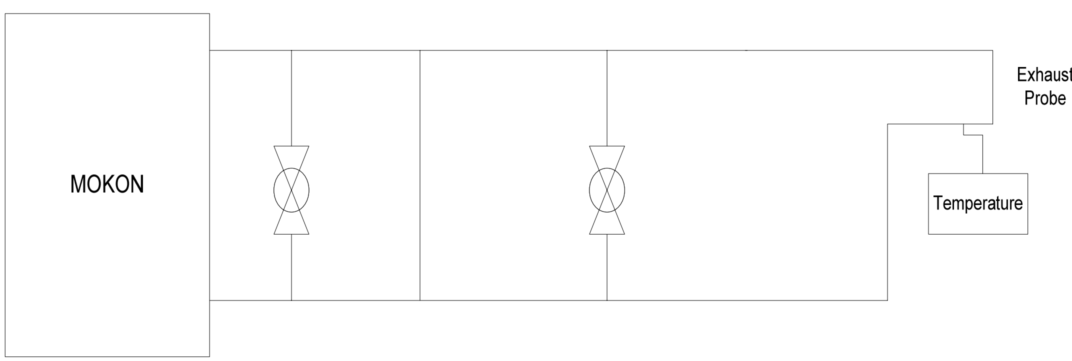

Figure 12 Oil Line

The air line then splits into two different lines. The first line is a low pressure line that passes through a regulator that brings the pressure down to 25-30 psi. This line then continues onto the current to pressure module that receives the input from the process controllers to fine tune the combustor air lines.

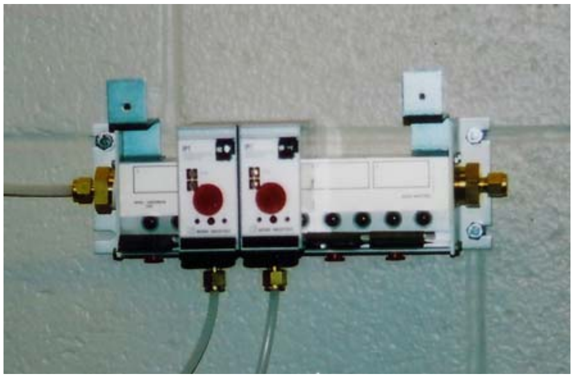

Figure 13 Current to Pressure Transmitter

The second line passes through a regulator that reduces the pressure to the 90-100 psi range. This line provides the pressure needed to run the pneumatic ball valves and the solenoid switching system for the fuel pumps.

Monitoring System

With air lines, fuel systems, and emissions monitoring equipment in place, the hardware and software to control and log the data from these systems is needed. The entire system is controlled and monitored from a computer control enclosure. The computer is a Pentium 4 system running Windows XP operating system software. The main control software running the control and monitoring system is LabVIEW 8.0. This system receives the signals from the various pressure transducers, thermocouples, the fuel pumps, and the CAI analyzer. It also sends signals to the CAI analyzer, the fuel pumps, heaters, and other devices. The computer tower contains two PCI cards, the National Instruments (NI) PCI-6052E multi-channel card and the NI PCI-6750 32 channel card. The PCI-6052E card is connected to the NI SCXI-1000 chassis. The SCXI chassis is a

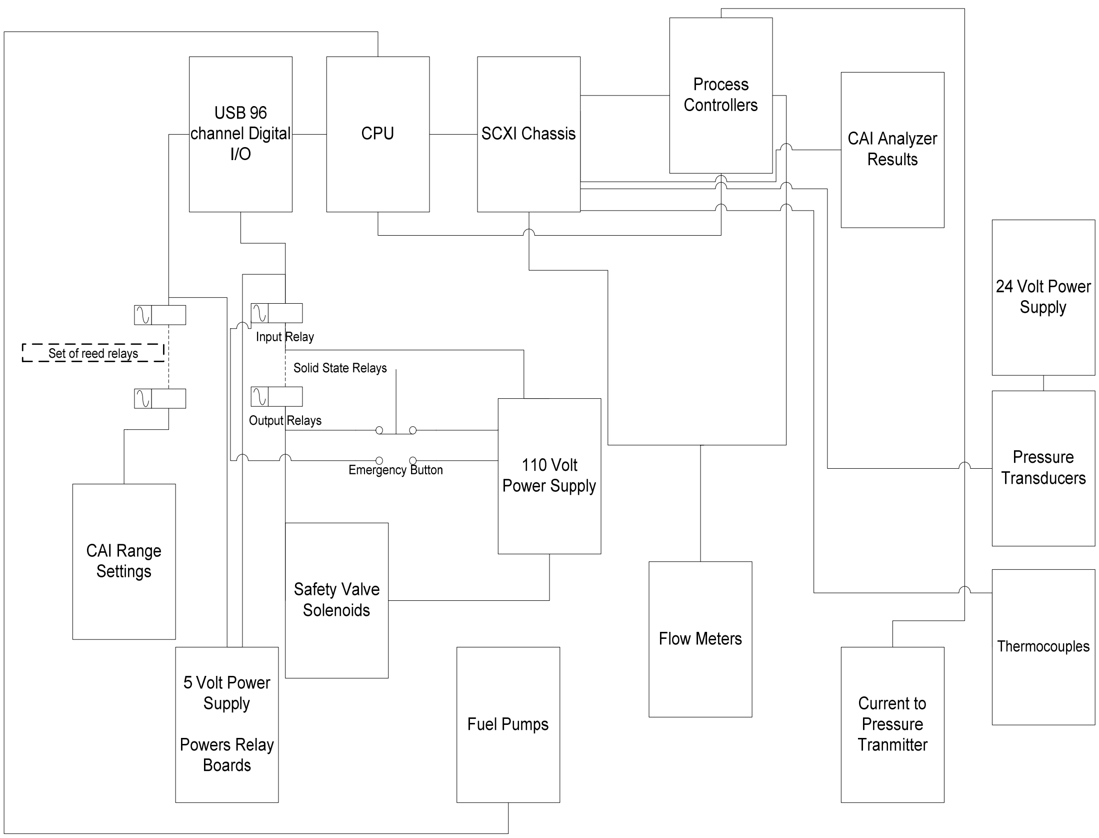

Figure 14 Wiring Diagram

signal receiving and transmitting device that allows for easy expansion of various input and output modules. Within the SCXI-1000 chassis, there are six modules. They are two SCXI-1102 32 channel voltage/current receivers, the first receives all the 4-20 mAmp signals from the CAI analyzer. These include the analyzer results and the temperatures of the various ovens in the CAI tower. The second SCXI-1102 receives the signals from the pressure transducers and thermocouples arranged in the air line. It also reads the temperatures from the flow meters and the heaters. A SCXI-1124 six channel digital-to-analog converter controls the process controllers by sending the user setpoints. A SCXI-1132 32 channel digital input receiver reads the signal from the vacuum switch in the exhaust system. This allows the user and system to know that the exhaust fan is running correctly. Finally a SCXI-1163 32 channel digital output transmitter is included in the system but does not currently control any sub-system.

Figure 15 Computer Enclosure

Different signal processing is used by these modules based on the type of signal they are receiving. The modules are controlled by the LabVIEW software which determines the signal conditioning based on user input.

A third USB connect module is used for the processing of digital inputs an outputs for the system. An NI DAQPad-6508 is connected to the computer using a USB connection and it is capable of processing 96 different digital channels of input and output. The NI DAQPad is connected to two OPTO 22 relay boards that contain 24 relay modules each. One solid state relay board contains 24 optically isolated reed relays. The reed relay modules are used to control the remote range selection function on the CAI analyzer. The user can manually control the analyzer ranges from the front panel of the CAI analyzer, but they can also be controlled by means of a contact closure. A contact closure is a simple means of reading when a certain range is to be used. When the range is to be used, the contact closes, or the resistance in the loop goes to zero effectively. When a range is not in use, the resistance in the loop is infinite. The Reed Relays, when activated by the computer, close the loop, making the resistance in the loop effectively zero.

The second solid state relay board also contains optically isolated modules. Optically isolated modules keep any signal from the computer from being transmitted to the controlled devices directly and vice versa. It does this by illuminating a small light-emitting diode (LED) inside the module when it is activated. A second photosensitive diode picks up the light and activates the relay. This insures there is no hard contact between the computer signal and the voltages in the sources. The second OPTO 22 board contains a mixture of different modules. The output modules allows the user to turn on different system through the computer. The emergency valves in the air and fuel lines are turned on and off by the output modules. The heaters are also turned off in an emergency by the output modules. The input modules read when current from a system is running. These are used to read if the emergency button is pressed.

The most complex system in the combustion facility is the software used to run the entire facility. Not only does the software collect data from the various gauges in the room, it also runs the fuel pumps, exhaust vents, the CAI analyzer, and controls the flow of air and fuel into the test section. Figure 16 Software Flow Chart shows how the software goes through and controls the systems. LabVIEW was chosen as the software to use for a couple of reasons. The first reason is the software is made by National Instruments, which also makes the data acquisition hardware used in the testing facility. NI makes it easy to monitor the data acquisition in LabVIEW by using prewritten code. The second reason for using LabVIEW is its prevalent use throughout industry for monitoring and controlling systems. Since the program is used by many different people in many different types of environments, more users will be familiar with the advantages and shortfalls to the software and can make better use of the code. Lastly, LabVIEW was chosen because it is a graphical programming language. The graphical nature of the language allows future programmers to modify and change code with greater ease. They can graphically follow the logic and insert or move code for any future improvements.

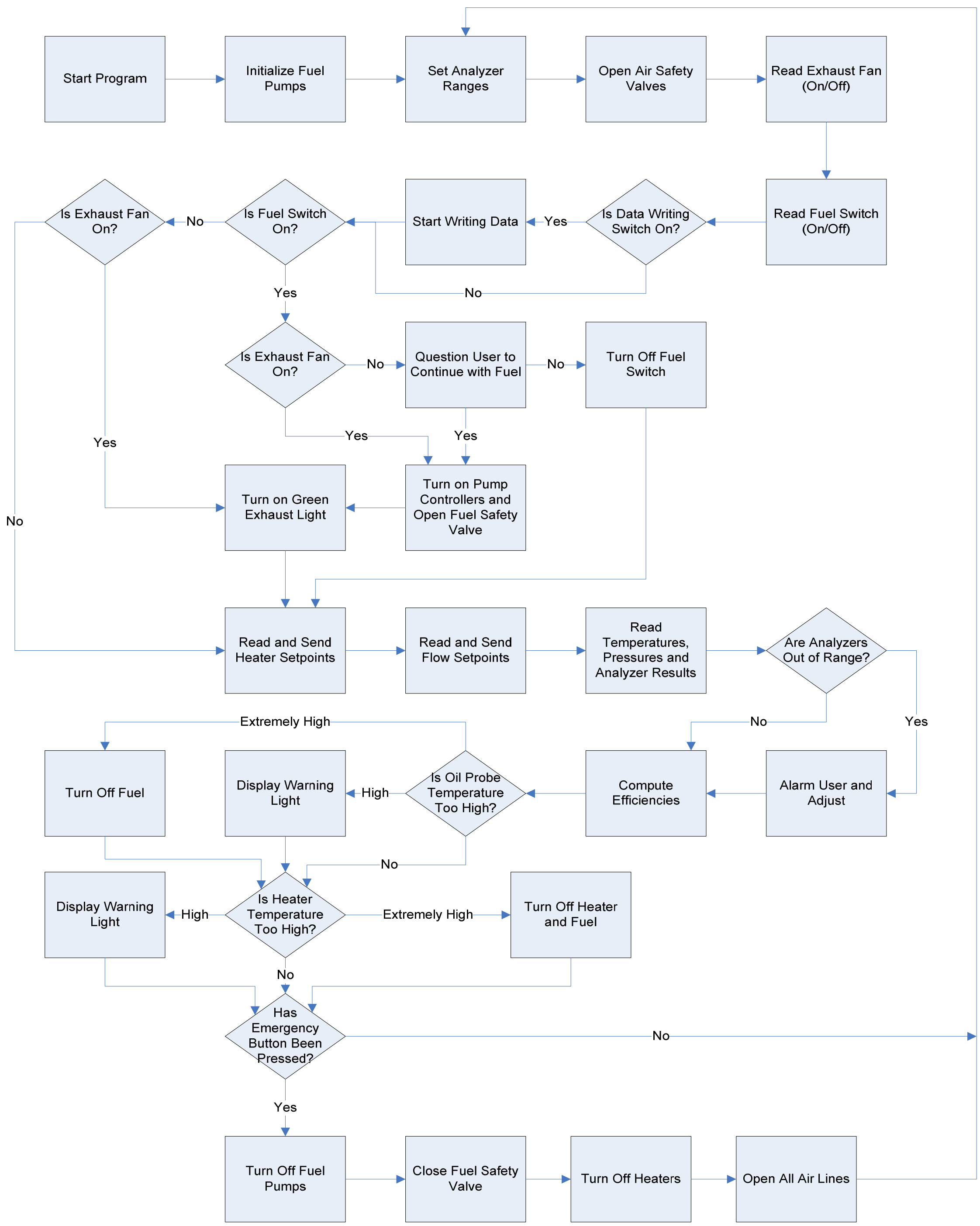

Figure 16 Software Flow Chart

The monitoring of the different systems in the testing facility is easy to do in LabVIEW. LabVIEW has prewritten code in the language that allows the programmer to set-up data acquisition from a variety of different sources with little effort. These prewritten codes are called Virtual Instruments (VIs) by LabVIEW. VIs were used extensively when possible to simplify the code and increase the ability to make modifications when needed. These VIs were used for data acquisition and signal transmission from the SCXI chasis and the modules therein.

The fuel pumps came with LabVIEW software prewritten by ISCO for use in controlling flow rates and other functions of the fuel pumps. This code was incorporated into the overall software for the entire room with minor modifications. The modifications to the existing software were made to better synchronize the fuel pumps into the rest of the system. Modifications include initializing the pumps first, incorporating safety issues and improving user interface. The fuel safeguards that were written into the code prevent the user from turning on the fuel pumps with out the exhaust system on unless the user clicks that it is appropriate to proceed. It also was modified to turn off the fuel pumps should the emergency button be pressed or if the heater temperature exceeds the limits.

The software interface with the USB connected 96-channel digital I/O unit (DAQPad-6508) was programmed differently from the other data acquisition devices. In LabVIEW the different data acquisistion devices are broken down into two groups, Traditional DAQ and DAQmx. The Traditional DAQ are either older units or do not have the newest programmability in them. The DAQmx are either newer or have the newest coding built in. The DAQmx devices are able to use the previously mentioned VIs to make programming easier, while the Traditional DAQ devices cannot use the easy

VIs and help wizards. The DAQPad-6508 is a Traditional DAQ device and so different, but simple, code was used to control the digital I/O functions. Rather than using a wizard to setup the location of the channels and how to send the digital signal, it was done using code by the programmer.

The remainder of the code handles the user interface functions and analysis of the data. After the data is received by the different data acquisition devices, the signal is modified to reflect the real world situation it is reporting. Different scales and constants are used on the different signals to change the 4-20 mAmp signals to numbers that are being recorded. After the signals are converted, they are displayed on the user interface as graphs and values. The graphs are used to show how things change over a short time interval for the user. Graphs are only used for visualizing the results of the various gas concentrations from the CAI analyzer. The other results are displayed as simple values so the user can keep an eye on them. Certain values, like the heater temperatures, have warning lights connected to them to alert the user if a value is approaching a dangerous level.

Support System

Support structures and equipment complete the facility. The dominant support structure is the Unistrut bracing. It was decided to elevate all the fuel, air and control lines above the ground to facilitate access to the testing area and allow for easier expansion. The Unistrut bracing keeps all the lines ten feet above the ground, allowing ample clearance for moving and almost any possible expansion of the testing area.

The exhaust venting system allows the exhaust produced during the combustion process to be vented out and away from the personnel running the experiment. The system uses a large circular fan to accelerate air out of the room at 1800 SCFM. The fan will vent the volume of air in the room completely four times per hour. This high rate of air flow will insure that all exhaust gasses from the combustor, minus the sample taken by the sampling probe, are vented outside the building and away from people. The duct work allows for a great deal of flexibility in use. The twin inlet system allows for the exhaust gasses to be removed when the combustor is working horizontally or vertically, as the case is needed by the user. Multiple doors in the hoods also allow outside air to be pulled into the vents so that the exhaust gasses are not sucked out of the combustor but allowed to flow out the combustor and pulled into the exhaust vent. Also, the volumetric flow of the fan allows for other projects in the room to use the same exhaust system should the need arise.

Different bottles of calibration gasses are needed to calibrate the analyzers on the CAI. These gasses include carbon monoxide, carbon dioxide, oxygen, zero air, nitrogen, and others. For this, a large bottle farm is needed. The pad will be partially covered to help protect the regulators that will be attached to the bottles and to shield the bottles from the environment in general. The concrete pad needs to be close enough to the building to make the lines carrying the gasses shorter and easier to run. A large grounding rod is buried next to the pad and connected to a lightning rod to protect the bottle farm from possible strikes. Also, the bottles not being used are kept in a different section built out of cinder block. This section is divided into three parts for the full and empty bottles. See Figure 17 Proposed Layout of Bottle Farm for a detailed drawing of the bottle pad.

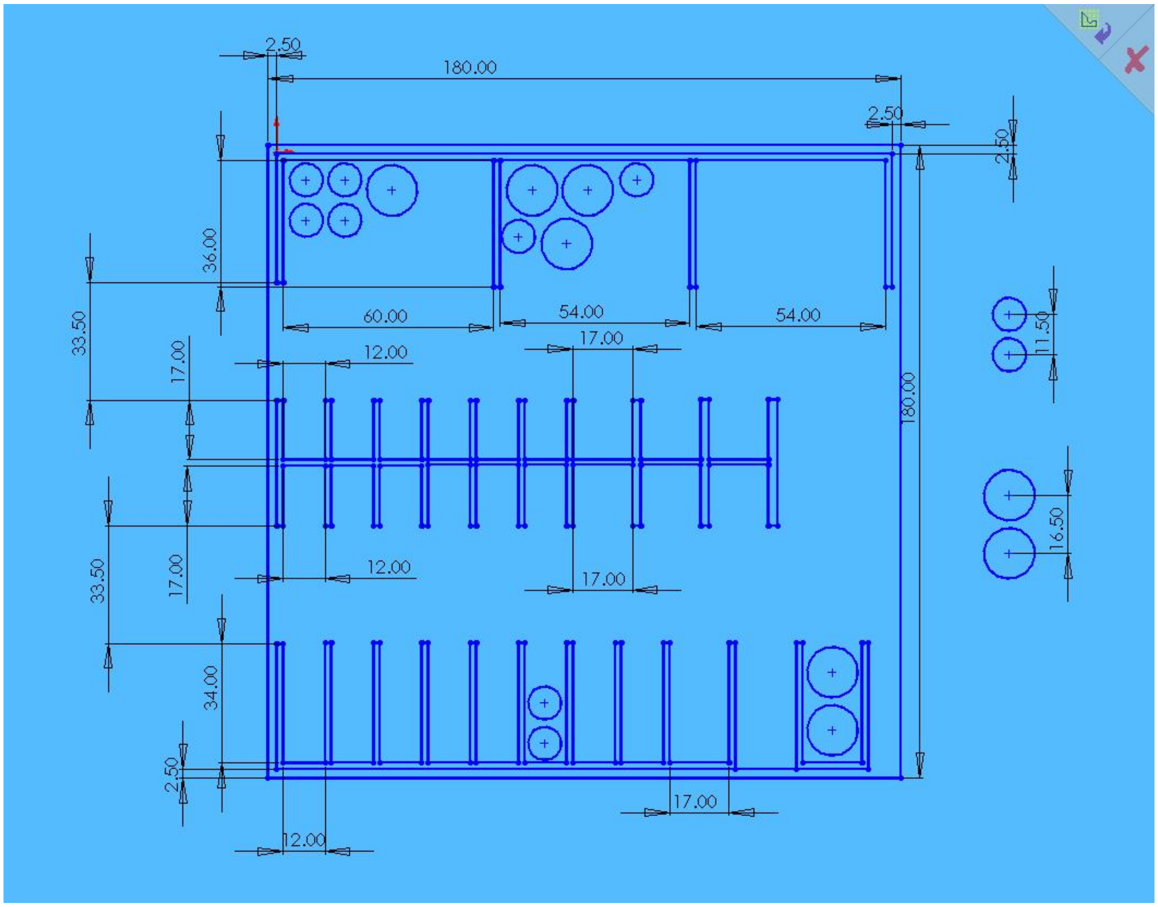

Figure 17 Proposed Layout of Bottle Farm in inches

Safety

The safety features in the laboratory allow for the user to conduct the experiments in a safe and controlled environment. The first type of safety precautions taken are designed to prevent accidents and keep the system running safely. To help prevent accidents, the floor has been kept clear of most objects. Time and effort has been taken to keep all wires, pipes, and other objects elevated and away from where the researcher may need to walk. This also allows maximum flexibility in the placement of future diagnostic systems. All heated equipment is wrapped and insulated to keep the heated fluids and air at the proper temperature and also to help prevent serious burns should anyone come into contact with the pipes. While a burn may still occur even with the fiberglass insulation with a self sealing jacket on the pipes, the severity of the burn will be far less. Another designed safety feature is the decision to keep all fuel and electrically components apart from each other. The safety valve for the fuel line needs an electric signal to activate the solenoid, opening the valve. This solenoid has been located remotely from the valve, using shop air to open the valve. Also, the pressure transducers for the fuel lines are located remotely so any possible problem between the fuel and electrical lines are kept away from the rest of the testing facilities. The software system also helps keep the researcher safe. Safeguards have been incorporated to prevent systems from being activated unless other systems are already functioning. The fuel system will not turn on unless the exhaust system is running. The heaters will turn off with the fuel system if temperatures exceed limits. Finally, if any system does not respond properly, the fuel system will be disabled.

The second type of safeguard protects the user and facility should the power go out. Without power, the computer cannot control the test and so it is required that the combustion process would stop in a controlled manner. To stop the combustion two things are wanted: the fuel to shut off, and the air to extinguish any flames. To accomplish the first, there are a couple of safety features. The first is that with the power off, the fuel pumps cannot pump fuel. However, there may still be fuel in the line and it could conceivably work its way out to continue the combustion process. The second safeguard is the safety valve. The valve is a normally closed pneumatic type valve. It requires an electrical current to open the valve and let the fuel flow. Without power, the computer would not be able to send a signal through a solid state relay to the solenoid activating the valve. Without this signal, the valve simply slams shut. As for the air to extinguish the flame, the air lines have safety valves that are normally open. These valves require an electrical current to close, so the loss of electricity will not hamper the air from continuing to flow. Also, the needle valves will open full since they close with an external signal and are normally open as well. This signal comes from the current to pressure transmitter, which receives the current from the process controller. With a single point failure anywhere in the system, safe conditions will remain. Once again, without power, the needle valves will not receive a signal.

Other components that may be affected by a power outage include the heaters, exhaust system, and the data acquisition system. The heaters will turn off with a loss of power, and since the air lines will be still running, the elements in the heaters will be protected from burning out. The exhaust fan will turn off with a loss off power. Since the fuel system will turn off as well and the flame will be extinguished, the loss of the exhaust fan should not adversely affect any users in the room.

The final safety system is in case of an emergency and the user needs to get out of the room for personal safety. For this severe case, an emergency button has been installed. This button is only pressed when the user needs to exit the building quickly and shut down the system. The emergency button cuts off the voltage to the solenoids that activate the safety valves. This closes of the fuel line as if the power went off. It also opens the air lines. The emergency button does not shut off the computer nor the data acquisition system. The data acquisition system in fact reads the closure of the emergency button through a solid state relay. After the relay senses the throwing of the emergency button, the software shuts off the fuel pump, and turns off the heaters. The heaters are turned off using another solid state relay that sends a 5 volt signal to the heater. The emergency button is a last resort safety feature and should be used as such.

IV. Results

After all the design decisions were made and the build was completed, a flexible testing facility emerged. The high degree of flexibility was due to the design choices made to allow for future adaptation and trying to see what might be needed in other experiments. This section will list and detail some of the design features of the final testing facility and how future experiments can benefit from it.

One of the features of the testing facility that can benefit other difficult to perform experiments is the permission granted to allow open flame experiments in the room. Clearly in a combustion testing facility, the need for open combustion is apparent. However, many other disciplines can benefit from the ability to use open flame. Rocket nozzle designs can now be tested with the open flame permission, along with any other experiment that needs an open flame. This opens up the possibilities of different experiments being conducted.

Another feature of the room is the exhausting system. The combination of a hood and an open vent allows for noxious fumes to be directed out of the room and away from any personnel. The fan incorporated into the exhaust system can turn over the air in the room every 15 minutes, or in other words, the fan replaces the volume of air in the room completely four times an hour. This high amount of turn over was designed to insure that any gasses from the combustion chamber would be vented outside and not left in the room, but it also allows a large degree of freedom for what types of gasses can be used in the room. With the air being replaced every 15 minutes, gasses will not be leaking out of the room and into other rooms in the building.

The controlled and heated air lines in the room can provide the ability to create a large spectrum of experiments. The air lines are sized and controlled to allow up to 260 standard cubic feet per minute (SCFM) of air together. Individually, the main line can transport up to 200 SCFM and the smaller secondary line can provide the other 60 SCFM. The air in these lines can also be heated up to 500 degrees Fahrenheit. While this is the upper limit of the supporting structure, the heaters could in theory supply heated air up to 1000 degrees Fahrenheit. The usefulness of supplying two controlled and heated air lines in visible. Heated jet experiments could be run with additional equipment. It also allows the use of jet fuels in combustion experiments.

Table 3 Overall Air Flow Rates and Equivalence Ratios

	Main Air Leg	Secondary Air Leg	Total
Flow Rate	200 SCFM	60 SCFM	260 SCFM
Equivalence Ratio for JP-8	0.0018 to 1.3	0.0061 to 4.3	0.0014 to 1.0
Equivalence Ratio for propane	0.0045 to 0.9	0.015 to 3.0	0.0035 to 0.7

Perhaps one of the most important results of the design of the facility is the ability to provide test results that follow the SAE ARP 1256. Since this document outlines how to sample and analyze combustion emissions in a standard way, a design that did not incorporate this would not do. By designing to this standard, any and all test results that come from this facility can be repeated and duplicated by others using the same standards. This increases the regard by which any research conducted in the facility can be reported.

Another key design feature that adds to the flexibility of the room is the use of LabVIEW software. Future users can easily modify the existing software should the need arise. The frequent use of DAQmx VIs allow the future user to change and modify the existing data acquisition channels with minimal effort. The easy interface also allows the expansion of future signals such as more pressure transducers or extra thermocouples. Even with the slightly more complex coding for the DAQPad-6508 is easy to modify by using the code written for the purpose of using the DAQPad-6508. LabVIEW also allows future users to modify the user interface and add or remove indicators and controls as needed. Future users can also create diagrams outlining the combustion process and track the changes from the front panel if they desire. It is this flexibility and the large support network, that make LabVIEW an important tool in the room.

The facility also boasts the ability to make visual measurements. While not a permanent part of the room, a laser table can be easily moved into the room to allows laser velocimetry measurements. This gives the user the ability to accurately measure the speed of the flow. While this feature will be used initially to analyze the cavity-vane interactions of the UCC, it is also a powerful tool that can be used for many other future experiments that need to be run in the room.

VI. Conclusions and Recommendations

Conclusions

AFIT now has a highly capable testing facility that will allow for many future research projects. The facility allows for future researchers to use two heated and controlled air lines that allow for up to 260 SCFM of air with up to 200 SCFM in one leg and 60 SCFM in the other. Each line can be heated independently to temperatures up to 500 °F. The facility also has the ability for allowing the researcher to use two syringe type pumps for highly controlled flow of liquid fuels. These can flow 340 mL/min of liquid fuel, which allows for equivalence ratios up to 4 in the cavity of the test section of the 2-D planar UCC. These liquid fuels can be JP-8, ethanol, or any other liquid fuel. The twin syringe pumps allow for uninterrupted flow of fuel until the storage containers are empty. The use of a fuel filter also insures that particulates do not enter the fuel spray. The facility also allows for reporting combustion data in accordance with ARP 1256 which gives added credit to the results. The facility also allows for accurate tracking of line pressures, changes in temperature, and analyzers able to detect the composition of the emission gasses. The additional benefit of using optical measurements in the lab also yields added functionality that other labs may not possess.

Recommendations

Further work still needs to be done to the facility to help improve upon the usefulness of the parts. The software can be revised to improve efficiency of code. The calibration gasses still need to be plumbed into the room from the concrete pad. The concrete pad still needs to be poured and the shelter for the bottles needs to be built. Finally, the entire system needs to be validated as a whole.

The software that is written controls the entire system and all the sub-functions that are needed to run a combustion and testing facility. However, as with all software codes, there are parts that can be modified for better efficiency or improved performance. It was discussed earlier that one of the great benefits of using LabVIEW for controlling the lab is the ease in modifying the code for future use. That flexibility also can allow for inefficiencies in the code. These inefficiencies can be spotted and coded better as more test are run and the system shows where improvements can be made.

Due to problems outside the scope of the author, the concrete pad for the bottle farm has not been poured. While this aspect of the design is not critical for running the air or fuel lines, without the pad, it is extremely hard to store the calibration gasses needed to set up the CAI analyzer. As discussed earlier, all the analyzers need baseline reading of know concentration in order to insure accuracy. Safety concerns do not allow for the storage of these bottles inside the room, so calibration of the CAI analyzer is very difficult.

Once the bottle farm is built, the gas lines need to be run into the room to the various parts that need the gasses. Most of the calibration gasses run to the CAI analyzer. One of the important gasses that will be used once the bottle farm is built is propane. This gas will be used as a gaseous fuel in the test sections. Until the bottle farm is finished, the laboratory is a liquid fuel only facility, Other lines do need to be brought into other parts not only for the facility discussed in this thesis, but also for other parts of the room.

Another item that will need to be investigated and built later is a system for using gaseous fuels in a combustion scenario. Certain parts needed for the use of gaseous fuels have already been purchased such as a mass flow meter for gasses, but a majority of the system still needs to be designed and implemented. The software code in LabVIEW has been written already to allow the use of different measurements needed with gaseous fuels. More code may need to be written to for proper control and measurement of this fuel.

One last recommendation is a final validation of the entire system after all the pieces are built and installed. While all parts have been checked for proper functioning, they have not been checked together as a system. This needs to be done after the final parts of the system are in place to verify that the results and process are going as planned. It will also allow the user to fine tune any code or other parts of the facility as needed.

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Appendix A

This is a comprehensive list of all parts in Room 256, Bld 641 and their respective specifications.

Pressure Transducers						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
					±0.13% of full scale	
Dwyer	682-3	2649303	0-250 psig	Main line pressure	±0.13% of full scale	
	682-3	2649304	0-250 psig	Secondary line pressure	±0.13% of full scale	
	682-0	2623272	0-25 psig	Main line plenum	±0.13% of full scale	
	682-0	2673169	0-25 psig	Secondary line plenum	±0.13% of full scale	
	655-5		0-1 diff	Main line combustor differential	±0.5% of full scale	300 psi continuous
	655-5		0-1 diff	Secondary line combustor differential	±0.5% of full scale	300 psi continuous
	682-1	2518196	0-50 psig	Liquid fuel pressure at combustor	±0.13% of full scale	
	682-4	2633896	0-500 psig	Gaseous fuel pressure at combustor	±0.13% of full scale	
Omega	PX305-015AI		0-15 psia	Ambient pressure	±0.25% of full scale	
Flow Meters						
	Model	Serial #	Range	Use	Accuracy	Pressure

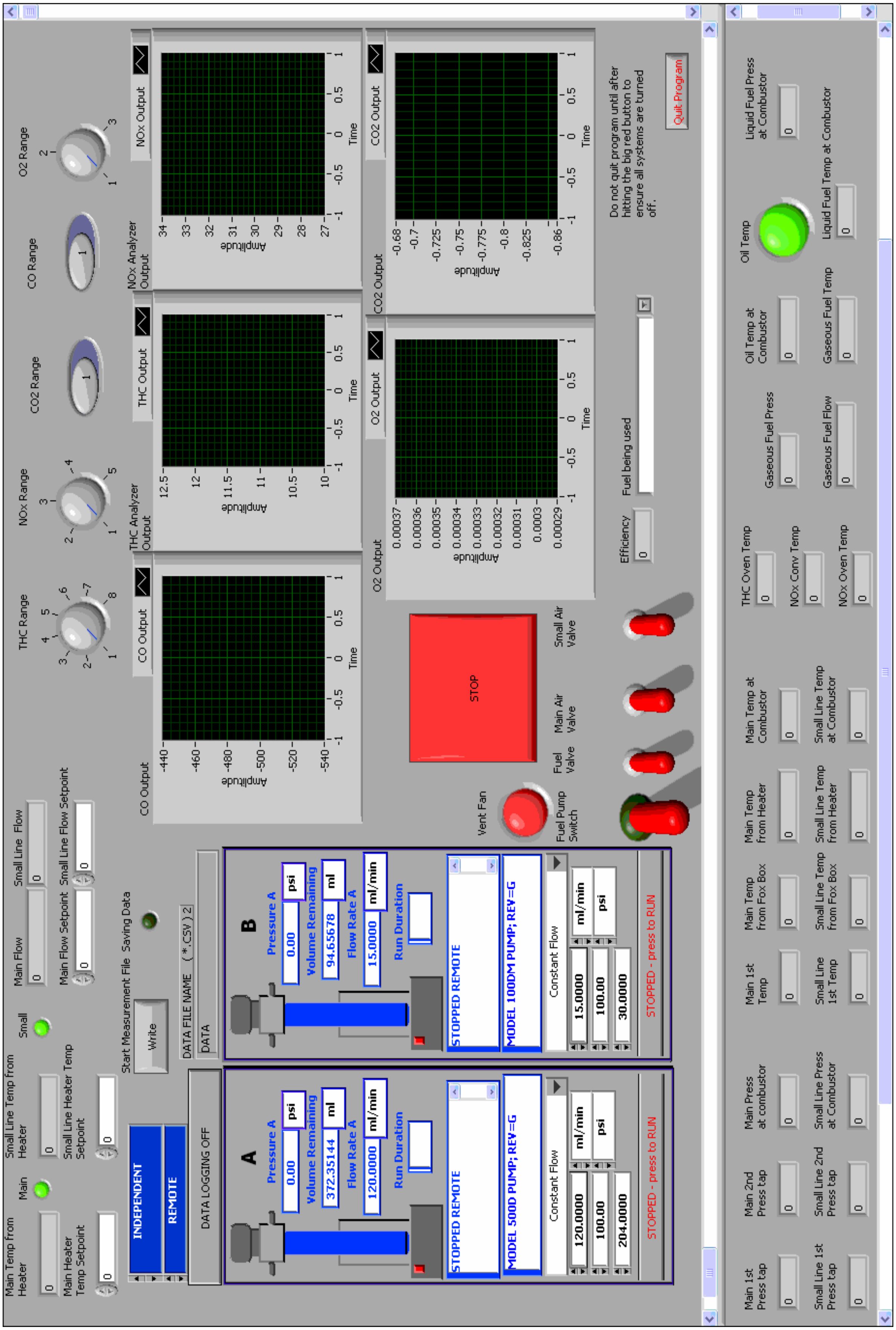
						Limits
Fox Thermal Instruments	FT2	W749	0-7.0 kg/min	Measure air flow in main line	±1% of reading	300 psi
	FT3	W382	0-2.0 kg/min	Measure air flow in secondary line	±1% of reading	300 psi
Needle Valves						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
Badger Meter	Research Control Valves	48072200101		Main line control	NA	1500 psi
	Research Control Valves	48072200701		Secondary line control	NA	1500 psi
Pressure Reducing Valve						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
CASHCO	1/2" NPT DA3	AA4098-001-06	0-400 psig	Change pressure in the main line		400 psi
	1/2" NPT DA3	AA4098-001-05	0-400 psig	Change pressure in the secondary line		400 psi
CAI Module						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
California Analytical Instruments	Model 300-HFID	P10009		Hydrocarbon detection	Better than ±0.5% of full scale	
	Model 400 HCLD	P10010		Oxides of Nitrogen detection	Better than ±1% of	

					full scale	
	Model 300 CO and CO2 infrared analyzer	P09022			Better than ±1% of full scale	
	Model 300 paramagnetic analyzer	P09022			Better than ±1% of full scale	
Fuel system						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
ISCO	ISCO 1000D syringe Pump	A	1 to 408mL/min	Liquid Fuel delivery	±0.5% of flow	137.9 bar
	ISCO 1000D syringe Pump	B	1 to 408mL/min	Liquid Fuel delivery	±0.5% of flow	137.9 bar
	Brooks Instrument Mass Flow Controller Model 5853	105090294658001	1 to 200 SLPM	Gaseous fuel delivery	±1% of full scale	100 bar
Heated Oil system						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
MOKON	MOKON H22103AJ Heated Thermal Fluid System	7000363	Room Temperature to 350 °F	To maintain the emission sample at 320 °F		
Current to Pressure Transmitter						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
Moore Industries	IPT[2]	1725762	3-15 psig	Takes signal from process controller and converts	±0.1% of output pressure	Supply pressure must be 5 psi greater than upper

				to pressure value for the needle valves		signal
	IPT[2]	1725763	3-15 psig	Takes signal from process controller and converts to pressure value for the needle valves	±0.1% of output pressure	Supply pressure must be 5 psi greater than upper signal
Air Heaters						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
Process Controllers						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
Eurotherm	2404 Control Setpoint Programmer	2404/NSGC/D6/D6/D5/Left		Controls the flow in the Main air line		
	2405 Control Setpoint Programmer	2404/NSGC/D6/D6/D5/Right		Controls the flow in the Secondary air line		
Gaseous Fuel Meter						
	Model	Serial #	Range	Use	Accuracy	Pressure Limits
Brooks Intrument	Model 5853	105090294658001	0-200 SLPM	Controls the flow of gaseous fuel	±1% of full scale	100 bar

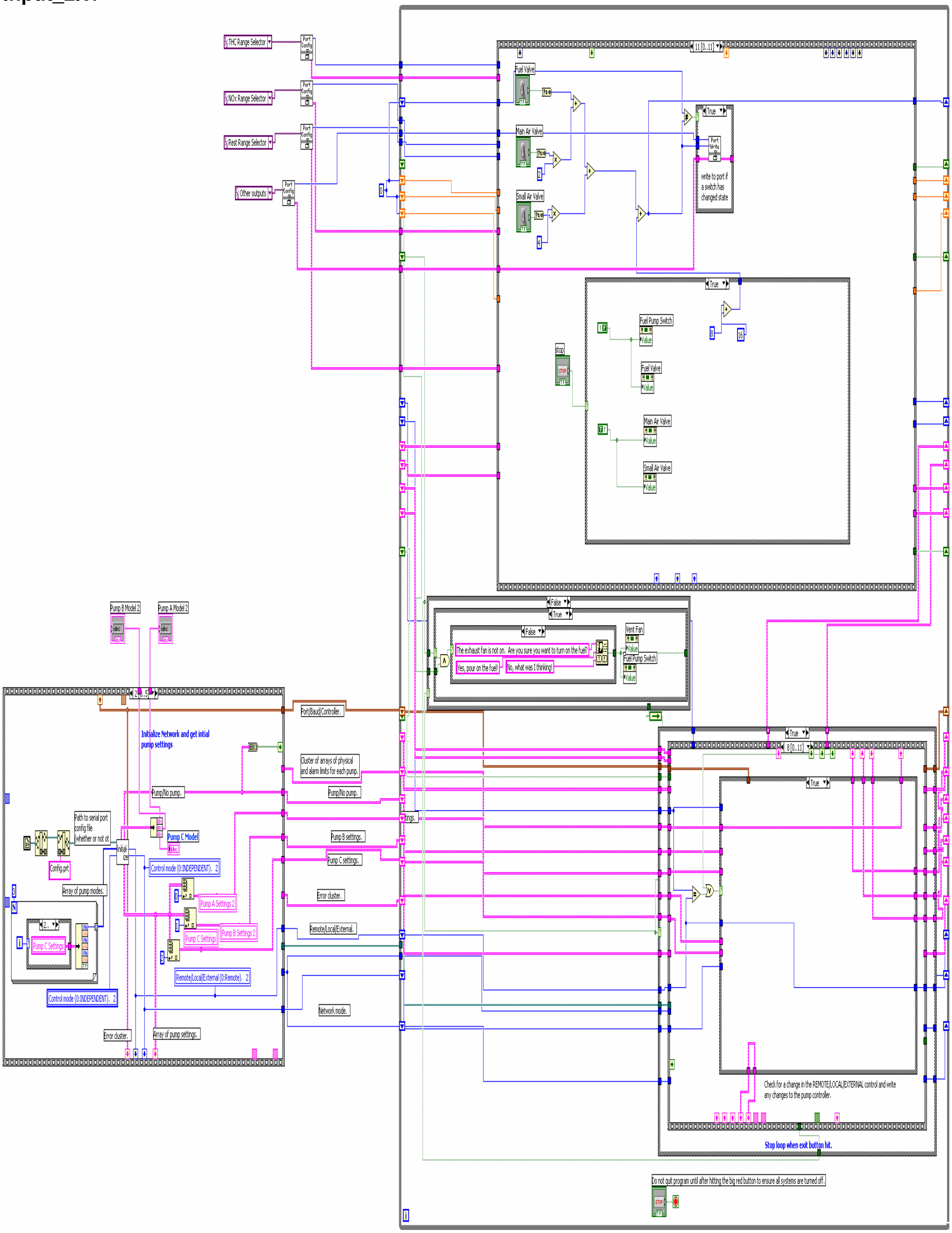
Appendix B

This Appendix contains the graphical code for the software used by the combustion facility. Due to the nature of a graphical code nested loops are printed for each iteration of the code. The first image is the user interface, followed by the many different nested code loops. The first image of the code shows the overall structure. The following images step the reader through the code and the nested loops. Please refer to the overall structure of the code when reading the code. The code starts on the left with the fuel pump initialization and proceeds from there.

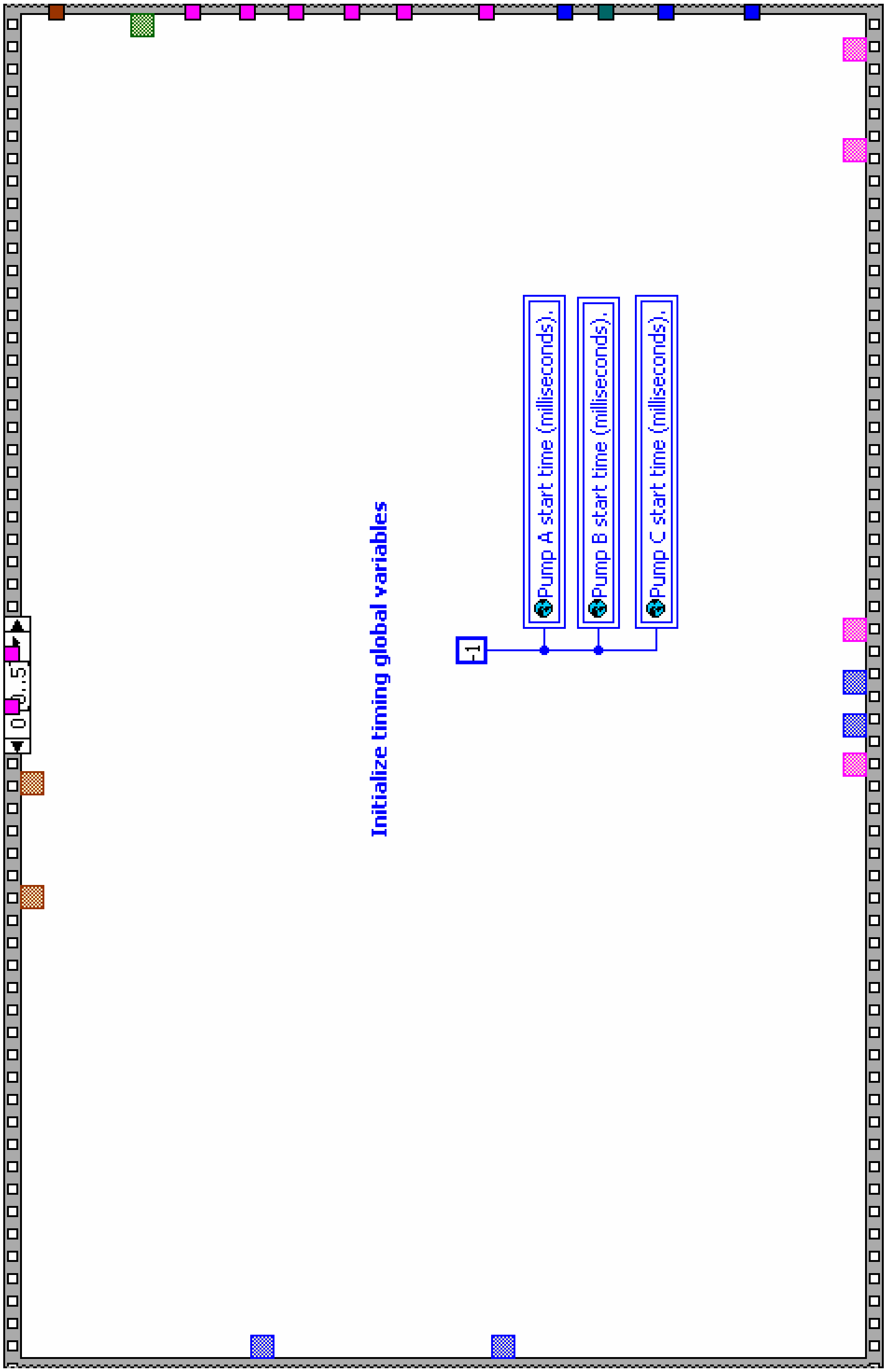


Main Temp from Heater
Main Heater Temp Setpoint
Main
Small Line Temp from Heater
Small Line Heater Temp Setpoint
Small
Main Flow
Small Line Flow
Main Flow Setpoint
Small Line Flow Setpoint
INDEPENDENT
REMOTE
Start Measurement File
Write
Saving Data
DATA LOGGING OFF
DATA FILE NAME (*.CSV) 2
DATA
A
Pressure A
0.00
psi
Volume Remaining
372.35144
ml
Flow Rate A
120.0000
ml/min
Run Duration
STOPPED REMOTE
MODEL 500D PUMP; REV=G
Constant Flow
120.0000
100.00
204.0000
STOPPED - press to RUN
B
Pressure A
0.00
psi
Volume Remaining
94.65678
ml
Flow Rate A
15.0000
ml/min
Run Duration
STOPPED REMOTE
MODEL 100DM PUMP; REV=G
Constant Flow
15.0000
100.00
30.0000
STOPPED - press to RUN
THC Range
NOx Range
CO2 Range
CO Range
O2 Range
CO Output
THC Analyzer Output
THC Output
NOx Analyzer Output
NOx Output
O2 Output
CO2 Output
Amplitude
Time
STOP
Vent Fan
Fuel Pump Switch
Fuel Valve
Main Air Valve
Small Air Valve
Efficiency
Fuel being used
Do not quit program until after hitting the big red button to ensure all systems are turned off.
Quit Program
Main 1st Press tap
Main 2nd Press tap
Main Press at combustor
Main 1st Temp
Main Temp from Fox Box
Main Temp from Heater
Main Temp at Combustor
THC Oven Temp
NOx Conv Temp
NOx Oven Temp
Gaseous Fuel Press
Gaseous Fuel Flow
Oil Temp at Combustor
Gaseous Fuel Temp
Oil Temp
Liquid Fuel Press at Combustor
Liquid Fuel Temp at Combustor
Small Line 1st Press tap
Small Line 2nd Press tap
Small Line Press at Combustor
Small Line 1st Temp
Small Line Temp from Fox Box
Small Line Temp from Heater
Small Line Temp at Combustor

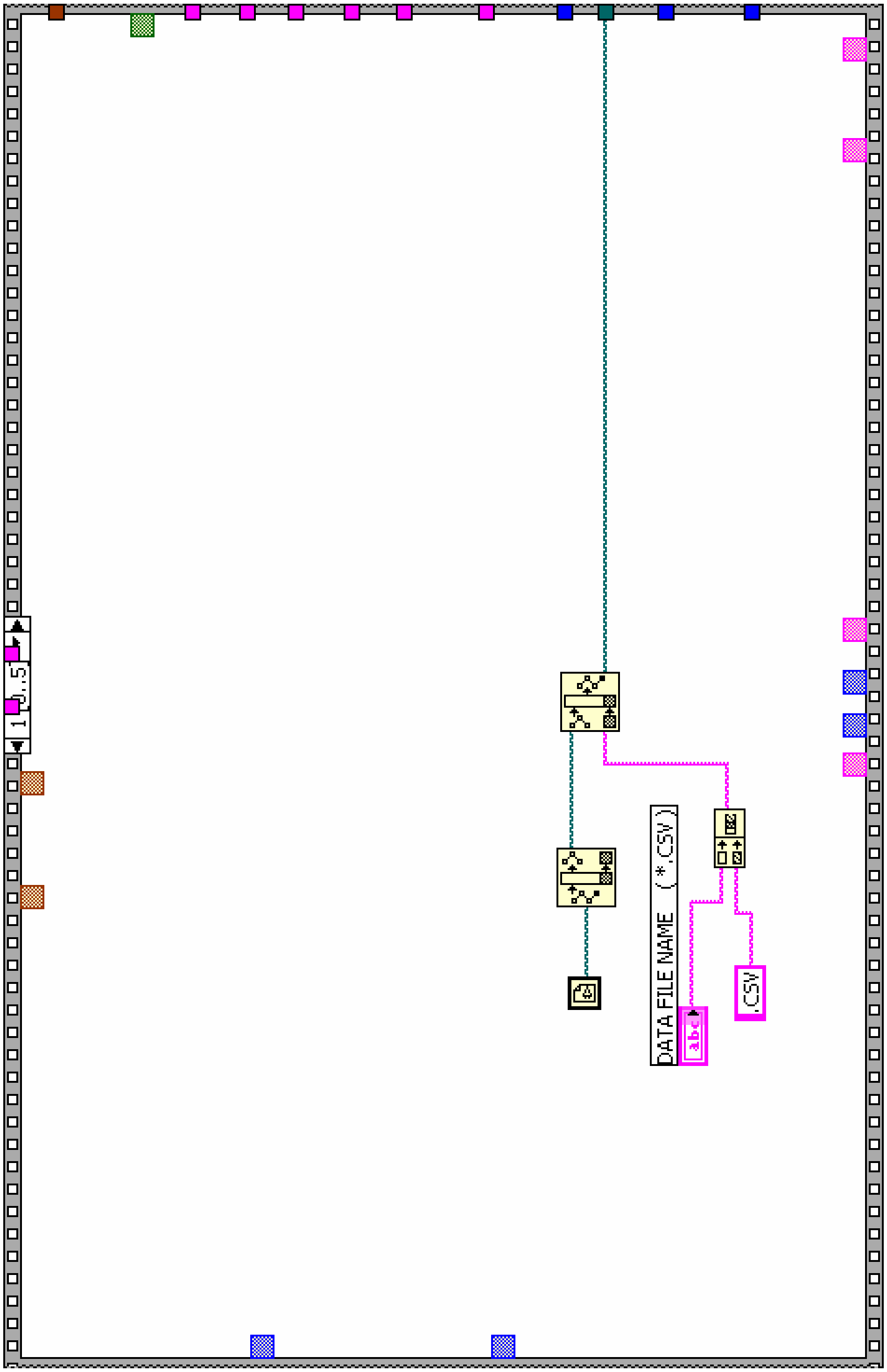
Input_2.vi

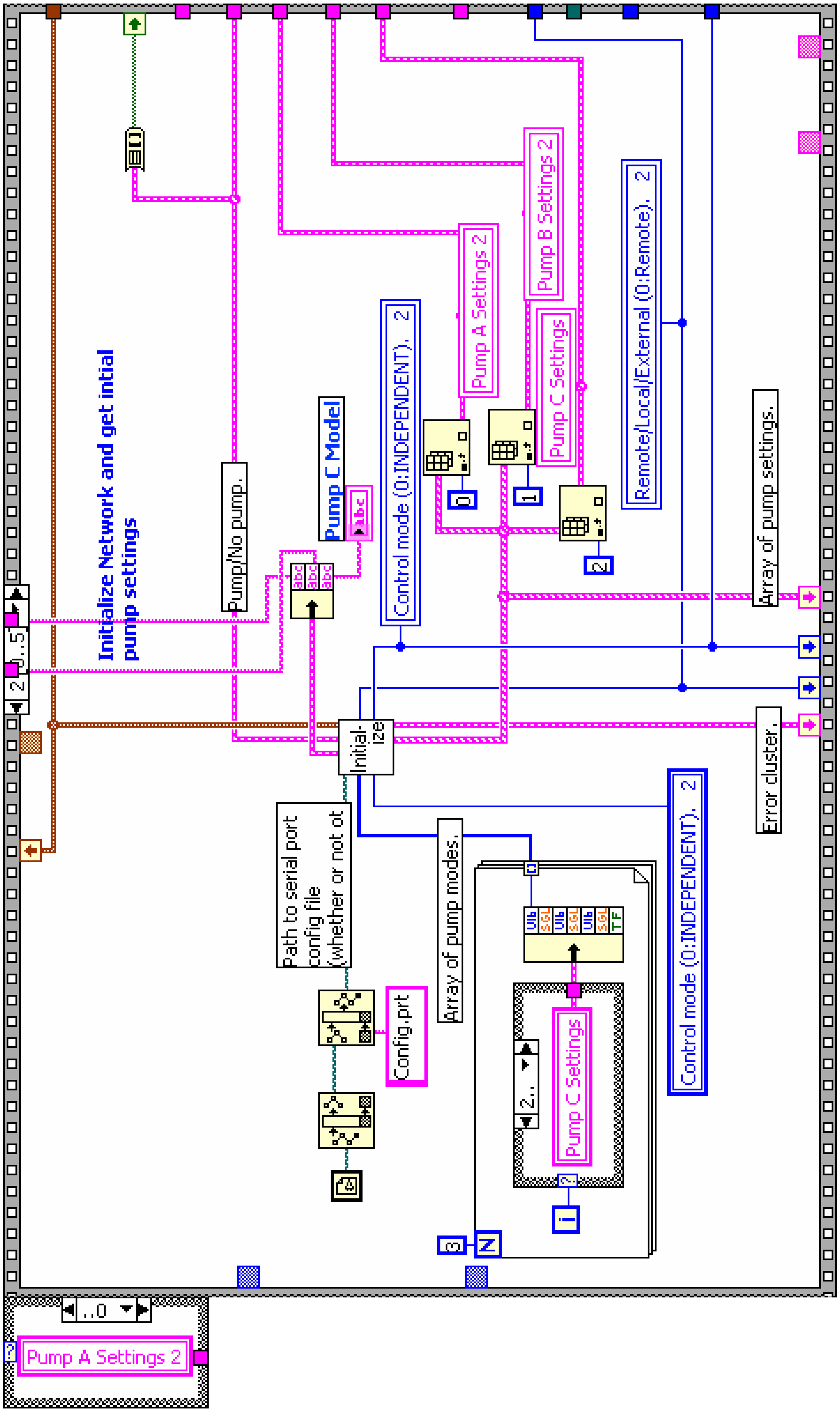


THC Range Selector
NOx Range Selector
Rest Range Selector
Other outputs
Fuel Valve
Main Air Valve
Small Air Valve
write to port if a switch has changed state
Fuel Pump Switch
stop
The exhaust fan is not on. Are you sure you want to turn on the fuel?
Yes, pour on the fuel!
No, what was I thinking!
Vent Fan
Pump B Model 2
Pump A Model 2
Initialize Network and get intial pump settings
Port/Baud/Controller.
Pump/No pump.
Pump C Model
Config.prt
Array of pump modes.
Error cluster.
Array of pump settings.
Pump B settings.
Pump C settings.
Remote/Local/External.
Network mode.
Check for a change in the REMOTE/LOCAL/EXTERNAL control and write any changes to the pump controller.
Stop loop when exit button hit.
Do not quit program until after hitting the big red button to ensure all systems are turned off.

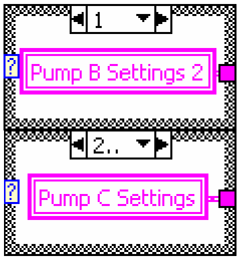


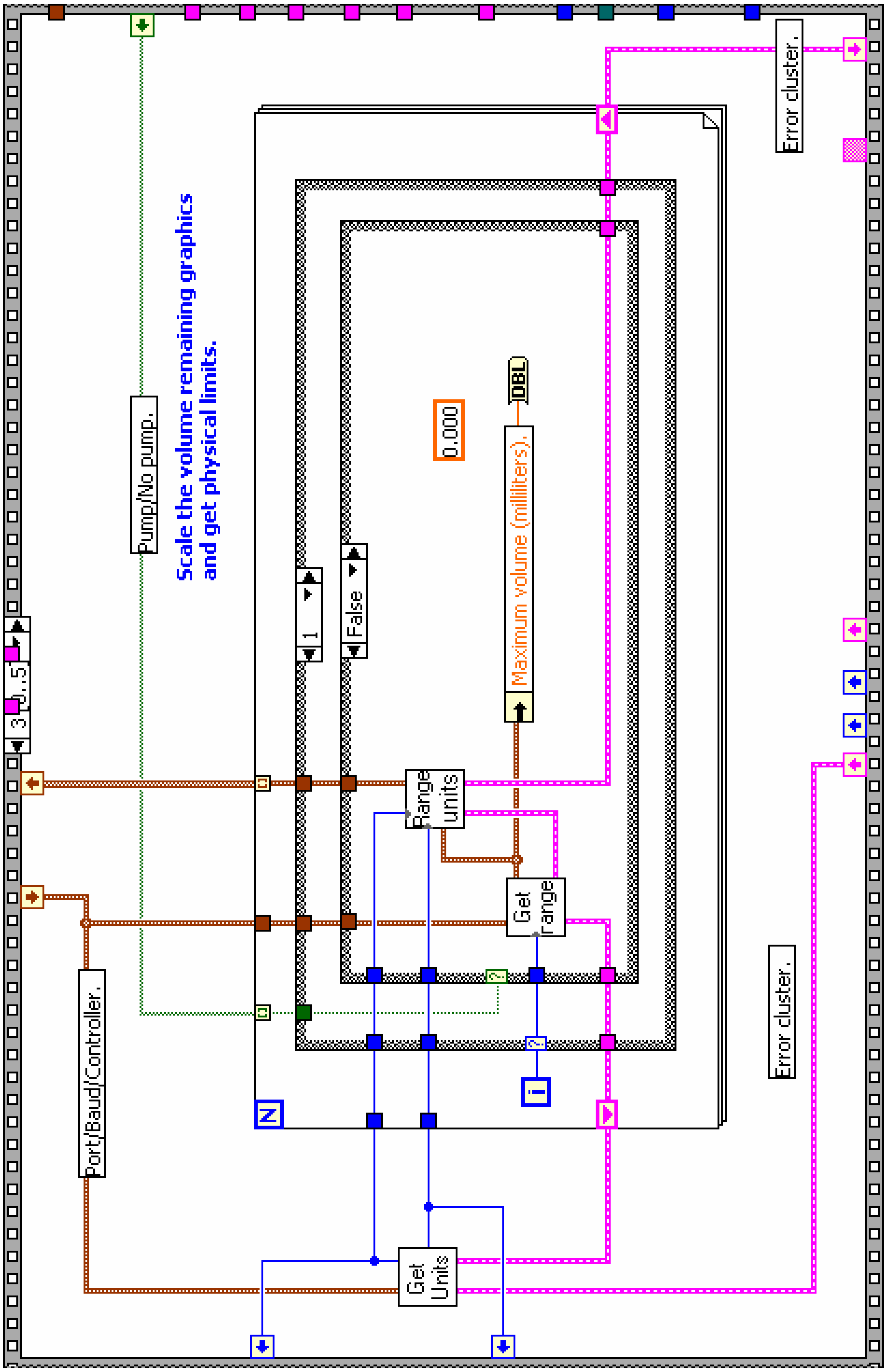
0..5
0
Initialize timing global variables
-1
Pump A start time (milliseconds).
Pump B start time (milliseconds).
Pump C start time (milliseconds).


DATA FILE NAME (*.CSV)
.CSV
abc
1 [0..5]

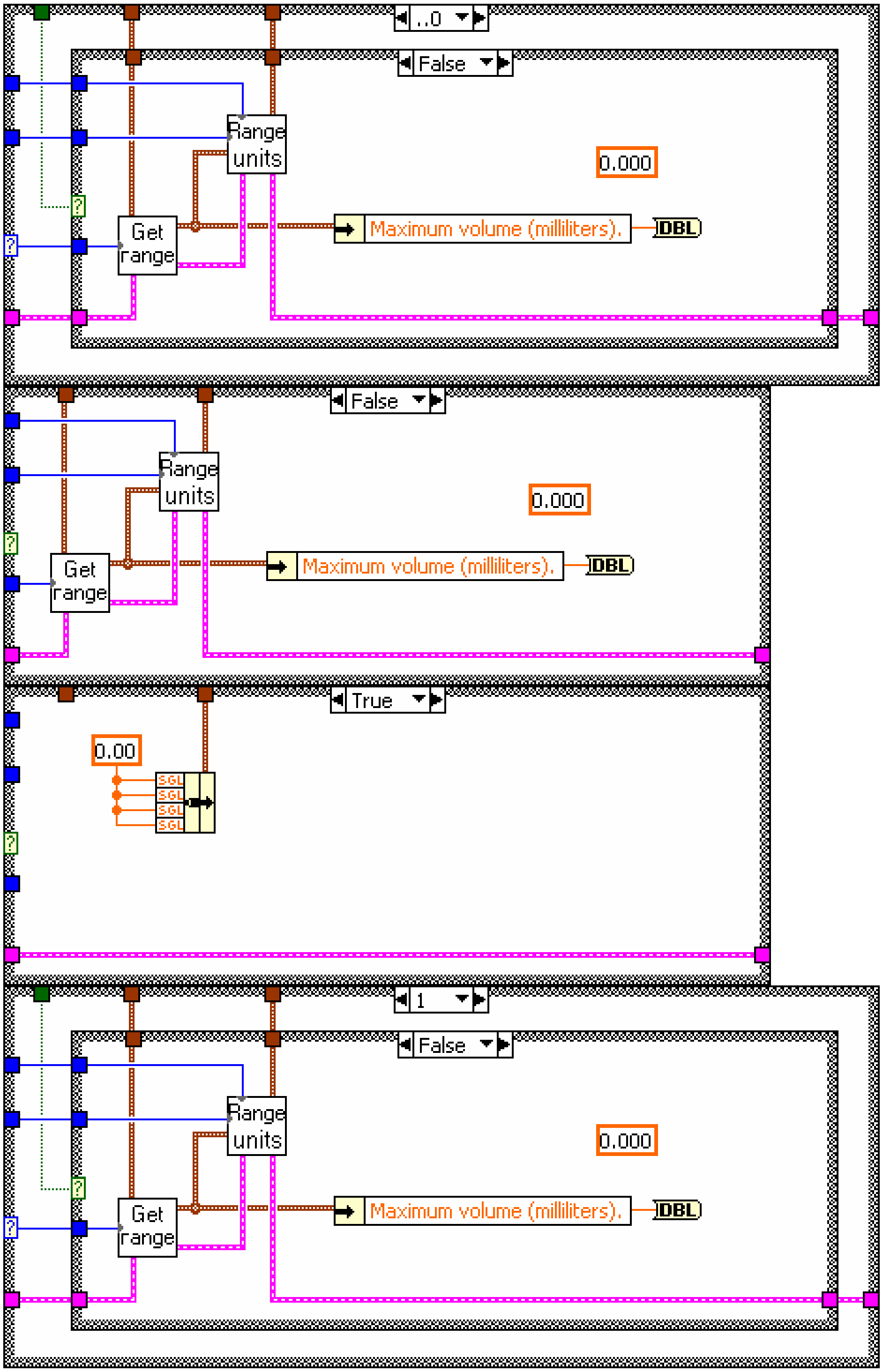


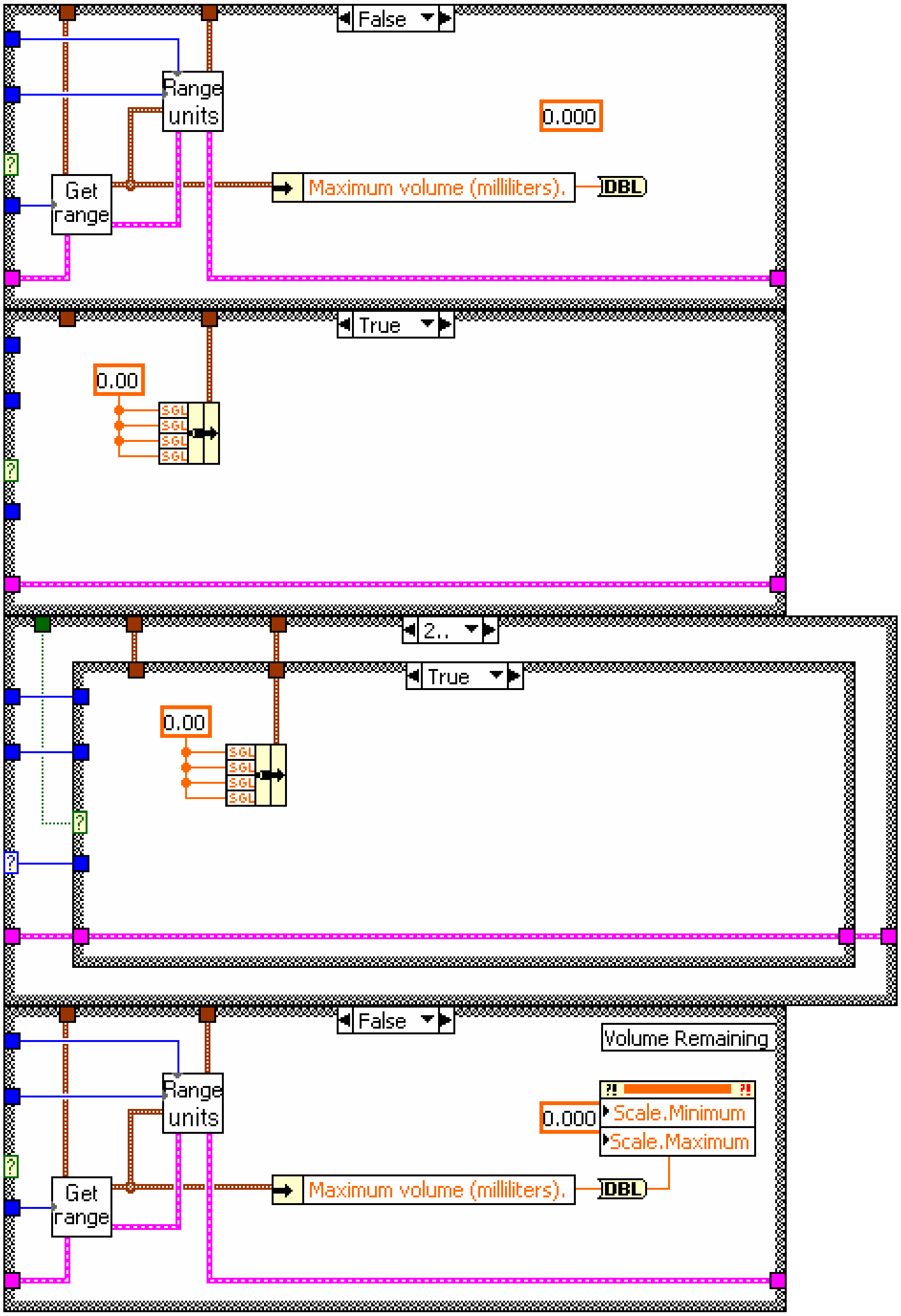
Initialize Network and get intial pump settings
Pump/No pump.
Pump C Model
Control mode (0:INDEPENDENT). 2
Pump A Settings 2
Pump B Settings 2
Pump C Settings
Remote/Local/External (0:Remote). 2
Array of pump settings.
Initial-ize
Path to serial port config file (whether or not ot
Config.prt
Array of pump modes.
Pump C Settings
Control mode (0:INDEPENDENT). 2
Error cluster.
Pump A Settings 2

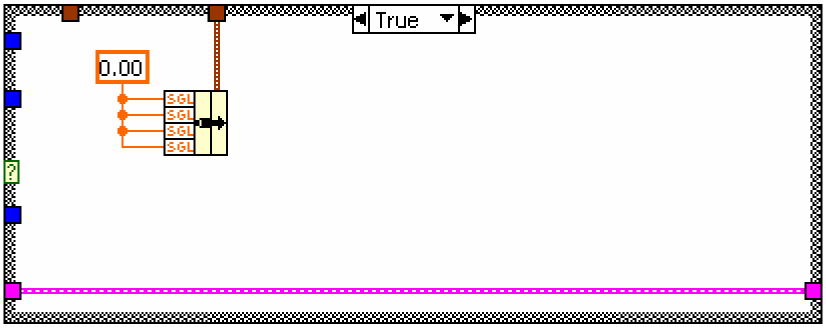

1
Pump B Settings 2
2..
Pump C Settings

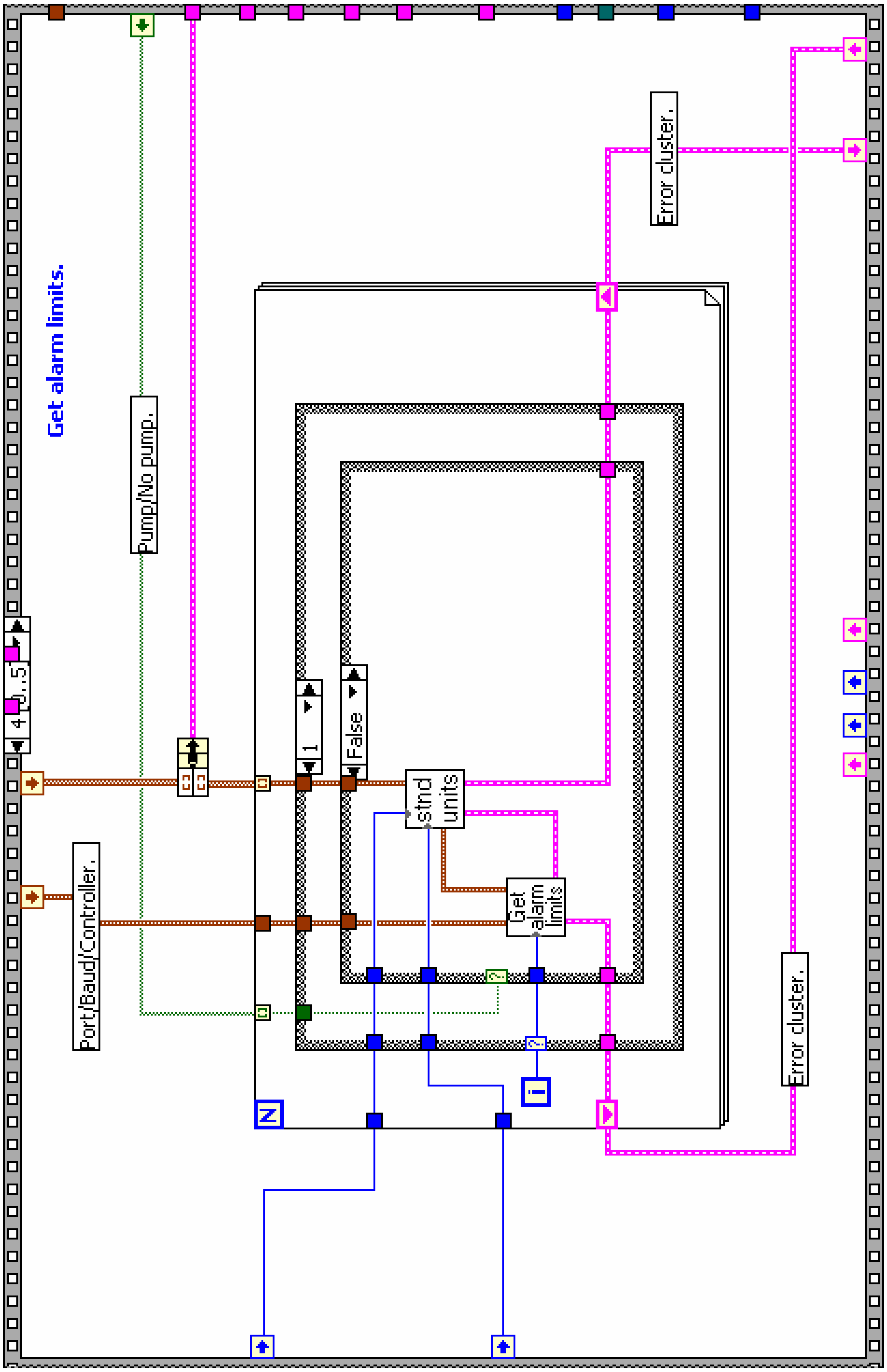


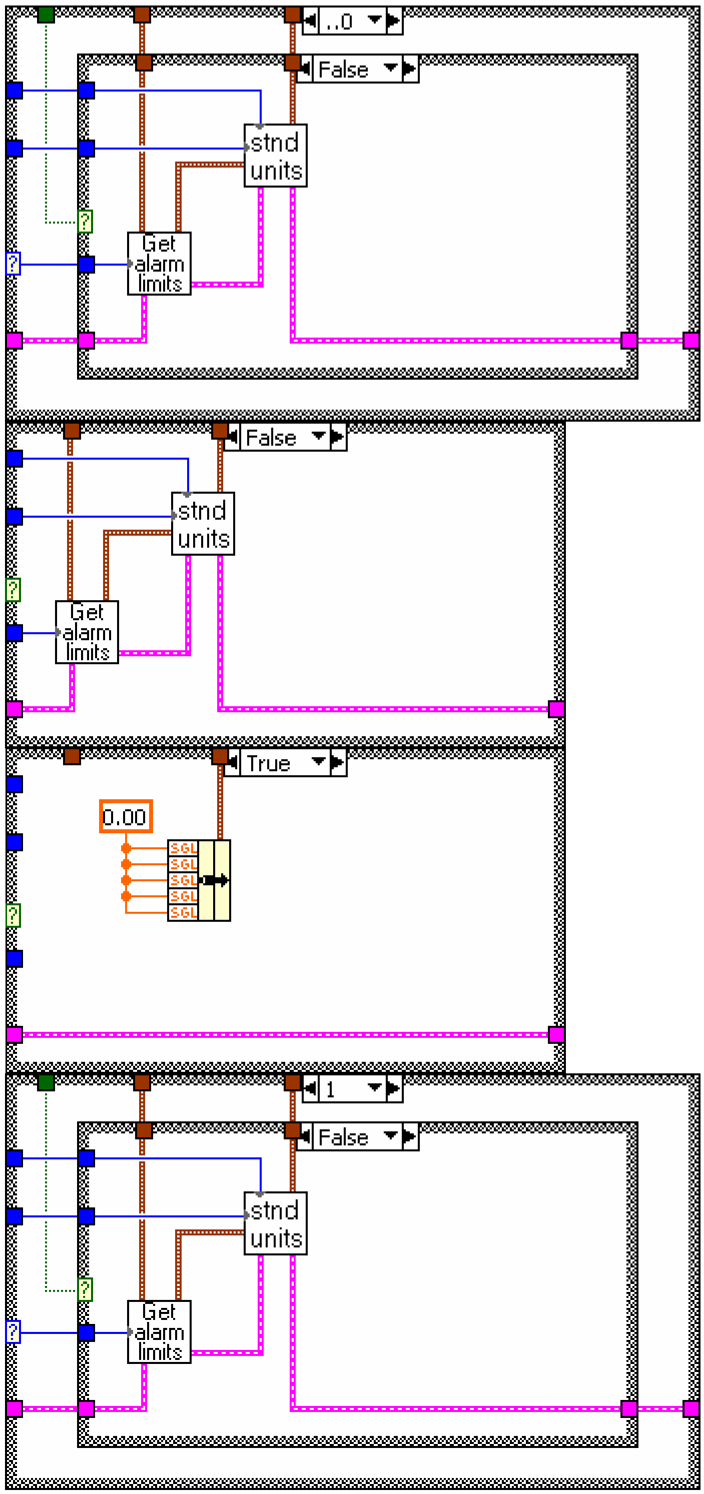
Scale the volume remaining graphics
and get physical limits.
Pump/No pump.
Port/Baud/Controller.
Error cluster.
Error cluster.
Maximum volume (milliliters).
0.000
DBL
False
Range units
Get range
Get Units

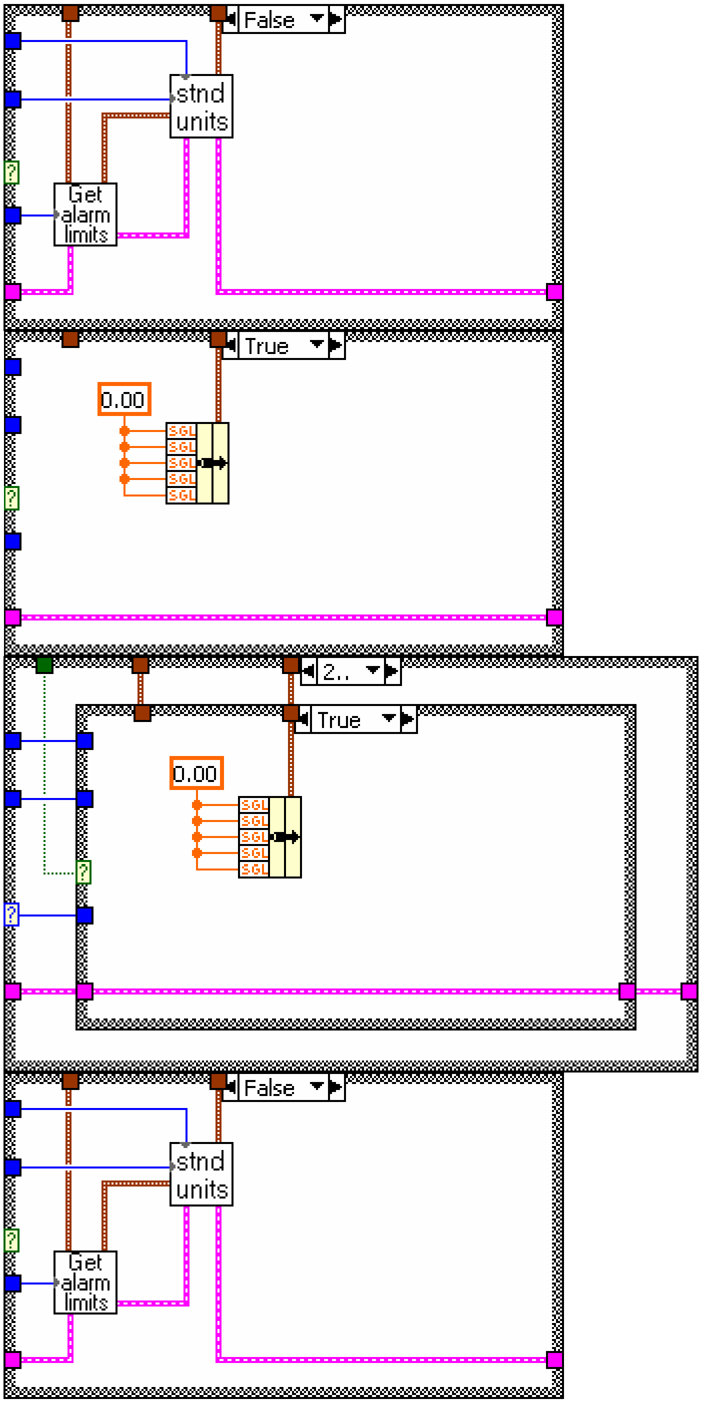

..0
False
Range units
0.000
Get range
Maximum volume (milliliters).
DBL
False
Range units
0.000
Get range
Maximum volume (milliliters).
DBL
True
0.00
SGL
SGL
SGL
SGL
1
False
Range units
0.000
Get range
Maximum volume (milliliters).
DBL

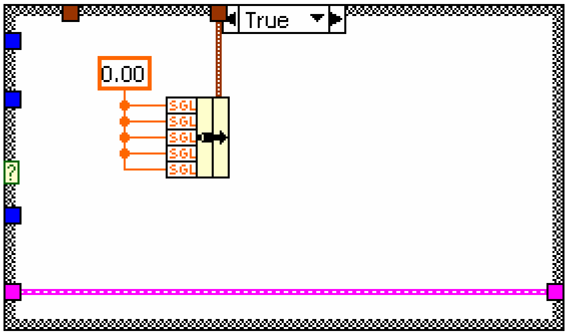

False
Range units
0.000
Get range
Maximum volume (milliliters).
DBL
True
0.00
SGL
SGL
SGL
SGL
2..
True
0.00
SGL
SGL
SGL
SGL
False
Volume Remaining
Range units
0.000
Scale.Minimum
Scale.Maximum
Get range
Maximum volume (milliliters).
DBL

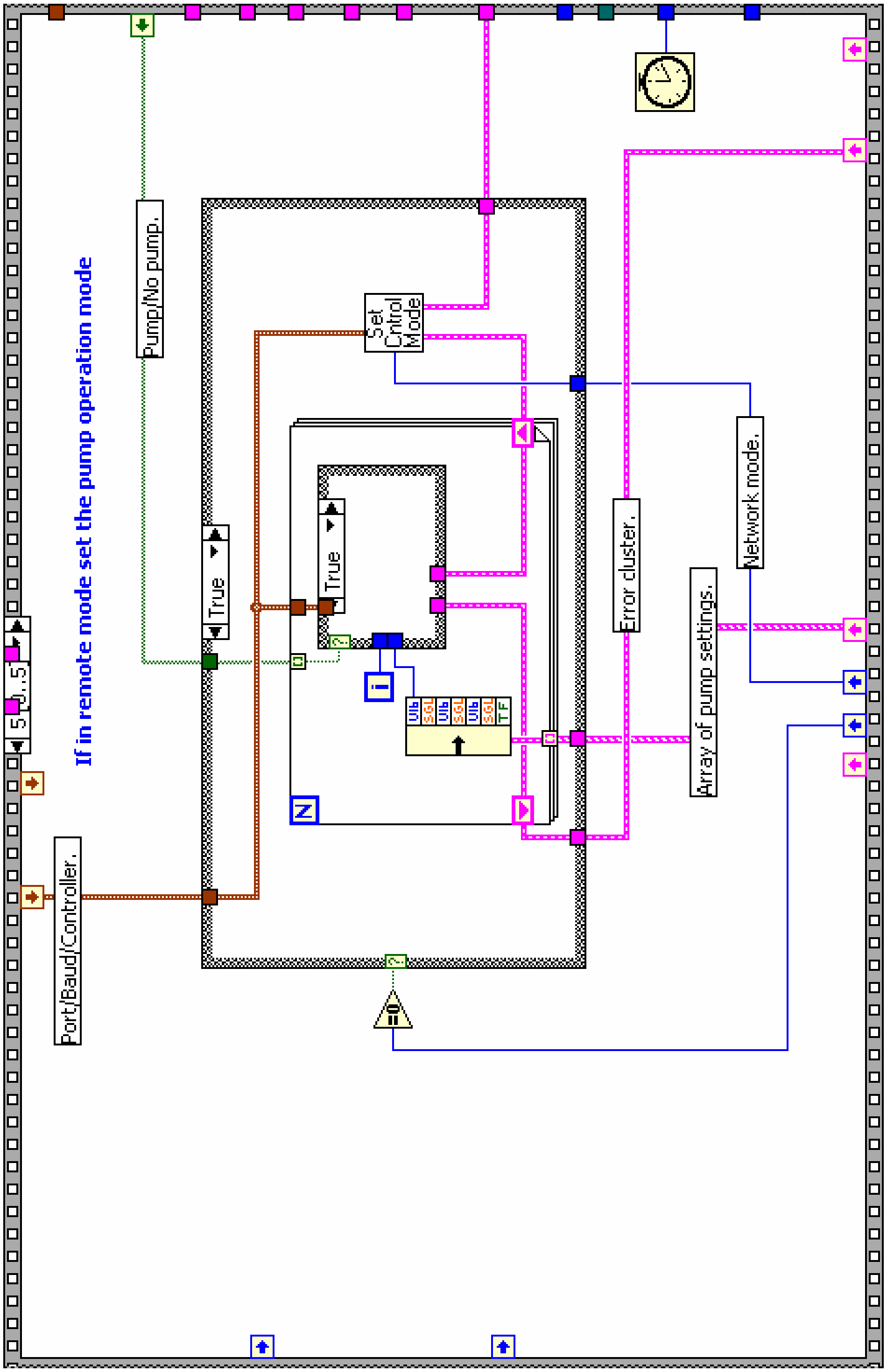

True
0.00
SGL
SGL
SGL
SGL

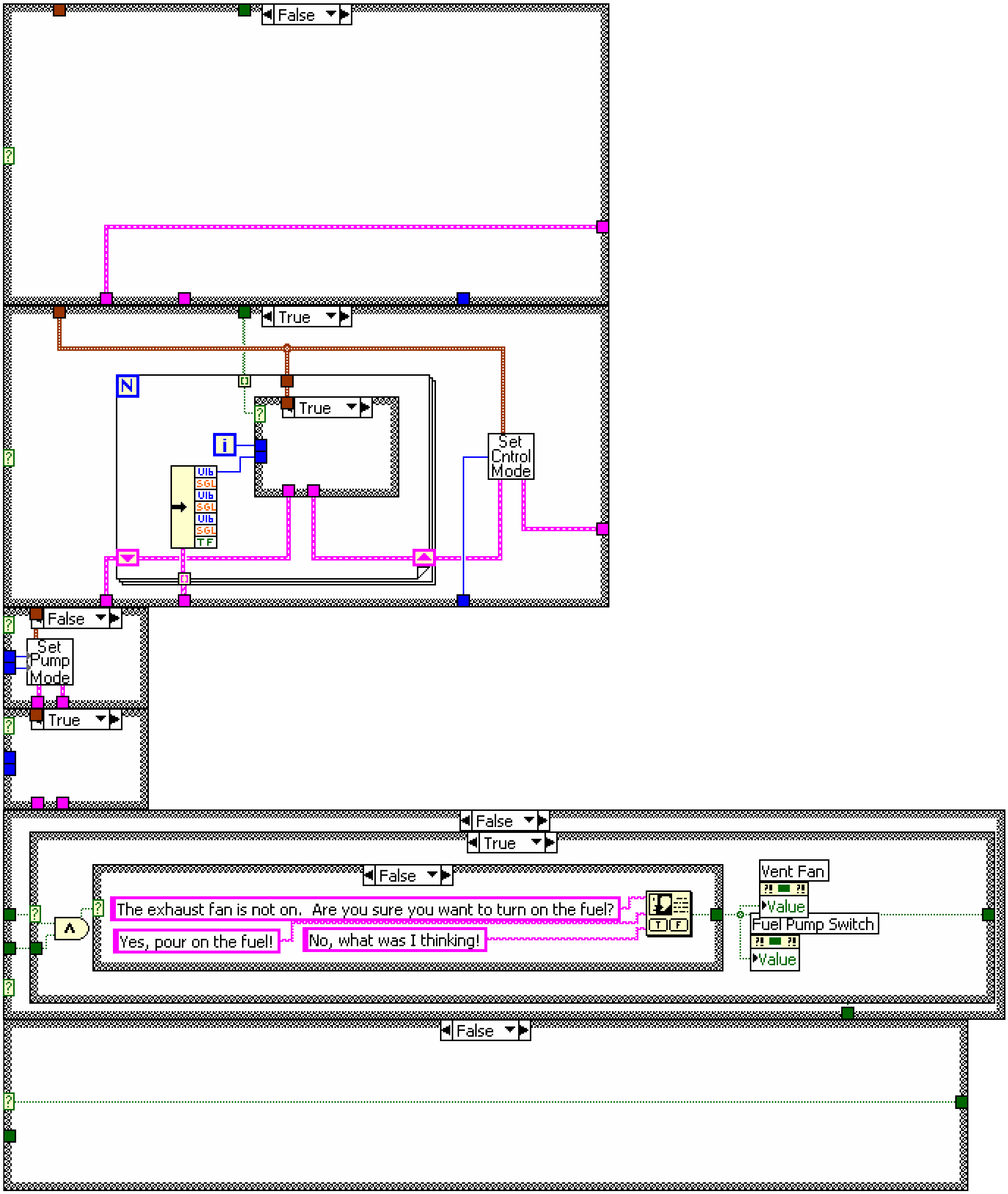

Get alarm limits.
Pump/No pump.
Port/Baud/Controller.
Error cluster.
Error cluster.
4 [0..5]
1
False
stnd units
Get alarm limits


..0
False
stnd units
Get alarm limits
False
stnd units
Get alarm limits
True
0.00
SGL
SGL
SGL
SGL
SGL
1
False
stnd units
Get alarm limits

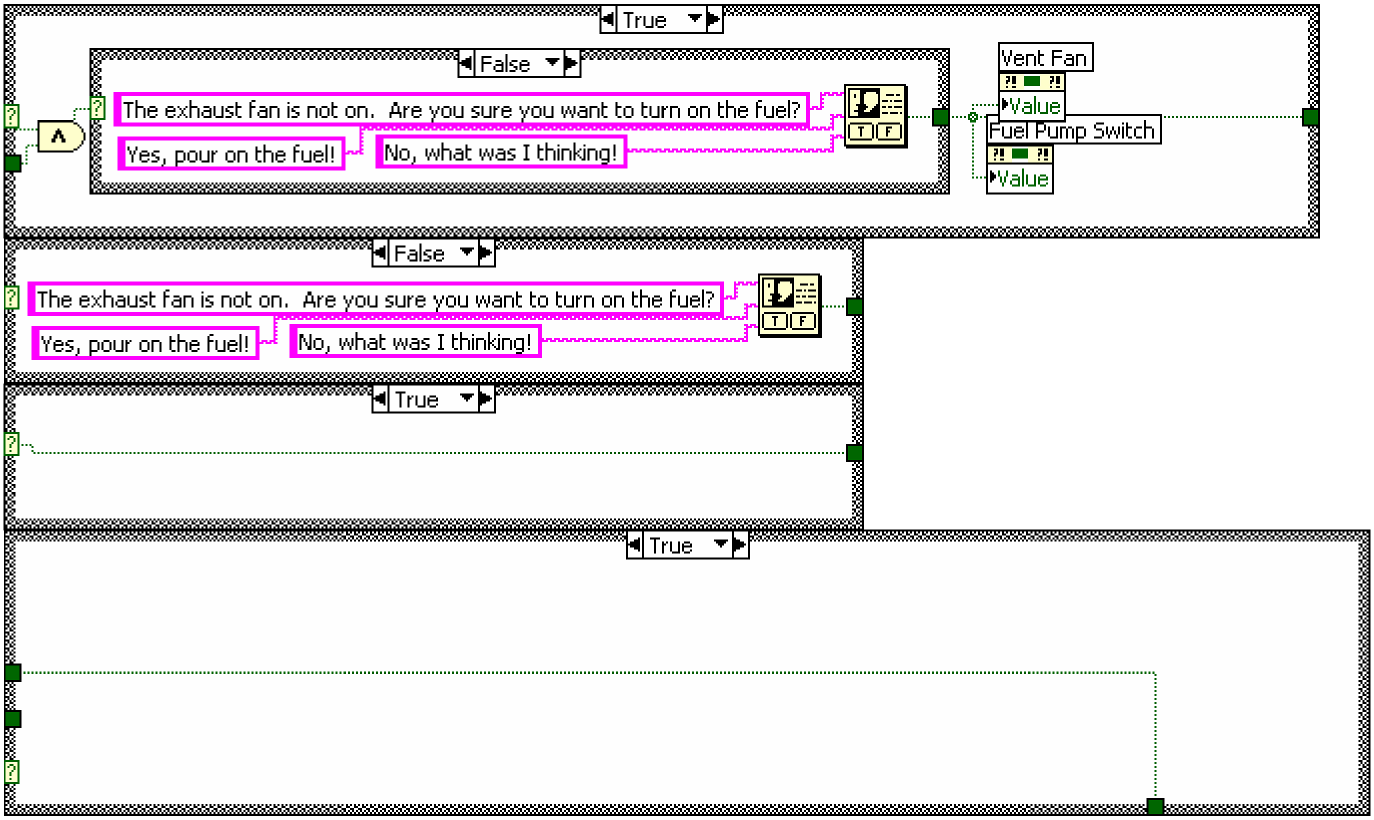

False
stnd units
Get alarm limits
True
0.00
SGL
2..
True
0.00
SGL
False
stnd units
Get alarm limits

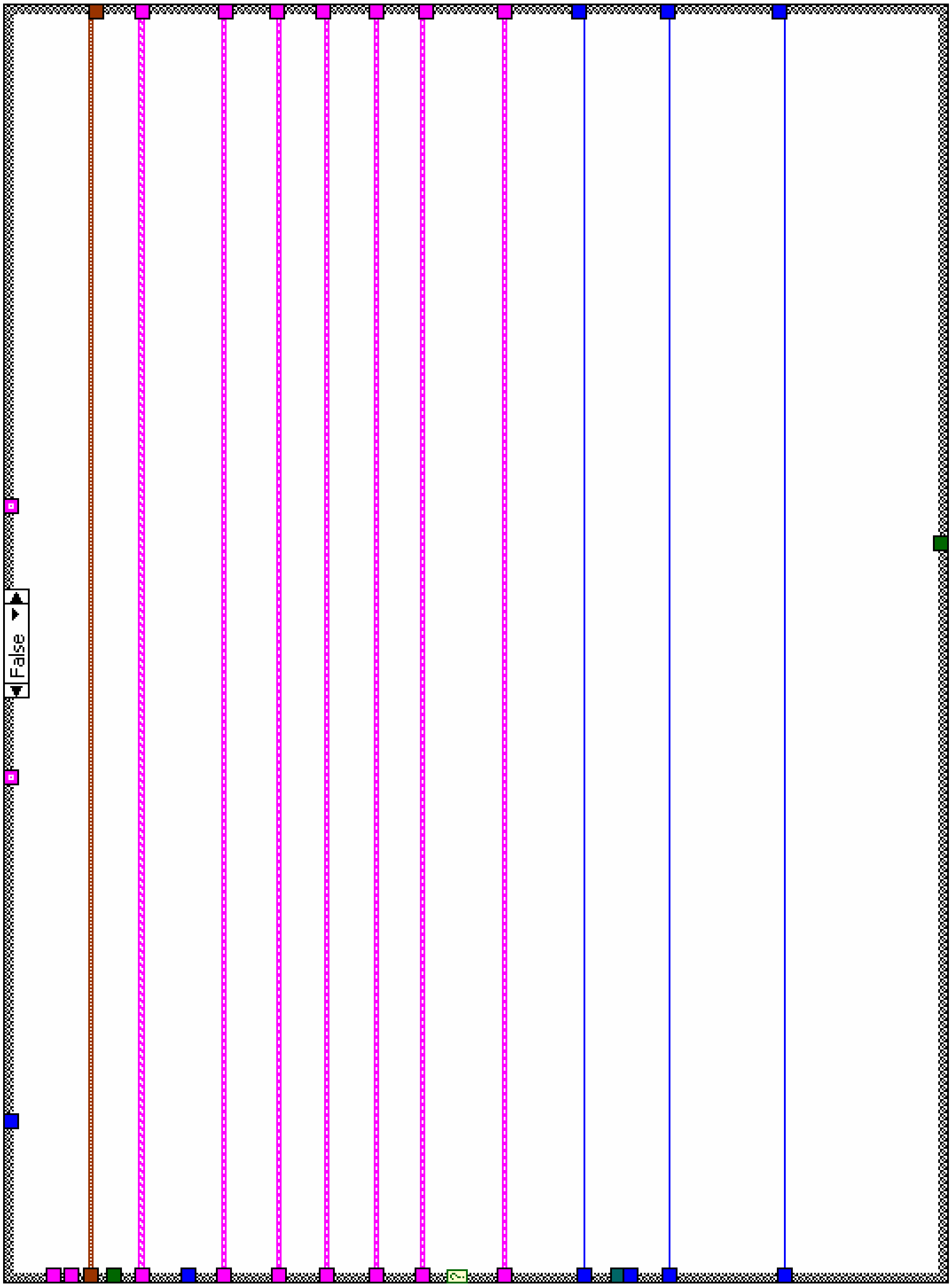

True
0.00
SGL
SGL
SGL
SGL
SGL

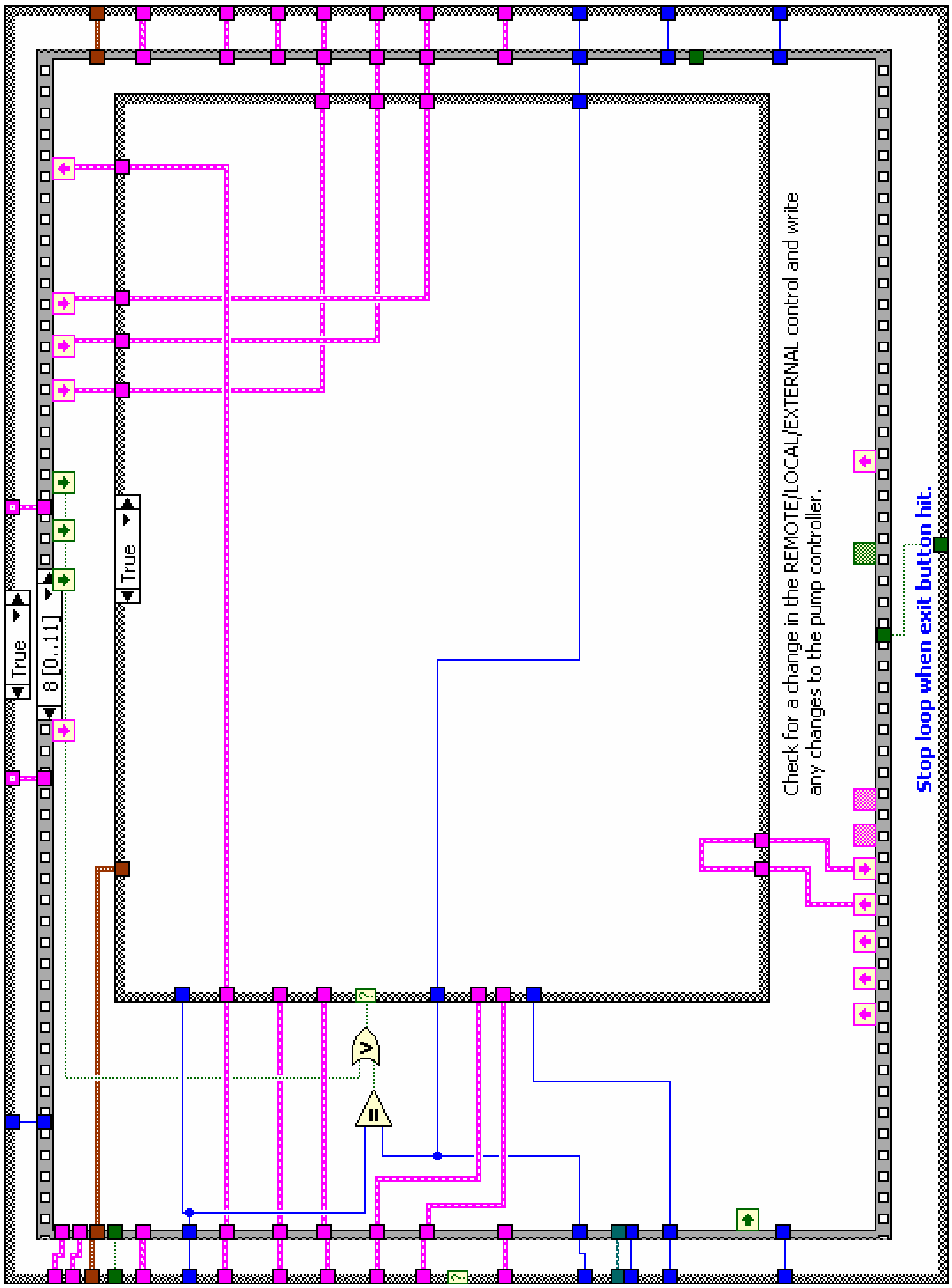

If in remote mode set the pump operation mode
Pump/No pump.
Port/Baud/Controller.
Set Cntrol Mode
True
True
Error cluster.
Network mode.
Array of pump settings.
5 [0..5]

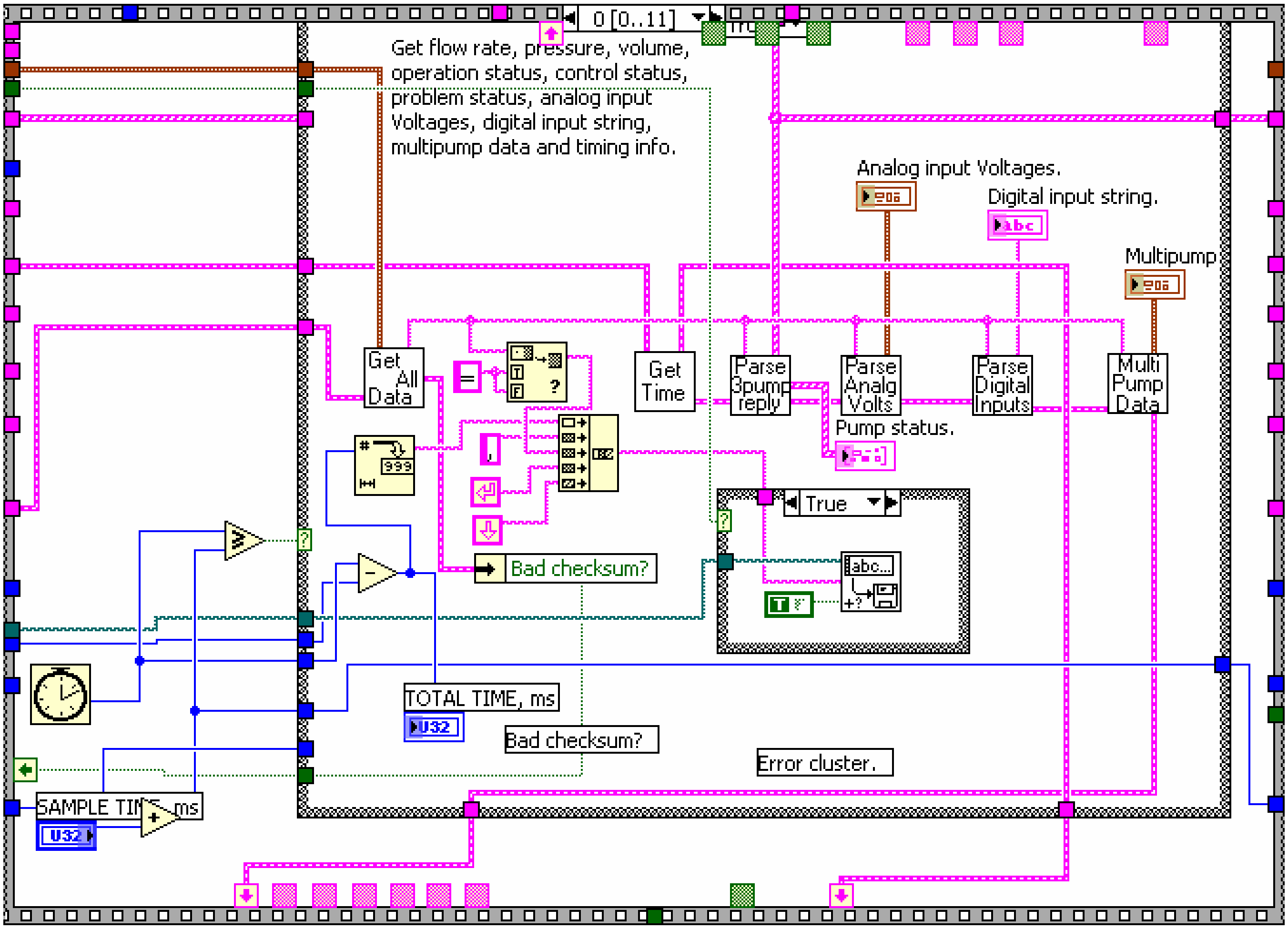


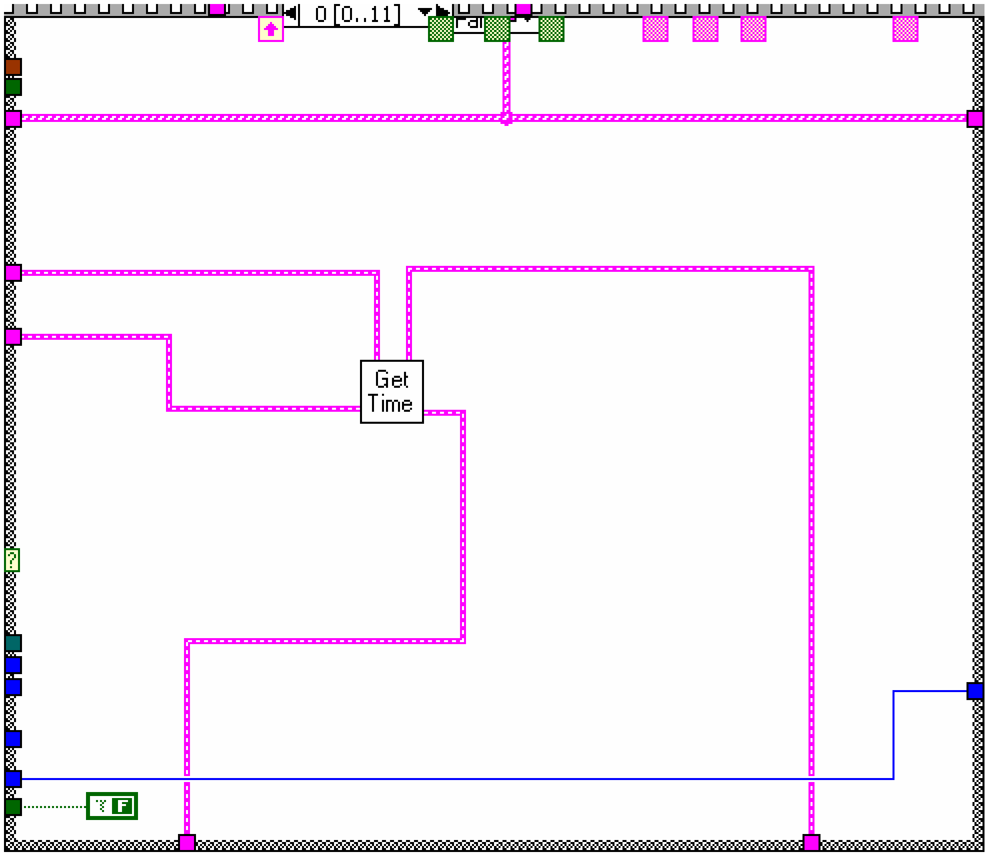
False
True
N
True
i
Set
Cntrol
Mode
False
Set
Pump
Mode
True
False
True
False
The exhaust fan is not on. Are you sure you want to turn on the fuel?
Yes, pour on the fuel!
No, what was I thinking!
Vent Fan
Value
Fuel Pump Switch
Value
False

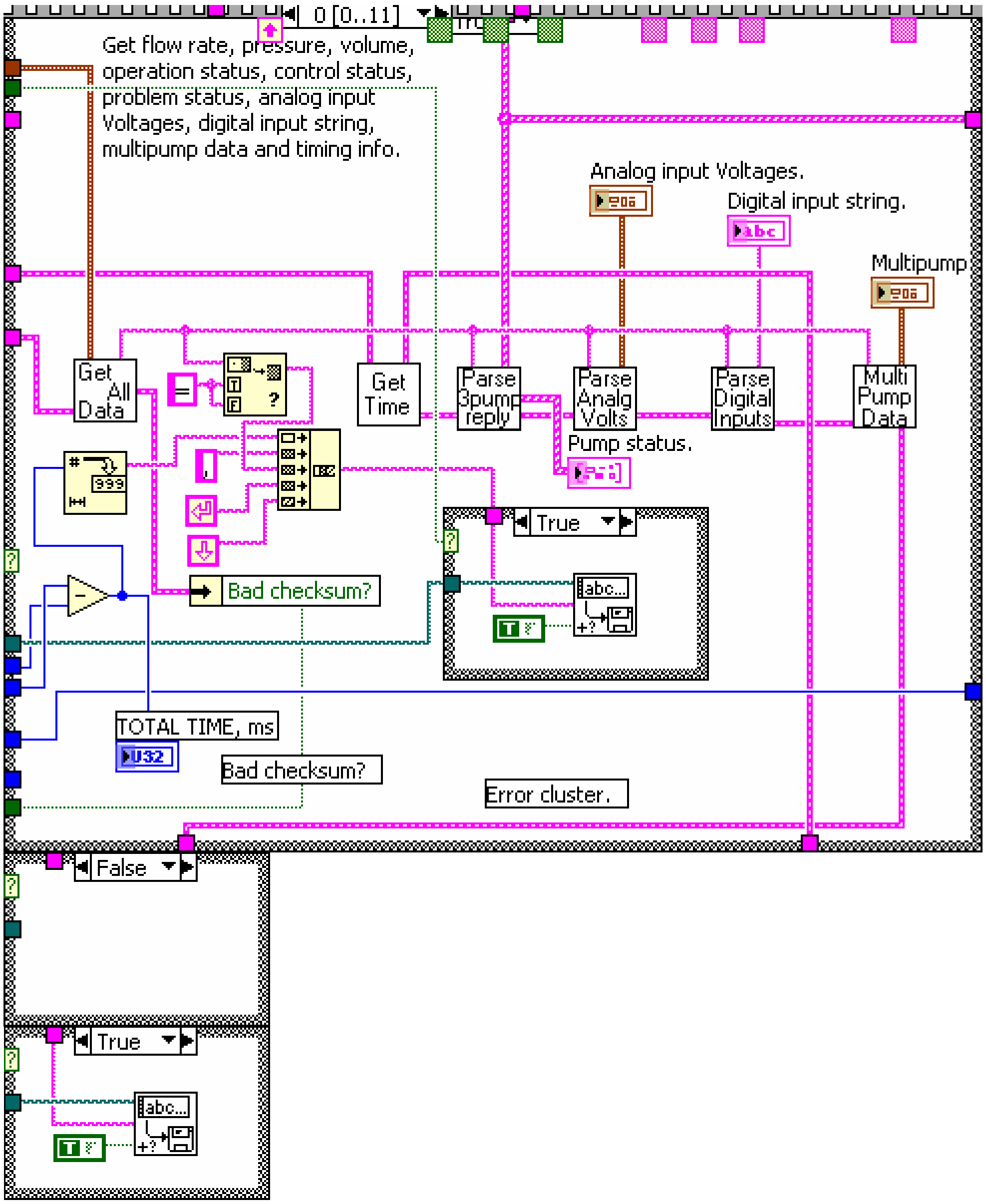

True
False
The exhaust fan is not on. Are you sure you want to turn on the fuel?
Yes, pour on the fuel!
No, what was I thinking!
Vent Fan
Value
Fuel Pump Switch
Value
False
The exhaust fan is not on. Are you sure you want to turn on the fuel?
Yes, pour on the fuel!
No, what was I thinking!
True
True

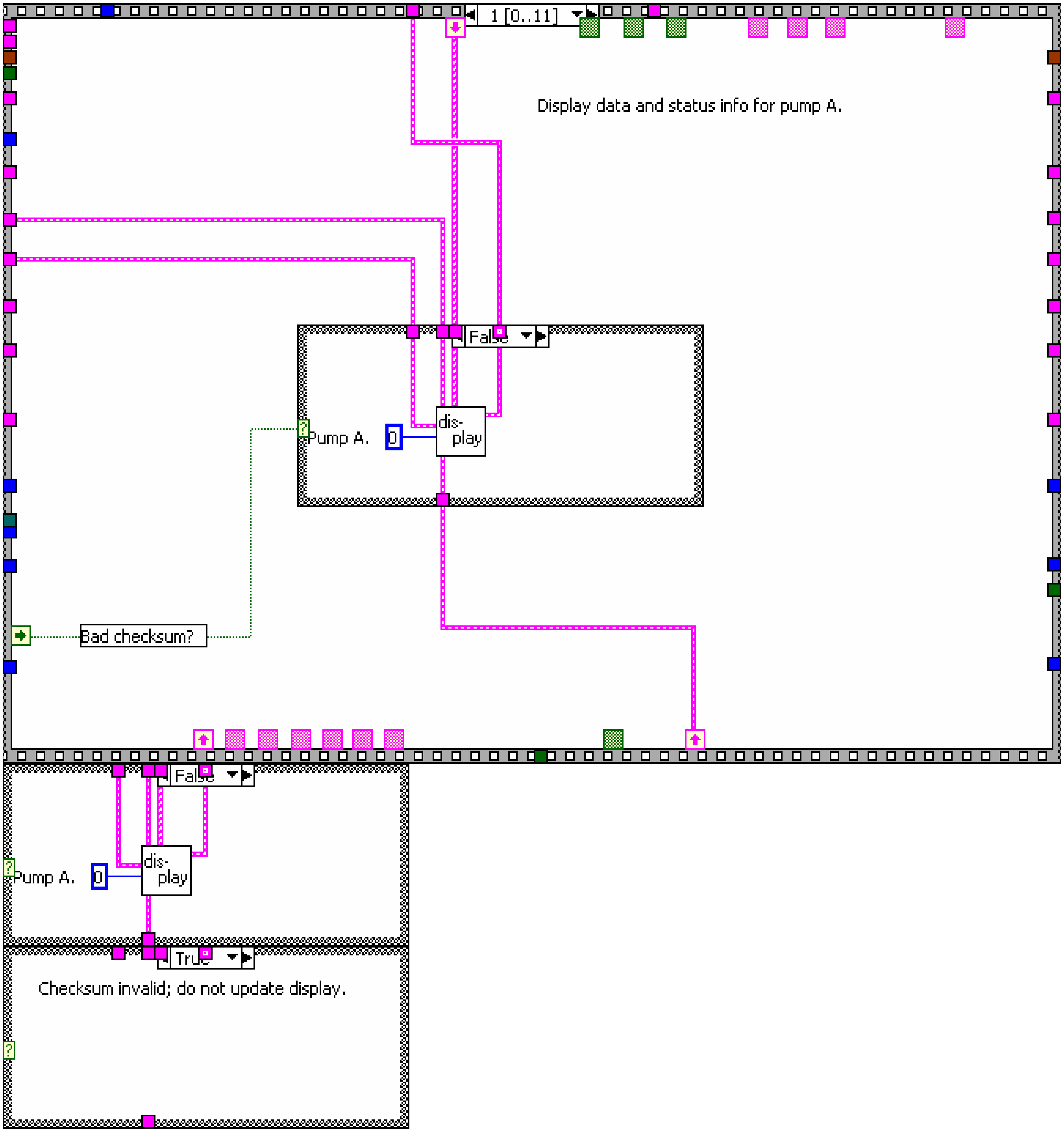

False

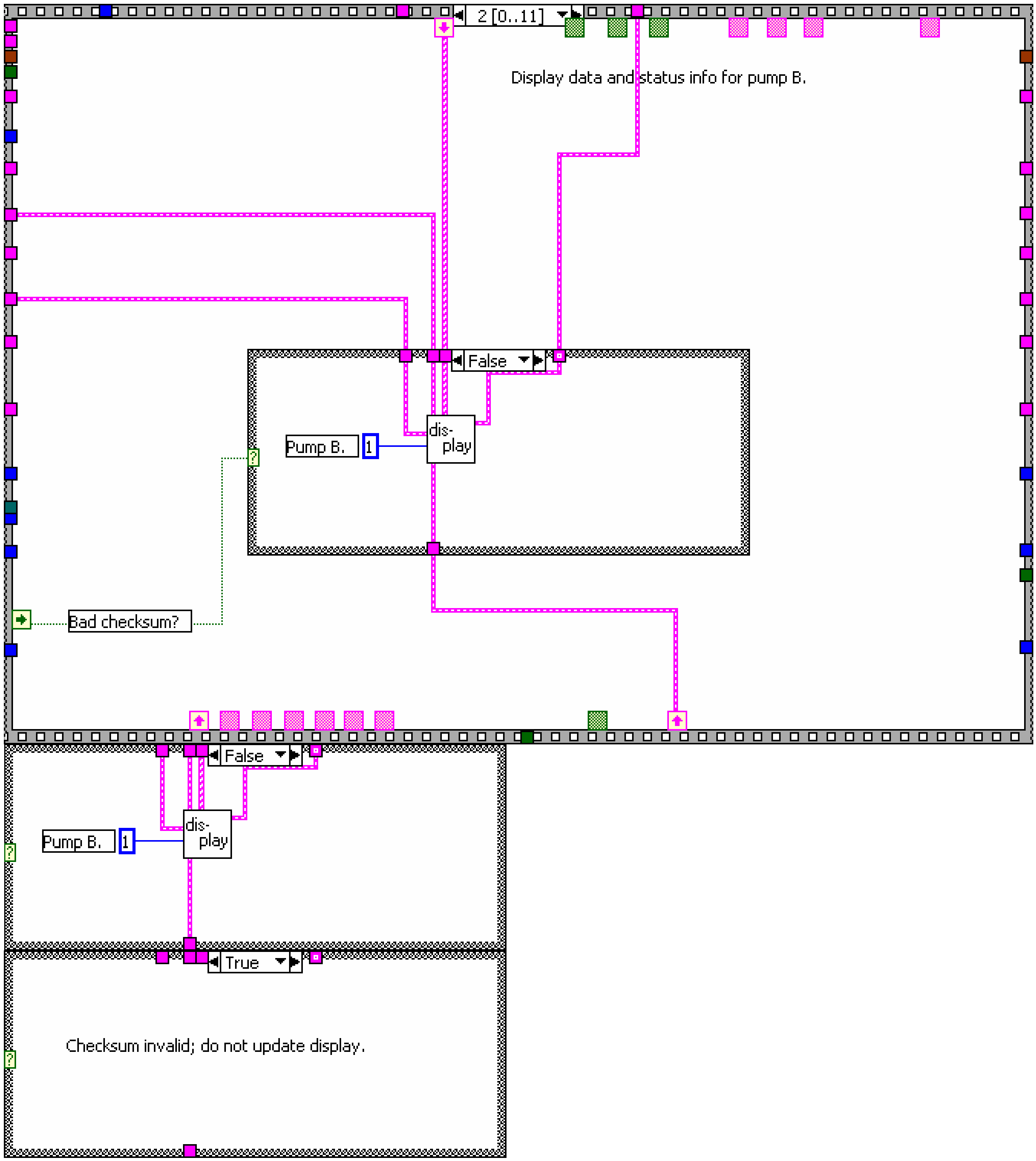

True
8 [0..11]
True
Check for a change in the REMOTE/LOCAL/EXTERNAL control and write any changes to the pump controller.
Stop loop when exit button hit.


0 [0..11]
Get flow rate, pressure, volume, operation status, control status, problem status, analog input Voltages, digital input string, multipump data and timing info.
Analog input Voltages.
Digital input string.
Multipump
Get All Data
Get Time
Parse 3pump reply
Parse Analg Volts
Parse Digital Inputs
Multi Pump Data
Pump status.
True
Bad checksum?
TOTAL TIME, ms
U32
Bad checksum?
Error cluster.
SAMPLE TIME, ms
U32

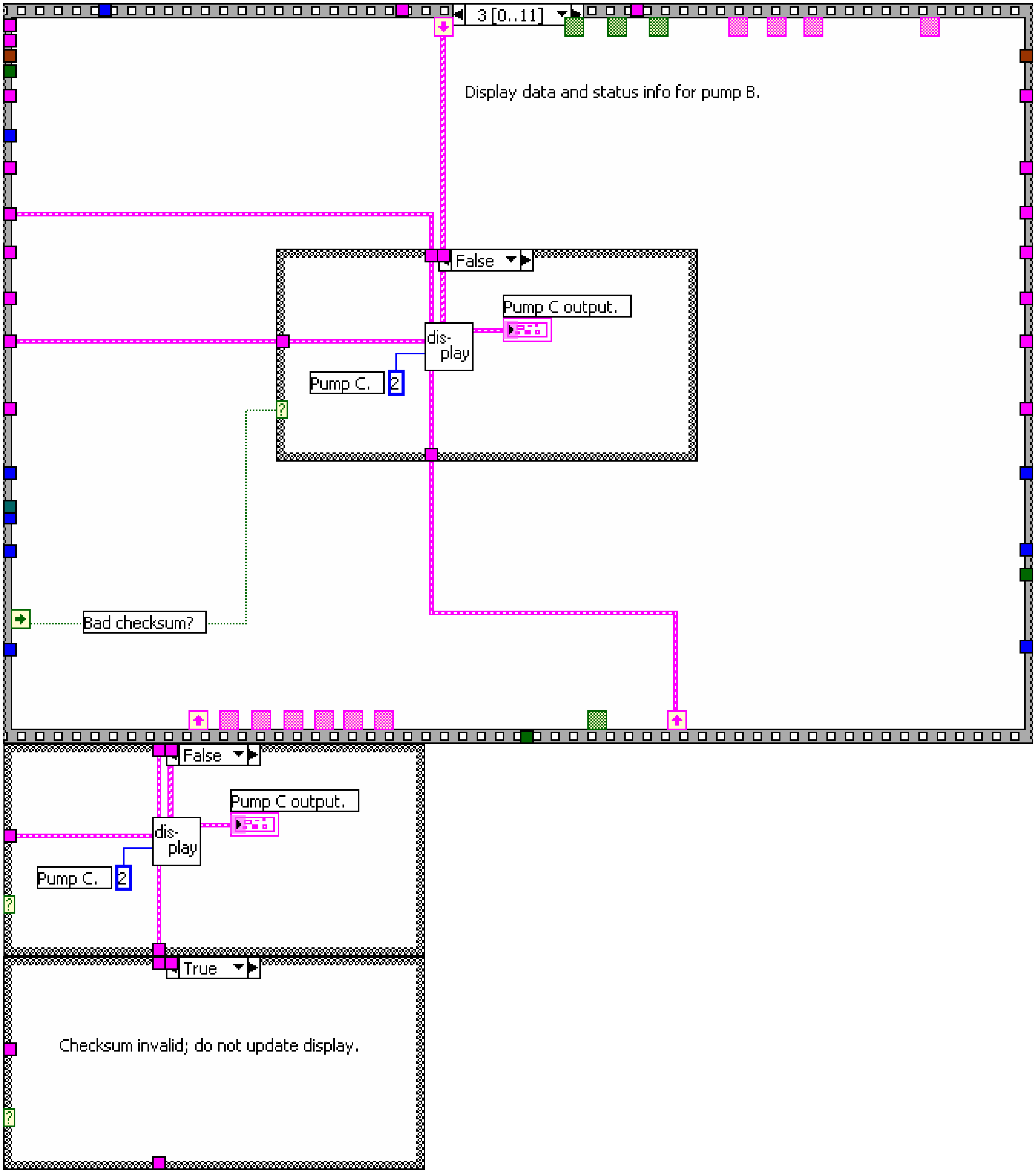

0 [0..11]
Get
Time

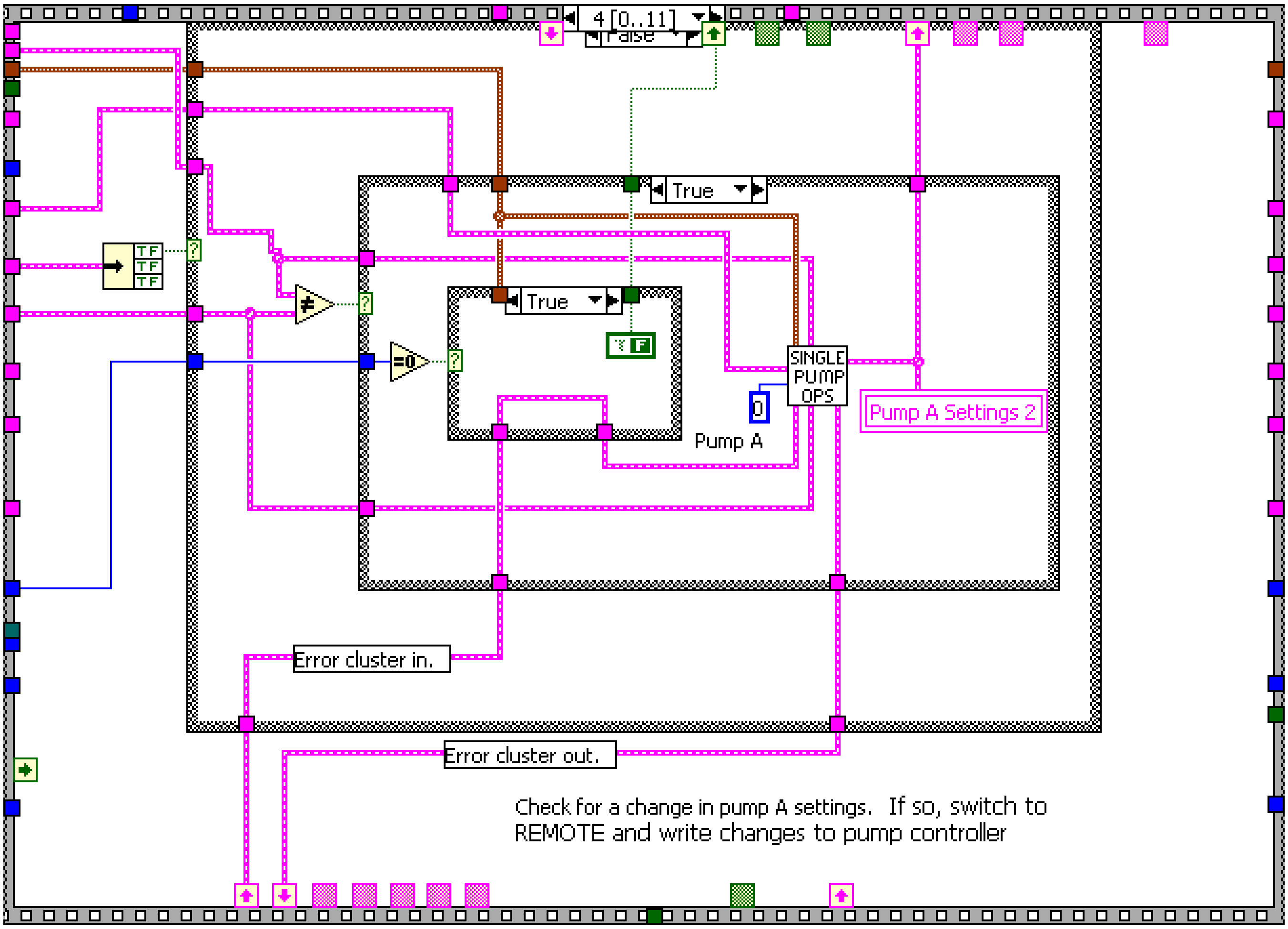

0 [0..11]
Get flow rate, pressure, volume, operation status, control status, problem status, analog input Voltages, digital input string, multipump data and timing info.
Analog input Voltages.
Digital input string.
Multipump
Get All Data
Get Time
Parse 3pump reply
Parse Analg Volts
Parse Digital Inputs
Multi Pump Data
Pump status.
True
Bad checksum?
TOTAL TIME, ms
U32
Bad checksum?
Error cluster.
False
True

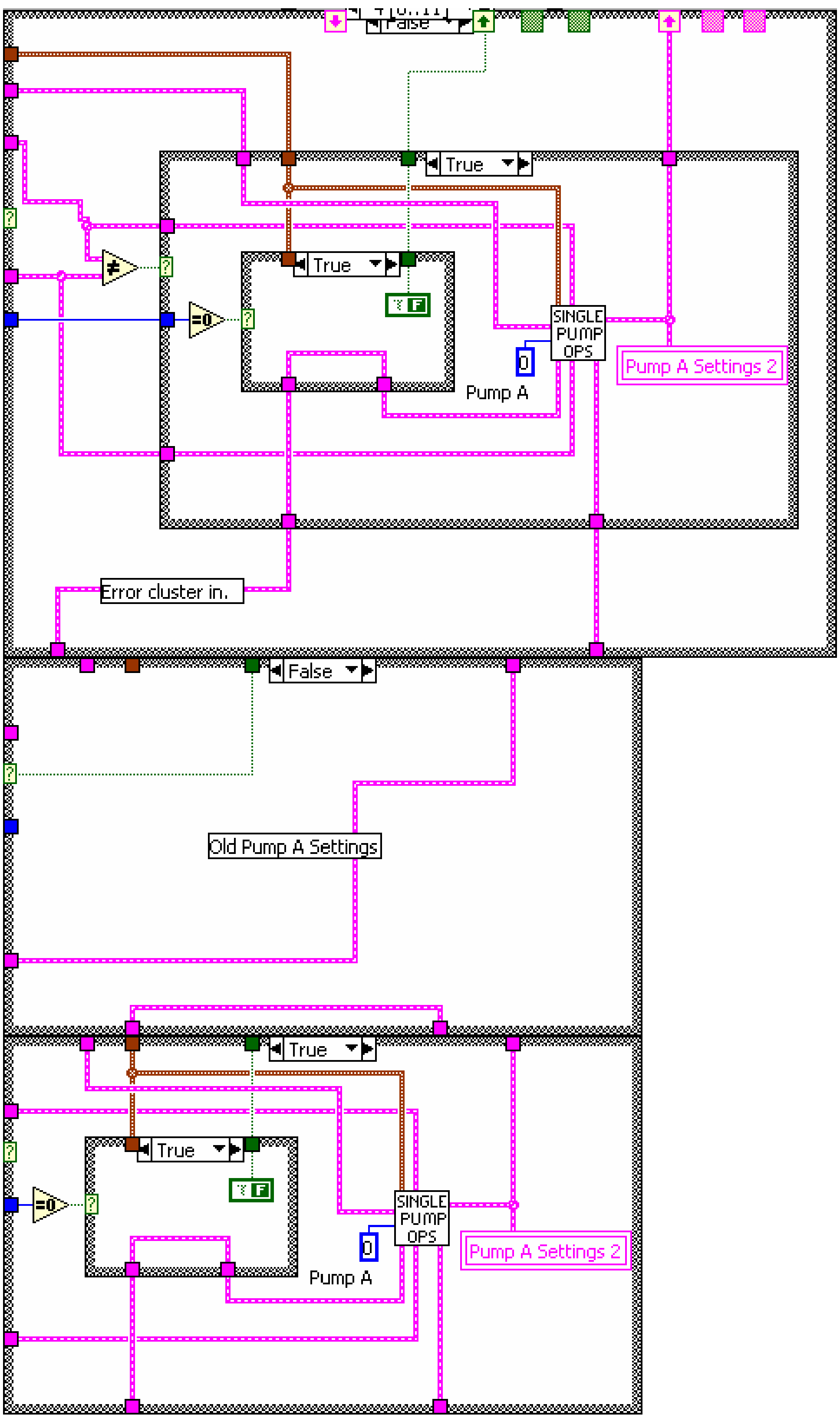

1 [0..11]
Display data and status info for pump A.
False
Pump A.
0
dis-
play
Bad checksum?
False
Pump A.
0
dis-
play
True
Checksum invalid; do not update display.

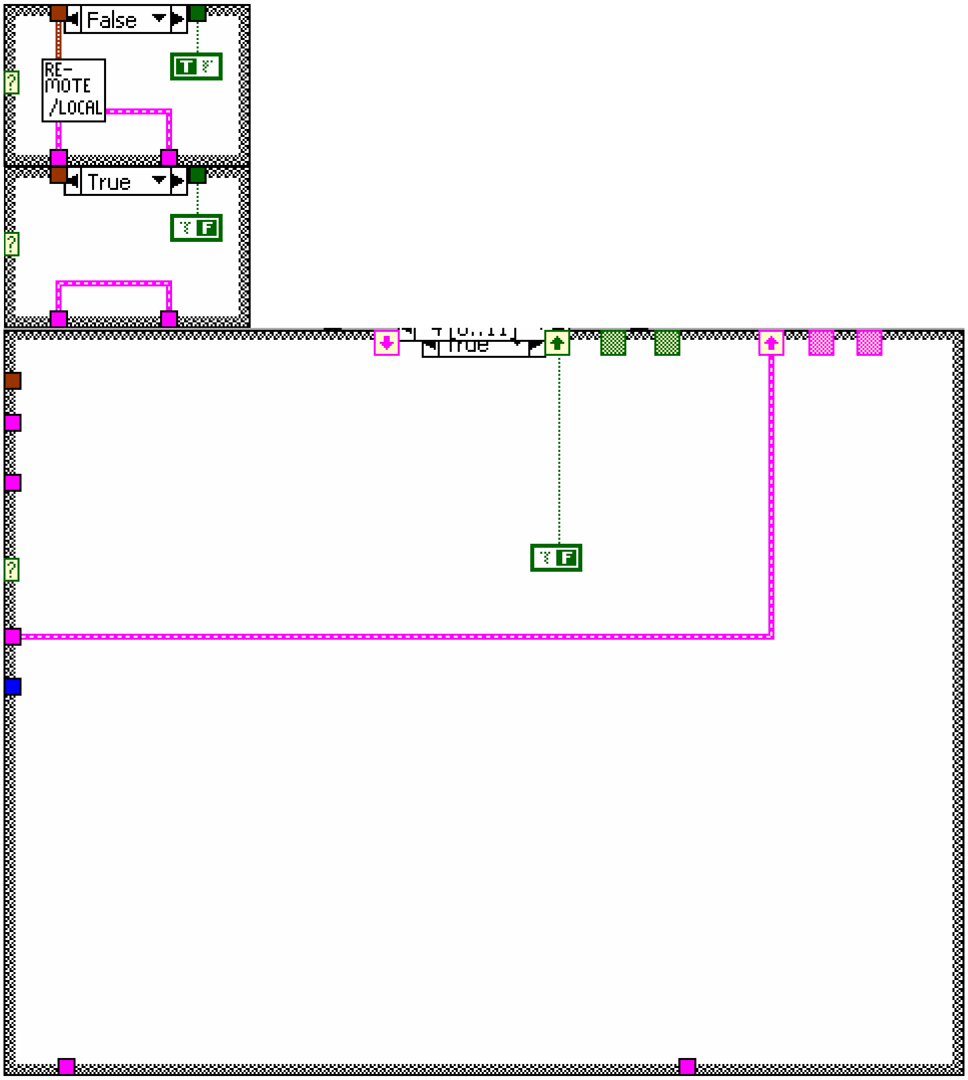


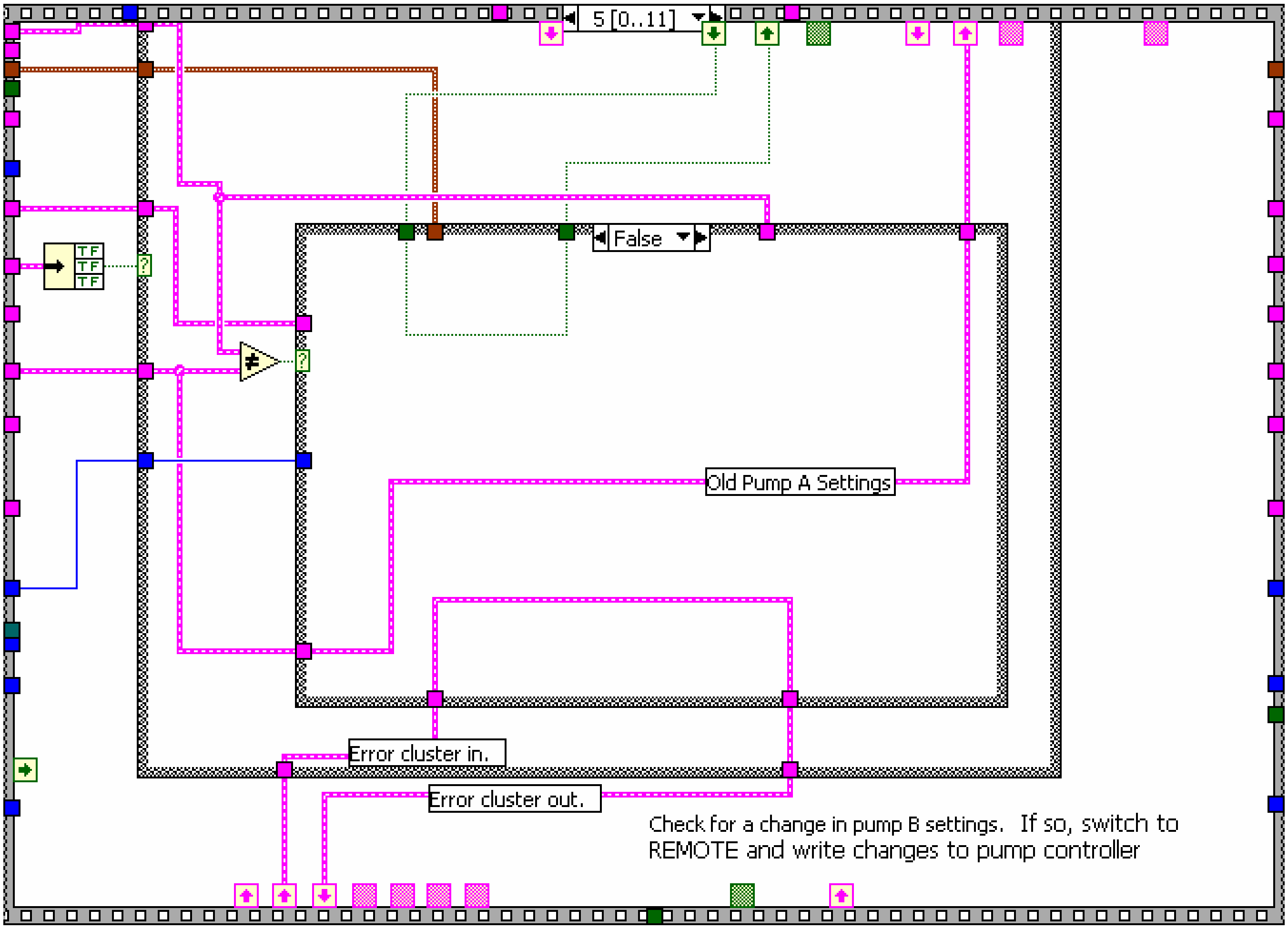
2 [0..11]
Display data and status info for pump B.
False
Pump B.
1
dis-
play
Bad checksum?
False
Pump B.
1
dis-
play
True
Checksum invalid; do not update display.

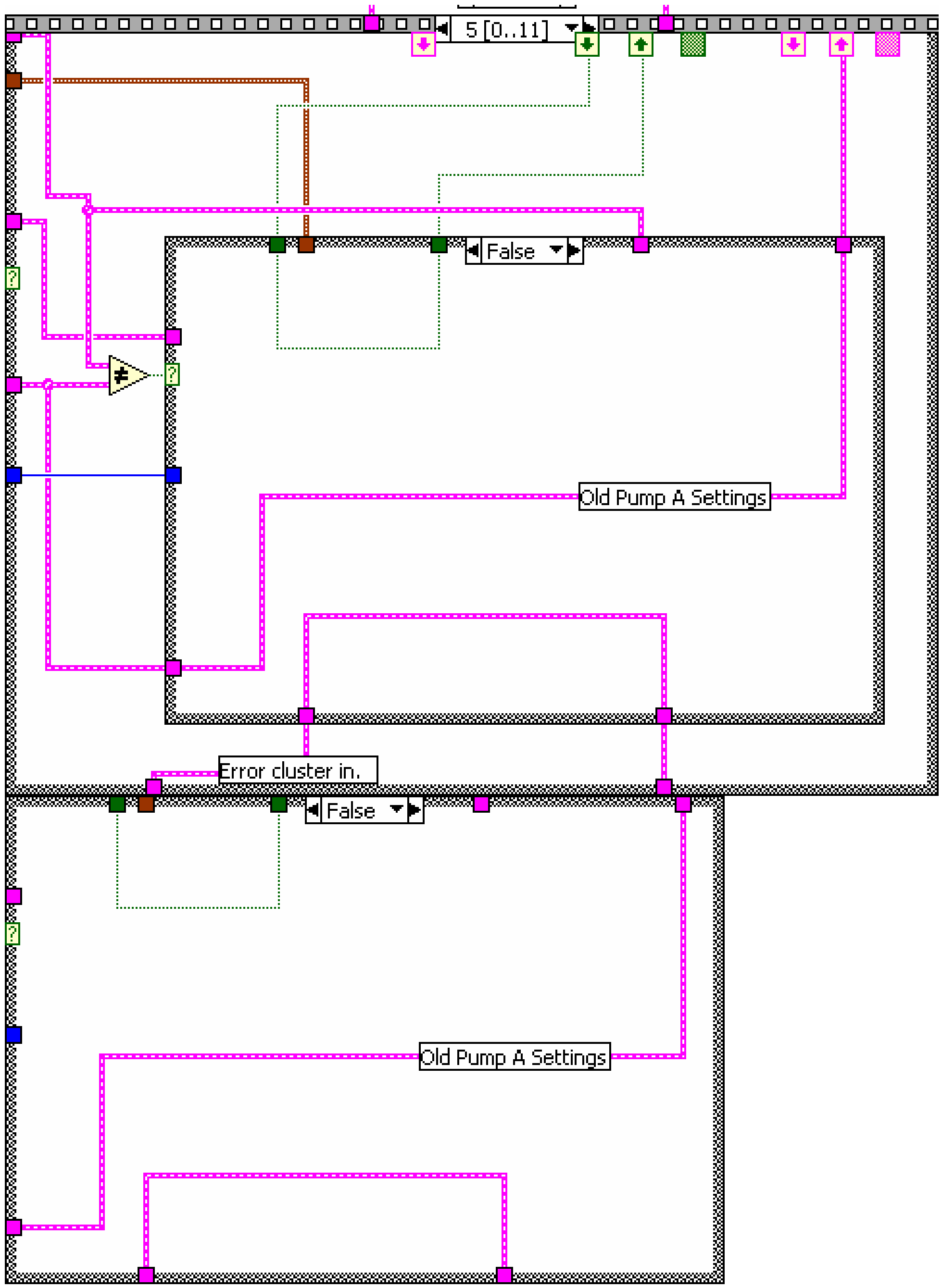

3 [0..11]
Display data and status info for pump B.
False
Pump C output.
dis-
play
Pump C.
2
Bad checksum?
False
Pump C output.
dis-
play
Pump C.
2
True
Checksum invalid; do not update display.

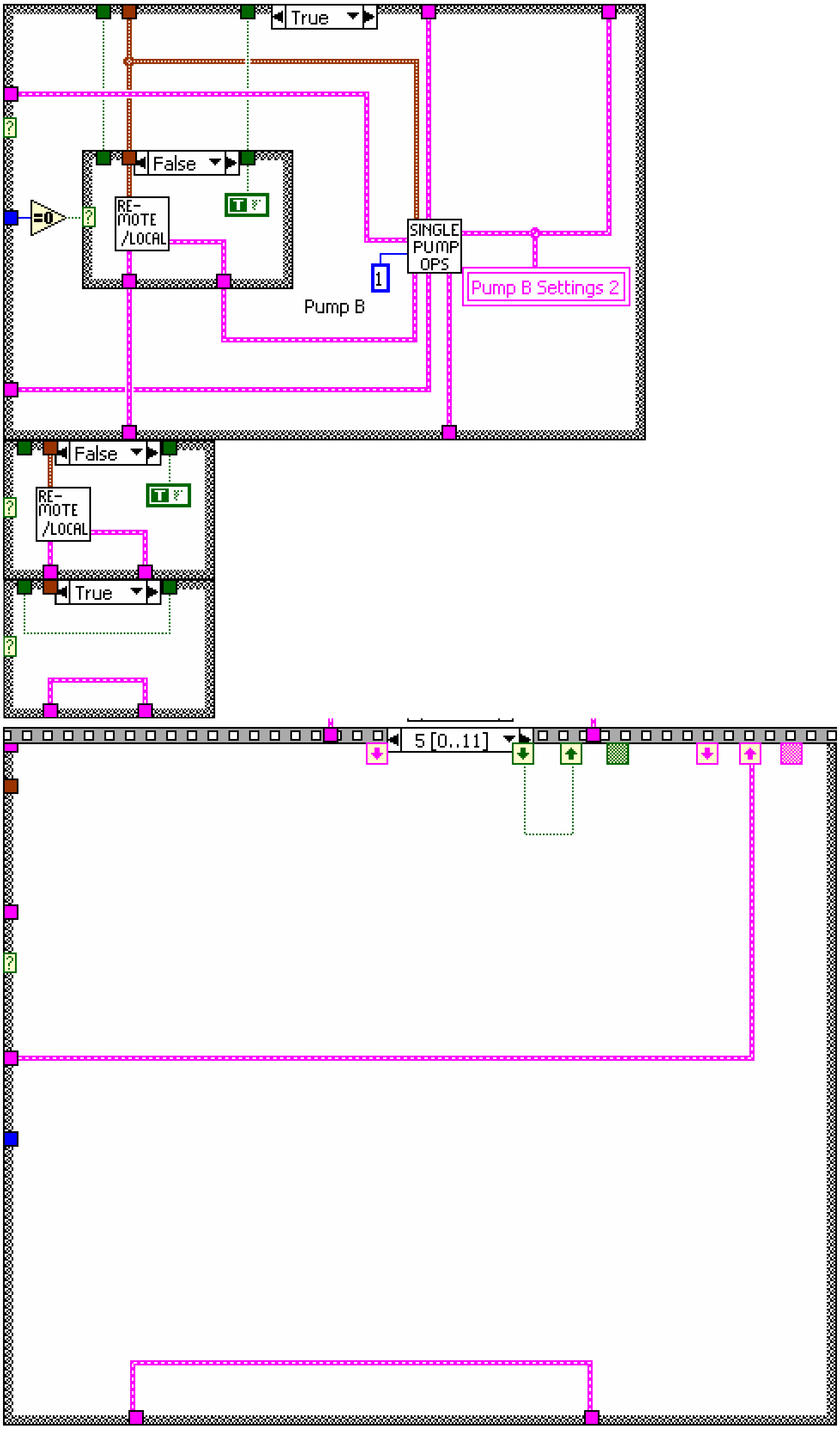

4 [0..11]
False
True
True
SINGLE PUMP OPS
Pump A Settings 2
Pump A
Error cluster in.
Error cluster out.
Check for a change in pump A settings. If so, switch to REMOTE and write changes to pump controller

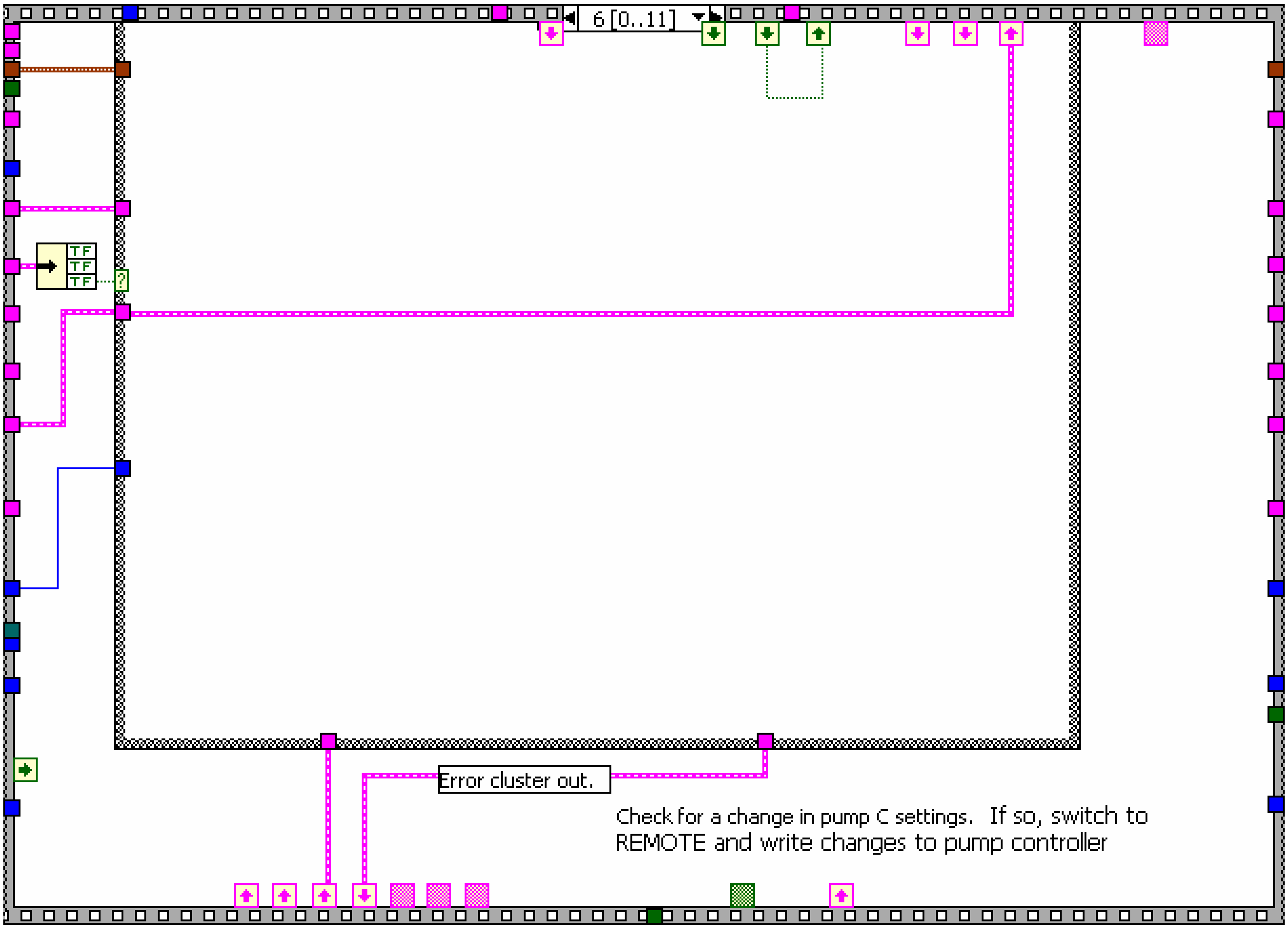

False
True
True
SINGLE PUMP OPS
0
Pump A
Pump A Settings 2
Error cluster in.
False
Old Pump A Settings
True
True
SINGLE PUMP OPS
0
Pump A
Pump A Settings 2

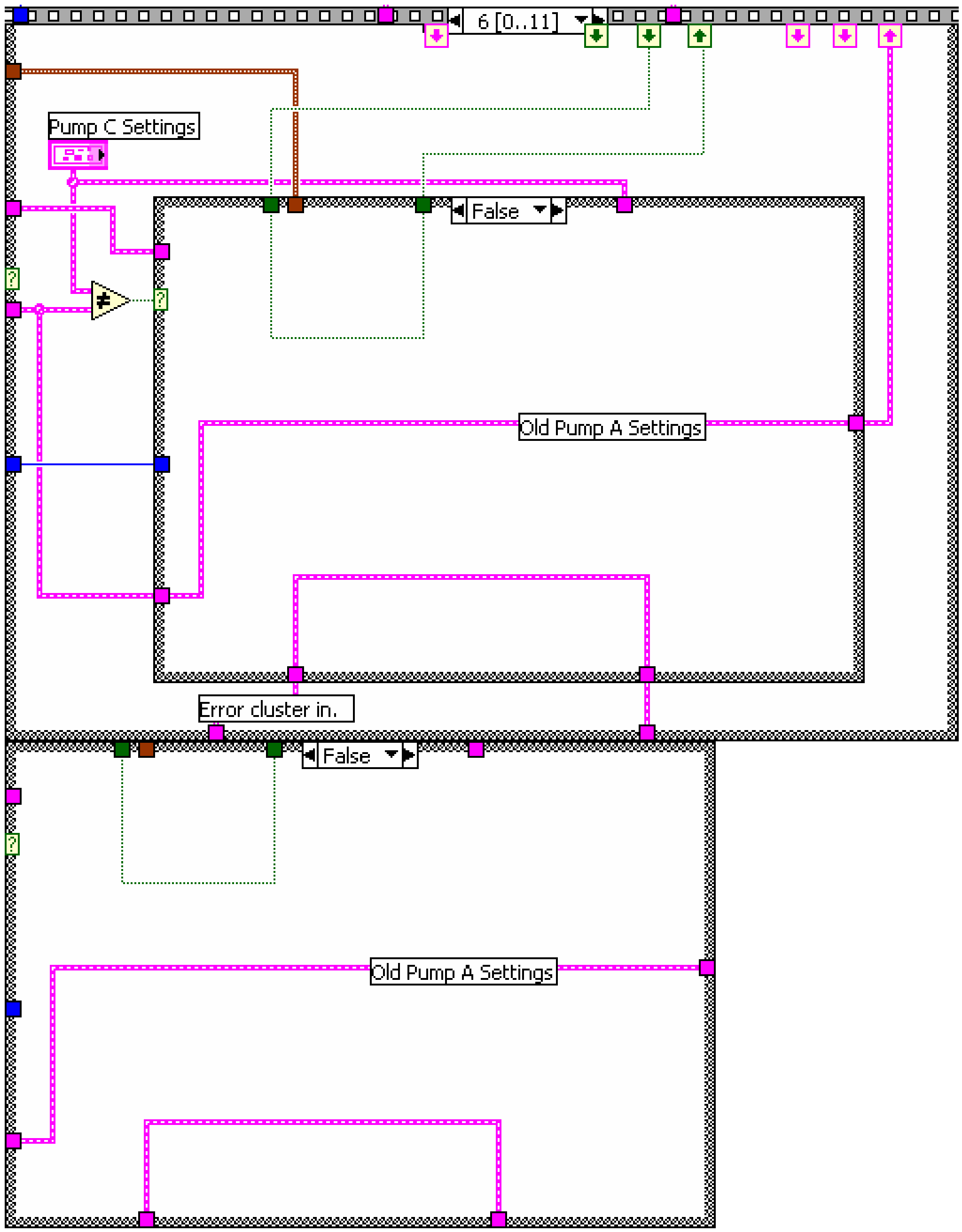

False
RE-
MOTE
/LOCAL
True
True

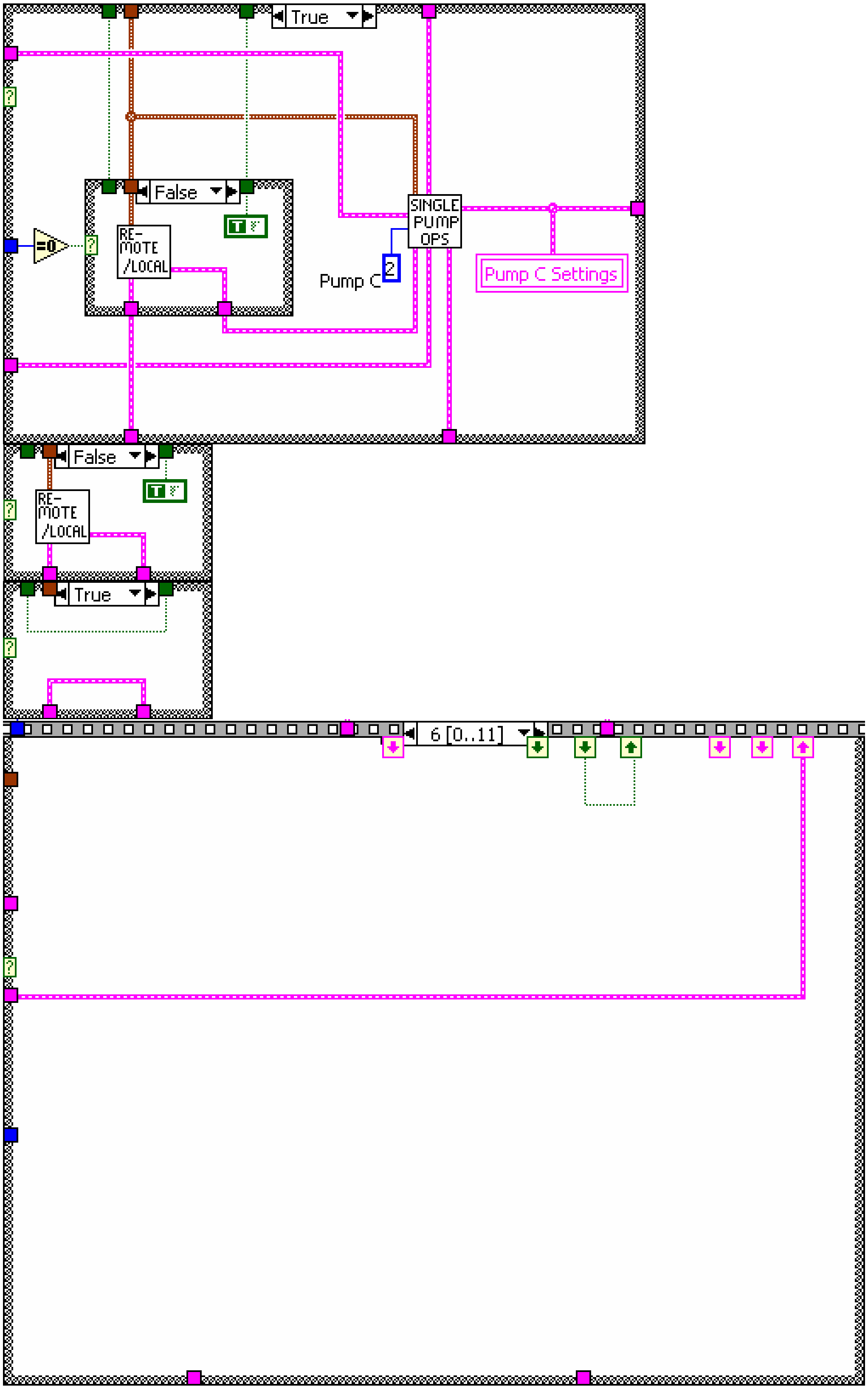

5 [0..11]
False
Old Pump A Settings
Error cluster in.
Error cluster out.
Check for a change in pump B settings. If so, switch to REMOTE and write changes to pump controller


5 [0..11]
False
Old Pump A Settings
Error cluster in.
False
Old Pump A Settings

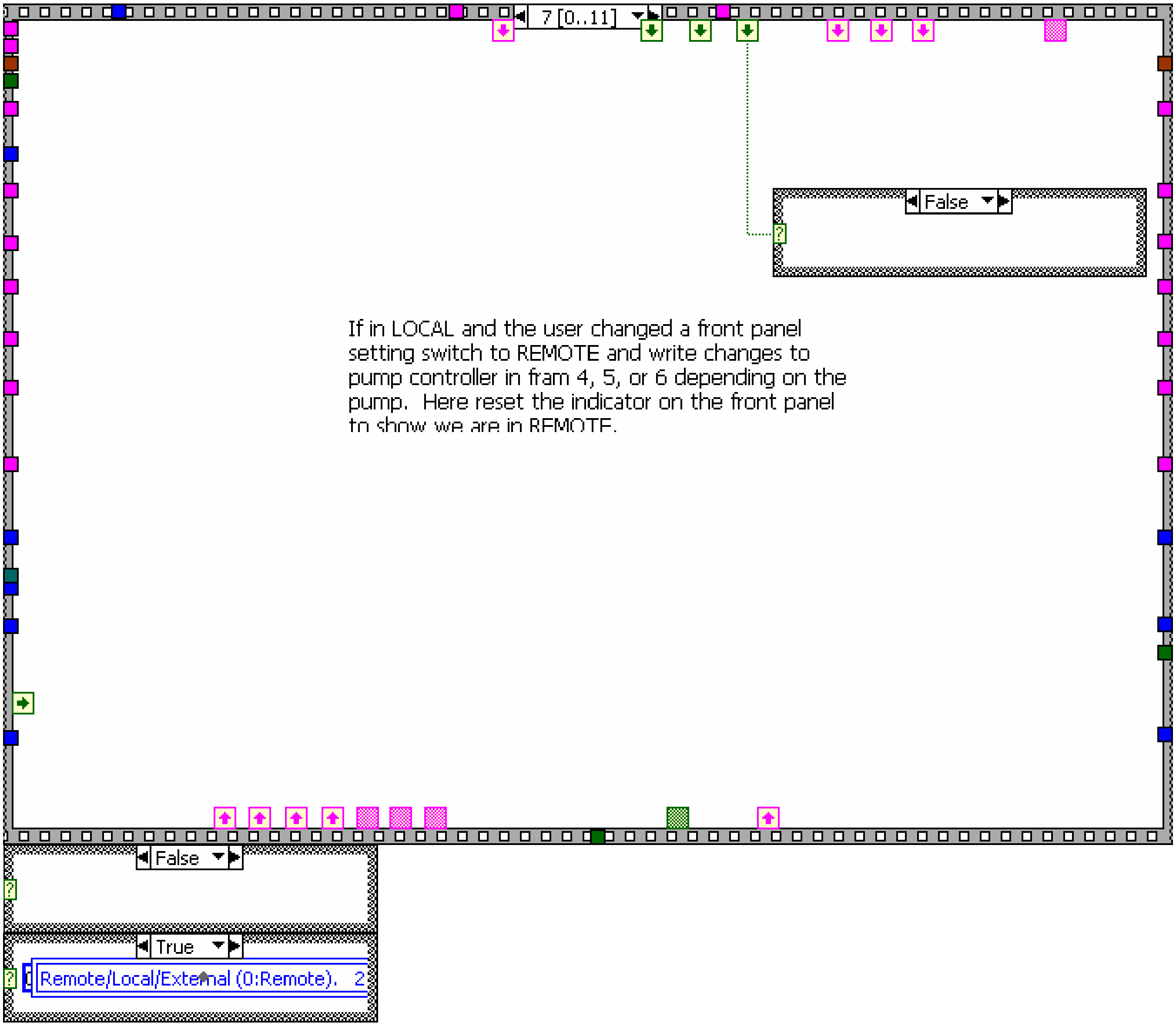

True
False
RE-
MOTE
/LOCAL
SINGLE
PUMP
OPS
1
Pump B Settings 2
Pump B
False
RE-
MOTE
/LOCAL
True
5 [0..11]

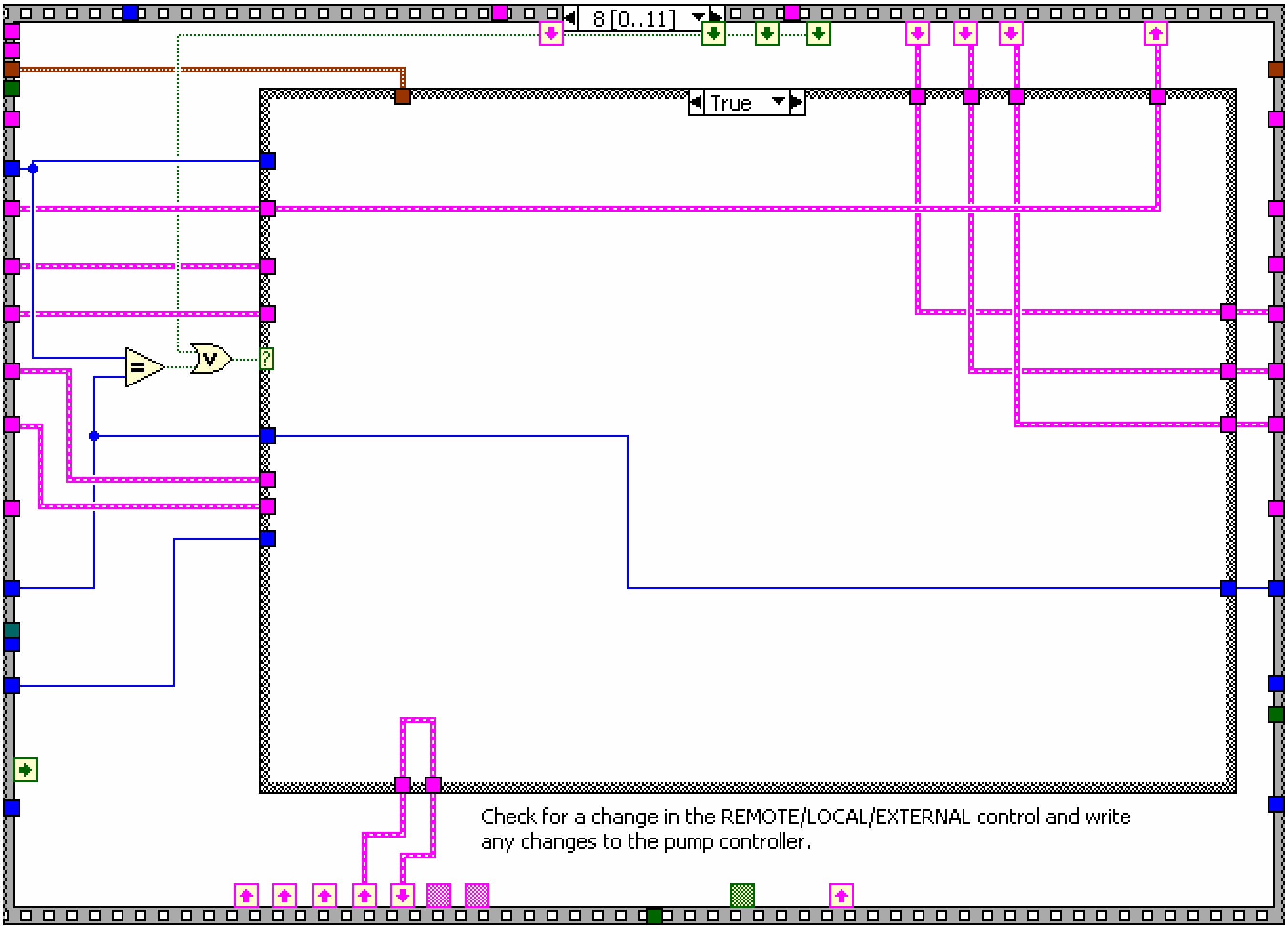

6 [0..11]
Error cluster out.
Check for a change in pump C settings. If so, switch to REMOTE and write changes to pump controller

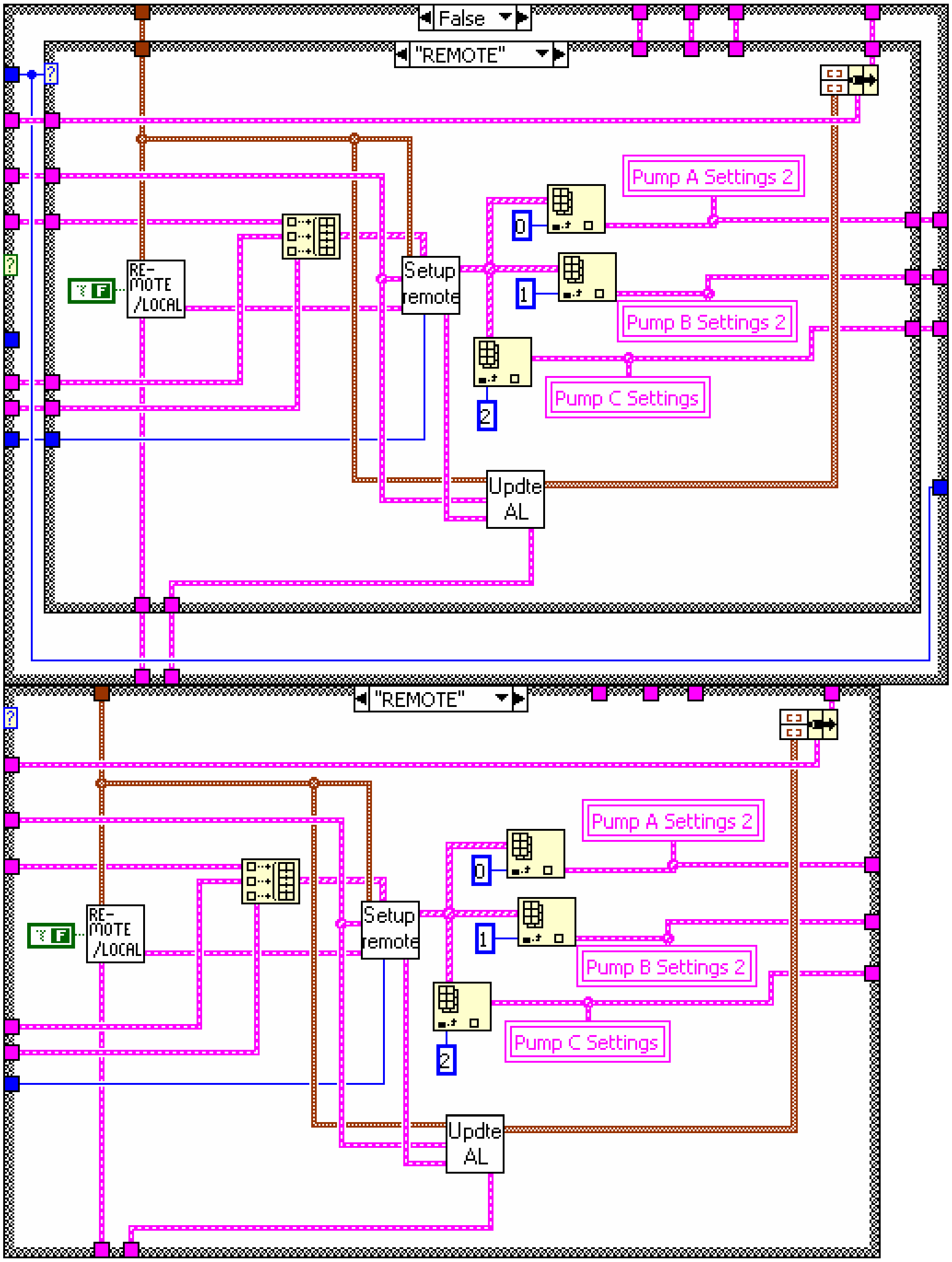

6 [0..11]
Pump C Settings
False
Old Pump A Settings
Error cluster in.
False
Old Pump A Settings

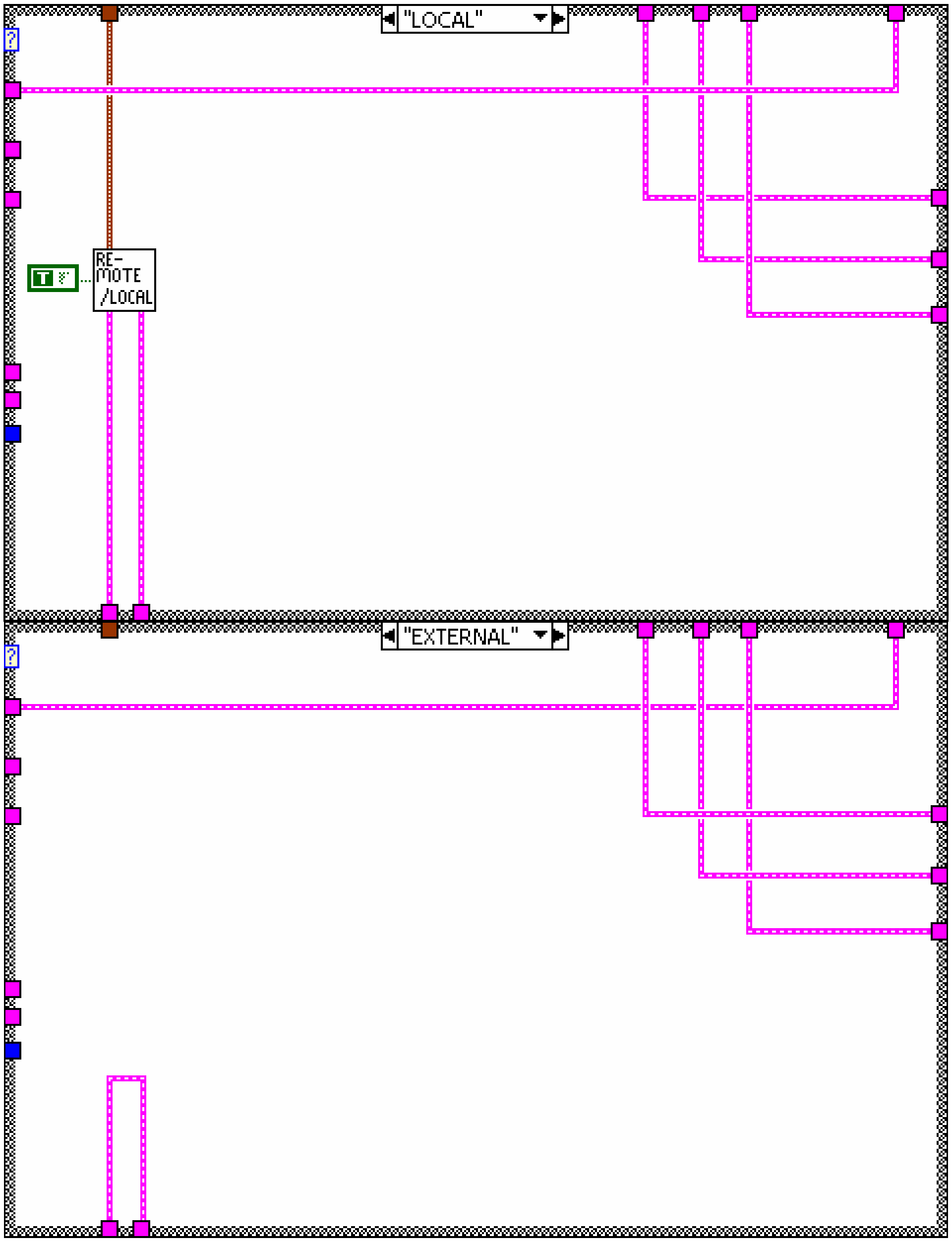


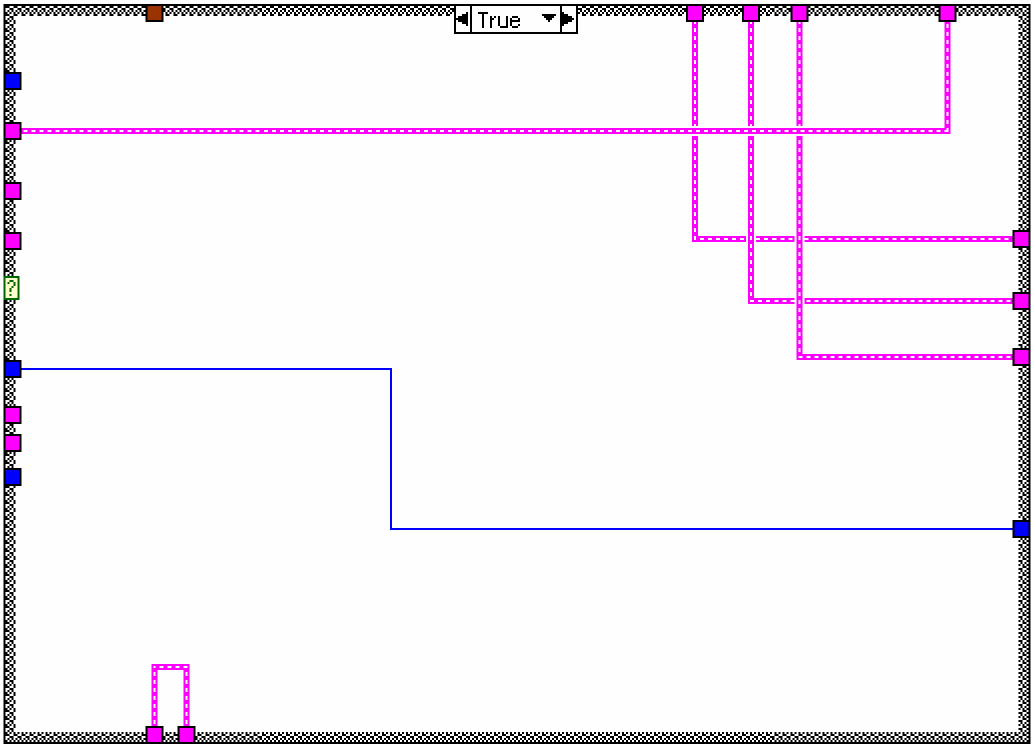
True
False
RE-MOTE /LOCAL
SINGLE PUMP OPS
Pump C
2
Pump C Settings
False
RE-MOTE /LOCAL
True
6 [0..11]

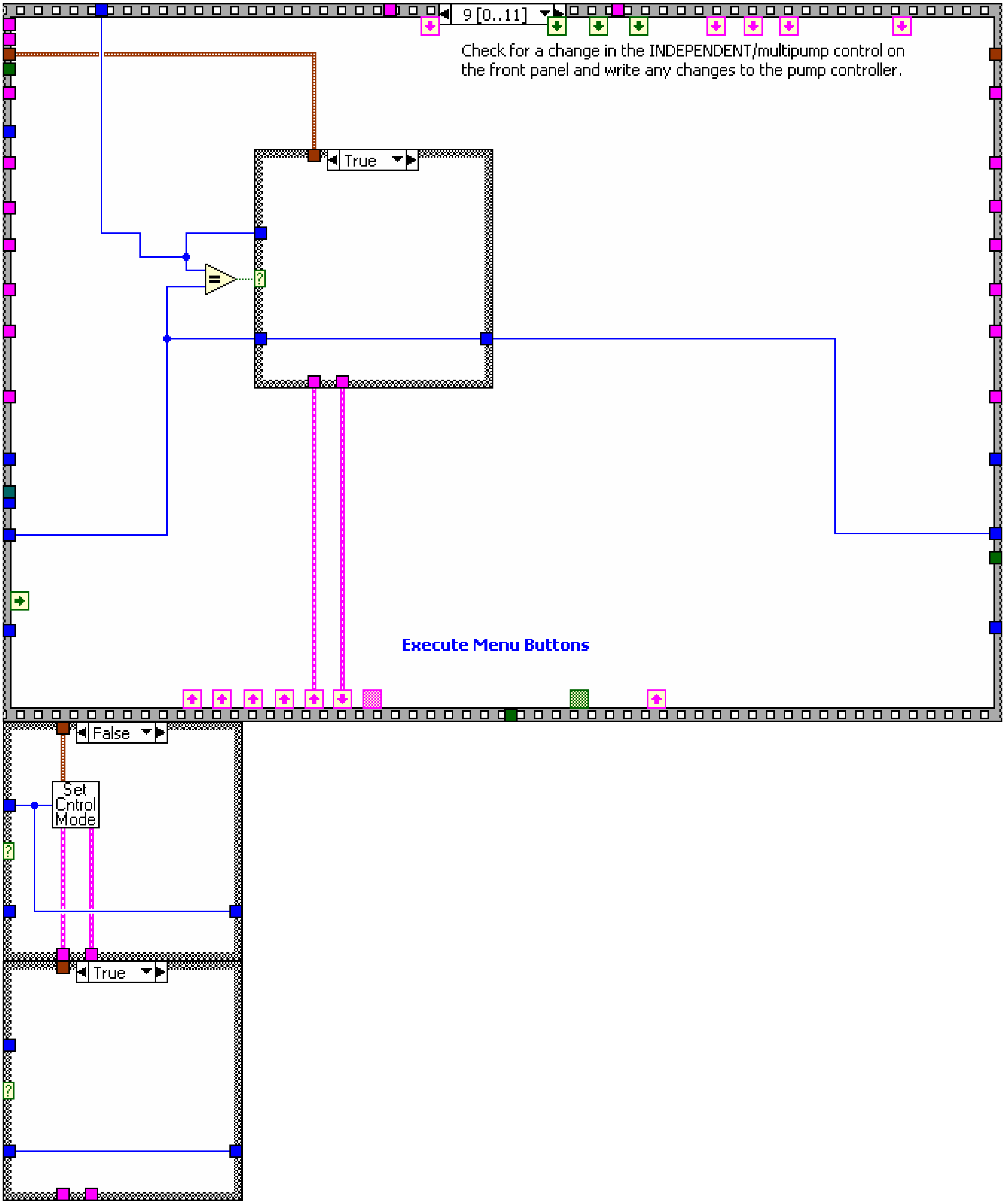

7 [0..11]
False
If in LOCAL and the user changed a front panel setting switch to REMOTE and write changes to pump controller in fram 4, 5, or 6 depending on the pump. Here reset the indicator on the front panel to show we are in REMOTE.
False
True
Remote/Local/External (0:Remote). 2

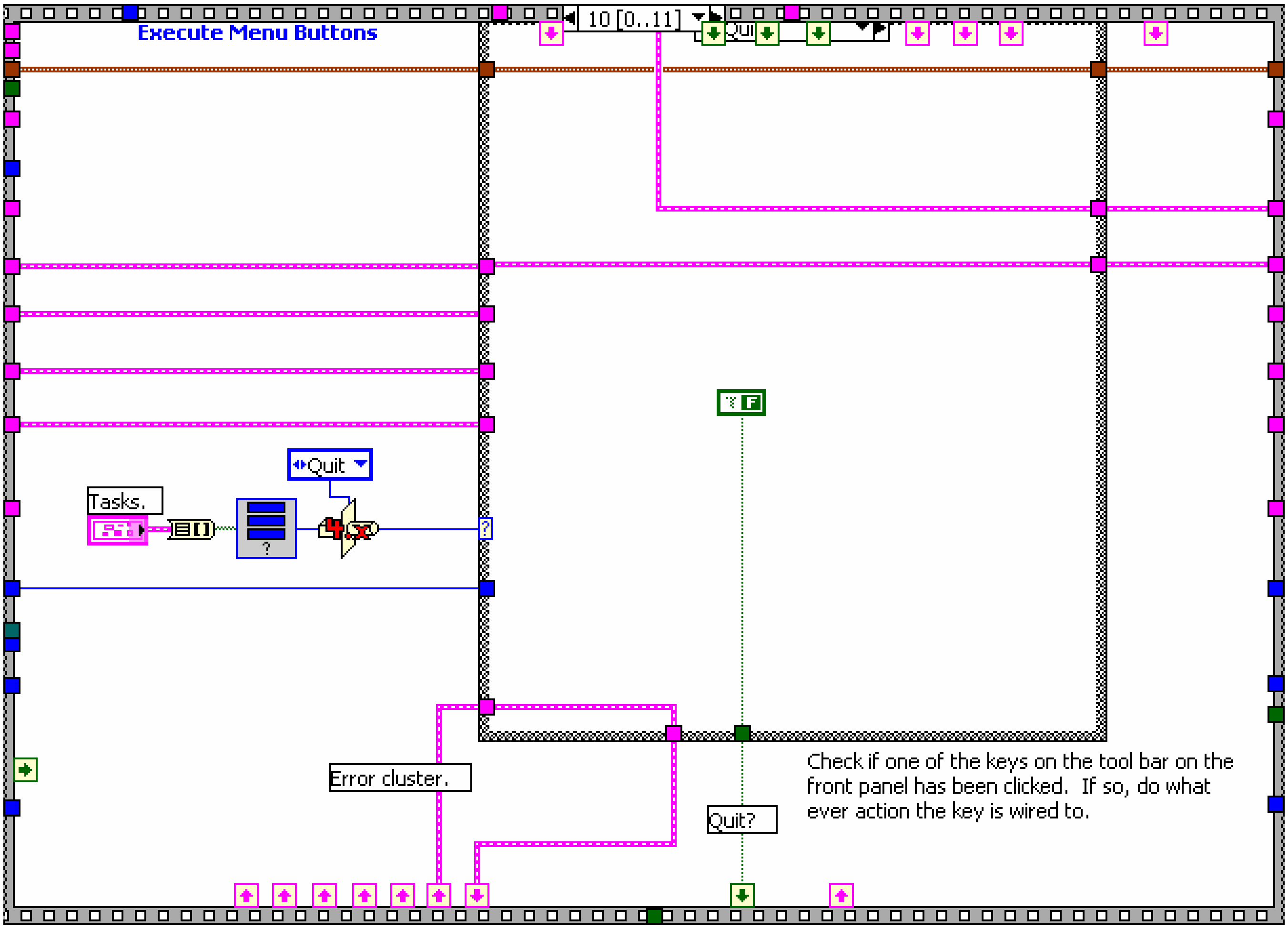

8 [0..11]
True
Check for a change in the REMOTE/LOCAL/EXTERNAL control and write any changes to the pump controller.

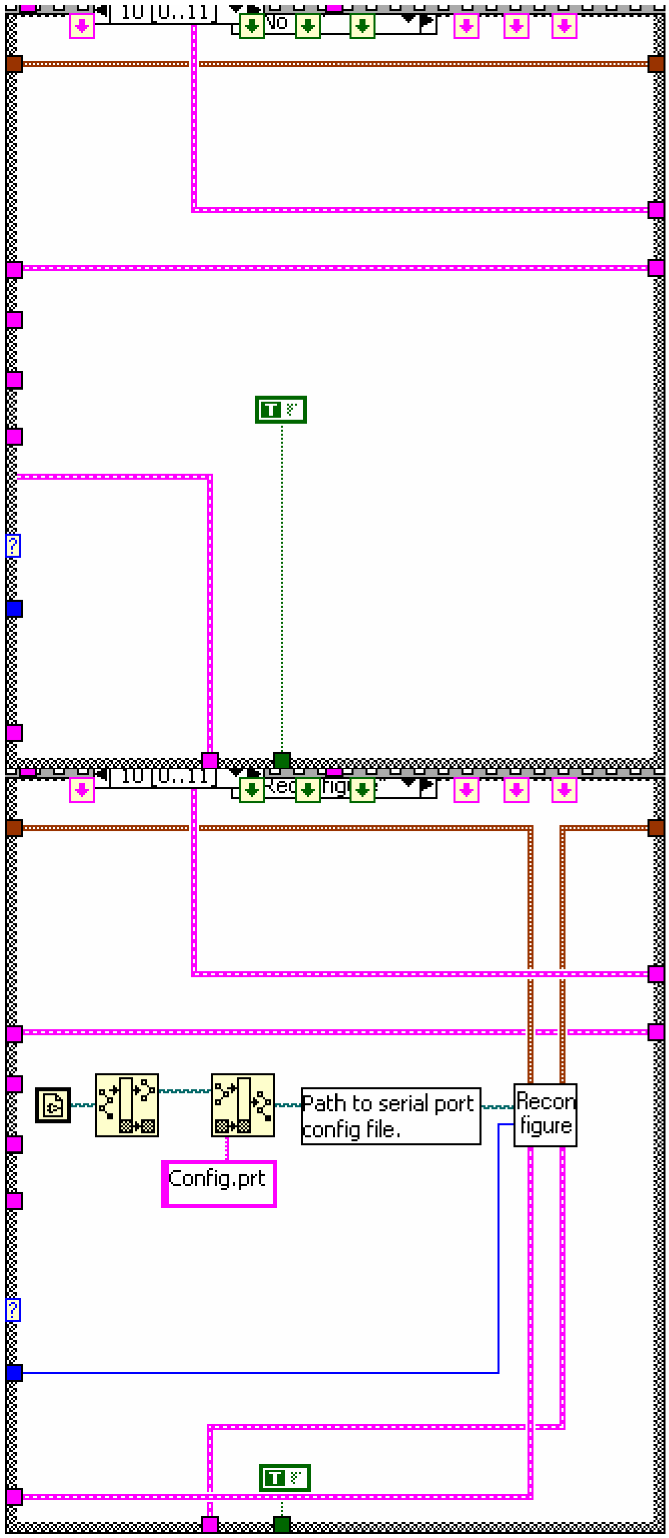

False
"REMOTE"
Pump A Settings 2
RE-MOTE /LOCAL
Setup remote
0
1
Pump B Settings 2
2
Pump C Settings
Updte AL
"REMOTE"
Pump A Settings 2
RE-MOTE /LOCAL
Setup remote
0
1
Pump B Settings 2
2
Pump C Settings
Updte AL

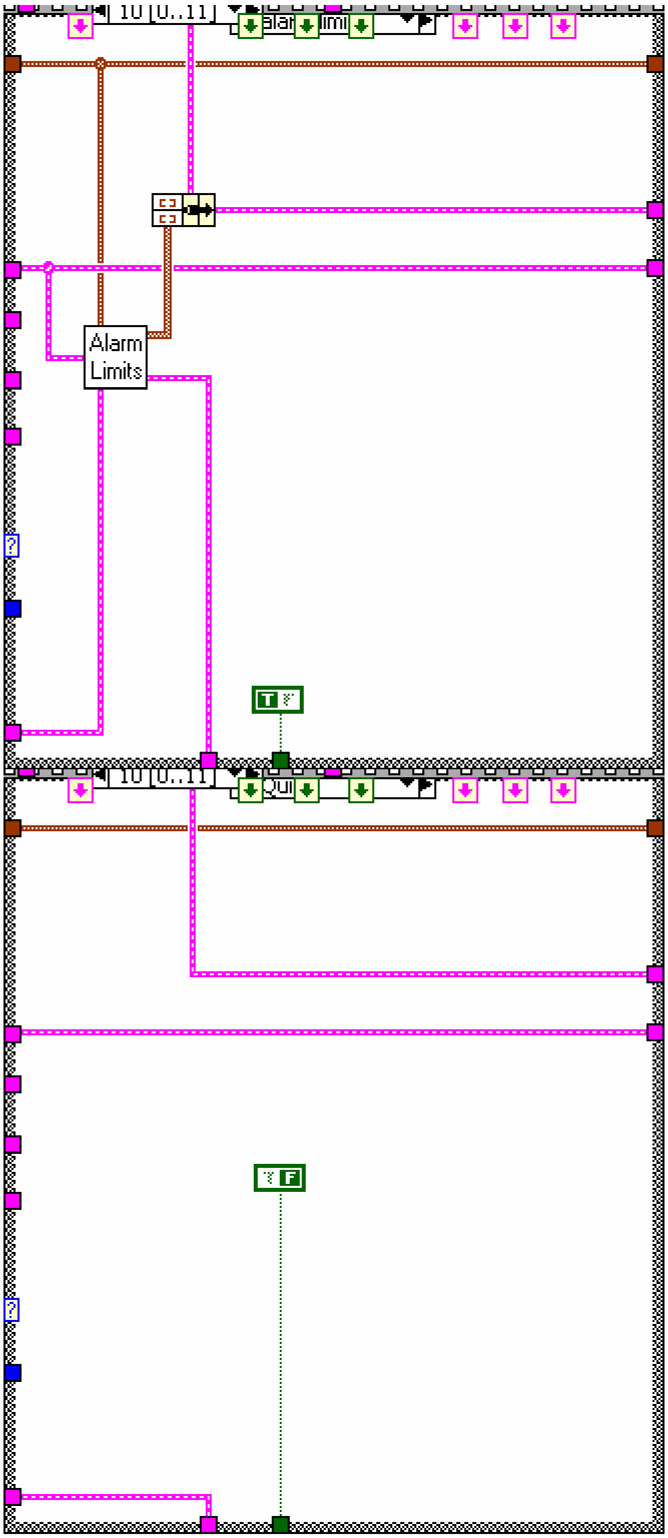

"LOCAL"
RE-
MOTE
/LOCAL
"EXTERNAL"


True

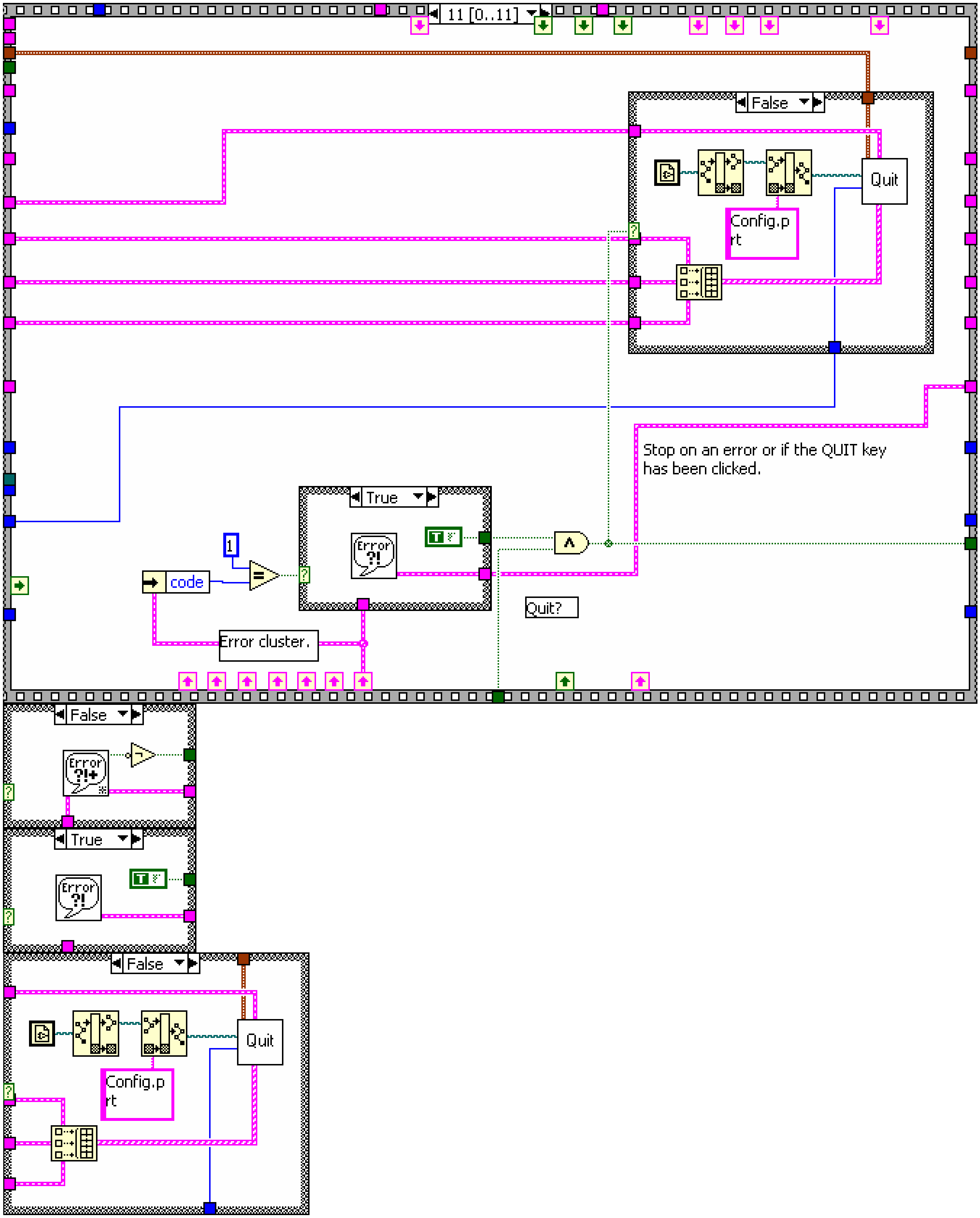

9 [0..11]
Check for a change in the INDEPENDENT/multipump control on the front panel and write any changes to the pump controller.
True
Execute Menu Buttons
False
Set Cntrol Mode
True

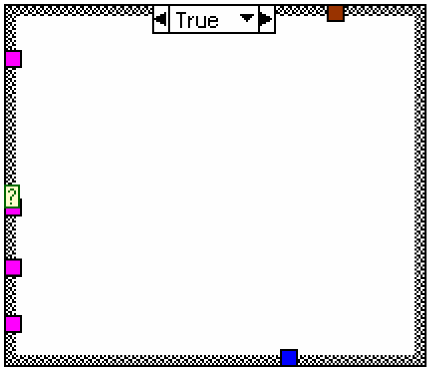

Execute Menu Buttons
10 [0..11]
Quit
Tasks.
Error cluster.
Quit?
Check if one of the keys on the tool bar on the front panel has been clicked. If so, do what ever action the key is wired to.

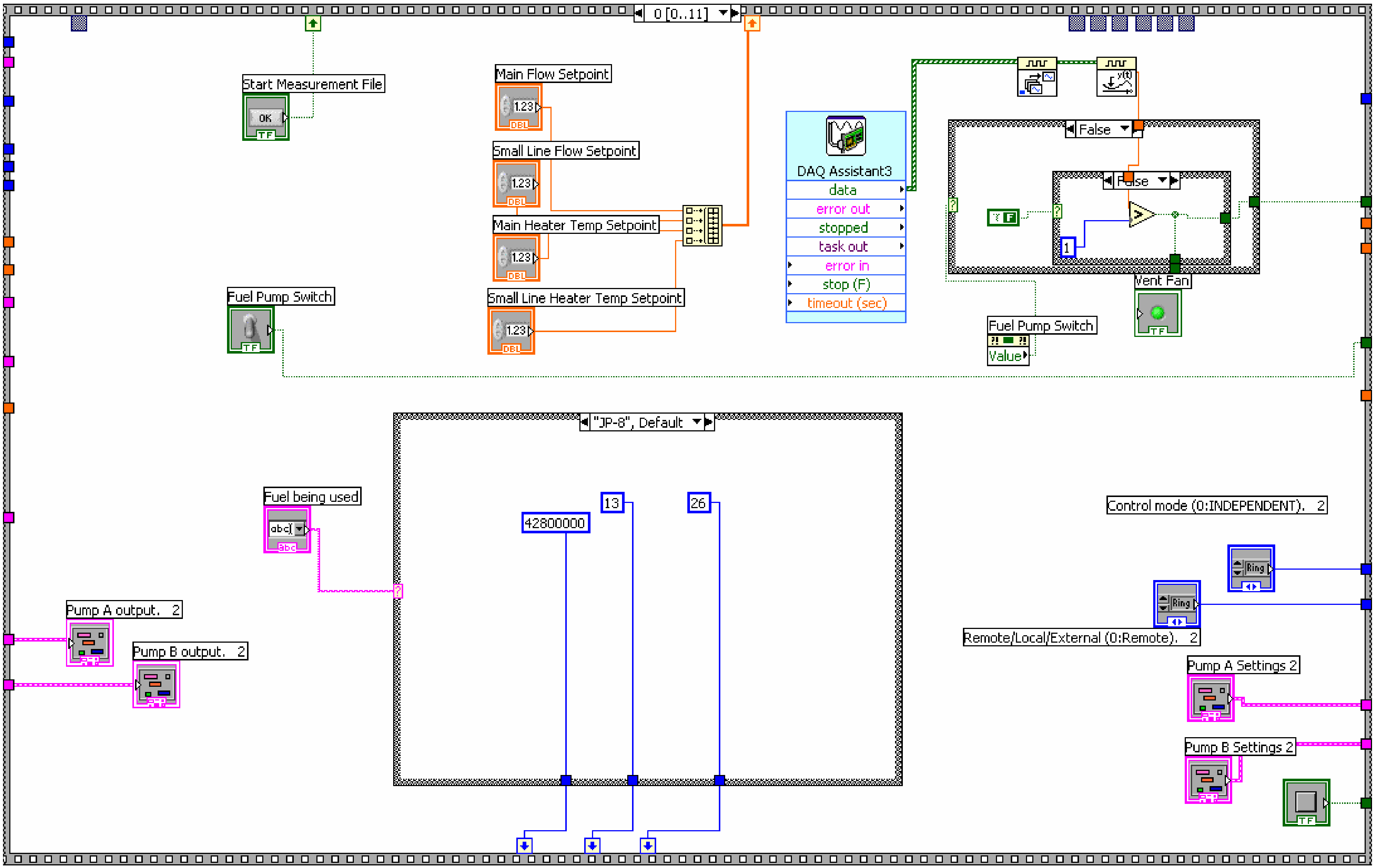

10 [0..11]
No
Path to serial port config file.
Reconfigure
Config.prt

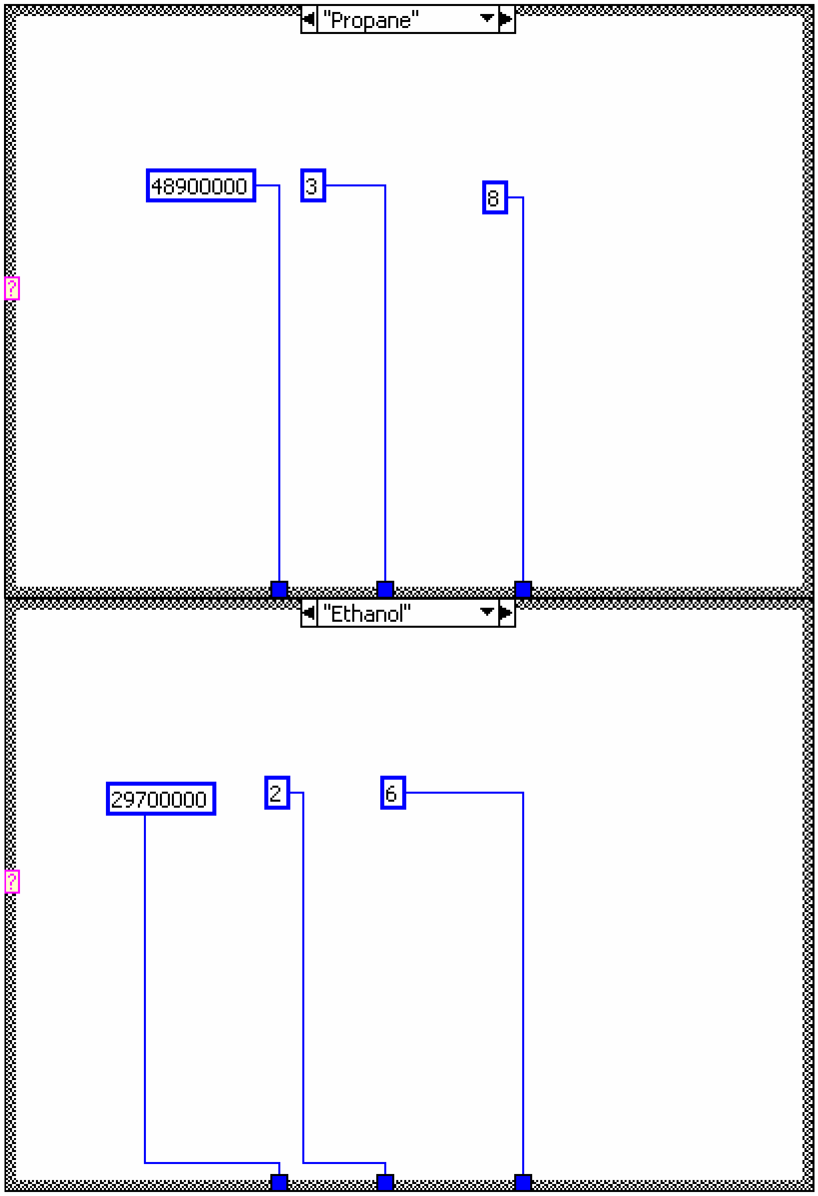


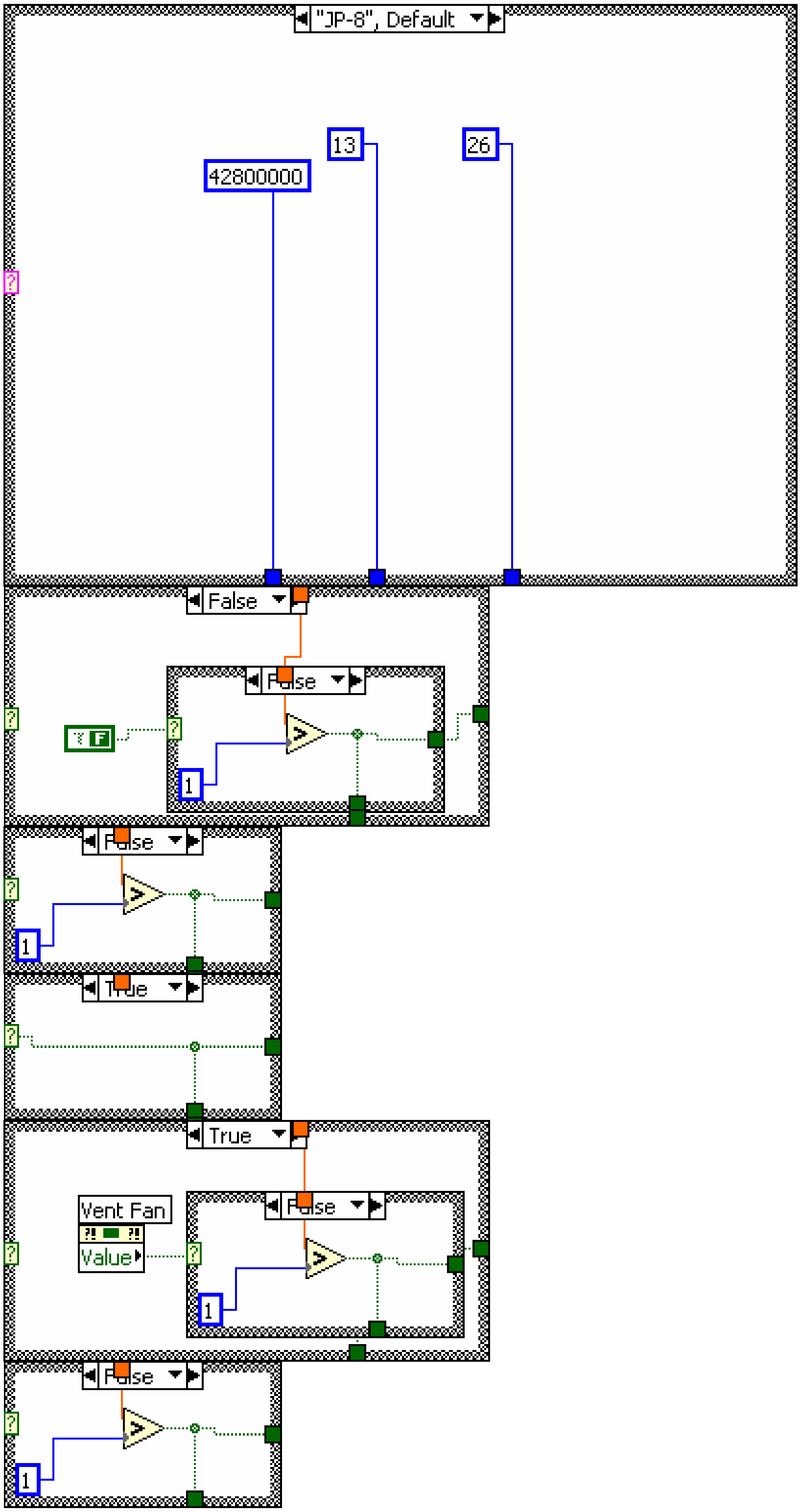
10 [0..11]
Alarm
Limits
10 [0..11]

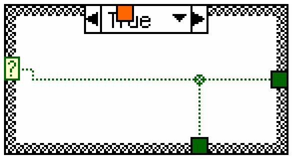

11 [0..11]
False
Quit
Config.prt
Stop on an error or if the QUIT key has been clicked.
True
Error ?!
1
code
Quit?
Error cluster.
False
Error ?!+
True
Error ?!
False
Quit
Config.prt

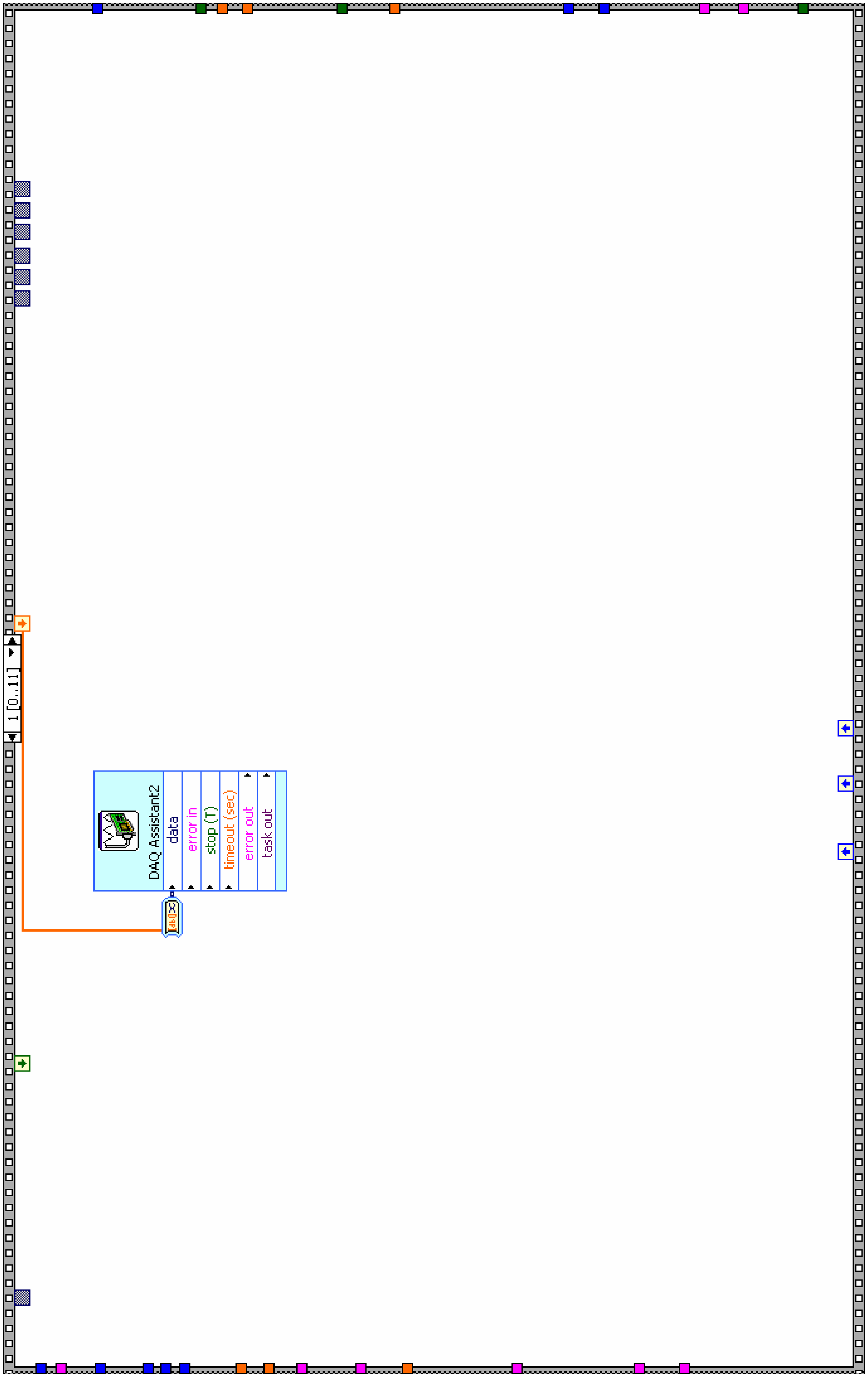

True

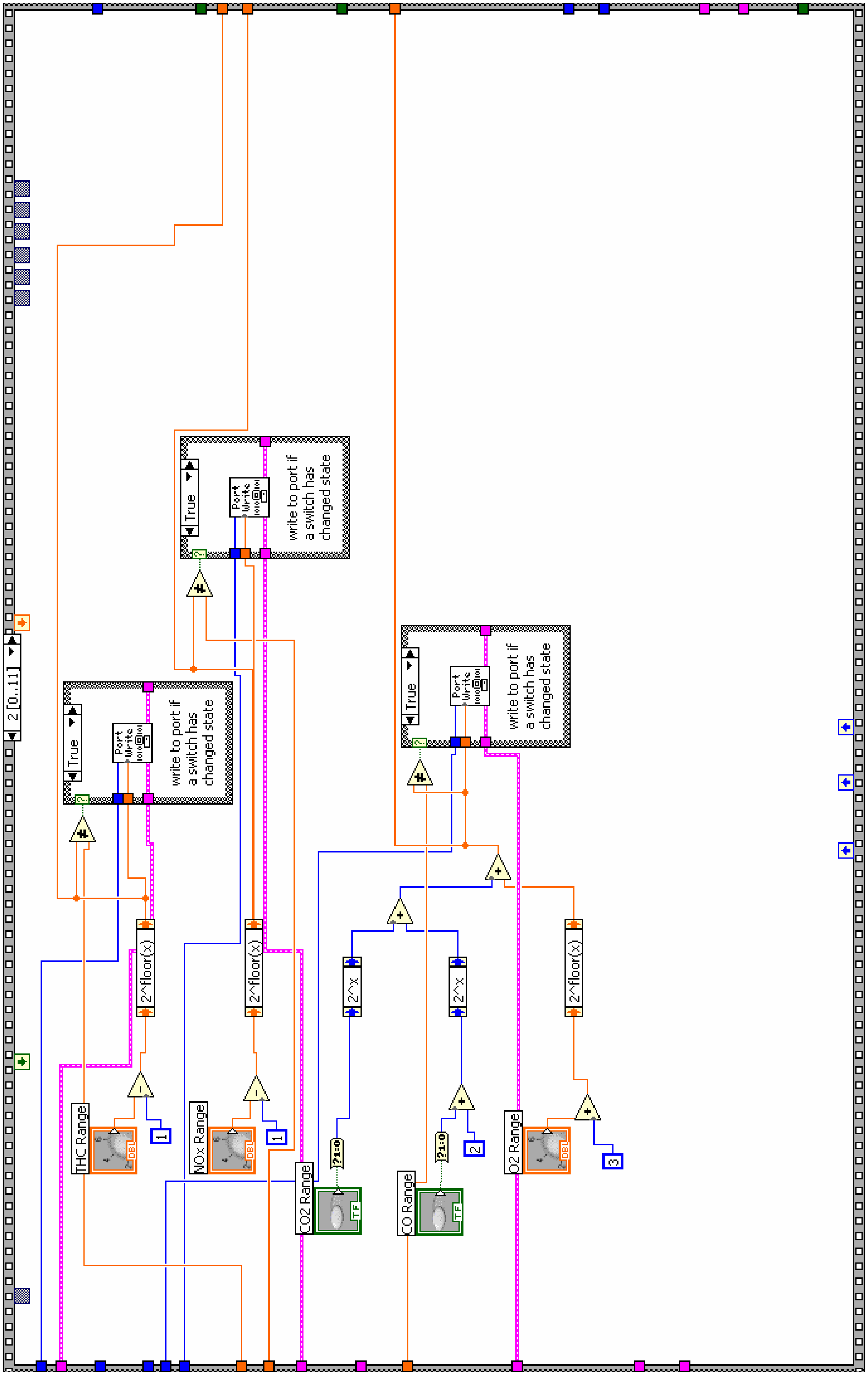

0 [0..11]
Start Measurement File
Main Flow Setpoint
Small Line Flow Setpoint
Main Heater Temp Setpoint
Small Line Heater Temp Setpoint
Fuel Pump Switch
DAQ Assistant3
data
error out
stopped
task out
error in
stop (F)
timeout (sec)
False
Vent Fan
Fuel Pump Switch
Value
"JP-8", Default
42800000
13
26
Fuel being used
Pump A output. 2
Pump B output. 2
Control mode (0:INDEPENDENT). 2
Remote/Local/External (0:Remote). 2
Pump A Settings 2
Pump B Settings 2

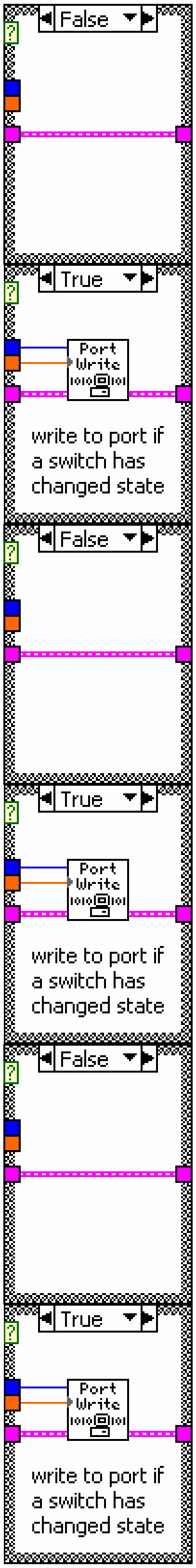

"Propane"
48900000
3
8
"Ethanol"
29700000
2
6

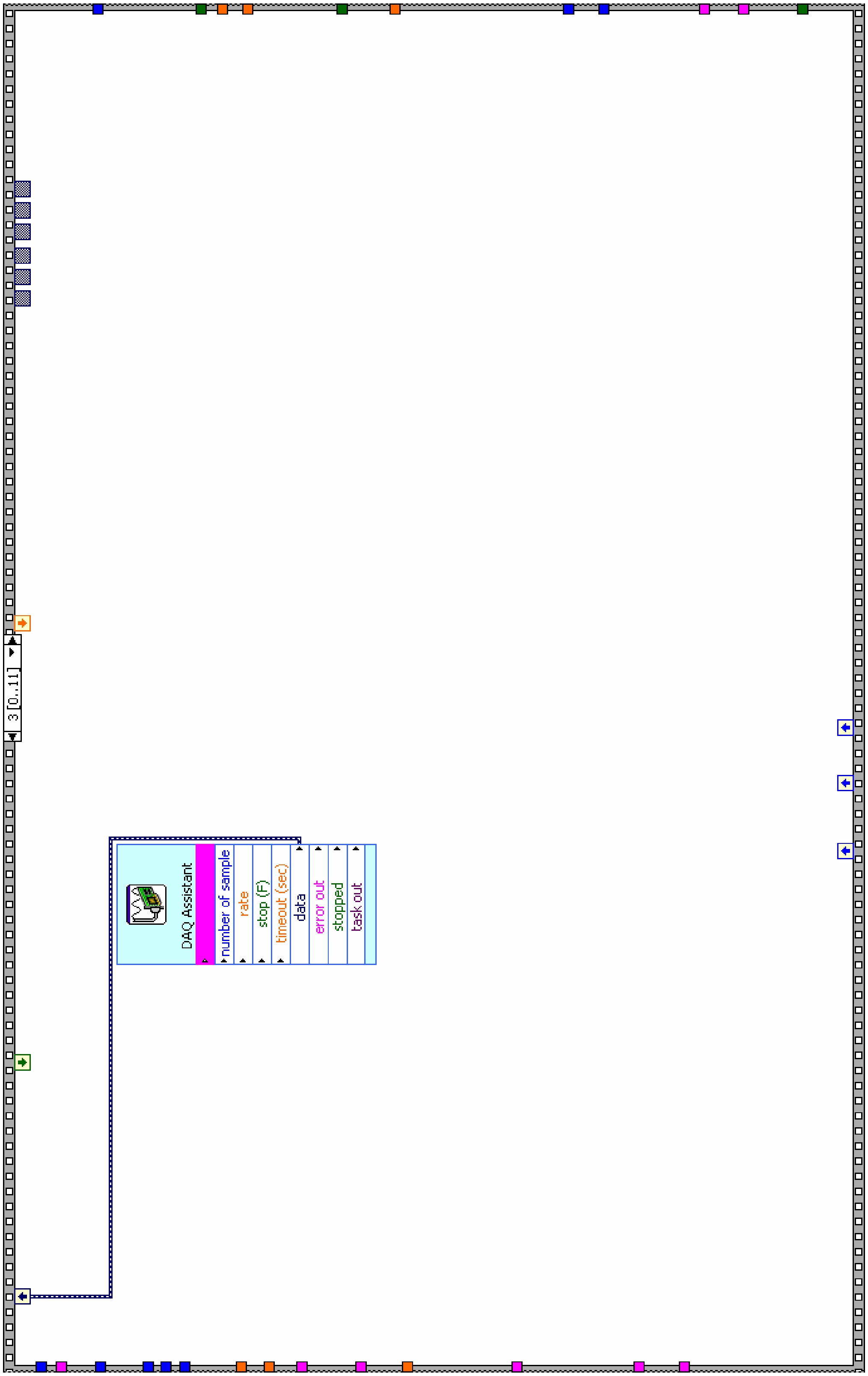

"JP-8", Default
42800000
13
26
False
False
1
False
1
True
True
Vent Fan
Value
False
1
False
1

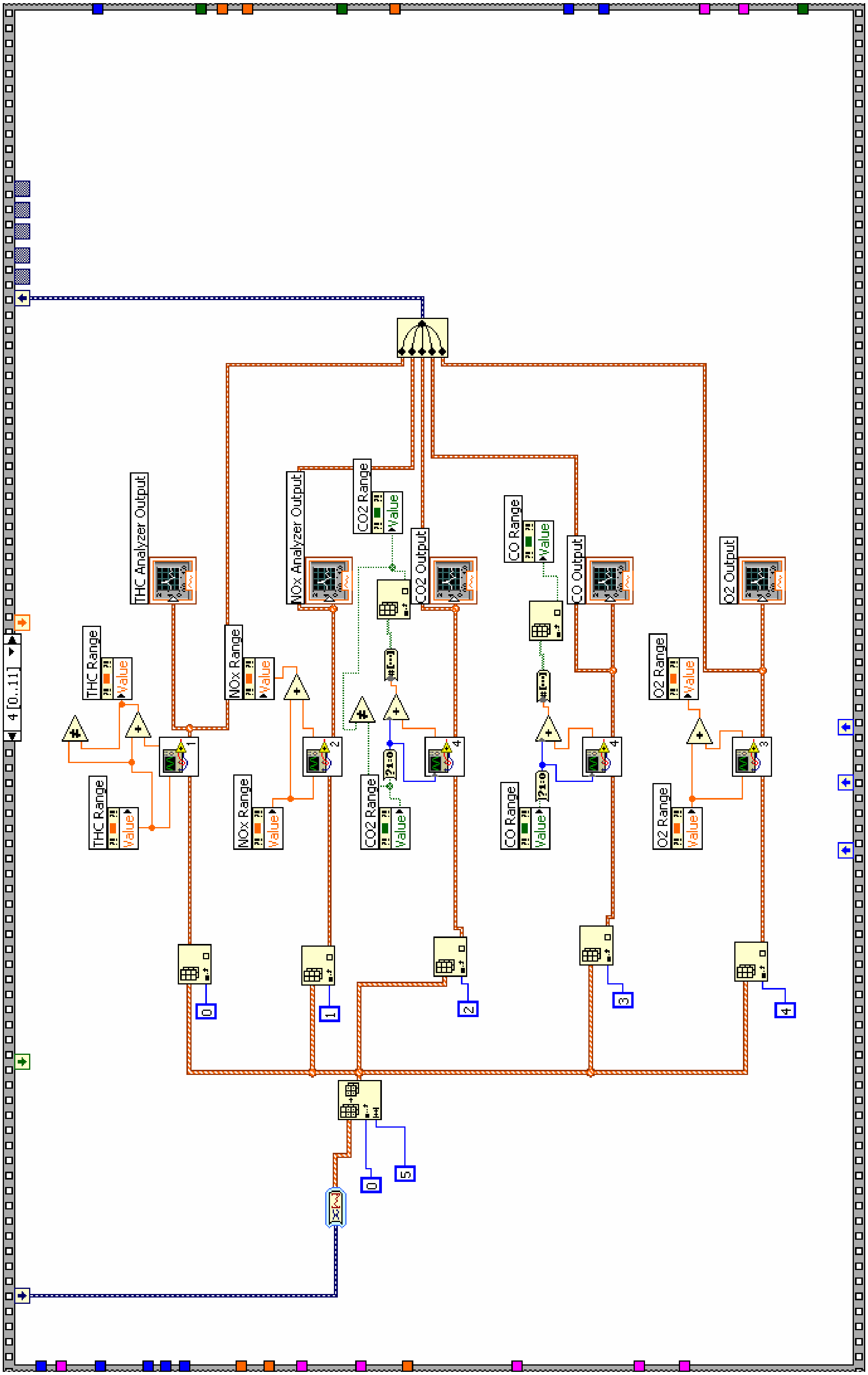

True

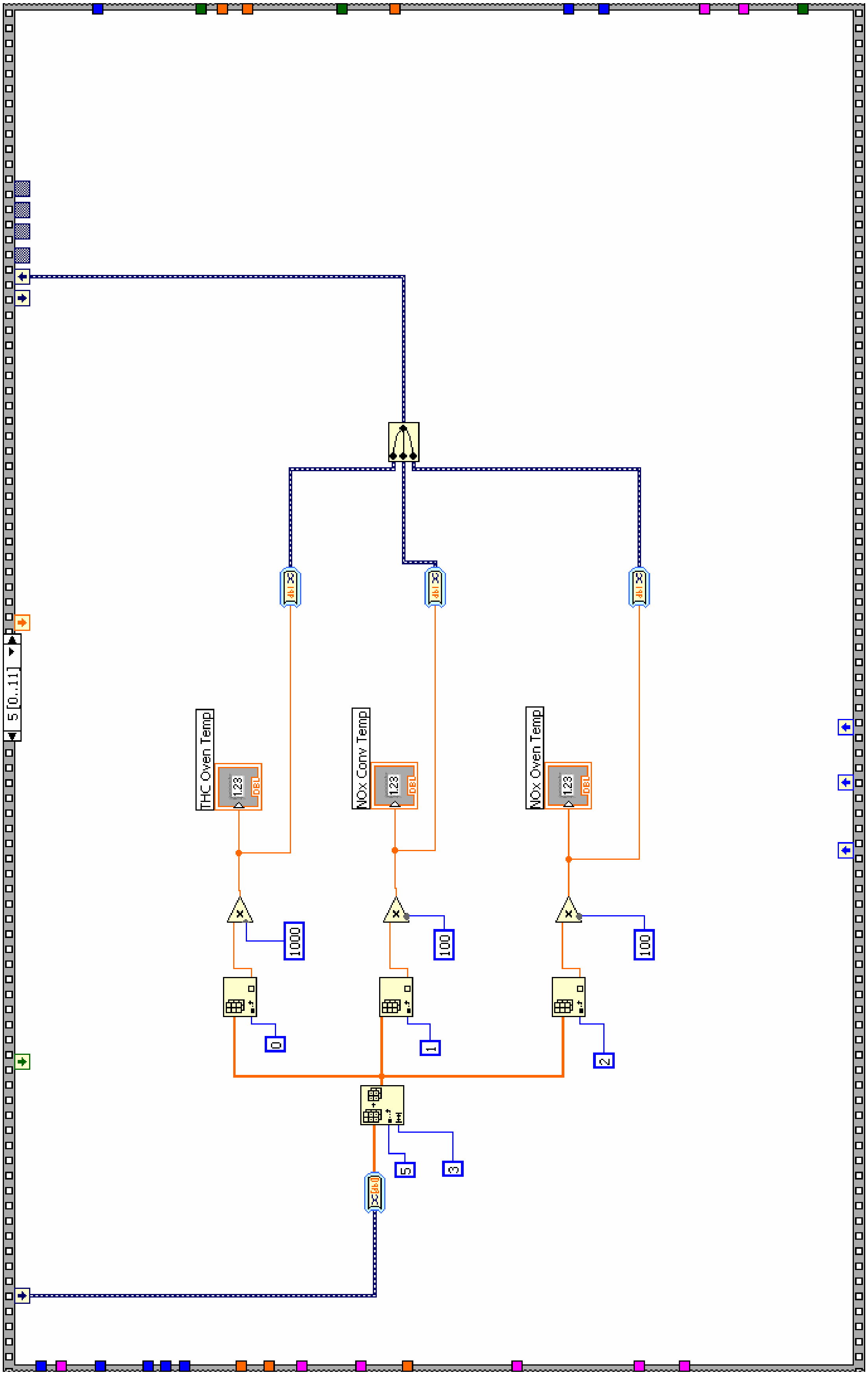

1 [0..11]
DAQ Assistant2
data
error in
stop (T)
timeout (sec)
error out
task out

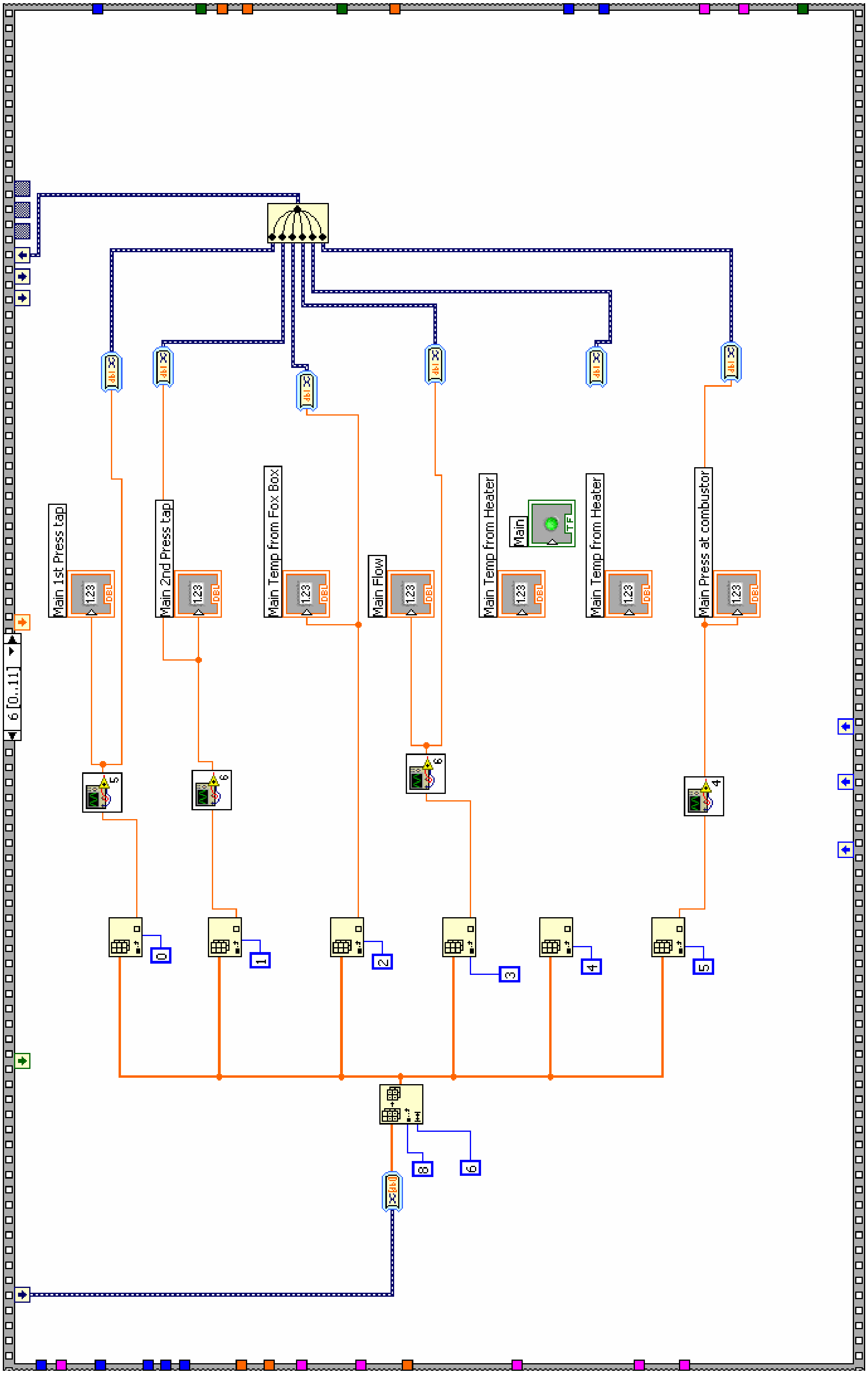

2 [0..11]
True
Port Write
write to port if a switch has changed state
True
Port Write
write to port if a switch has changed state
True
Port Write
write to port if a switch has changed state
2^floor(x)
2^floor(x)
2^x
2^x
2^floor(x)
THC Range
NOx Range
CO2 Range
CO Range
O2 Range
1
1
2
3


False
True
Port Write
write to port if a switch has changed state
False
True
Port Write
write to port if a switch has changed state
False
True
Port Write
write to port if a switch has changed state

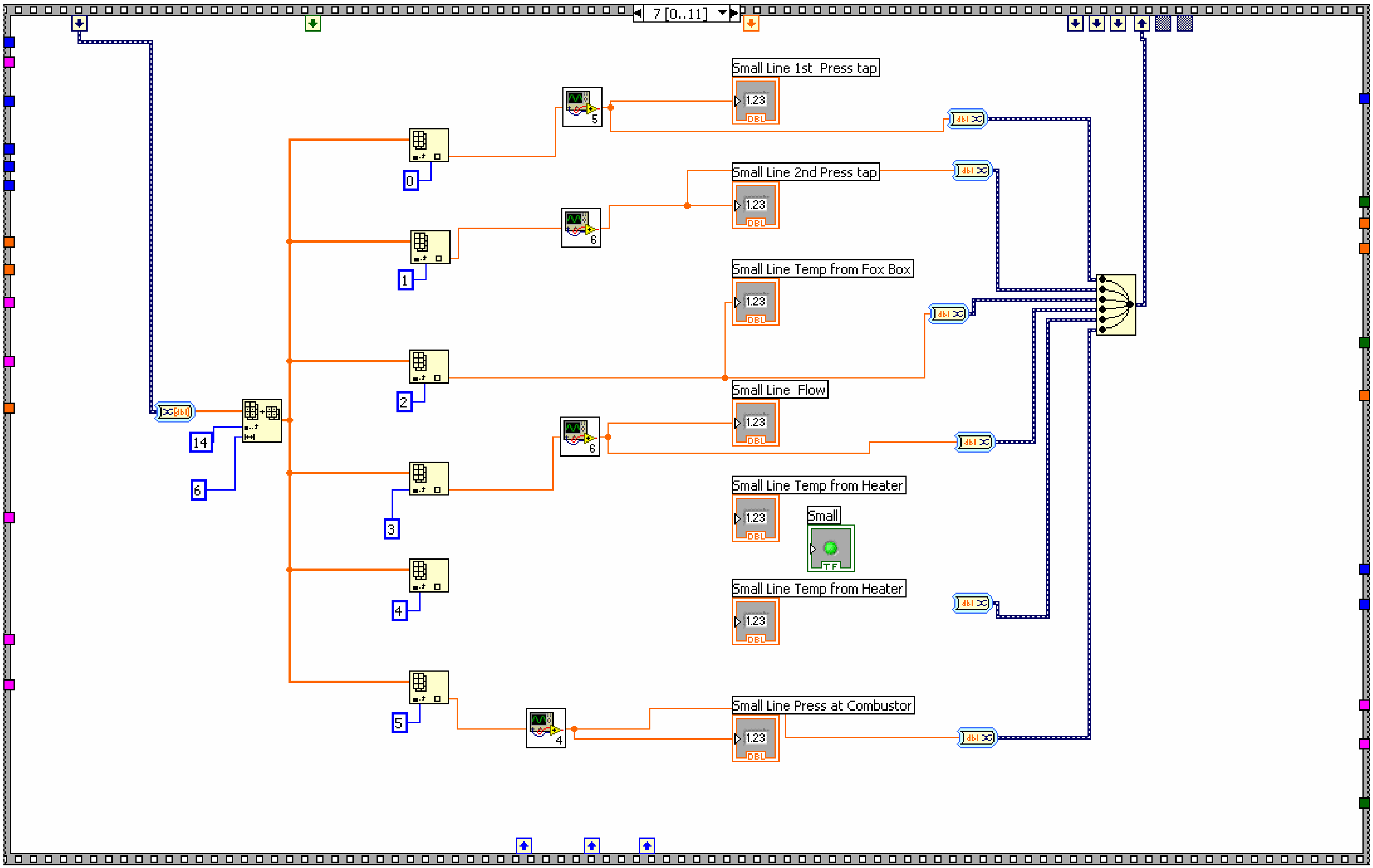

3 [0..11]
DAQ Assistant
number of sample
rate
stop (F)
timeout (sec)
data
error out
stopped
task out

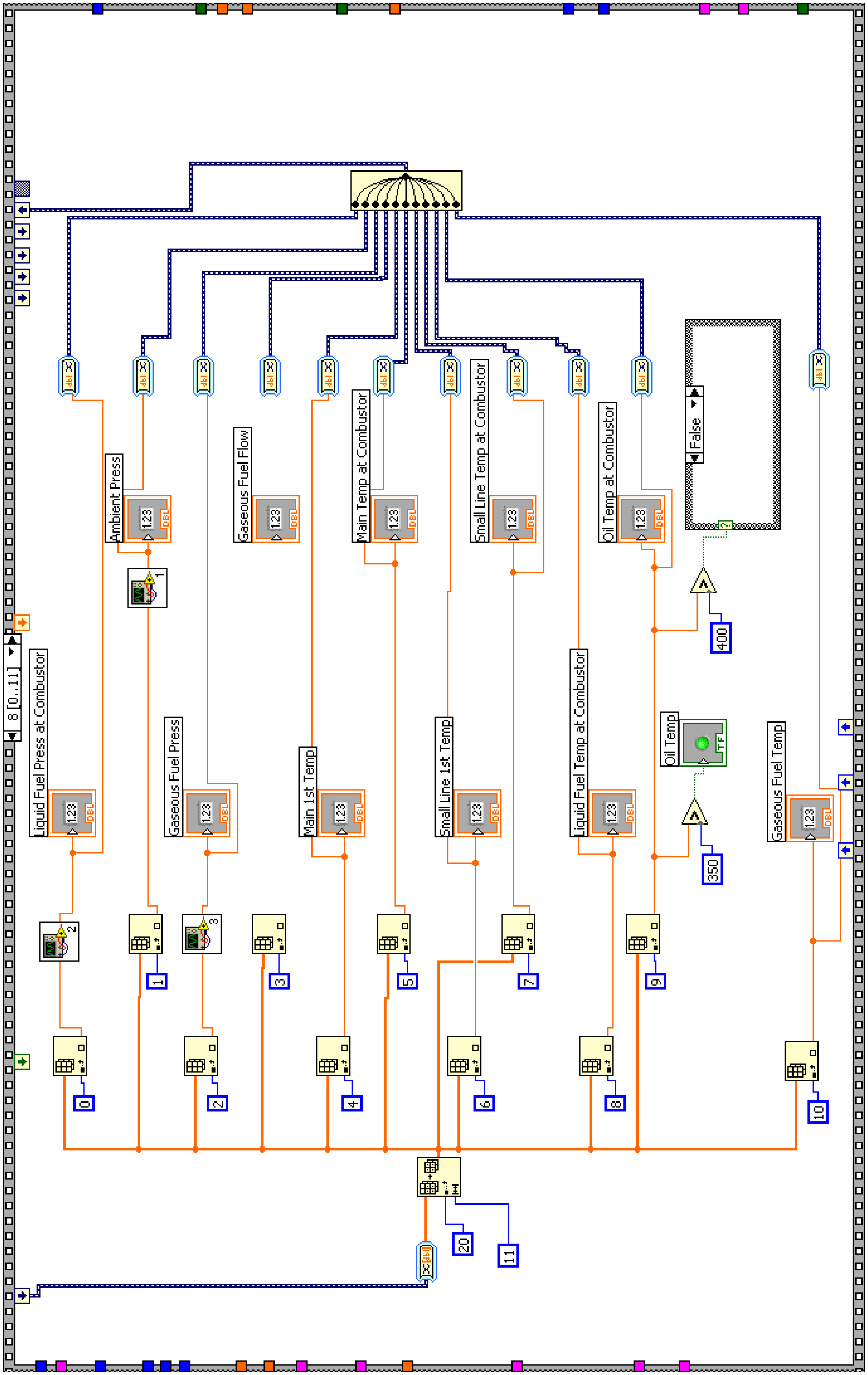

THC Analyzer Output
NOx Analyzer Output
CO2 Range
CO2 Output
CO Range
CO Output
O2 Output
THC Range
NOx Range
O2 Range
Value
4 [0..11]
0
1
2
3
4
5

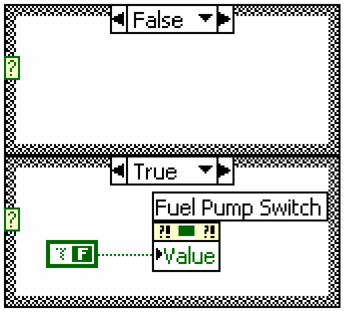

5 [0..11]
THC Oven Temp
NOx Conv Temp
NOx Oven Temp
1000
100
100
0
1
2
5
3

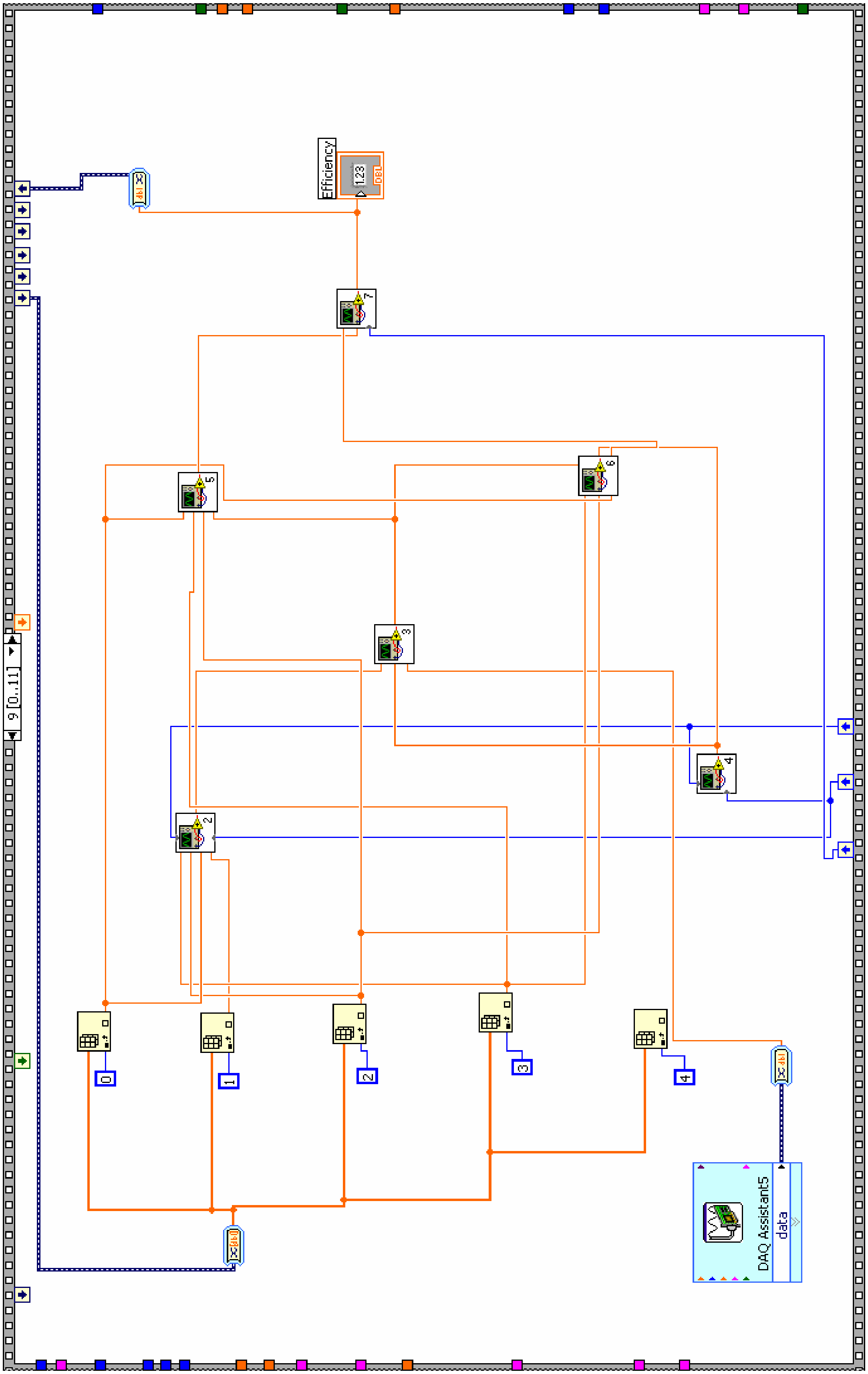


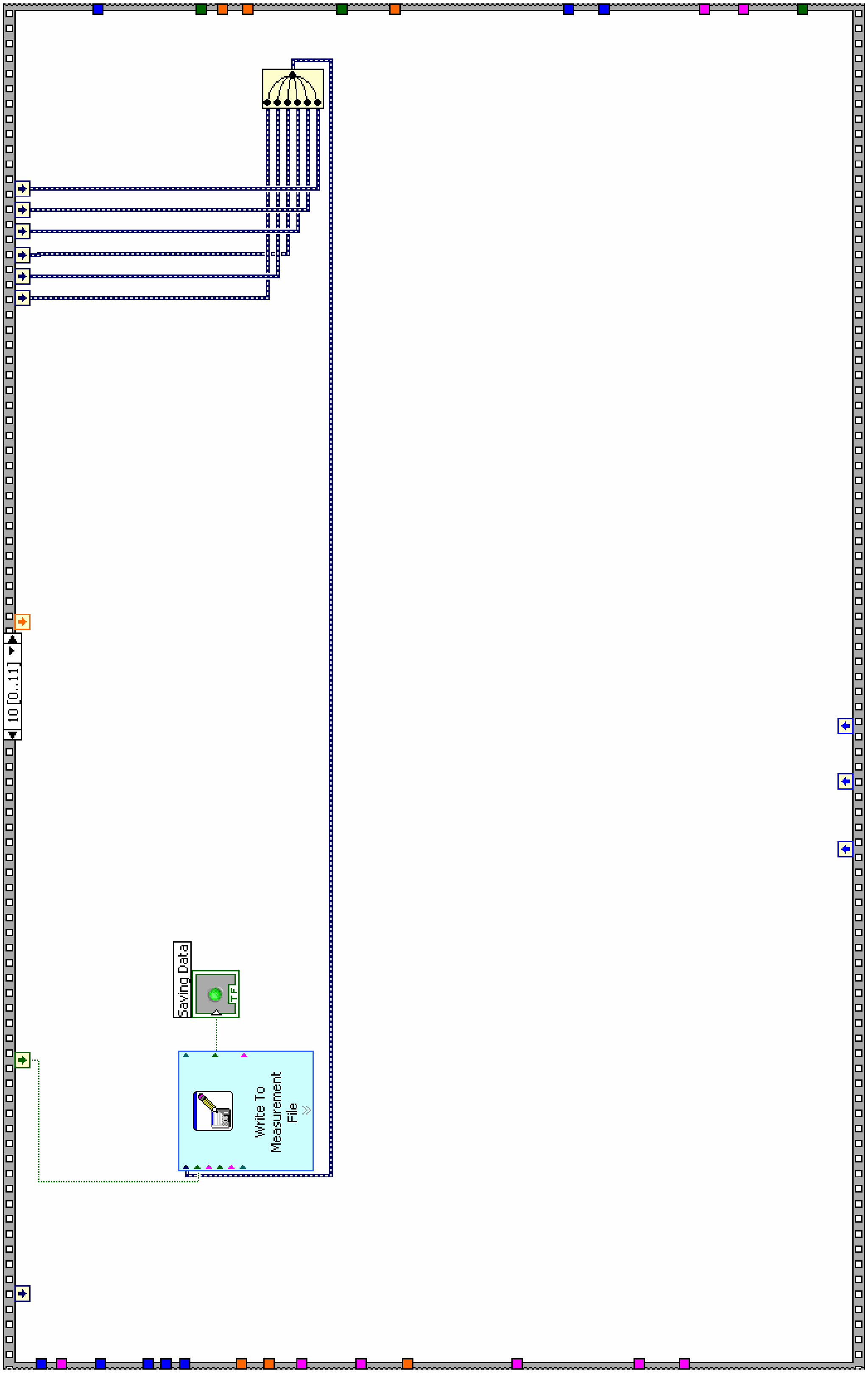
6 [0..11]
Main 1st Press tap
Main 2nd Press tap
Main Temp from Fox Box
Main Flow
Main Temp from Heater
Main
Main Temp from Heater
Main Press at combustor
0
1
2
3
4
5
8
6

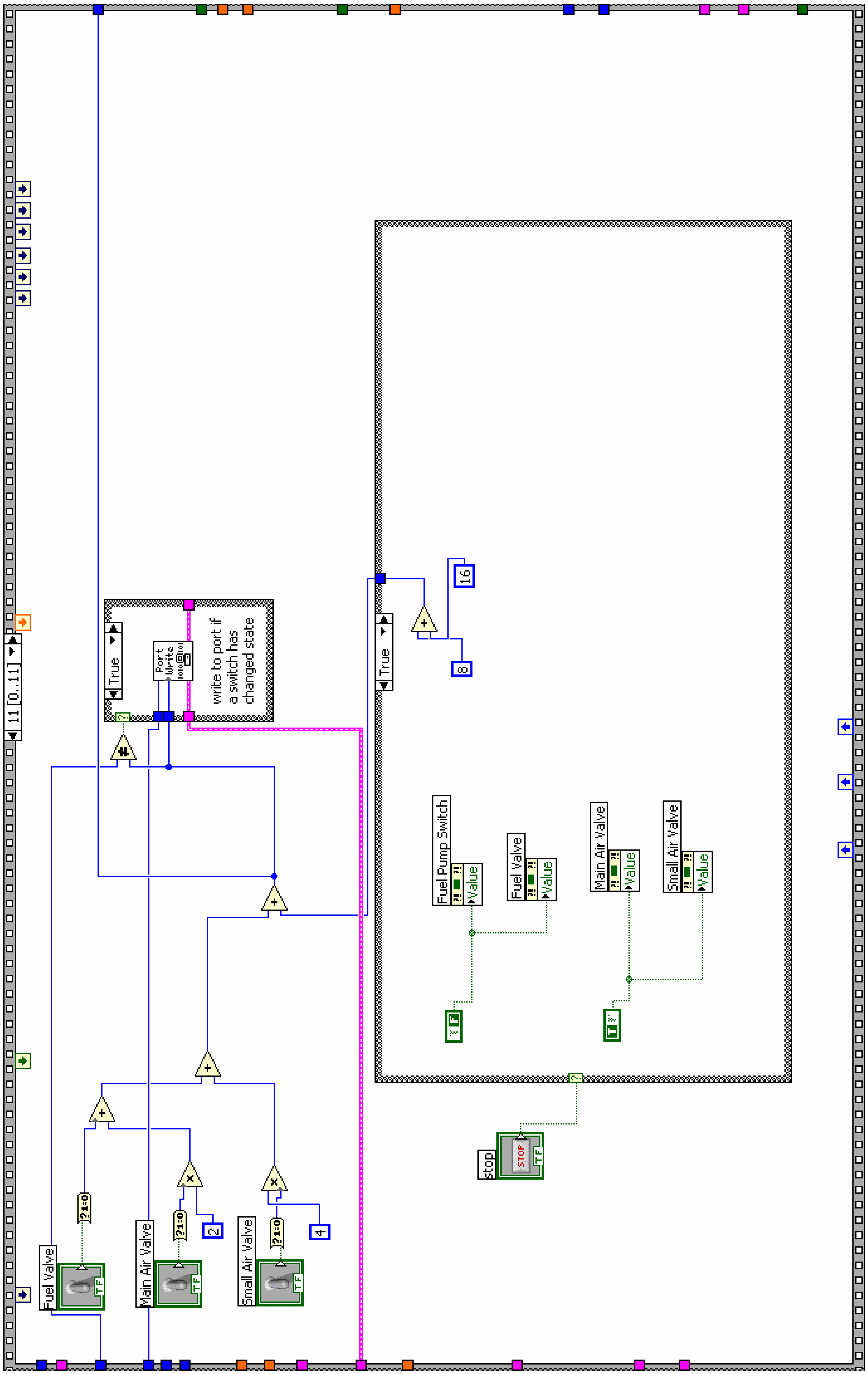

7 [0..11]
Small Line 1st Press tap
Small Line 2nd Press tap
Small Line Temp from Fox Box
Small Line Flow
Small Line Temp from Heater
Small
Small Line Temp from Heater
Small Line Press at Combustor
0
1
2
3
4
5
14
6

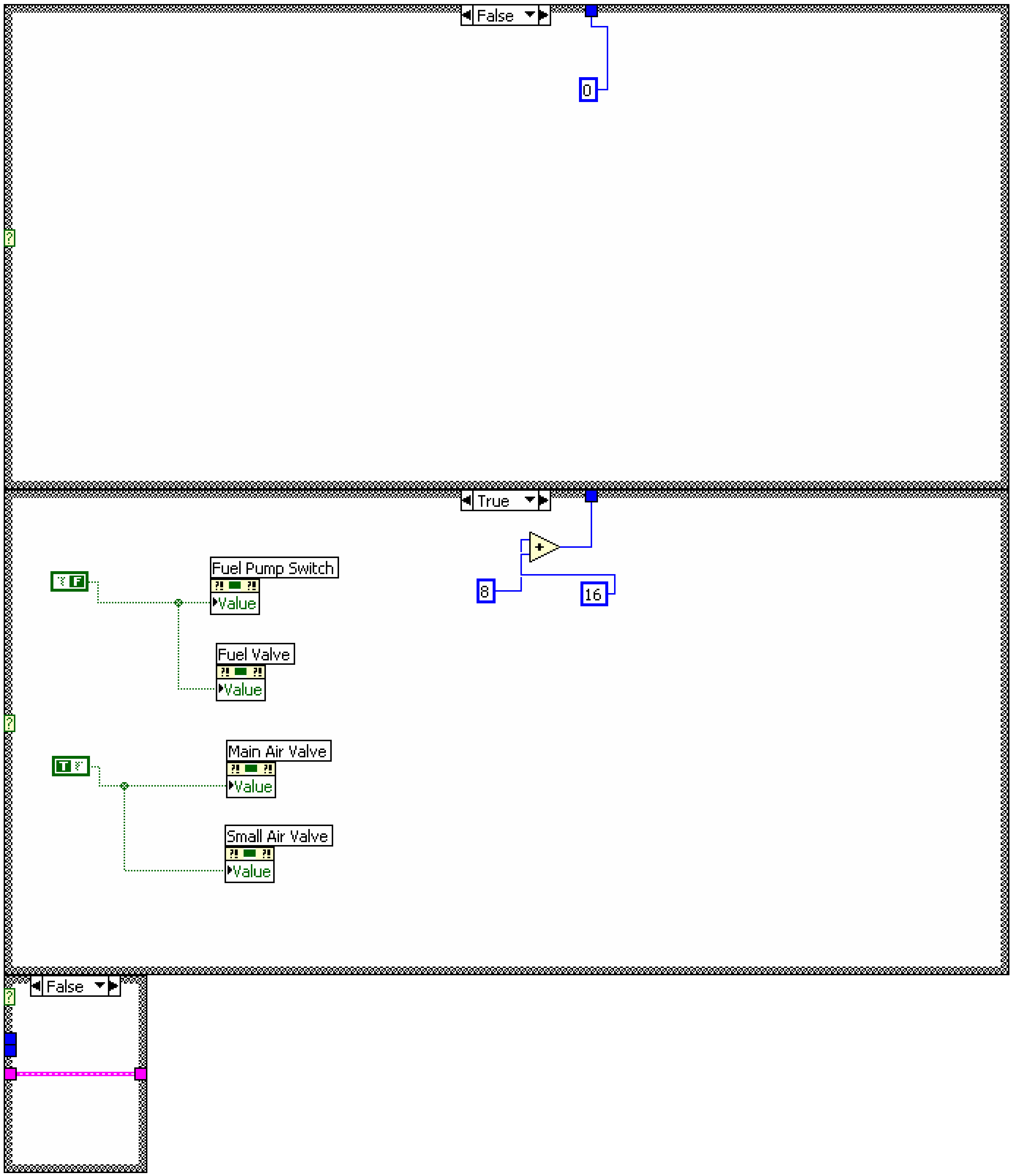

Ambient Press
Gaseous Fuel Flow
Main Temp at Combustor
Small Line Temp at Combustor
Oil Temp at Combustor
False
400
8 [0..11]
Liquid Fuel Press at Combustor
Gaseous Fuel Press
Main 1st Temp
Small Line 1st Temp
Liquid Fuel Temp at Combustor
Oil Temp
350
Gaseous Fuel Temp
0
1
2
3
4
5
6
7
8
9
10
20
11

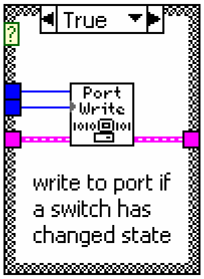

False
True
Fuel Pump Switch
Value
F


Efficiency
1.23
9 [0..11]
DAQ Assistant5
data
0
1
2
3
4


10 [0..11]
Saving Data
Write To Measurement File


11 [0..11]
Fuel Valve
Main Air Valve
Small Air Valve
2
4
True
Port Write
write to port if a switch has changed state
True
16
8
Fuel Pump Switch
Value
Fuel Valve
Value
Main Air Valve
Value
Small Air Valve
Value
stop


False
0
True
Fuel Pump Switch
Value
Fuel Valve
Value
Main Air Valve
Value
Small Air Valve
Value
8
16
False


True
Port
Write
write to port if
a switch has
changed state

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12. DISTRIBUTION/AVAILABILITY STATEMENT

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This study investigated the design parameters necessary for the construction and use of a testing facility built to test the combustor section of engines. User inputs were acquired by interview and used in the decisions made in arrangement of pieces of machinery and how different systems were to interact. The design was then carried out as the various parts of the facility were built and installed. Software was designed which controlled the different parts of the combustion process and monitored the different products of combustion as well as the properties of the air and fuel used in the combustion. These measurements were analyzed to determine the efficiency of combustion in the combustor. All systems and measurements were conducted and operated while following the guidance set forth in SAE ARP 1256. Safeguard systems were also designed into the facility to maintain a safe work environment for the user. These safeguards include automatic fuel shut-offs, heater shut-offs, and general system power downs. While the system was originally designed to handle the testing of a planar 2-D combustion chamber, the labs now have the capability to analyze any type of system that requires a combustion analyzer that follows SAE ARP 1256, a system that requires heated air or fuel, a system that requires an exhaust system to pull gasses out of the testing area, or a system that needs open flame. These additional capabilities allow further research to be conducted on site with an increase in ability to report different results.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
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