

APPLICATIONS OF RADIO TELEMETRY IN AGRICULTURE:  
A LOW COST APPROACH TO SOIL MONITORING FOR PRECISION AGRICULTURE  
AND CLOSED-LOOP CONTROL OF POULTRY TUNNEL VENTILATION BASED ON  
DEEP BODY TEMPERATURE

by

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(Under the Direction of Takoi K. Hamrita)

ABSTRACT

Continuous improvement of agriculture is necessitated by growing demand for products. Two applications of agricultural radio telemetry are proposed that could improve production and research. Precision agriculture requires up-to-date information, but data telemetry can be too expensive for academic researchers. The first application is a low cost soil telemetry system based on RFID equipment, and a bench level prototype was developed to show feasibility. For the second application, modern poultry production often relies on "tunnel ventilation" in houses to remediate the effects of high temperature and humidity. Air speed control is generally based on ambient temperature, ignoring the state of the birds themselves. An experimental system was assembled to determine the feasibility of closed-loop control of air speed in a tunnel ventilation enclosure based on a bird's deep body temperature (DBT). Results show that DBT feedback can be used in a closed-loop system controlling poultry tunnel ventilation.

INDEX WORDS: Radio telemetry, soil telemetry, poultry deep body temperature, tunnel ventilation, environmental control of poultry housing

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## DEDICATION

To Joannie, Juju and Emmy – the only ones who ever mattered.

*Some wanted me to stay home and play,  
but I knew better things could be done.  
Some thought time was short and  
better spent on love, but I stood apart and said  
investment now is better than none.  
Some told me the mistake is made again and again,  
leaving only regret and bitterness in the end.  
Some had plans within plans within plans,  
but pride refused to be a pawn and paid the price.  
In the end, when all was finally said and done and burned,  
It came down to this:  
She warned me not to go to grad school,  
and damn if she wasn't right.*

This work is also dedicated to those who involuntarily gave their lives to  
this fool's errand – if I catch you guys on the flip side, first round is on me.

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## **CHAPTER 1**

### **INTRODUCTION**

Telemetry is the act of performing measurements at a distance. Despite the broad definition, general use of the term is usually limited to situations where some device is generating measurement data remotely and returning the information to a more accessible location. The variety of data transport medium is open to the needs of the application, from electrical current on wire to modulated pressurized air to light through optic fiber lines or simply through the air. Despite the number of options, the majority of telemetry applications transmit in the radio band of the electromagnetic spectrum due to the scalability and generally robust nature of the link that can be established.

Precision agriculture, a promising area with the potential of maximizing crop yields while minimizing the waste of resources, depends on accurate and up to date information about growing conditions. With reliable data, efficient decisions can be made regarding management of the growth cycle for crops, such as planting, irrigation and fertilization. Radio telemetry is well suited to many aspects of precision agriculture, since acquiring data from large fields with diverse conditions can be time consuming and expensive. Without in-situ measurement capability that can communicate data across the fields to a location where the decision making occurs, much time and effort must be expended to visit each sampling site to gather information.

An example of this sort of telemetry application as developed by academic researchers can be seen in the work of Cromer and McLendon (1984), who generated a RF wireless link for a soil moisture telemetry system with multiple individually addressable moisture sensors in a field. Active transmission telemetry had many advantages over other technologies, but can be costly. A lower cost approach to radio telemetry is RFID (Radio Frequency IDentification) technology, first developed for simple identification applications but versatile enough to be put to more complex purposes. Already made in mass quantities for non-agricultural purposes, reasonably cost effective RFID components and equipment can be used as a short-range radio link to communicate with field located telemetry devices, making low cost radio telemetry possible.

The term “precision agriculture” is usually used in relation with the collection of data on crop conditions and acting upon that data to improve yields. The field of animal husbandry – specifically controlling their environment – could also benefit greatly from the approach. Like many southern states, Georgia is well suited for poultry production due to reduced heating costs in the winter. Unfortunately, mild winters lead to hot, humid summers, and considering the small operational margins of the poultry industry, air conditioning in poultry houses to date has not been economically feasible. Simple passive ventilation with outside ambient air has been the traditional method used to reduce high temperatures resulting from housing thousands of animals in an enclosed space, but when the outside temperature and humidity are high, passive ventilation is often insufficient in maintaining acceptable growth temperatures inside (Lott et.al., 1998).

In recent years, “tunnel ventilation” has gained in popularity among poultry producers in an effort to combat this problem. Drawing outside air into the building, banks of electrically powered fans generate a noticeable breeze within the chicken house, cooling the birds. Different

banks of fans are often installed so that they can be turned on in different combinations to create a variable airflow depending on environmental conditions, and generally ambient temperature alone is used to determine the number of energized banks in operation at any one moment. More environmental variables could be included in the determination of desired air speed in the house, but that approach can become unwieldy and expensive as greater numbers of transducers are added in an attempt to fully measure the environment that the birds are experiencing. A simpler alternative is to measure the deep body temperature (DBT) of the birds themselves using radio telemetry, and by doing so monitor a metric of the total thermal effects experienced by the birds due to any conditions that they experience. In fact, Hamrita et. al. (1998) found that radio telemetered poultry DBT showed responsiveness to ambient conditions before any outward signs of stress were manifested.

## RESEARCH OBJECTIVES

Radio telemetry could potentially increase productivity in agriculture. To gain widespread acceptance of the technology, it will require both low cost and proof of efficacy. Two agricultural applications of radio telemetry were explored in this work to determine if further development was warranted.

The first objective of this work is the design and assembly of a bench level telemetry sensor prototype that could be used in monitoring of soil conditions in a precision agriculture application. By using low cost commercial electronic components and RFID as the telemetry channel, a sensor platform is created lower in cost than currently available commercial telemetry. In the case of farm field telemetry, much work has already been done to show the value of up-to-date data, but costs are generally prohibitive to develop precision agricultural systems. What is

needed is an approach that can provide cost reduction through the re-engineering of currently available low cost technology to suit the needs of agricultural researchers. RFID is a widespread and well-understood technology and the mass manufacture of monolithic RFID components and systems could provide agriculture a cost-effective source of radio telemetry. Chapter 3 details the design, construction and benchmarking of a bench level prototype of a soil temperature telemetry sensor built around a stand-alone micro-controller collecting and collating temperature data that was transmitted to a PC using commercial RFID equipment.

The second objective of this work is to determine the feasibility of using radio telemetered poultry DBT as the feedback source in a closed-loop controlled wind tunnel ventilation system. The efficacy of using poultry DBT as the feedback source in an environmental controller needs to be determined before the broader question of radio telemetry installation cost can be addressed. The first step in this process is the design and construction of an experimental tunnel ventilation assembly that controls air velocity with a closed-loop controller based on the DBT of the poultry residing inside. Then, with this equipment, we establish the working parameters of a control scheme that illustrates the potential capabilities of telemetered DBT as the basis of an environmental controller for poultry housing. Chapter 4 details the design and construction of the experimental tunnel ventilation assembly, test subject preparation, closed-loop controller designs and the results of several experimental runs.

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## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **AGRICULTURAL FIELD TELEMETRY**

The literature details many examples of telemetry in the pursuit of data or automation in farm fields (Irmak et.al., 2001; Luo et.al., 2001; Schomberg et. al. 2002; Thomson and Threadgill, 1987). At the primitive end of the spectrum, Humphreys and Fisher (1995) investigated a surface water telemetry system that provided open loop feedback for a surface irrigation application for basins and borders in field segments. The telemetry sensor was placed at the end of the slope of a basin or border and monitored the moisture content of the location. Irrigation was initiated, and when the water arrived at the sensor location the sensor would signal the irrigation valve or gate to close using alternately an infrared or hardwired link. The authors suggest that this simple cost system could provide a convenience to the farmer who would no longer need to observe the surface irrigation progress to manually disengage the water flow.

To overcome the regulatory and bandwidth limitations of radio telemetry, infra-red (IR) communication has been suggested as a superior telemetry channel over RF. Cockerham and Ortega (1989) used an IR link to connect climatic and soil data collection equipment to a base operator station for monitoring the environmental and soil status in a citrus orchard and reported good success. A more technologically comprehensive telemetry and automation example can be found in the work of Ahmed and Al-Amoud (1993). Using infrared telemetry, multiple moisture sensors in a test wheat field monitored soil water content and relayed this data over the infrared link back to a base station. A PC running custom software would then determine when and for



how long irrigation was required by the crop. The base station would signal the pumping station, also over an infrared link, to start and stop the water flow. The authors found that although commercial infrared systems had lower overall cost than telemetry by radio or hardwired cable, other problems were apparent. The infrared transmitter/receiver pairs were very sensitive to alignment issues, and great care also had to be taken to insure that the arc of the sun was never eclipsed by the transmitter as the signal would have been washed out by sunlight. Atmospheric effects were also an important consideration, with communication degrading during heavy rain, fog, or dust storms.

A similar irrigation approach was examined by Thomson and Threadgill (1983) with a system that used cables to carry moisture data back to a central processing station to control a center pivot irrigation system. However, they found hardwired communications in an agricultural field to be an unwieldy solution. This problem was solved by a radio telemetry system from Cromer and McLendon (1984). They developed a micro-processor based radio telemetry system that replaced the cables and allowed for multiple sensors to be addressed for data queries from the central receiving station over a radio link. Modulated using frequency shift keying (FSK), the data was pulse code modulated between the frequencies 1070 and 1270 Hz.

## RADIO TELEMETRY WITH RFID

Very little literature describes RFID use in telemetry. Troyk (1999) surveyed various telemetric implant approaches for use in humans, and he concluded RFID technology shows the greatest promise for applications of implanted muscle stimulants for the paralyzed. Since loss of muscle use due to nerve damage leaves the muscle intact, long range planners envision surgical implants, triggered from external controllers, stimulating muscles artificially so that some

mobility can be returned. Since batteries have a limited life and are bulky, Troyk supports the concept of using the backscatter transmission technology used in RFID for both communication to the implant and to power stimulation. The FCC (2001) has recently increased the allowed radiated power for RFID transmission in the United States by approximately 50%, bringing the US more in line with European regulatory limits, potentially increasing the transmission distance that a RFID telemetry systems can operate legally in this country.

## RESPONSIVENESS OF POULTRY TO ENVIRONMENT

Like mammals, birds are able to auto-regulate their body temperature to exist in environments that would be otherwise too hot or cold for exothermic animals to behave normally (Dawson and Whitlow, 2000), but like any animal, extremes in temperature do adversely effect them. Due to the important commercial concerns involved in poultry production, the literature has many examples of studies interested in the effects of high temperatures on poultry. Many factors are important in maintaining a healthy poultry facility, and Heier et. al. (2002) found that mortality rates correlated closely with the quality of the housing environment, like ammonia levels, ambient heat and the general quality of the ventilation. Meltzer (1986) found that heat stress caused by temperatures higher than 28° C (82.4° F) has a serious negative impact on feed conversion rates (growth per food eaten) in commercial broilers. In an examination of tunnel ventilation as amelioration of heat stress, Yahav et. al. (2001) found that at ambient conditions of 35°C (95° F) and 60% RH, optimal weigh gain was achieved at air speeds of 1.5 to 2.0 m/s. In a more comprehensive experiment, Lott et. al. (1998) found a direct correlation between feed conversion and wind speed for poultry contained in an environment that caused heat stress in the control group due to high temperatures, but excellent growth in those exposed to non-still air.

In terms of deep body temperature, Kettlewell et.al. (1997) developed an implantable radio telemetry transmitter/reciever system that monitored both DBT and heart rate, and in experiments where the bird was subjected to a transit simulation in a heat-stress inducing environment, determined that both heart rate and DBT rose noticeably higher than on control days. Lacey et.al. (2000) established that DBT was directly and noticeably effected by ambient temperature and humidity, and was thus a good indicator for predicting heat stress. Additionally, as of yet unpublished data from that overall study (Hamrita and Lacey, 2003) suggests that if wind velocity in a tunnel ventilation system were modulated proportionally to the difference between DBT and nominal body temperature, heat stress could be averted in an early enough stage that any adverse effects could be reduced.

#### TUNNEL ENCLOSURES FOR STUDYING POULTRY

Tunnel ventilation has been found to improve yields and cost of operation in poultry production facilities (Lacy and Czarick, 1992). Research regarding the optimization of tunnel ventilation in the laboratory requires special equipment. Mitchell (1985) used a wind tunnel style calorimeter to measure the effects of air velocity from sensible heat loss (convection from the skin) and latent heat loss (evaporative, mostly from respiration) in poultry at 20° and 30° C. Among other results, he found that the impact on poultry DBT of two different air speeds, one 0.3 m/s and the other 1.05 m/s, was not significant when the environment was 20° C but was notable at 30° C. Although not a conclusion explicitly made by the author, this suggests that poultry thermal auto-regulation alone is capable of overcoming low levels of hypothermic environments, but not as able to handle hyperthermic ones.

Simmons et. al (1997) constructed a much larger tunnel containing hundreds of birds to also measure the effects of air velocity on sensible and latent heat loss. They tested the subjects at 29°, 32° and 35° C and air speeds of 1, 1.5, 2, 2.7 and 3 m/s. Results led the authors to conclude the following:

- Sensible heat loss increased while latent loss decreased at higher air speeds;
- Sensible loss decreased while latent loss increased as temperatures rose;
- Total heat loss was fairly constant as temperatures rose (for air speeds of 2 m/s).

Yanagi et. al. (2002) constructed a wind tunnel enclosure for placement in an environmental control room for the determination of responses of laying hens to heat stressing conditions and their surface and internal temperature reaction to subsequent surface wetting using telemetry. The assembly was designed to maintain constant airflow (speed set manually) and measure the animal responses to the environmental conditions without taking automatic action to alleviate the eventual heat stress.

## CLOSED-LOOP CONTROL OF ANIMAL ENVIRONMENTS BASED ON BIO- TELEMETRY DATA

The implementation of a closed-loop control system with telemetered data from freely moving chickens to maintain environmental conditions had not been previously explored in the literature, but it has been with lab rats and gerbils. Colbourne et. al. (1996) used surgically implanted radio telemetry temperature sensors in rodents as a feedback source for regulating their environment while conducting experiments concerning therapeutic hypothermia after ischemia events. The telemetry system, from the same manufacturer and system architecture used in our research as described in chapter 4, transmitted the brain temperature to the telemetry

system where the data was placed in a database. Software, running in parallel with the database logging program, sampled this temperature data and controlled a heat lamp, fan and water misting system to initiate and maintain a long term (>24 hours) hypothermic state in the rodents after a brain hemorrhage had been surgically induced.

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**CHAPTER 3**  
**A LOW COST APPROACH TO SOIL MONITORING FOR PRECISION**  
**AGRICULTURE**  
**INTRODUCTION**

The potential uses of radio telemetry in agriculture are broad and varied, but one that can have the most immediate impact is its use in precision agriculture. Precision agriculture is a fast growing area with great potential for maximizing crop yields while minimizing the waste of resources such as water, fertilizer or pesticides by directing the materials where the crops need them most. Historically, determining the allotment of resources to crop areas was a matter of anecdotal experience and observation, or based on previous end-of-season crop yields. Precision agriculture requires a different approach. Since crop yield can already be effected if plant distress is noticeable (Taylor, 1965), precision agriculture programs use current data to make reliable determinations of resource application. This can only be achieved through timely and systematic data collection, which can be costly if measurements require lab analysis. A less accurate but more cost effective alternative is onsite measurement using hand held calibrated sensors. However, this still requires direct human involvement in the measurement. A better solution is automated in-situ data telemetry.

Wireless radio frequency (RF) communication has been suggested as a more attractive alternative. Active RF telemetry has many benefits, including transmission range and robust resistance to weather effects. It also has drawbacks, including power requirements, regulatory limitations, cross-talk noise and, often most significantly, cost. A potential approach to low cost field radio telemetry is RFID technology, first developed for simple identification applications



but versatile enough to be put to more complex purposes. Traditional RF telemetry transmitters are generally more complex than RFID devices, requiring more electronics for amplification and modulation. Additionally, active transmitting telemetry nodes need sufficient onboard power to achieve reliable RF transmission. Passive RFID devices do not have this difficulty. Monolithic RFID devices are already produced in large quantities for non-agricultural purposes, and their unit cost is much lower than traditional RF telemetry equipment.

The first objective of this overarching study of radio telemetry in agriculture is to determine the feasibility of using RFID technology as a telemetry channel for a simple soil measurement application. By constructing a laboratory prototype telemetry system using low cost commercial electronics and an adapted commercial RFID device, we wish to provide a low-cost alternative to commercial telemetry systems.

## MATERIALS AND METHODS

### Design Analysis

The prime technical objectives of this telemetry device are:

- Relatively small size – exposed portions of a field deployed device should have a small horizontal and vertical profile to be unobtrusive to the various farm implements that would pass by and over it.
- Inexpensive – cost must be sufficiently low to allow for large-scale installations.

Regardless of the nature of the measurement, design and operation of the sensor electronics can be broken down into four main blocks:

- Communications: Consists of RF components as well as modulation and data storage/manipulation circuitry needed to transfer the collected information out of the module and to a receiver.
- Physical transducers: Consists of components that are required/available to measure quantities of interest and then provide a proportional electrical signal.
- Data acquisition and processing: Consists of microprocessor and associated components. Raw data (electrical signal) is provided by the transducer(s) to the processor, which samples and manipulates (filters, quantizes, performs mathematical operations, etc.) this data and transfers the result to the communications block.
- Power – Energy is required to run the microprocessor and related components, and supply long term power for the duration of any experiments or monitoring conducted.

### Communications

An RFID (Radio Frequency IDentification) device, generically called a "tag", consists of an antenna, modulating circuitry, and non-volatile memory containing relevant information, such as a serial number or lot code, that is transmitted by the modulation circuitry when the tag is queried by an interrogator reading device. An interrogator consists of an antenna and RF transmission and demodulation electronics, and provides the demodulated data contained on the tag to its supervisory system. RFID tags are used in many commercial applications where automated non-intrusive identification is preferred over more traditional methods of inventory control or as an anti-theft measure, such as in warehouses or retail outlets. RFID is also used in identifying domesticated animals, both in agricultural settings and for companion animals. The ISO has established standards ISO 11784 and 11785 to aid the shape and growth of this technology (Finkenzeller 1999). Although several uses for RFID style devices in other non-

product tracking applications have been explored where low power and small size are needed (Troyk 1999), very little has been published regarding its use as a method for in-situ agricultural field telemetry.

RFID tags are queried for stored data by the interrogator using a RF electromagnetic carrier wave. Generally speaking, RFID devices almost exclusively use backscatter modulation as the method of RF transmission. The quality of a backscatter modulation system is dependent upon the level of electromagnetic coupling between the interrogator antenna and tag antenna. The interrogator and tag together act as an air core transformer, the interrogator antenna being primary coil and the tag antenna the secondary. The interrogator produces a carrier signal (in our case 13.56MHz) that, by Ampere's and Faraday's laws, induces a current on the closed conductive circuit of the tag antenna. This induced current is proportional to three factors: strength of the broadcast EM field from the interrogator, distance between the transmitting and tag antennas, and orientation of the tag antenna in the generated field. Additionally, if the tag antenna length is a multiple of the wavelength of the transmitted carrier wave or is tuned with resonant components, greater coupling is achieved.

In most RFID applications, this AC current on the tag antenna is rectified and used as the power source for the RFID data retrieval and modulation circuitry. This is designated as "passive" RFID, while those tags that actively transmit data with an onboard power source are called "active" RFID. Passive systems have an advantage over active systems in that the device does not require a local power source for transmission activities. A smaller and less obtrusive unit can be produced because the additional mass of a power source is absent.

Once the induced voltage on the passive tag antenna reaches a sufficient level to power the unit, modulation circuitry begins sequentially shorting a section of the antenna tuning circuit in a

pattern corresponding to its stored data. Changing the inductive or capacitive values of a tuned antenna circuit will alter its resonant frequency. By electrically shorting a section of the antenna, the circuit reactance changes reducing the amount of energy conferred to the circuit. At the interrogator, a small fluctuation in the voltage applied to the transmission antenna occurs since the magnetically coupled circuit (interrogator and tag) experiences a changing load as the tag antenna goes from resonant to non-resonant. The interrogator continuously monitors fluctuations in this output voltage, demodulating any patterns that emerge. This reproduces the data transmitted from the RFID device.

Biphase-L encoding, also called Manchester encoding, is used for the transmission of data in our selected RFID device (the Microchip<sup>1</sup> MCRF355). The RFID device has an internal oscillation circuit that generates a 70KHz timing signal used to sequentially clock out the data stored in the onboard memory array. Manchester encoding combines both the transmitted data and bit frame timing by having each symbol contain a low/high (bit = 0) or high/low (bit = 1) transition. In this way, the demodulating device can synchronize bit frames with the tag. A representation of a sample bitstream is shown in Figure 3.1.

The MCRF355 also has anti-collision procedures built into the operational parameters of the chip. Since all RFID devices of this variety will respond to a 13.56 MHz carrier signal, the MCRF355 is designed to respond immediately after power up, but then go into sleep mode for approximately 100ms,  $\pm 50$ ms. The variation in the 100ms sleep timer is vital to the anti-collision protocol. The value, which is randomized in each device due to intentionally broadened manufacturing parameters, allows multiple RFID devices to operate in the same field at the same

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<sup>1</sup> Microchip Technologies Inc., Chandler, AZ 85224 USA

time. If fewer than 100 are activated the manufacturer asserts that their transmissions are sufficiently spaced out in time so that they do not conflict.

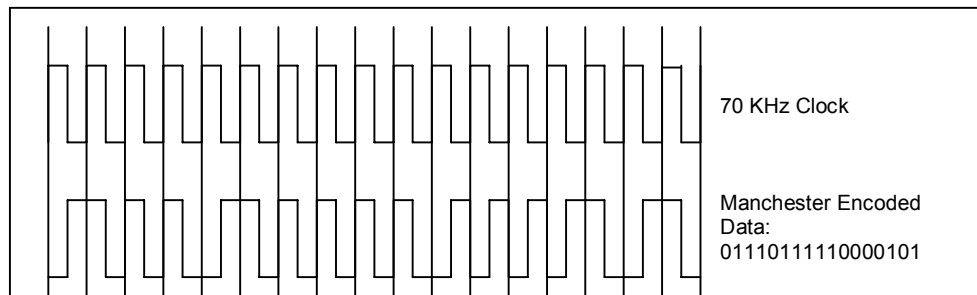


Figure 3.1: Example Manchester encoding sequence. The polarity of the transitions in the Manchester encoded data bitstream on the negative slope of the transmission clock signal determine the value of the binary datum that is transmitted, with high to low being logic 0 and low to high being logic 1.

Several manufacturers of RFID products have products ranging from basic components to complete systems. With the desire to use off-the-shelf integrated components when possible, the MCRF355 device from Microchip Inc. is selected for our system due to its availability in IC form as well as its adaptability to our application. The MCRF355 is an 8-pin 13.56 MHz passive RFID device with 154 bits of user configurable EEPROM that is programmed with 20 Vdc along with TTL level voltages.

Using RFID in a telemetered sensor is a fairly novel method of establishing a communications channel. It does have a few drawbacks, most appreciably a severe limitation in transmission range. Like all RF transmissions in the USA, 13.56 MHz devices are regulated by the FCC and operate under limitations of the interrogator transmission power. Because passive RFID must operate in strong enough fields to gain operational power, we must either boost the reader transmission power or accept a short reading distance (less than 1m). The FCC has recommended increasing the current transmission power allowed under Section 15.225 by approximately 50% (FCC 2001) to bring US standards in line with other international regulatory

agencies. Even with this added field strength, the reading range will still most likely be under 3 meters. This limitation is not severe if interrogators in a field deployed system were placed on farm implements or center pivot boom arms that pass by the telemetry unit on a regular basis. Further generations of this device may explore alternatives to this difficulty, such as microwave RFID, which has longer read distances with the same power but requires directional antennas.

### Physical Transducers

A few low cost options exist for commercially available sensors that could be implemented in a soil monitoring station, namely temperature and soil moisture content. Other soil variables (e.g. nitrogen levels, pollutant concentrations, pathogen presence) can be measured, but at the time of this writing are too expensive or impractical for an in-situ telemetry unit. Our telemetry platform is designed to be flexible to accommodate the range of possibilities of measurement that might be required for any given application.

This first generation sensor platform has been tested with a single transducer that measured temperature. Soil temperature is a significant variable affecting germination and the overall health of the soil, which is reflected in its importance to crop modeling algorithms (Schomberg, et.al. 2002; Luo, et.al. 2001; Irmak, et.al. 2001). Although several options are available for monitoring temperature that met the project goals, such as thermocouple or RTD devices, we wish to build a platform that in the future could be constructed with a small, low cost, low power microcontroller. This potential future microcontroller may not be capable of the analog to digital conversion (ADC) that these temperature devices would require.

The Serial Digital Output Thermometer (TMP04, from Analog Devices<sup>2</sup>) is well suited to this application. An integrated IC that measures its own internal temperature, it produces a

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<sup>2</sup> Analog Devices Inc, Norwood, MA 02062 USA

PWM (pulse width modulated) output proportional to this temperature with a base frequency of approximately 35 Hz and an accuracy of  $\pm 1^\circ\text{C}$ . This output is easily integrated with a microprocessor TTL input, requiring only software in the microprocessor to measure the duty cycle of the PWM signal.

#### Data Acquisition and Processing

A Motorola<sup>3</sup> MC68HC811E2CFN2 microcontroller is used in this prototype due to its availability, widespread familiarity, and ease of use. Although far more powerful than what was needed for this first generation demonstration application, programming code generated for it will provide a flexible starting point for any future sensor prototypes.

#### Power

The power source for this assembly can be of reduced size in comparison to an active transmitting telemetry system due to the use of passive RFID communication. Nevertheless, power is still required to operate the sensor and data acquisition circuitry. Although some energy could be gained from the RFID interrogator field, the reader would generally not be within range during measurement operations. For a field deployed system based on this prototype, the amount of time the interrogator would be in range is limited to what is necessary for the telemetry unit to transfer data. Depending on the specifics of each installation these data transfer events could be hours, days or weeks apart. Since measurement and data acquisition should occur regardless of sunlight, powering a field unit from only photovoltaic cells is not feasible. Thus, some form of chemical battery would be used, potentially augmented with photocells. However, as this experiment is intended to generate a bench level prototype, standard lab DC power supplies are used to provide 5Vdc to power the logic and 20Vdc to write to the EEPROM in the RFID device.

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<sup>3</sup> Motorola Inc, Northbrook, IL 60062 USA

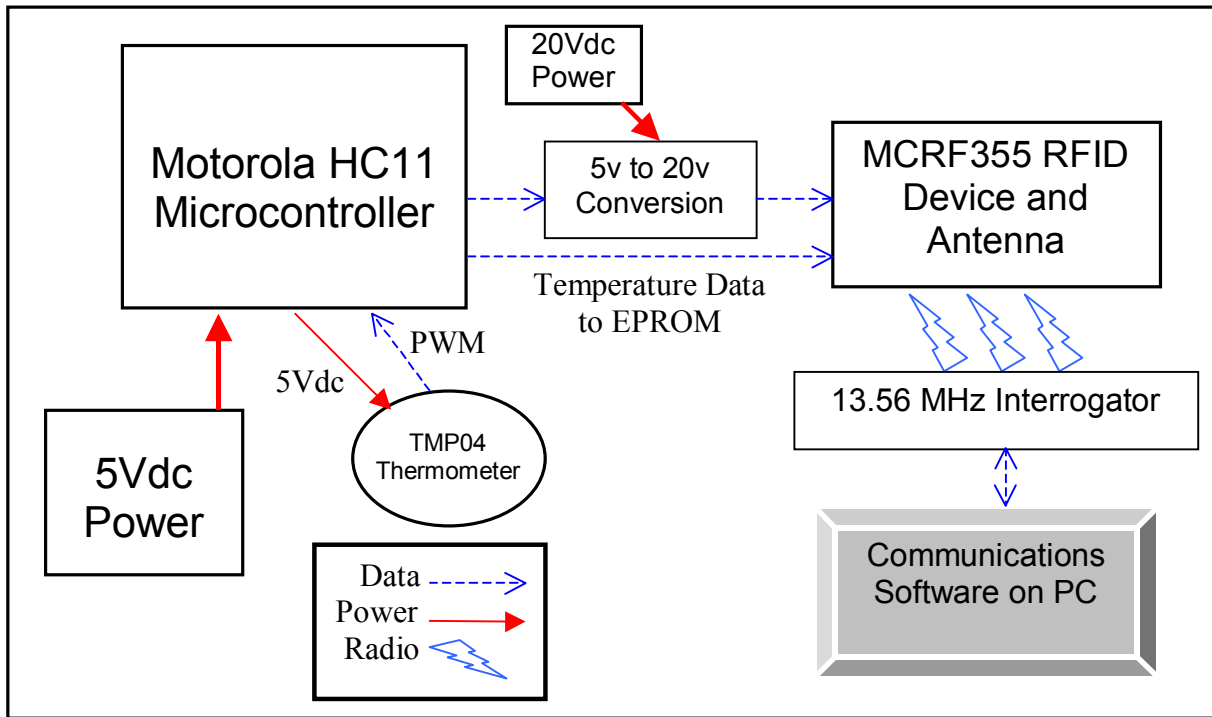


Figure 3.2: Block diagram of sensor prototype. Microcontroller powers the electronic thermometer that provides a PWM signal proportional to the measured temperature. The microcontroller averages and formats temperature data and writes it to the EPROM on the RFID device, which is then free to passively transmit the data to the interrogator and PC.

## IMPLEMENTATION

### Hardware

A block diagram of the sensor is shown in Figure 3.2. The microprocessor is the heart of the system, acting as a data collection hub for the sensor as well as the programming source for the RFID transmitter. For this prototype the Motorola MC68HC811E2CFN2 is mounted in a JDR Microdevices<sup>4</sup> CGN-1001 stand-alone microcontroller board. I/O use is limited to the eight

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<sup>4</sup> JDR Microdevices Inc, San Jose, CA 95112 USA



pins of port A, with the goal of making the sensor easily scalable to smaller, lower power 8-bit microcontrollers in the future. The stand-alone board provides all the necessary support circuitry needed by the microcontroller (e.g. 8 MHz oscillator, startup delay circuit, ModA/B select, etc.). When provided with power, the microcontroller is configured to automatically start operation.

The RFID chip requires a resonant antenna circuit connected between 3 pins (Ant A, Ant B, and Vss) tuned to the interrogator carrier frequency. The manufacturer's recommended method for finding antenna/resonant circuit component values is based on the operational frequency of the RFID device, 13.56 MHz:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = 13.56\text{MHz}$$

Where L : impedance of conductor that forms the antenna

C : capacitance electrically parallel with antenna.

Several prototype antennas were constructed and tested, but they failed to achieve an acceptable performance level. Due to our limited access to exacting fabrication equipment, our preliminary prototypes were dimensional approximations of what would be required. As this first generation device was purely a bench top prototype, a commercially available solution available from the RFID manufacturer that consists of an antenna with pre-selected tuning capacitors is used.

The Analog Devices TMP04 Serial Digital Output Thermometer generates a PWM signal with a duty cycle directly proportional to the temperature at a frequency of approximately 35Hz. It is powered by an output from port A pin 3 (PA3), allowing the suspension of the device when not needed. This is done to further power efficiency, as an eventual field sensor would be battery powered and would have a limited lifetime. The signal line is monitored by port A pin 0 (PA0), configured as a real time interrupt. This I/O point induces a capture of an internal free

running timer value on each transition of the PWM signal, allowing the duty cycle and frequency to be measured.

Programming of the RFID chip is accomplished by manipulating the four dedicated RFID outputs on the microprocessor. They place the device in programming mode, send it serialized programming codes, and the actual temperature data that is to be retained and transmitted. To program the EEPROM in the RFID chip, it is placed in hardware read/write mode by applying logic high to Vdd from port A pin 7 (PA7). Command code sequences (high =1, low =0) are provided to the Vprg pin on the RFID by port A pin 5 (PA5) while being clocked on the CLK pin by port A pin 4 (PA4). The high voltage required for erasing or writing to the EEPROM array is triggered from port A pin 6 (PA6). This line is connected to the gate of a FET circuit, which amplifies the 5V signal to 20V. Like the command code signals, these 20V pulses are passed to the Vprg pin of the RFID IC through a diode to eliminate backfeeding current. When the data write is complete, Vdd is taken low and the RFID is free to modulate the signal on its antenna circuit with the newly written data whenever the interrogator is within range.

### Software

As this RFID device can only hold 154 bits of data in memory, measurement data must be stored efficiently. For this prototype, we limit the numeric resolution to 8 bits to achieve this aim. The functional temperature range of the sensor is 0.0 to 51.0°C with a 0.2°C resolution. The value corresponding to the measured temperature written to the RFID EEPROM ranges between 0 – 255 (00 – FF hex). As the eventual vision of this telemetry unit is to have multiple stations in the same field environment, an identifying marker specific to the unit must be included in the data structure so that the multiple data sources could be tracked individually. This prototype has 8 bits dedicated to the sensor ID to match the format of our prototype reading

device, the Microchip Technologies 13.56 MHz Anti-Collision Interrogator for MCRF3XX and MCRF4XX. Additionally, an 8 bit incrementing counter is also included to identify when new data had been written to the EEPROM array. Depending on how many bits are available to be dedicated to this purpose in future implementations, it could be used for both identifying the age of the data read by the interrogator as well as predicting the remaining functional life of the sensor.

As mentioned previously, the PWM signal generated by the digital thermometer is monitored by the microcontroller with a real time interrupt input. When the first positive edge is detected, the two-byte value (0000-FFFF hex, 0-65535) that is contained in the free-running counter is captured and stored in memory. The same occurs on the next negative edge and its following positive edge. These three 16 bit numbers form the basis of one temperature measurement. The conversion of the PWM signal to temperature, provided by Analog Devices, is:

$$235 - 400 \times \left( \frac{T1}{T2} \right) = \text{degrees C}$$

Where T1 : time duration of high level of PWM signal (5 Vdc)  
T2 : time duration of low level of PWM signal (0 Vdc).

T1 is found from the difference between the captured time of a positive edge and the subsequent negative edge, while T2 is found from the difference between that negative edge and its subsequent positive edge. For simplicity, computation was limited to integer only, so the above equation is modified to use 2530 and 4000 to provide resolution to one decimal place. After computation, this value is reduced to 0.2° resolution in an 8-bit register and offset and scaled based on calibration data. The value is stored, and the process is repeated 255 more times, summed, and the least significant byte dropped to find the average temperature for that particular

sampling sequence. In this prototype, the entire measurement process occurs over a span of 17 seconds. However, this is merely a minimum span dependent on the selected hardware and averaging method. Depending on the nature of the measurement in future field installations, the sampling span could be extended to the requirements of the application.

### Experimental Procedures

The programming code for the microcontroller was assembled with Axiom Manufacturing<sup>5</sup> AxIDE v3.61 software, and the op-code file provided to the EEPROM burning software of a BP Microsystems<sup>6</sup> BP1200 Universal Device Programmer. After writing the program to the EEPROM of the microcontroller, it was mounted in a JDR Microdevices CGN-1001 daughterboard, and all appropriate electrical connections made. The remaining components of the system, excluding the digital thermometer, were mounted in a 4x7 inch (10.2x17.25 cm) Archer breadboard. The leads for the digital thermometer IC were left long, approximately 40 cm, so that it could be placed in a plastic bag for immersion in a temperature controlled water bath and separate from the rest of the sensor assembly. A thermocouple probe was inserted into the bag as well, and was connected for measurement to a Fluke<sup>7</sup> 16 multimeter to gather calibration data. A 1.5 inch (3.8 cm) microID 13.56 MHz PDIP Hard Tag from Microchip Technologies was wired onto pins 3, 5 and 6 of the MCRF355 so that it could act as the antenna for the sensor. RFID EEPROM programming voltage (20 Vdc) and logic bus (5 Vdc) were supplied by bench DC voltage supplies.

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<sup>5</sup> Axiom Manufacturing Inc., Garland, TX 75041 USA

<sup>6</sup> BP Microsystems Inc., Houston, TX 77055 USA

<sup>7</sup> Fluke Corporation, Everett, WA 98203 USA

The bag containing the digital thermometer and thermocouple, with leads connected to their appropriate terminations, was immersed in a Thermo Neslab<sup>8</sup> GP-100 water bath. Water bath temperature was set at increasing levels within the sensor's desired operational range, with temperatures below room ambient (15 – 20 °C) achieved with the addition of ice directly into the bath. Measurements were taken approximately five minutes after each temperature change to allow for temperature stabilization. Results of each successful read by the Microchip Technologies 13.56 MHz Anti-Collision Interrogator of the RFID memory were displayed on a PC running RFLAB v3.4 (supplied by Microchip Technologies with the interrogator), which communicates with the reader over an RS-232 serial link. Each successful measurement was hand logged by an observer. After initial experimentation, calibration data was gathered and applied to the program within the microcontroller, and final data collection took place with the same procedures as above.

## RESULTS

Figure 3.3 shows a scatter plot of sensor measured temperature points versus thermocouple measured temperature points for 5 different experimental days. The sensor performed as expected, but calibration proved unwieldy and time consuming as modifying the calibration parameters required altering the program stored in the microcontroller EPROM.

The sample correlation coefficient  $r$  (Bhattacharyya and Johnson, 1977) for each trial day as well as for the whole data set is shown in Table 3.1. The results show a strong linear relationship between the measurements taken by the sensor prototype and those registered by the thermocouple.

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<sup>8</sup> Thermo Electron Corporation, Waltham, MA 02454 USA

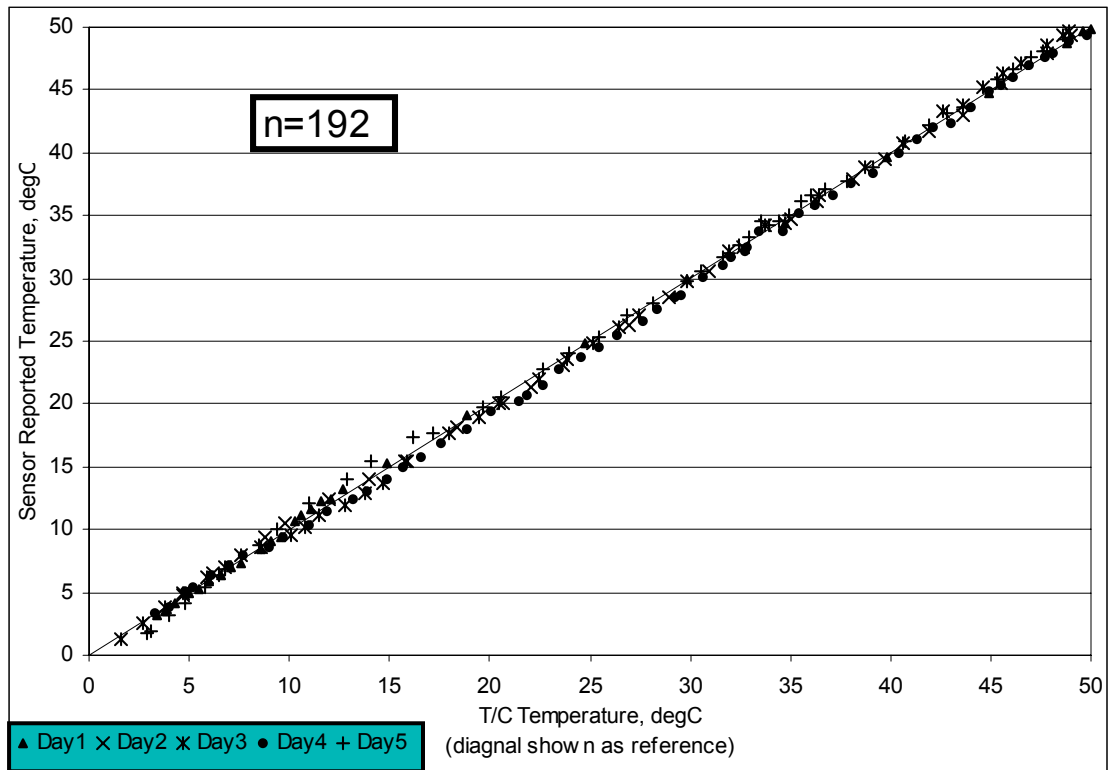


Figure 3.3: Reported sensor temperatures vs. thermocouple response

Table 3.1: Sample correlation coefficients for sensor trials. The reported temperatures of the sensor prototype and thermocouple showed a strong linear relationship.

Trial	Sample Correlation Coefficient $r$
Day 1	0.999856
Day 2	0.999578
Day 3	0.999682
Day 4	0.999565
Day 5	0.991380
<b>Overall</b>	<b>0.999441</b>

## CONCLUSION

The known area that this device falls short (transmission range) can be overcome with focusing new efforts on designs for RFID interrogators and antenna. Failing that, microwave range RFID transmission can be used as a replacement with minimal additional costs. The retail price for all active electrical components used is less than US\$20, in marked contrast with costly commercially available active transmitting telemetry equipment. Powering the TMP04 thermometer by enabling an output of the microcontroller provides a means to power down components that are not needed, increasing energy efficiency of the sensor assembly.

Further iterations of the system will require a greater level of automation in the transfer of the collected data into a usable database, most likely requiring software development for execution on a PC. Future field deployment will also require investigation of a long-term, reliable power source to supply both TTL and EPROM programming voltage levels. The limited amount of data that can be stored in this particular RFID EPROM could be a problem if long periods between data offloading events are planned. However, the time division multiplexing capability of the selected RFID device would allow for multiple RFID components in the same sensor platform to provide increased storage capacity.

Although many questions remain, this project has established the potential for further development on the subject. The low comparative cost of this approach partially offsets the limited transmission distances, which will provide opportunities to investigate precision farming applications using near real-time radio telemetry that would otherwise be too costly.

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# **CHAPTER 4**

## **CLOSED-LOOP CONTROL OF POULTRY TUNNEL VENTILATION BASED ON DEEP BODY TEMPERATURE**

### **INTRODUCTION**

The use of tunnel ventilation has gained in popularity among poultry producers where simple passive ventilation of outside ambient air is sometimes insufficient in maintaining acceptable growth temperatures inside the poultry facility (Lott et.al., 1998). A tunnel ventilation system uses forced air drawn from outside the grow building to cool the fowl, and improved weight gains have been noted using this system over standard cross-ventilated facilities (Lacy and Czarick, 1992). However, most implementations control the fans in a purely on/off mode, and often depend on human intervention to determine when the fans should be energized. When an automated controller is used, it generally determines the energized state based on ambient air temperature, and does not monitor the state of the poultry themselves.

By implanting birds in a grow facility with telemetry devices that provide their deep body temperature (DBT) to the environmental controller for the house, the actual state of the birds could be used as the determining factor for varying air speed in the tunnel ventilation system. Previous work in our lab (Hamrita et.al., 1998; Hamrita and Mitchell, 1999; [1]Lacey et.al., 2000; [2]Lacey et.al., 2000; [3]Lacey et.al., 2000) as well as the work of other researchers (Mitchell, 1981; Kettlewell et.al., 1997; Yanagi et.al, 2002; Tao and Xin, 2003) has shown that DBT is a good indicator of poultry heat stress and that it is possible to measure it online without disturbing the animals.

In applications of systems theory, to properly control the behavior of a system it is crucial to take measurements of important variables and provide them to the controller so decisions can be made about the level of response required. This is called feedback control. Since the ultimate goal in controlling tunnel ventilation in poultry housing is making an environment that the birds find comfortable enough to grow efficiently, it is important to measure and feed back physiological variables which are indicative of the birds' comfort levels. This work details a new approach for tunnel ventilation control based on feedback of DBT measurements from the birds using radio telemetry.

This is still a developing field, and evidence in the literature of attempts to control poultry environments with a closed-loop system based on DBT are non-existent. Thus, the objective of this work is to make an initial foray into closed-loop control of poultry environments (specifically tunnel ventilation air speed) using radio telemetered DBT to determine the feasibility of this approach. To do so we construct a wind tunnel experimental enclosure that houses three subject birds. They are then exposed to heat stressing conditions generated by an environmental control room wherein the enclosure is housed. Surgically implanted telemetry transmitters are used to measure a chicken's DBT that is provided as feedback to a closed-loop controller generating variable air velocity in the tunnel. As in commercial tunnel ventilation systems, this moving air cools the birds and is intended to maintain their DBT within safe limits during the stressing conditions. Using standard industrial control equipment and a proportional response control scheme, we establish a closed-loop control architecture that is tested under various operating conditions with various operational parameters.

## MATERIALS AND METHODS

### Wind Tunnel Construction and Equipment

The enclosure is constructed from standard pine lumber and Plexiglas sheeting, with the habitat area fairly small (measuring 180cm in length with a cross section of 47x45 cm) due to the constraining size of the available environmental control chamber that the experiments were conducted in. The two sides and the bottom are made from joining two 72x10in (183x25cm) planks, while the top is made from two 1x1in (2.5x2.5cm) members 72in (183cm) in length and two 18.5in (47cm) in length constructed into a frame. This frame is a mounting for a sheet of corrugated Plexiglas that allows light into the enclosure as well as visual observation access. The frame is attached to the box through mounted hinges. The paired planks that make up the sides and bottom of the tunnel are joined together with 6x4 in (15x10 cm) spiked mending plates and 0.25 in (0.6 cm) wide self-adhesive weather stripping in the junction to minimize vacuum leaks.

The sides of three 18x9x5in (46x23x13cm) cat litter pans were cut down to create litter containment wells of approximately 7 cm in depth to improve enclosure cleanliness and maintenance. Each pan is located in the enclosure, with animals segregated by chicken wire mesh and separated from their neighbor by at least 25 cm. These segregation and separation dimensions are required to eliminate cross talk in the telemetry transmitters, with individual receivers mounted underneath, supporting the pans. The separation area is covered by a false floor, 6.5 cm above the main floor, to maintain laminar airflow in the tunnel that would otherwise be disrupted by the vertical sides of the litter pans. Feed pans are placed on the false floor, and segments of the wire mesh are removed to allow access by the birds. A 2m long

Ziggitty Poultry Systems<sup>1</sup> nipple-drinking pipe is mounted down the entire length of the habitat to allow water ad-libitum.

A centrifugal blower fan with a 9.5 in (24cm) wheel is used to generate vacuum airflow in the tunnel. As the fan was salvaged from storage, specifics on the make and model are unavailable. However, it is very similar in form and function to a Dayton<sup>2</sup> 2C971 blower fan. The outboard 8 in (20.3cm) drive pulley is threaded with a 0.5 in (1.3cm) belt to a 5 in (12.6cm) pulley mounted on the output shaft of a 0.5 HP (370 W) 3 phase 1725 RPM 220VAC motor. The motor is driven by an Allen-Bradley<sup>3</sup> 160-AA12NSF1P1 3-phase variable speed AC drive, itself powered by dual phase line 220VAC. The drive is configured to adjust its output frequency based on a 0-10Vdc analog output from an Allen-Bradley MicroLogix 1500 PLC. The PLC receives DBT feedback from a subject through an analog link to the telemetry and data acquisition hardware.

Initial experimentation with the system was plagued with noise in the telemetry system, which was traced to EMF from the variable speed AC drive. Subsequent removal of the AC drive from the environmental control chamber decreased the noise markedly. To smooth the remaining electrical noise, the real time temperature data tapped from the Data Sciences telemetry system was filtered in a ten minute moving average by the controlling PLC.

### Telemetry System

The telemetry, provided by Data Sciences International<sup>4</sup> (DSI), monitors DBT and other variables with implanted transmitters and associated equipment. The DSI telemetry system

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<sup>1</sup> Ziggitty Poultry Systems, Middlebury, IN 46540, USA

<sup>2</sup> Dayton is a registered trademark of Grainger Industrial Supply, Lake Forest, IL 60045 USA

<sup>3</sup> Allen-Bradley is a registered trademark of Rockwell Automation, Milwaukee, WI 53204 USA

consists of four groups of components: the implant, the receiver, the data exchange matrix, and the data acquisition computer. The implant measures, quantizes and transmits data from within the host animal. The implant used in this work, the TA11CTA-F40, can measure temperature, heart rate, and in conjunction with the receiver, animal movement. The manufacturer calibrates the implants at the factory, and provides configuration data with each unit to implement the calibration when used with the Data Sciences telemetry software. When properly calibrated, the sensors have an initial accuracy of  $0.1^{\circ}\text{C}$  and a resolution of  $0.01^{\circ}\text{C}$ . Photographs of a receiver and telemetry implant used are shown in Figure 4.1.

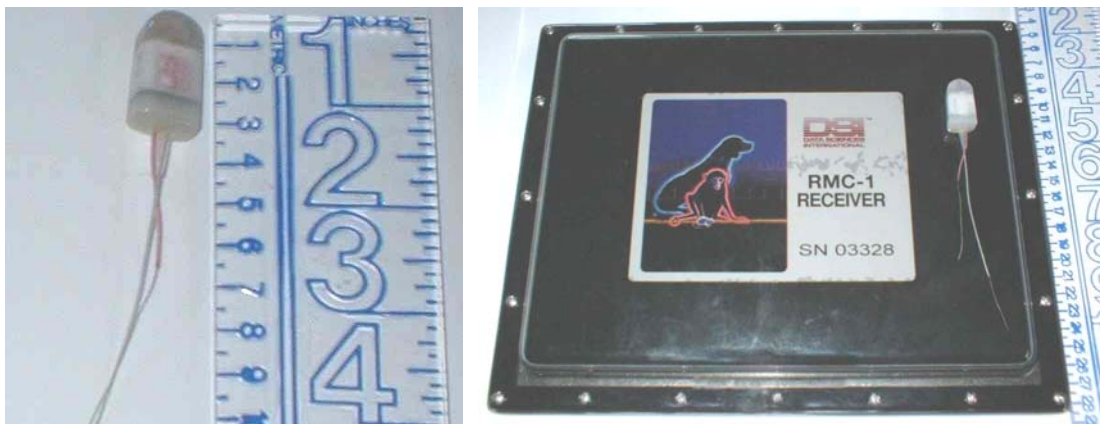


Figure 4.1: Photographs of telemetry hardware. From left to right – TA11CTA-F40 temperature/ECG telemetry implant (tails are ECG leads); RMC-1 receiver and telemetry implant.

The receiver (in our case a RMC-1) detects the transmission from the implant, and then communicates the data by wire to the data exchange matrix. The receiver itself measures animal movement by monitoring changes in signal strength emanating from the transmitting implant, and generates a value based on the rate of variation. The data exchange matrix is a

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<sup>4</sup>Data Sciences International, St. Paul, MN 55126, USA

communications hub for the data acquisition computer, capable of multiplexing 20 different receivers or four other matrixes. It also acts as a power supply for the receiving units that are connected to it. Additionally, a direct temperature measurement probe that was used to monitor the room temperature during experiments was also connected to the matrix. The data acquisition system records the data from the receivers (and temperature probe) via the matrix, filters out noise, and converts the information to common units. The software can be configured to continuously monitor and record all data or just specific data points, or can be set to only collect data for specified periods at specified times. An analog input on the PLC, used as feedback for the closed-loop control of fan speed, is driven by a DSI model #273-0016 Temperature Analog Output Adapter. The adapter is placed inline between one of the DSI telemetry receivers and the data matrix module, meaning only one bird is the feedback source at any one time. This device outputs an analog signal proportional to the current temperature reading being received by one RMC-1 receiving unit, thus allowing us to close the control loop in real time. A block diagram of the DSI telemetry system and PLC fan control is shown in Figure 4.2.

Although previous work from our lab (Lacey, et.al. [1],[2] 2000) utilized a different commercial telemetry system, the selection of this Data Sciences telemetry system for these experiments was made due to its ability to measure heart rate along with DBT. Unfortunately, the ECG signal provided by the telemetry implant did not provide tangible results in this experimental battery, possibly due to surgical placement of the electrical leads or distance from the implant to the receiver. As the implant was designed specifically for larger rodents, and not chickens, differences in musculature may have injected further noise into the signal. Although some ECG waveforms were generated, they contained too much noise to be useful as a reliable

metric for determining experimental difference. Further investigation into lead placement will hopefully ameliorate this difficulty in future experimentation.

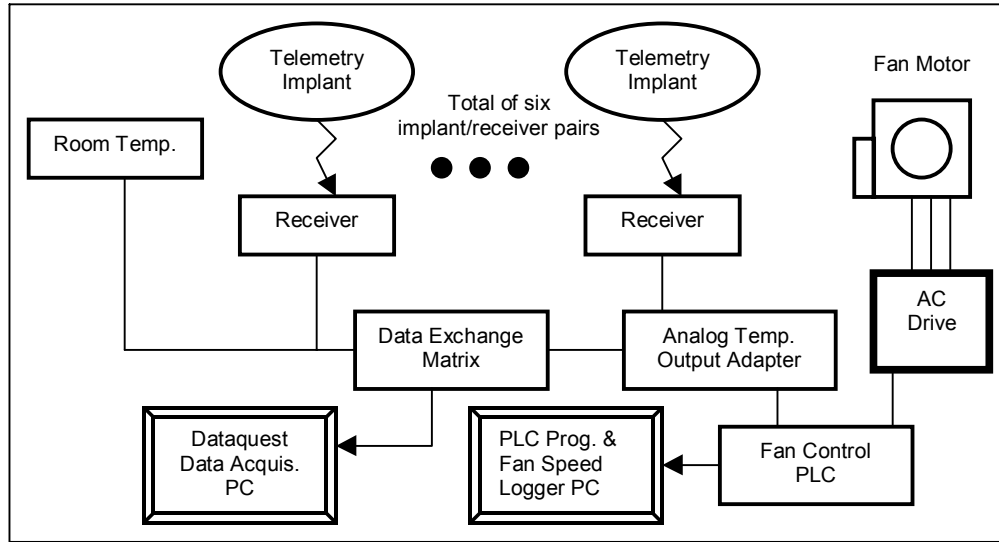


Figure 4.2: Overview block diagram of telemetry and control system. Data Quest telemetry system receives DBT and other data from implants, temperature data is provided to a PLC that controls fan speed by adjusting the output of the variable speed AC drive. The drive powers the motor that turns the fan.

Other difficulties with this telemetry system were due to hardware limitations. To achieve the small size and fairly long functional life (90+ days) of the implants, the manufacturer limited transmission distance to less than 30 cm for reliable DBT data transmission. We also found that ECG data transmission improved dramatically at close range (<5cm), but such proximity was only possible when the birds were settled and laying approximately at the center of the receiver. This issue was also a factor in the meaningful monitoring of activity. Additionally, all DSI telemetry implants of this variety transmit at the same carrier frequency, making communal enclosures impossible if monitoring is desired. Despite these drawbacks, the rich data available made the described DSI system a valuable tool for this laboratory level research.



## Controller Design

Most modern poultry house controllers that implement control of tunnel ventilation generally use ambient temperature as the determining factor. Tunnel ventilation with these controllers operates by drawing outside air into the building with independent banks of electrically powered fans. Based on a series of threshold values, increasing temperatures in the house results in more banks of fans being energized. For our work, fan speed is controlled based on the response of a bird's DBT. A block diagram of the closed-loop control system is shown in Figure 4.3. Although an accurate and consistent measure of bird comfort based on its DBT is not yet fully established in the literature, we chose DBT control setpoints that were approximately 41.5°C, as that value is the average DBT of *G. gallus* (Dawson and Whitlow, 2000) and thus a promising starting point.

Several experimental trials were run using different controller parameters, with changes made between the runs in an attempt to improve the response of the controller. A single treatment bird is used as the feedback source, although not every run used the same bird. It would not be feasible in any future field deployed tunnel ventilation system based on poultry DBT to monitor the entire flock in the grow house, so study is required to determine the appropriate number of animals to sample for such a system. However, the issue is not directly addressed in this work.

Ignoring the differences in parameters, the controller structure for the first four runs detailed consist of a proportional output incremental "trimming" structure. If the deviation from setpoint exceeded the deadband of  $\pm 0.05^{\circ}\text{C}$ , an incremental adjustment was made to the output following the rules of Table 4.1 with the goal of bringing the DBT of the feedback source bird to the setpoint level for that run. The structure for the controller was selected to provide maximum

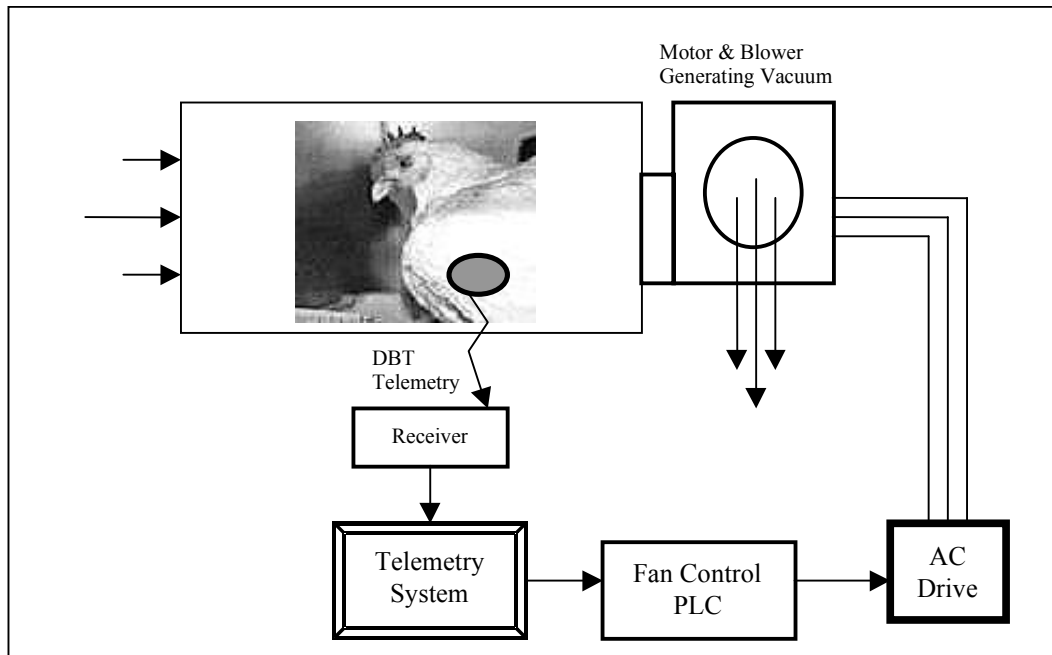


Figure 4.3: Block diagram of closed-loop tunnel ventilation system. The telemetry implant transmits DBT to the receiver, and it is provided to the PLC by the telemetry system. The PLC determines the closed-loop response, and provided it to the variable speed AC drive. The drive powers the fan motor, setting the desired air speed.

flexibility during the testing phase to allow for simple adjustment of both the update rate and incremental trim amount without overbalancing one range in favor of another. We arrived at the values of Table 4.1 through incremental adjustments based on observations of either overshoot or sluggish DBT responses made during testing in the five week interval between initial implantation and the first experimental run detailed here. The threshold of the last row of the table only acted on positive error, an addition made during testing to further accelerate bird cooling when this dangerous state occurred due to poor tuning parameters. Generally, the controller was able to reduce air speed before negative error rose to this same magnitude, so no accommodations were made to account for it.

Table 4.1: DBT error ranges for establishing trim rates.

Error	Induced Trim Change @ Rate	Effective Air Speed Trimming Rate
$E_{DBT} < \pm 0.25^{\circ}\text{C}$	0.025m/s @ 150 sec	$\pm 0.01$ m/s per minute
$\pm 0.25^{\circ}\text{C} \leq E_{DBT} < \pm 0.35^{\circ}\text{C}$	0.025m/s @ 75 sec	$\pm 0.02$ m/s per minute
$E_{DBT} > \pm 0.35^{\circ}\text{C}$	0.025m/s @ 30 sec	$\pm 0.05$ m/s per minute
$E_{DBT} > 0.7^{\circ}\text{C}$ (for positive $E_{DBT}$ only)	0.05m/s @ 30 sec	+0.1 m/s per minute

The first four experimental runs use the described structure and the parameters of Table 4.1 exclusively. The last three runs use the structure of Table 4.1 with some modifications to the parameters along with an additional threshold structure. The additional threshold structure monitors the error, and if the preset error thresholds are exceeded the output is immediately increased or decreased to a predetermined level. This is included as an attempt to reduce over and undershoot of the DBT responses. The two of the last three runs detailed had different parameters associated with this structure, and the specifics of each is included in the results sections with their respective DBT response plots.

#### Surgical Preparation of the Subjects

A total of six commercial breed broilers were selected randomly from a commercial broiler house at 21 days of age. At 24 days they were implanted with the DSI TA11CTA-F40 telemetry transmitters under veterinary supervision. Subjects were initially anesthetized with a mix of pure oxygen and 5% isoflurane, reduced to 2% isoflurane after loss of consciousness. The chickens were placed dorsally, and the operative area was cleaned with a 10% povidone solution and draped with a surgical cloth. A small ventrimesial incision, approximately 4cm in length, was made just below the sternum and into the peritoneal cavity with surgical scissors. The implant was inserted into the cavity and affixed to the muscle wall with polyglycolic acid absorbable

suture. Two smaller incisions, approximately 1 cm in length, were made on the upper left breast and lower right abdomen. One of each of the two ECG leads from the implant were routed subcutaneously to both of the incisions where they were cut to length, electrical insulation was stripped on the last 5 mm, and the bare wire affixed to the muscle with suture. The abdominal cavity and ECG lead sites were irrigated with an antibiotic (amikacin sulfate, brand name Amiglyde-V) and were sutured closed. The birds were removed from anesthesia and placed in an enclosed box on top of a heating pad for 20 minutes to recover. After surgery, subjects were returned to their pen with food and water ad-libitum.

#### Subject Maintenance and Experimental Enclosures

Over the course of the experiment, subjects were housed together in the environmental control room in an uncovered pen of approximately 3 square meters. The pen floor was covered with standard pine shaving litter to a depth of 4cm, changed out twice during the 9 week span the broilers were housed there. Feed was always available, as well as water from a drinking pipe running down the length of the pen. Lights were controlled with a timer on a 12-hour cycle (transition at 7 AM and PM), and experiments were initiated during normal daylight hours. On experiment days, however, the stress inducing temperature profile duration generally exceeded the normal illumination span. When this occurred, the lights were left on until that day's experimentation was concluded.

At the start of each experimental day, the three test subjects were weighed and placed in their respective isolation sections of the wind tunnel in the previously described litter pans containing standard pine shavings to a 3cm depth. Feed of the same type that they were currently consuming on resting days was provided ad-libitum. The three control subjects were also weighed, and placed in cat litter pans of the same size and containing the same amount of

litter as used in the test tunnel. Each pan was placed on top of a telemetry receiver, and three walled enclosures made from cardboard (with plastic mesh on the top and one side to contain the animal) of the same approximate dimensions to the test subject isolation sections of the tunnel was placed over and around the pan and telemetry receiver so that the broiler had access to the drinking pipe that ran the length of the pen in the environmental control room. The control subjects were then placed within, and that day's experimental run began. A Digi-Sense<sup>5</sup> 91090-00 temperature/humidity logger stored room humidity during experiments. As shown in Figure 4.2, room temperature was monitored during experiments by a temperature probe (DSI part #C10T) that fed temperature data into the DSI telemetry logging computer. Photographs of the blower fan, tunnel box, and control subjects containment structures is shown in Figure 4.4.



Figure 4.4: Photographs of poultry experimental assemblies. From left to right: Blower fan and motor generating vacuum flow in tunnel; Tunnel with lid open showing litter bins with telemetry receivers underneath (without watering pipe or feed trays); Two control enclosures showing setup on experimental day with birds in litter bins placed on top of telemetry receivers.

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<sup>5</sup> Digi-Sense is a registered trademark of Cole-Parmer Instrument Co., Vernon Hills, IL 60061 USA

## RESULTS

The seven experimental runs detailed here occurred after several weeks of experimentation and testing. The goal was to characterize both the effectiveness of the controller and the responsiveness of the chicken's DBT to the closed-loop regime. The experimental runs had the following features:

- Three treatment birds were placed in the ventilation tunnel. Two or three birds were placed as controls (variation described in appropriate section).
- The experimental run of May 4 had different group membership than the rest, with the treatment group having 1 male and 2 females, the control group having 3 males. Group membership was established before clear sexually dimorphic traits had developed.
- Membership in each group was realigned after the experimental run of May 4, with new groups having one female each.
- Over the course of the experimental runs all were fed poultry crumble with a manufacturer published minimum of 16% protein and 3% fat ad-libitum.
- In each run, the stressing temperature profile was a square pulse, with the last two runs having two square pulses with a gap between, done to highlight intraday acclimation to heat stress and its effect on the controller.

### Run of May 4

All subjects were 62 days old (9th week), and their weights ranged from 1.7 to 2.4 kg. Feed was removed one hour before the run (8:00) and returned at 9:00 so that the DBT impact of feeding would be synchronized in all subjects, but results show that more time was necessary to generate a more noticeable response. Room temperature profile allowed the chickens to acclimate to their new containment for five hours at 20°C before temperature in the

environmental control room was raised. Room temperature rose to approximately 34°C and remained until the end of the four hour temperature pulse. Temperature was then reduced to approximately 21-22°C. Still early in the process of determining working parameters, several different setpoints for the feedback source DBT were established during the run, thus minimizing the value of an error data plot based on those setpoints. Also, good peak room temperature had not yet been found that impacted their DBT without being so high that the tunnel ventilation equipment was unable to curb the subsequent rise. Figure 4.5 contains three graphs showing the results of this experimental run plotted on the same time axis:

- 4.5.A shows the ambient temperature and humidity;
- 4.5.B plots the air speed;
- 4.5.C shows both the feedback source, in this case treatment #2 (the only male in the treatment group, weighing 2.2 kg), and control group mean DBT response.

#### Run of May 7

All subjects were 65 days old (9th week), and new groups were established different from the previous run with weights of treatments 1, 2 and 3 being 2.7, 2.5 and 2.0 kg respectively, controls 1, 2 and 3 being 2.4, 2.1 and 2.3 kg respectively, with #3 in each group being females. Feed was removed one hour before the run (8:00) and returned at 12:00 so that the impact of feeding on DBT would be synchronized in all subjects. Room temperature profile allowed the chickens to acclimate to their new containment for four hours at 22°C before the temperature in the environmental control room was raised. Due to equipment failure, room temperature rose to approximately 36°C before action could be taken. Once remedied, room temperature settled to 32°C until the end of the five-hour temperature pulse. The temperature was then reduced to approximately 22-23°C.

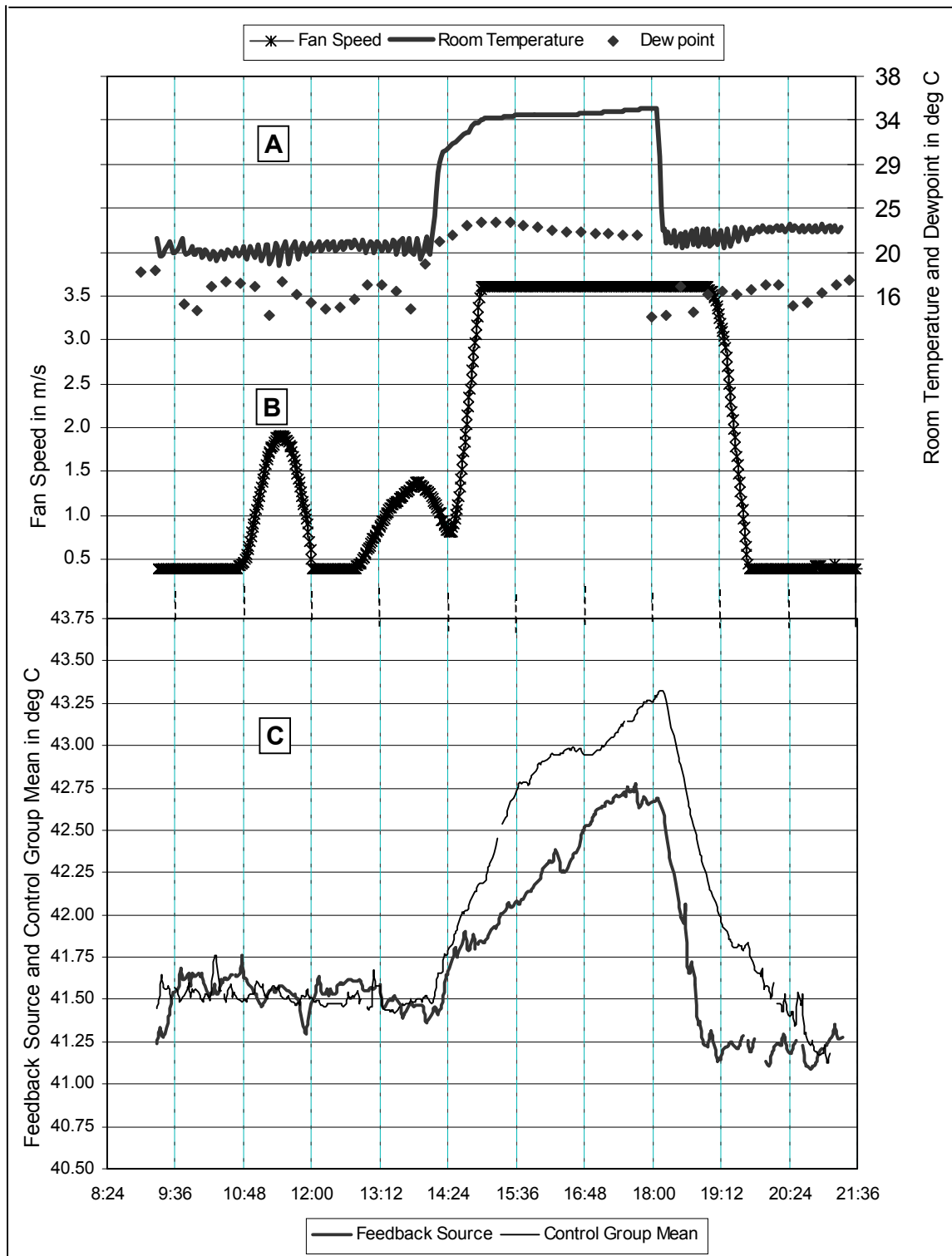


Figure 4.5: Plots of results for run of May 4th. Ambient conditions (A), air speed (B), feedback source and control group mean DBT responses (C).



Treatment bird #1 was the feedback source, and setpoint was initially set at approximately 41.2°C, as that was its DBT at the beginning of the run. However, the bird's DBT rose above this level due to natural variation before the temperature profile had started, causing the closed-loop controller to respond before it was necessary. We increased the setpoint at time 10:30 to approximately 41.3°C, where it remained for the rest of the experimental run. Figure 4.6 contains four graphs showing the results of this experimental run plotted on the same time axis:

- 4.6.A shows the ambient temperature and humidity;
- 4.6.B plots the air speed;
- 4.6.C shows both the feedback source bird and control group mean DBT response;
- 4.6.D shows a graph of the error for treatment bird #1 based on the second established setpoint.

Similar to the run of May 4, room temperature was too high for the controller to curb its rise, although the feedback bird's DBT does appear to come to a homeostasis level after the initial equipment failure period, although at nearly half a degree above setpoint.

#### Run of May 10

All subjects were 68 days old (9th week), with weights of treatments 1, 2 and 3 being 3.1, 2.9 and 2.4 kg respectively, controls 1, 2 and 3 being 2.8, 2.6 and 2.7 kg respectively, with #3 in each group being females. Feed was removed one hour before the run (8:15) and returned at 12:20 so that impact of feeding on DBT would be synchronized in all subjects. Room temperature profile allowed the chickens to acclimate to their new containment for 3.5 hours at 22°C before temperature in the environmental control room was raised. Temperature was raised to approximately 33°C for five hours. It was then reduced to approximately 22-23°C. Treatment bird #1 was the feedback source, and setpoint was initially set at approximately

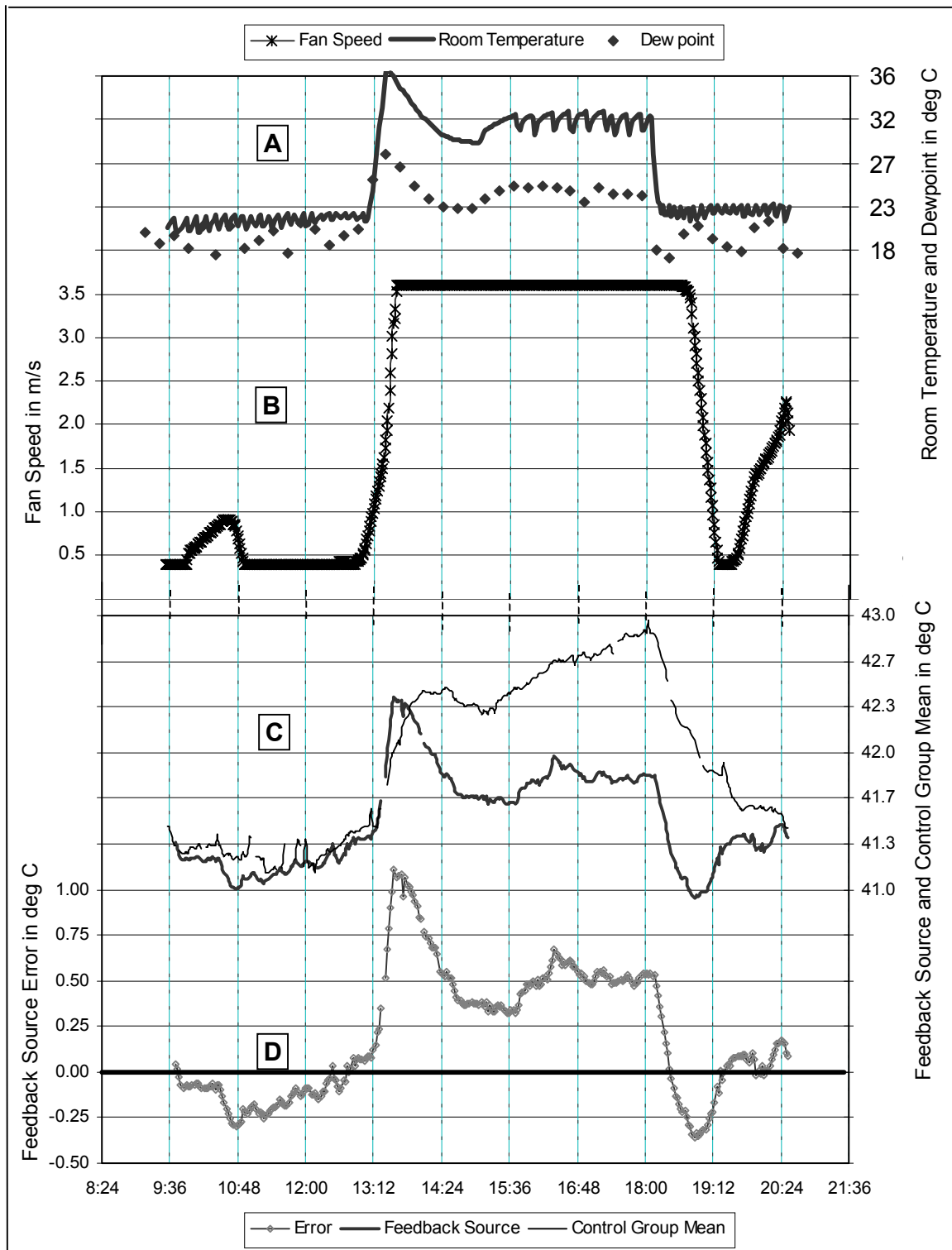


Figure 4.6: Plots of results for run of May 7. Ambient conditions (A), air speed (B), feedback source and control group mean DBT responses (C), and feedback source error (D).

42.1°C, half a degree higher than its initial state at the beginning of the run. This setpoint was established to avoid the problems with setting too low a setpoint initially like in the run of May 7 and improperly causing a premature increase in air speed by the system. Figure 4.7 contains four graphs showing the results of this experimental run plotted on the same time axis:

- 4.7.A shows the ambient temperature and humidity;
- 4.7.B plots the air speed;
- 4.7.C shows both the feedback source bird and control group mean DBT response;
- 4.7.D shows a graph of the error for treatment bird #1 based on the established setpoint.

Even though the error of the feedback bird DBT was sufficient to drive the controller output to saturation, the error was lower than in the previous two experimental runs, suggesting that the changes made to the room temperature target and the initial setpoint for this run were an improvement over the previous two runs.

#### Run of May 13

All subjects were 71 days old (10th week), with weights of treatments 1, 2 and 3 being 3.5, 3.3 and 2.7 kg respectively, controls 1, 2 and 3 being 3.2, 2.8 and 2.8kg respectively, with #3 in each group being females. Feed was removed one hour before the run (8:05) and returned at 11:15 so that the impact of feeding on DBT would be synchronized in all subjects. Room temperature profile allowed the chickens to acclimate to their new containment for four hours at 22° before temperature in the environmental control room was raised to approximately 30°C, ramping up in steps to a maximum of 33.5°C over the course of six hours. At the end of the six hours room temperature was reduced back to approximately 22°C.

At the end of the previous experimental run, a mesh shield on the air intake of the blower fan was impacted with feathers, restricting airflow. Starting with the May 13 experimental run,

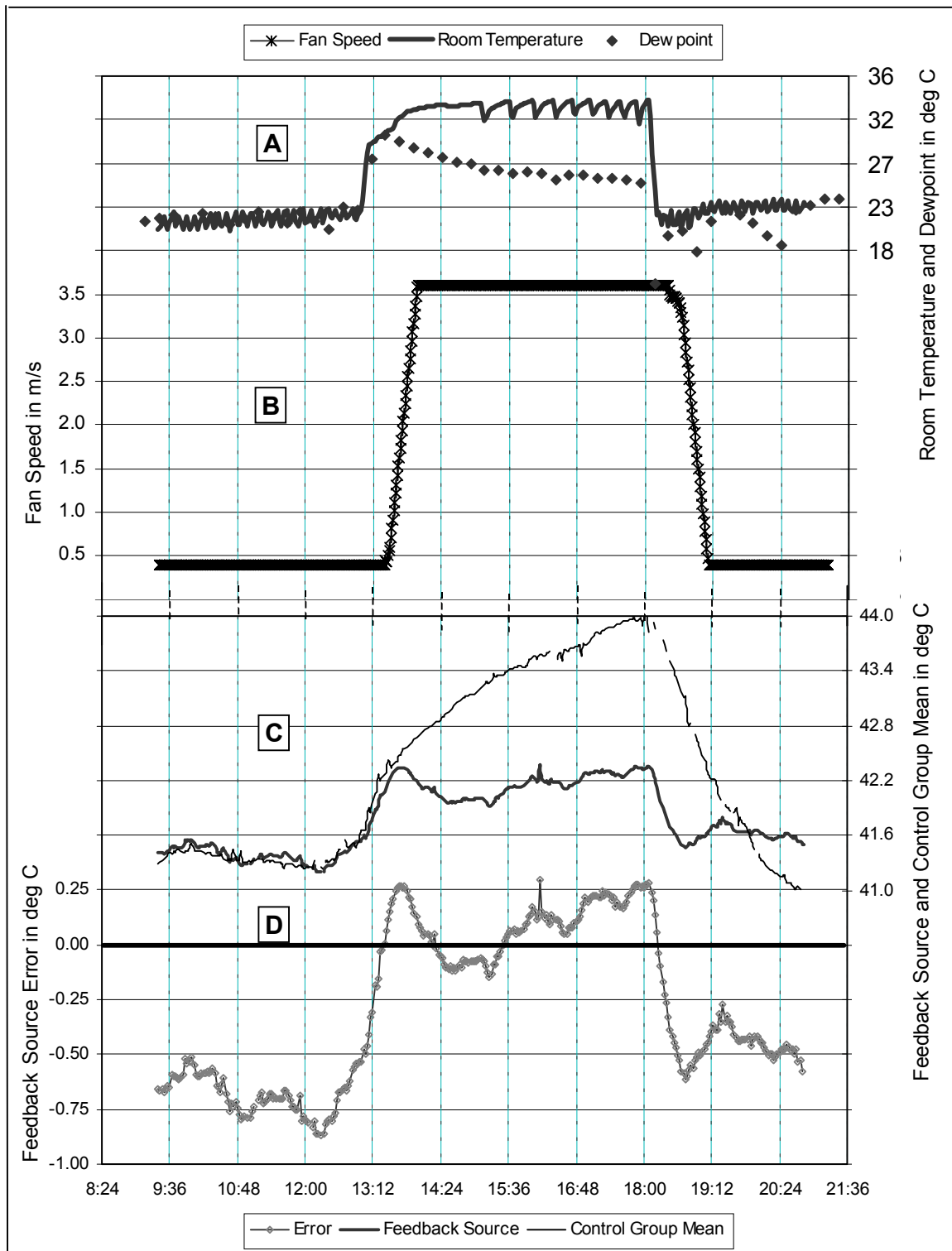


Figure 4.7: Plots of results for run of May 10. Ambient conditions (A), air speed (B), feedback source and control group mean DBT responses (C), and feedback source error (D).

the mesh was removed so accumulation of lost feathers would not interfere with the reliability of the controller to effect airflow.

Treatment bird #1 was the feedback source, and setpoint was set at approximately 41.8°C, half a degree higher than its initial state at the beginning of the run. Figure 4.8 contains four graphs showing the results of this experimental run plotted on the same time axis:

- 4.8.A shows the ambient temperature and humidity;
- 4.8.B plots the air speed;
- 4.8.C shows both the feedback source bird and control group mean DBT response;
- 4.8.D shows a graph of the error for treatment bird #1 based on the established setpoint.

It is important to note the gap in the data for the feedback source bird in Figure 4.8.C starting at 16:05 and lasting approximately 15 minutes. Treatment bird #1 had upset the litter bin within the tunnel enclosure and was no longer within the reliable transmission range for the telemetry system. On a loss of signal, the PLC was configured to assume a temperature of 36°C, a convenient programming number in the context of internal PLC operation. This is what causes the dramatic dip in air speed during that span before the situation was corrected.

#### Run of May 16

All subjects were 74 days old (10th week), with weights of treatments 1, 2 and 3 being 3.8, 3.7 and 3.0 kg respectively, controls 1, 2 and 3 being 3.5, 3.2 and 3.2kg respectively, with #3 in each group being females. Feed was removed one hour before the run (8:05) and returned at 9:10 to somewhat synchronize the impact of feeding on DBT in all subjects, but allow for the longer heating profile planned for the day. Room temperature profile allowed the chickens to acclimate to their new containment for two hours at 22°, again shortened from previous runs to extend the heating portion of the profile. Temperature in the environmental control room was

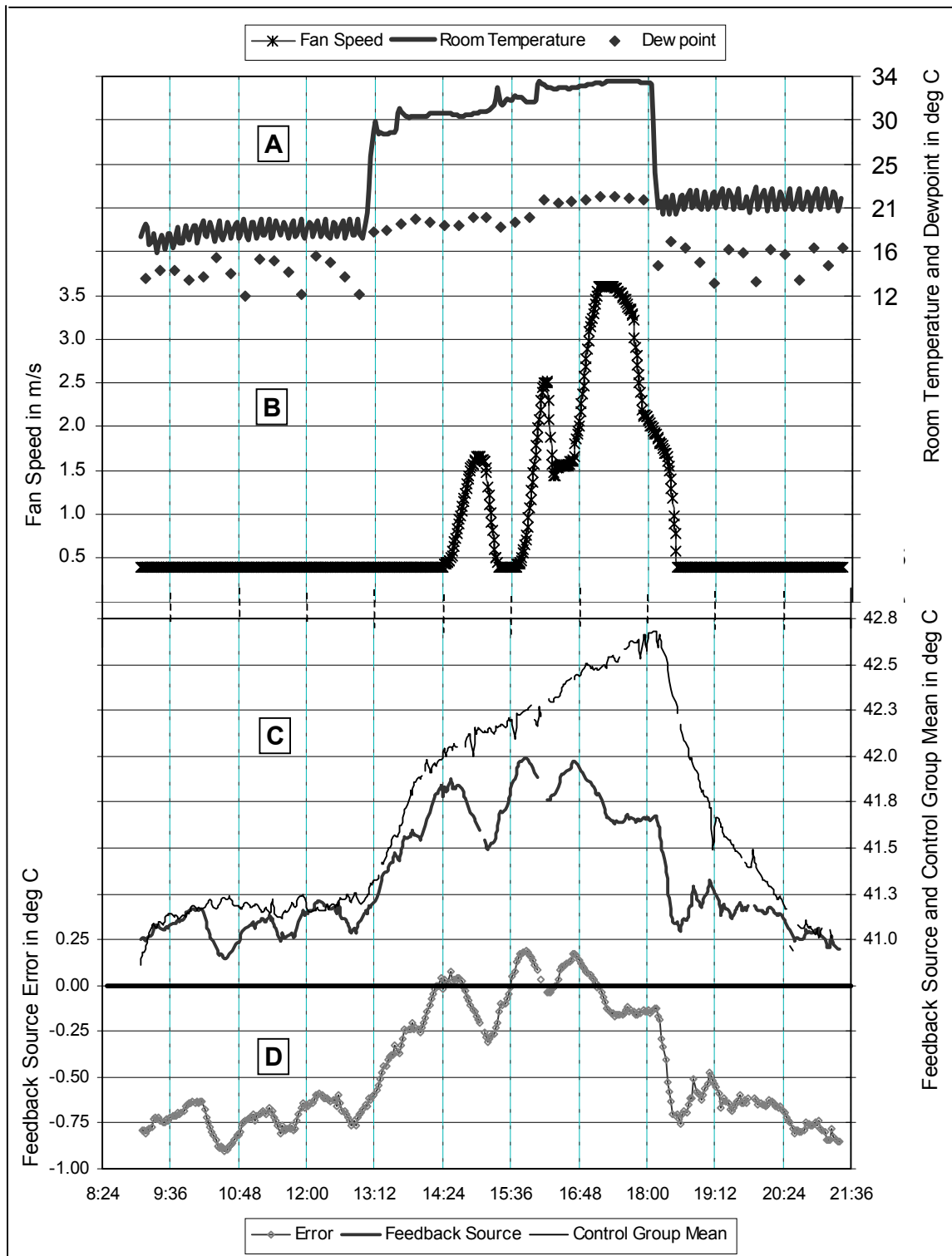


Figure 4.8: Plots of results for run of May 13. Ambient conditions (A), air speed (B), feedback source and control group mean DBT responses (C), and feedback source error (D).

then raised to approximately 32°C for seven hours. At the end of seven hours room temperature was reduced back to approximately 22°C.

The output response of the feedback source (changed to treatment #2 for this run) as seen in the results of the May 13 run (Figure 4.8.B) show the error does not exceed 0.25°C of setpoint. However, the over and undershoot of the error as seen in Figure 4.8.D suggests that the controller was not able to adequately maintain DBT in the stability sense. We chose to address this deficiency by adding a new structure to the existing proportional incremental trim. The new structure would work alongside the original, but would establish preset output levels that would be triggered by increasing error thresholds, or when the feedback bird's DBT dropped below setpoint. The intent was to allow the controller to respond more quickly to error, and thus reduce over and undershoot without increasing instability of the output. The parameters used in this structure for the run of May 16 are shown in Table 4.2.

Table 4.2: Threshold triggered air speeds for run of May 16.

<b>Error Threshold</b>	<b>Threshold Triggered Air Speed</b>
$E_{DBT}$ exceeds 0.05°C	1.3 m/s ( $\cong$ 33% max)
$E_{DBT}$ exceeds 0.25°C	2.5 m/s ( $\cong$ 66% max)
$E_{DBT}$ exceeds 0.35°C	3.0 m/s ( $\cong$ 90% max)

With both controlling structures in place, treatment bird #2 was used as the feedback source, and setpoint was set at approximately 41.8°C. This is the same as the previous experimental run and approximately a quarter of a degree higher than initial treatment #2 DBT at the beginning of the run. The setpoint was closer to the initial feedback source temperature in this run because

treatment #2 had a naturally higher DBT than that of treatment #1. Figure 4.9 contains four graphs showing the results of this experimental run plotted on the same time axis:

- 4.9.A shows the ambient temperature and humidity;
- 4.9.B plots the air speed;
- 4.9.C shows both the feedback source bird and control group mean DBT response;
- 4.9.D shows a graph of the error for treatment bird #2 based on the established setpoint.

The “spike” peaking at time 12:00 occurred due to an equipment failure at time 11:30. As can be seen in the plot of airspeed in Figure 4.9.B, airflow was stopped for those 30 minutes while the failure was remedied. When the fan was restarted at time 12:00, the feedback source DBT was driven below setpoint 75 minutes later at time 13:15. Until the end of the room temperature profile, average DBT for the treatment subjects did not appreciably exceed the range between nominal (41.5°C) and setpoint (41.8°C). This response is in sharp contrast to the control group, which experienced dramatically higher (and in one case fatal) DBT levels over the course of the room temperature profile. The data from the death of control #2 is omitted from the plot in Figure 4.9.C as it inordinately skews the control group mean for the run.

#### Run of May 19

All subjects were 77 days old (11th week), with weights of treatments 1, 2 and 3 being 4.1, 4.0 and 3.2 kg respectively, controls 1 and 3 being 3.9 and 3.3 kg respectively, with #3 in each group being females, and control #2 not included due to his death during the previous experimental run. Feed was removed the night before and returned at the start of data collection at time 9:00. Room temperature profile allowed the chickens to acclimate to their new containment for two hours before temperature in the environmental control room was raised to approximately 31°C and maintained for two hours. Temperature was then dropped to



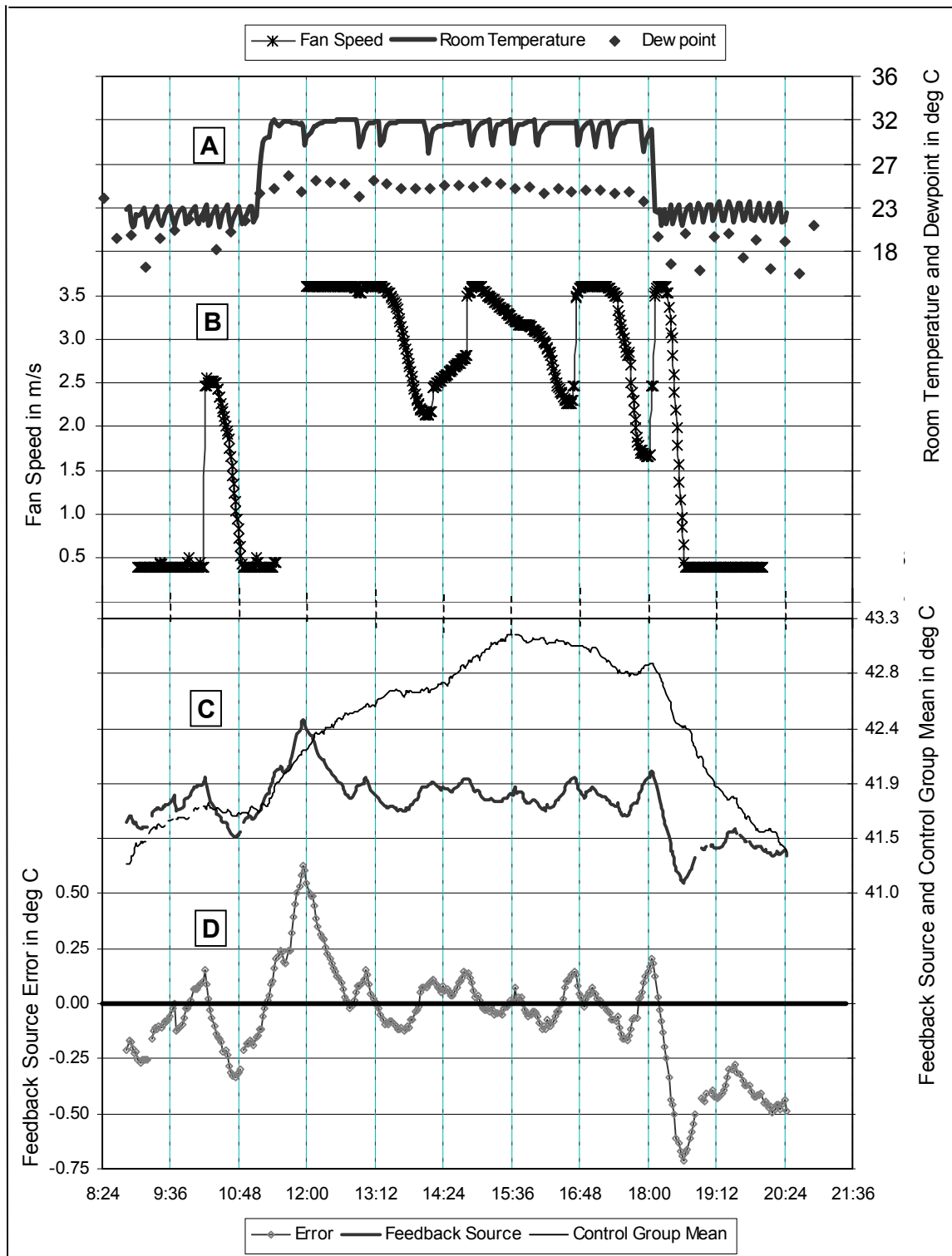


Figure 4.9: Plots of results for run of May 16. Ambient conditions (A), air speed (B), feedback source and control group mean DBT responses (C), and feedback source error (D).

approximately 22°C for three hours, and then raised a second time to 31°C for another two hours. At the end of the second two hours room temperature was reduced back to approximately 22°C.

The output response of the feedback source as seen in the results of the May 16 run (Figure 4.9.B) show an improvement in error over the run of May 13, discounting the period of equipment failure. However, the last cycle of temperature ring experienced by the feedback source DBT shows that the controller response does not reduce the fan speed fast enough to avoid undershoot of setpoint in some circumstances. This undershoot causes the fan speed to drop too low, thus initiating an overshoot. We attempted to further improve the DBT response in this regard by modifying the preset output level triggering structure to include a 15% reduction in current airspeed when the feedback DBT dropped below setpoint. The intent was to "feed forward" the reduction in airspeed to forestall the inevitable undershoot of DBT that occurred when DBT crossed below setpoint. Additionally, the preset levels for positive error were pushed higher for this same reason. The parameters used for the error threshold preset airspeed structure for the run of May 19 are shown in Table 4.3.

Table 4.3: Threshold triggered air speeds for run of May 19.

<b>Error Threshold</b>	<b>Threshold Triggered Air Speed</b>
$E_{DBT}$ exceeds 0.05°C	1.7 m/s ( $\cong$ 50% max)
$E_{DBT}$ exceeds 0.25°C	2.4 m/s ( $\cong$ 70% max)
$E_{DBT}$ exceeds 0.35°C	3.0 m/s ( $\cong$ 90% max)
$E_{DBT}$ goes below $-0.05^{\circ}\text{C}$	Reduce speed by 15% of current level

With both controlling structures in place, treatment bird #2 was used as the feedback source, and setpoint was set at approximately 41.7°C. We chose to tighten the gap between the initial feedback source DBT and the setpoint (during the run of May 7, while using the same feedback bird the setpoint was 41.8°C) as an attempt to more closely align non-heat exposed and heat exposed responses.

This experimental run had an environmental temperature profile of paired step changes in temperature, established to more closely observe the tendency of the bird's DBT response to change as the heat profile progressed. The controller response to the first temperature pulse was unexpected. It had much more instability in the air speed output and resultant DBT than the run of May 16, possibly due to the changes made in the threshold trigger air speed structure. We chose to address this instability by doubling the trim rates in the original structure for the second ambient temperature pulse. The parameters used in the proportional trimming structure for both temperature pulses is shown in Table 4.4.

Table 4.4: DBT error ranges for establishing trim rates for run of May 19.

<b>Error Ranges</b>	<b>Before 16:00</b>		<b>After 16:00</b>	
	<b>Induced Trim@Rate</b>	<b>Air Speed Trimming Rate</b>	<b>Induced Trim @ Rate</b>	<b>Air Speed Trimming Rate</b>
$E_{DBT} < \pm 0.15^{\circ}\text{C}$	0.025m/s @ 150 sec	$\pm 0.01$ m/s per minute	0.025m/s @ 70sec	$\pm 0.02$ m/s per minute
$\pm 0.15^{\circ}\text{C} \leq E_{DBT} < \pm 0.35^{\circ}\text{C}$	0.025m/s @ 75 sec	$\pm 0.02$ m/s per minute	0.025m/s @ 35 sec	$\pm 0.04$ m/s per minute
$E_{DBT} > \pm 0.35^{\circ}\text{C}$	0.025m/s @ 30 sec	$\pm 0.05$ m/s per minute	0.025m/s @ 15 sec	$\pm 0.1$ m/s per minute
$E_{DBT} > 0.7^{\circ}\text{C}$ (for positive $E_{DBT}$ only)	0.05m/s @ 30 sec	+0.1 m/s per minute	0.05m/s @ 15 sec	+0.2 m/s per minute

Figure 4.10 contains four graphs showing the results of this experimental run plotted on the same time axis:

- 4.10.A shows the ambient temperature and humidity;
- 4.10.B plots the air speed;
- 4.10.C shows both the feedback source bird and control group mean DBT response;
- 4.10.D shows a graph of the error for treatment bird #2 based on the established setpoint.

Inspection of the error plot for this run (Figure 4.10.D) suggests an improvement between the two temperature steps. This change could be attributed to the modifications made to the trimming parameters before the second temperature step, since they allowed the controller to react more quickly to the rising or falling DBT level and thus cut the over and undershoot responses seen during the first temperature step. However, it is important to note that a share of the difference between the response periods could be attributed to physiological acclimation. A lower peak control group mean DBT can be seen during the second temperature step in Figure 4.10.C. We believe that a similar adjustment in response had also occurred in the treatment birds as well, just to lesser extent as they were in air flow and thus less stressed overall.

#### Run of May 31

The interceding days between this run and the one of May 19 were spent investigating the responsiveness of the system during a simulation of the environmental diurnal temperature cycle that poultry in Georgia experience during the early summer months. By this point in the experimental battery, the birds had become adapted to heat stressing conditions after the weeks of experimentation, so they were all able to internally control their DBTs naturally without the interdiction of the closed-loop controller. As a final experiment with these subjects before cull,

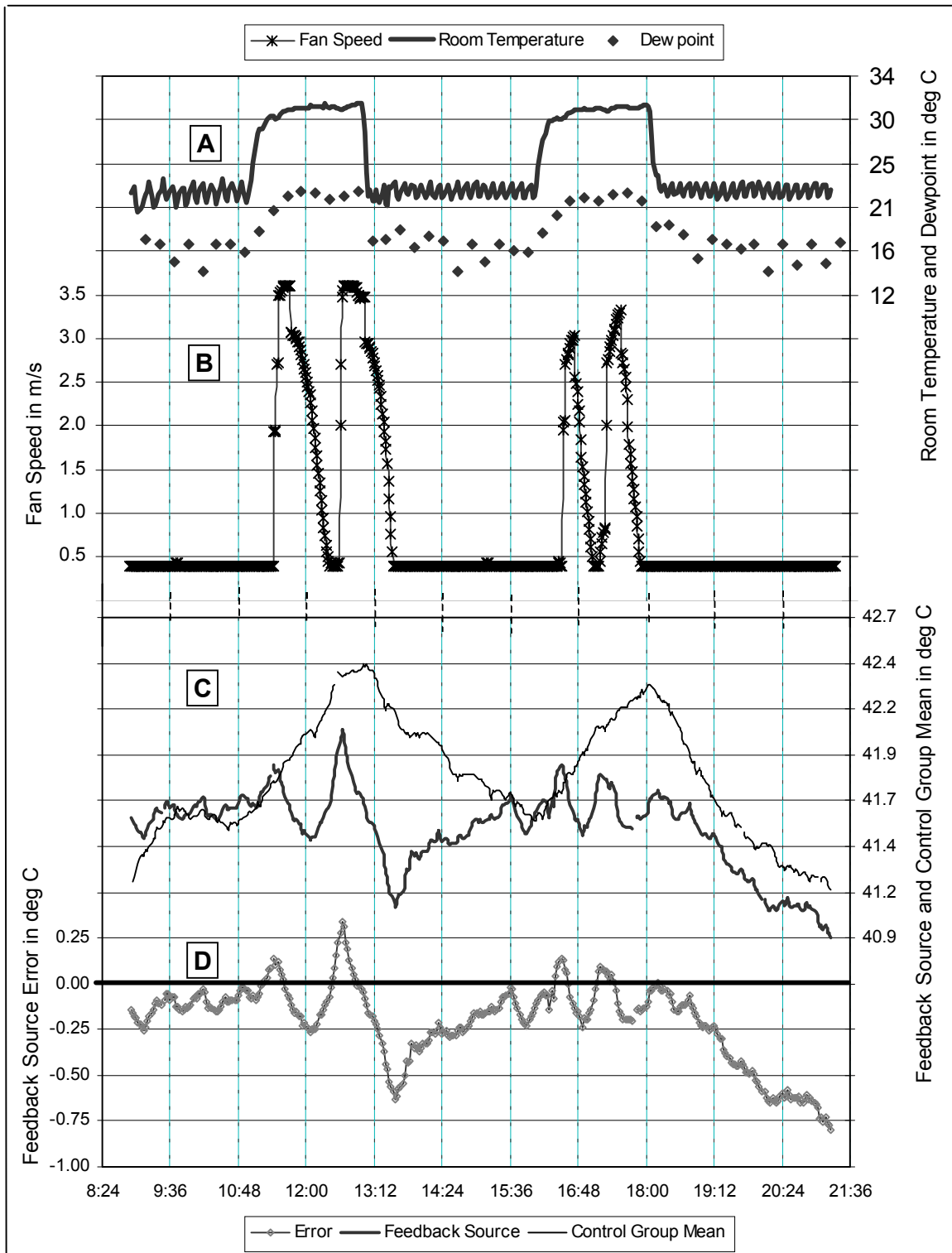


Figure 4.10: Plots of results for run of May 19. Ambient conditions (A), air speed (B), feedback source and control group mean DBT responses (C), and feedback source error (D).

we determined to return to a pulsed step temperature profile for easier comparison to previous results.

For this run, all subjects were 89 days old (12th week), with weights of treatments 1, 2 and 3 being 4.5, 4.4 and 3.9 kg respectively, controls 1 and 3 being 4.6 and 3.7 kg respectively, with #3 in each group being females. Feed was removed the night before and returned at the start of data collection at time 8:30. Room temperature profile allowed the chickens to acclimate to their new containment for two hours before temperature in the environmental control room was raised to approximately 31°C and maintained for two hours. Temperature was then dropped to approximately 22°C for three hours, and then raised a second time to 31°C for another two hours. At the end of the second two hours room temperature was reduced back to approximately 22°C.

The same parameters used for the second temperature step of the experimental run of May 19 were left intact, but the setpoint was decreased to approximately 41.5°C. Still using treatment #2 as the feedback source, we again chose to tighten the gap between his initial DBT and the setpoint (during the run of May 19, while using the same feedback bird the setpoint was 41.7°C) as an attempt to more closely align non-heat exposed and heat exposed responses.

Figure 4.11 contains four graphs showing the results of this experimental run plotted on the same time axis:

- 4.11.A shows the ambient temperature and humidity;
- 4.11.B plots the air speed;
- 4.11.C shows both the feedback source bird and control group mean DBT response;
- 4.11.D shows a graph of the error for treatment bird #2 based on the established setpoint.

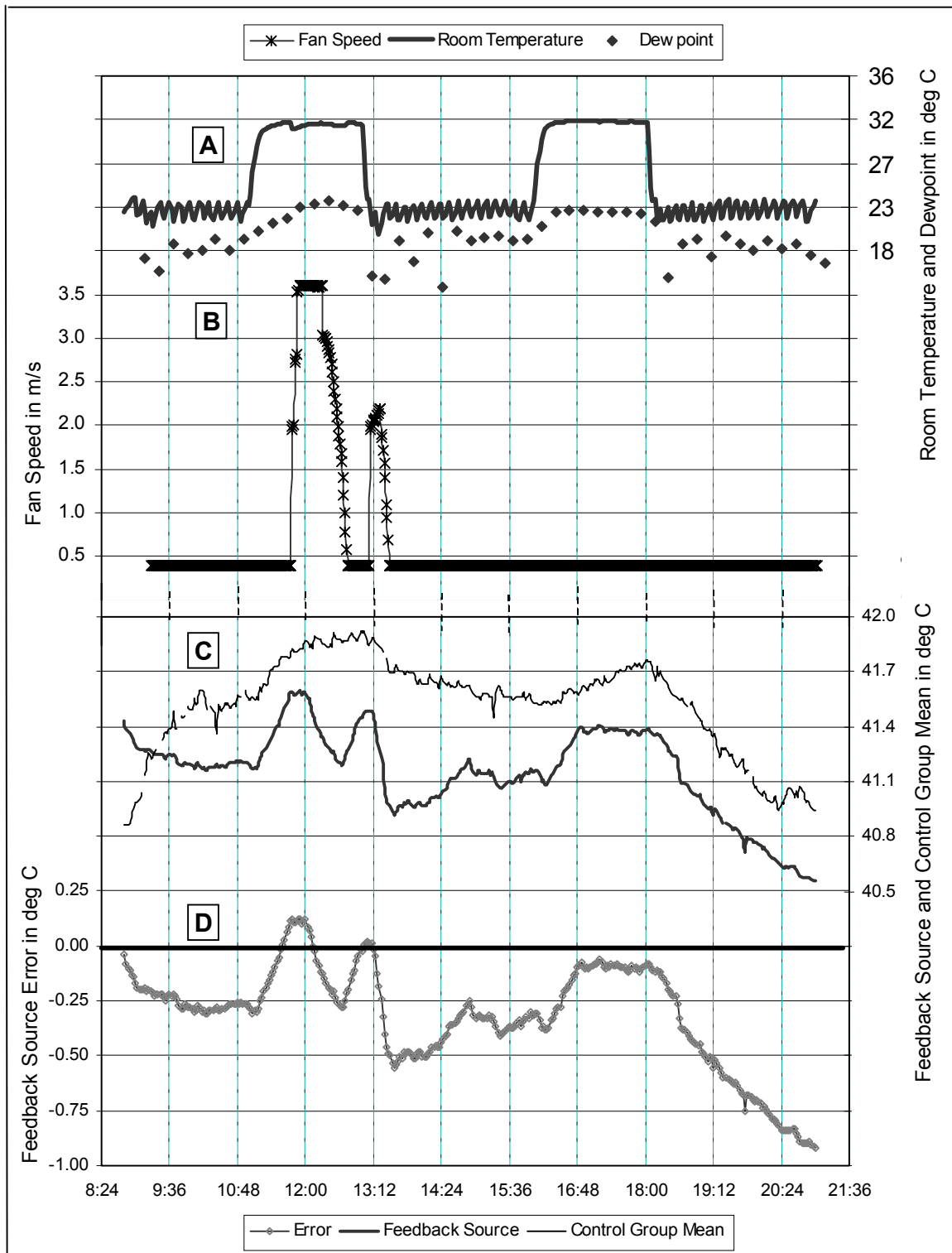


Figure 4.11: Plots of results for run of May 31. Ambient conditions (A), air speed (B), feedback source and control group mean DBT responses (C), and feedback source error (D).

Although environmental temperature and humidity were almost identical between this run and the May 19 run, a significant difference exists between the controller responses. This supports the proposition that the differences between the first and second temperature step in the May 19 run were closely related to the acclimation of the birds, and not the change in controller parameters. This is further supported by the differences between the two temperature steps in this experimental run, with the first temperature pulse impacting the feedback source bird's DBT sufficiently to trigger the controller to respond, while the second pulse did not.

#### Feedback vs. Non-Feedback Response

Although by the end of the runs all birds had acclimated somewhat to the stress stimulus regimen, there was still plainly observable difference between the control and treatment birds DBT responses. What is not reflected in Figures 4.5 through 4.11 is the variation of response within the treatment group, with the amount of variation seeming to be related to which treatment bird was the feedback source. A breakdown of the sample correlation values from the comparison of the DBTs of the two males of the treatment group (after the group realignment of May 4) is shown in Table 4.5.

The difference in sample correlation may be due to other factors as well, such as age, weight, control scheme, or simply random occurrence. The small sample size does not allow for any significant conclusions to be made, but does provide an interesting result for future investigation. Any future commercialization of a closed-loop control system of poultry environments based on DBT will depend on the determination of statistically significant number of birds to represent the flock.



Table 4.5: Sample correlation of male feedback vs. non-feedback sources. The correlations between the feedback and non-feedback sources for the six runs after group realignment show a small difference depending on which bird was the feedback source. May 13 and before, Treatment #1 was feedback source; May 16 and after, Treatment #2 was feedback source.

<b>Experimental Run Date</b>	<b>Feedback vs. Non-Feedback Sample Correlation</b>
May 7	0.922
May 10	0.881
May 13	0.915
May 16	0.584
May 19	0.838
May 31	0.818

## Discussion

Results affirm that DBT is sufficiently effected by both environmental conditions and air speed to use it as a feedback source for closed-loop control schemes. One major drawback to the system used in this research is the dependence on a single broiler for feedback information to the closed-loop control. While the nominal DBT distribution across the broilers possibly caused the non-feedback birds to experience different DBTs than the feedback source birds since the system only attempted to compensate for the single feedback animal, other factors may have had a role as well. Although the control scheme was able to curtail excessive DBT levels in treatment birds, the system was far from optimal. Results highlight the difficulty in finding tuning parameters that provide both a desirable DBT response and a fairly stable air speed output. The quality of the results from using a heuristic approach to determine operational parameters based on subjective observation and experience reflect the danger of using a non-systematic scheme to

control a poorly understood process, in this case poultry DBT. Clearly, future work will need to explore a different approach.

Modern closed-loop industrial control has been dominated by applications relying on various incarnations of the PID algorithm, an example of the basic form being (Dorf, 1989):

$$Output = K_p \times [e(t)] + K_I \times \left[ \int e(t) dt \right] + K_D \times \left[ \frac{de(t)}{dt} \right]$$

where      $K_p$  - proportional gain constant  
              $e(t)$  - error (difference between PV and setpoint)  
              $K_I$  - integral gain constant  
              $K_D$  - derivative gain constant.

Stand alone PID type controllers operate well when maintaining plants that are linear and experience reasonably low order responses to stimuli. However, their performance degrades when the controlled system is non-linear or has a significant higher order response. Problems also occur when the system contains significant time delays between process variable actuation and control variable response. In their work studying poultry heat production, Aerts et.al. (2003) suggest that poultry DBT may not experience a step response higher than second order, but the significant time delays between increased air speed and its impact on DBT as well as the apparent non-linear long term DBT responses (acclimation) that have been observed make clear that a basic PID implementation would be challenging to optimize.

These problems are not limited to our application, and the literature details many approaches to handle these drawbacks to the PID. The difficulty of the time delay between actuation of the control variable and process variable response is quite prevalent in the processing industries, where large batches of product can have inherent delays due to the size of containment vessels and length of connective piping. One method that is gaining interest due to the emergence of digital process controllers was first proposed by Smith (1957) in an analog setting, and has since come to be called the Smith Predictor. Simply, ideal models are created of the controlled process

and its time delay. The feedback loop includes the actual process as normally done, but also has a sub-loop in parallel that contains the process and time delay models. This modeled sub-loop operates concurrently with the real-world process loop, and the result from both branches is weighted, summed and provided to the controller as feedback for the process. The modeling loop "predicts" the effects of the time delay on the actual process, and to some extent it is the ideal model that is being controlled. This obviously has drawbacks, requiring a trade-off between the desire for low error due to time delay and low error due to process disturbances, as well as sensitivity of the system to accuracy in the ideal model. Much literature is devoted to the optimization of the Smith Predictor architecture, but as an ideal model of the process is generally required, implementation of a Smith Predictor or any other model based closed-loop system for the control of poultry DBT is dependant on further work developing such a model.

However, the non-linearity might in fact be due to poultry DBT being an intrinsically non-linear system, in which case other approaches are necessary. Complex, difficult to predict systems can often be better controlled using fuzzy logic, first proposed by Zaheh (1973). A more heuristic approach to logic, the shades of gray between "true" and "false" are given numerical weights. In terms of a control system, the process response determinant variables are measured in this light, and their relative importance in association with each other determines the level of actuation response of the fuzzy controller. This approach closely mimics human, manual control of a process, bringing automation to systems that were previously resistant to control by linear closed-loop methods. Carvajal et.al. (2000) proposed a hybrid fuzzy logic/PID architecture to control non-linear processes, like robotic manipulators, that need the low error afforded by PID without the linearity restrictions that it imposes. A similar approach applied to the control of poultry DBT might have the same benefits.

## CONCLUSION

Although the controller performance was far from optimal, and much work needs to be done to better understand the dynamic responses of poultry DBT, the work presented here shows the feasibility of closed-loop control of poultry tunnel ventilation based on DBT. This variety of telemetry equipment, while showing benefits in a laboratory setting, is an unlikely solution for a system deployed in the field due to transmission distance and crosstalk limitations. However, work limited to the lab will still provide greater understanding of the dynamic response of poultry DBT to environmental stimulus and effective methods in its control. As technology advances and biotelemetry implants become smaller and more energy efficient, it is reasonable to imagine that field deployment of closed-loop control environmental systems based on animal physiology as measured by a radio telemetry system can be instituted. Eventually, the use of direct feedback and closed-loop control in poultry production can lead to more effective and efficient production processes, providing producers the same productivity gains experienced by more technologically advanced industries that have embraced automation.

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## **CHAPTER 5**

### **CONCLUSION**

This research explored applications of radio telemetry in agriculture, since it can be a valuable tool for agricultural production if applied where remote data collection improves and streamlines both human and automated control of processes. Data that was previously difficult or even impossible to acquire can be put to use making real-time decisions on issues that would otherwise be based on guesswork, rules-of-thumb, or inferred through tangential information. The pressure is always on agriculture to reduce costs, improve quality, and increase production, so advances in current production techniques are always sought.

The first objective of this work was the design and assembly of a bench level sensor prototype that could be used as the basis of a low cost field unit for use in monitoring of soil conditions. The completed assembly achieved these ends. As cost was a significant concern, inexpensive mass-produced electronic components and a monolithic RFID integrated circuit were used to minimize system price. Commercially produced radio modems are available for around US\$500, while this system developed around RFID technology was US\$20. The low cost and simplicity of the finished design partially balance the downside of the application's communication range, which is shorter than most commercial radio telemetry systems. With further development using more efficient antennas and streamlining of power requirements, the work presented here could evolve into a highly customizable in-situ soil telemetry system.



The second objective was to determine the feasibility of using radio telemetered poultry DBT as the feedback source in a closed-loop controlled wind tunnel ventilation system. The results of the experimental runs, although not optimized, show that closed-loop control of poultry tunnel ventilation based on DBT is a feasible approach to controlling poultry house environments. We constructed an experimental tunnel ventilation enclosure for housing broilers. Surgically implanted radio telemetry devices measured and transmitted the animals' deep body temperature and provided it to a data logging computer and fan speed control mechanism. Using feedback from a single broiler, the closed-loop controller compensated for sub-nominal body temperatures by raising or lowering the air speed within the tunnel apparatus using simple proportional incremental adjustment schemes.

The radio telemetry applications for agriculture presented in this work show the technical feasibility of the proposed uses of the technology, but much work is yet required to generate field deployable systems. The continuous growth of human populations, as well as the myriad industrial uses for agricultural products, requires continual improvement in production techniques to keep up with the demand. Applying the advances in technology and methodology made in other industries to the practice of agriculture will provide for sufficient growth to meet the needs of the world today and in the future.

## APPENDICES

Appendix A: Radio Telemetry using RFID Bench Level Prototype

Appendix B: PLC Ladder Diagrams

## APPENDIX A

### Radio Telemetry using RFID

#### Bench Level Prototype

- Schematic Diagram of Sensor
- Microcontroller Assembly Code Program Listing
- Photographs of Bench Testing Setup

# Prototype Telemetry Sensor Electrical Schematic Diagram

ec hofacker  
2-13-2003

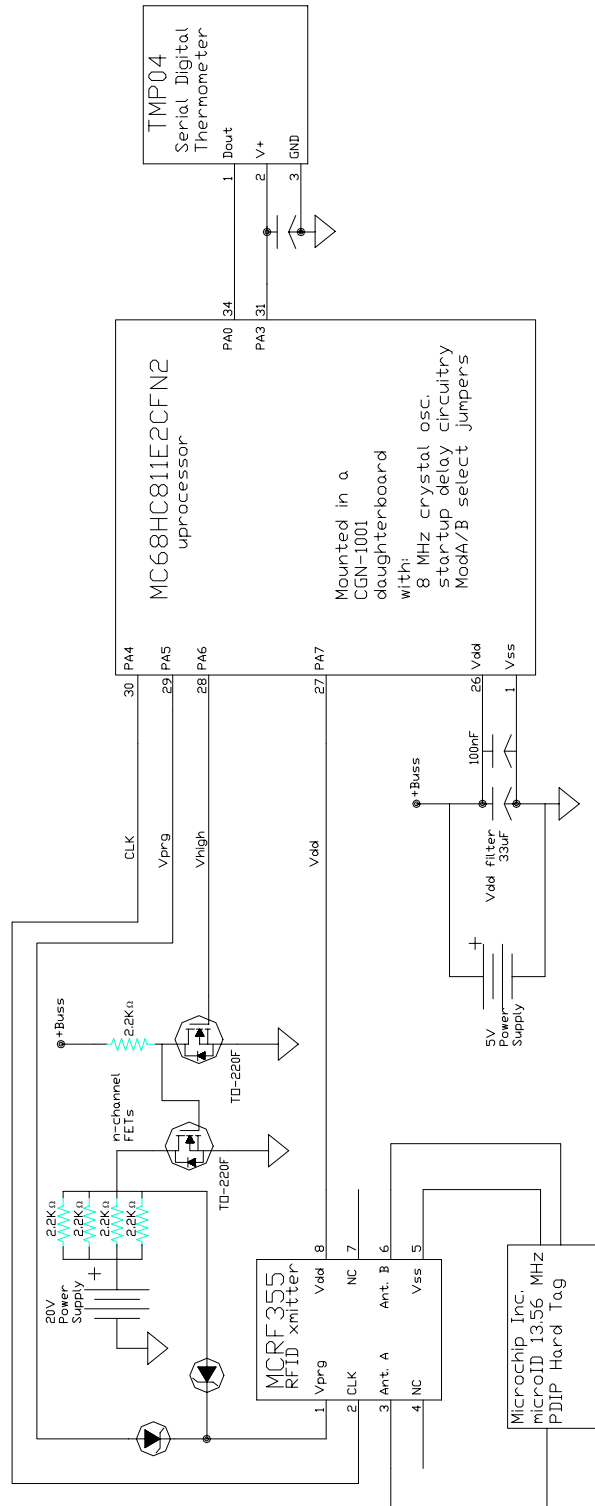


Figure A.1: Telemetry Sensor Schematic

```

*****
*                               Program RFSENSOR                               *
*                               *                                               *
*   By: E Chris Hoffacker                                             *
*   Feb 15, 2003                                                       *
*   *                                                                     *
*   This program was created as a test of concept for                 *
*   use of RFID technology as a radio telemetry channel                *
*   for in-situ agricultural soil sensors. It is run on a             *
*   Motorola HC811E2 microcontroller in stand-alone mode.             *
*   *                                                                     *
*   Temperature data is collected from a PWM generating               *
*   thermometer IC using an STI. The data is averaged and             *
*   collated and written to a MicroChip 13.56 MHz RFID chip*         *
*   using triggered 20Vdc pulses.                                       *
*   *                                                                     *
*   Copyright 2003 - E Chris Hoffacker                                 *
*   *                                                                     *
*   Released for unrestricted use for any academic or                  *
*   non-commercial purpose with inclusion of above                    *
*   copyright notice.                                                  *
*   *                                                                     *
*****

* Compiler Constants

PORTA      EQU      $1000      * Address for Port A
PORTB      EQU      $1004      * Address for Port B

TMSK1      EQU      $1022      * Timer interrupt mask reg 1
TMSK2      EQU      $1024      * Timer interrupt mask reg 2
TIC3       EQU      $1014      * Input capture #3 reg (2bytes)
TFLG1      EQU      $1023      * Input interrupt flags(IC 3,2,1 =bits 0,1,2)
TFLG2      EQU      $1025      * Flags for RTI, pulse accum, timer overflow
TCTL1      EQU      $1020      * Output compare control reg
TCTL2      EQU      $1021      * Input capture control reg (rise, fall)

SCCR2      EQU      $102C      * SCI control register 2, used to set SCI to
                                *   polling mode (no INT)
SPSR       EQU      $1029      * SPI interrupt control register
PACTL      EQU      $1026      * Pulse accumulator control register

INIT       EQU      $103D      * Ram and I/O locations initialization byte addr

*****
*                               Tables                               *
*                               *                                               *
*   Transmission characters that are xfered to RAM at startup.         *
*   First is the permanent sensor number, then update incremener.     *
*   *                                                                     *
*****
      ORG      $FE00

PERMWRITE   FCB      $ED,$00,$00,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$04

```

```

*****
*
*      Variables
*
*****

      ORG    $0000          * Starts RAM at $0000

SENSNUM      RMB    1      * These bytes are the working data locations for
BYTES        RMB    1      *   the sensor number, temperature data and
XNUM         RMB    1      *   iteration count that are written to the RFID.
THEREST      RMB   11
HICHECKSUM   RMB    1      * A two byte checksum is required by the
LOCHECKSUM   RMB    1      *   interrogator to properly read the RFID memory.

      ORG    $0020          * Moves RAM pointer to leave some space for future

CHAR         RMB    1      * Character count for when to determine checksum
TEMP_BYTE    RMB    1      * Holding byte that is shifted for output of bits
BIT_POINTER  RMB    1      * Counter for determining how many bits shifted
CPTRNOW      RMB    2      * Most recent captured timer value (16 bit)
CPTRLAST     RMB    2      * Last captured timer value
FIRSTPOS     RMB    2      * First edge value of PWM signal
MSBTWO       RMB    1      * Most sig byte of T2 - used in temperature calc
LSBTWO       RMB    1      * Least sig byte of T2- used in temperature calc
MSBONE       RMB    1      * Most sig byte of T1- used in temperature calc
LSBONE       RMB    1      * Least sig byte of T1 - used in temperature calc
LOOPCNT      RMB    1      * Loop counter for 255 iterations of temp. meas.
RUN0         RMB    1      * Least sig byte of sum of 255 temp. iterations
RUN1         RMB    1      * Most sig byte of sum of 255 temp. iterations
TEMPX        RMB    2      * Temporary storage for X register

RAM1         EQU    *      * RAM marker for later RMB statements


*****
* THIS ORG IS FOR SOFTWARE SIMULATION OF THE CODE.  IT IS THE IC3 SIMULATOR
* INTERRUPT, ALWAYS CHECK AFTER MAKING PROGRAM EDITS.
*      REMOVE COMMENT '*' TO COMPILE.
*****
*
*      org    $FFEA
*      fcb    $04,$ED
*
*****

```

```

*****
*
*      Main program
*
*      This subroutine contains the main operational loop that the
*      program continually runs through.
*
*****

      ORG    $F800

MAIN:
      LDAA  #$01
      STAA  INIT          * Initialize uP by setting RAM to start at $0000
                          * and I/O to start at $1000
      LDS   #$00FF        * Start the stack at top of RAM
      JSR   INIT_SUB      * Call device initialization subroutine
      NOP

AGAIN  LDAA  PORTA        * Beginning of main operational loop
      ORAA  #$08          * Turn on thermometer power
      STAA  PORTA
      JSR   PROMWAIT
      JSR   PROMWAIT      * Wait 20ms for TMP04 to startup
      LDAA  #$FF
      STAA  LOOPCNT       * Establish temperature averaging count at 255
COLLECTLOOP
      JSR   COLLECT       * Call pulse capture and temper. computation sub
      LDAA  RUN0
      ADDA  BYTES         * Add newest temperature to low byte of total
      STAA  RUN0
      LDAA  RUN1
      ADCA  #$00          * Add any carry bit to high byte. Since 255
      STAA  RUN1          * iterations, need only hi byte for ave at end
      LDAA  LOOPCNT
      BEQ   CLCTLOOP_DONE * Loop run thru 255 iterations?
      DEC   LOOPCNT
      JMP   COLLECTLOOP

CLCTLOOP_DONE
      LDAA  PORTA
      ANDA  #$F7          * Turn off thermometer power when collection done
      STAA  PORTA

      LDAA  RUN1
      STAA  BYTES         * Move high byte of average to RFID writing word
      INC   XNUM          * Increment write count to identify new temp

      CLR   RUN0
      CLR   RUN1

      JSR   XMIT          * Call writing to RFID EEPROM sub

```

```

        LDX    #$0010          * Looped time delay before next temperature sample
PAUSEOUTER
        LDD    #$FFFF
PAUSEINNER
        SUBD   #$01
        BNE    PAUSEINNER
        DEX
        BNE    PAUSEOUTER

        JMP    AGAIN           * Return to beginning of main loop

        JMP    ENDHERE        * Dead end if error

*****
* Subroutine INIT_SUB
*
*   Initializes all operational parameters that must be done early
*   after power up.
*
*****
INIT_SUB:
        LDAA   #$02
        STAA   TMSK2           * Set Timer Prescaler to clock every
                                *   2 microseconds

        LDAA   #$88
        STAA   PACTL           * DDRA bit 7 and bit 3 to output
        LDAA   #$01           * Loads accA with enable for IC3
        STAA   TMSK1           * Enables IC3
                                * Sets config for IC3 capture
                                *   to trigger at rise edge
        STAA   TCTL2

        LDAA   #$00
        STAA   SCCR2           * Disable any SCI interrupts
        STAA   SPSR            * Disable any SPI interrupts
        STAA   TCTL1           * Turn off output compare

        LDAA   #$FF
        STAA   TFLG2           * Clear pulse accum interrupts, RTI, timer
                                *   overflow

        LDX    #$FE00          * Load X and Y with source and destination of
        LDY    #$0000          *   sensor data for run

STARTFILL
        LDAA   0,X             * This loop initializes the working data bytes on
        CMPA   #$04            *   startup with values stored as constants.
        BEQ    FILLDONE        * Kick out if hit end of table
        STAA   0,Y
        INX
        INY
        JMP    STARTFILL

FILLDONE
        RTS

```



```

*****
* Subroutine ONEMILLI
*
*   Delays for 1ms if clock mult is set to 2us
*
*****
ONEMILLI:
    LDAA #$9A          * 154 clks
MSLOOP NOP
    NOP
    NOP
    NOP
    DECA
    BNE MSLOOP        * Kick out if done
    RTS

*****
* Subroutine WRT_WAIT
*
*   Loop for controlling the RFID clk pulse
*   during EEPROM writing sequence. Drops
*   clocking output for trough of RFID clk after
*   time elapses.
*
*****
WRT_WAIT:
    LDD  #$023B        * 4000 x 0.5us =2ms, so 4000/7clks= 571 = $23B
LOOP   SUBD  #$01
    BNE  LOOP
    LDAA PORTA
    ANDA #$EF          * Clear clock pulse
    STAA PORTA
    LDD  #$023B        * 4000 x 0.5us =2ms, so 4000/7clks= 571 = $23B
LOOP2  SUBD  #$01
    BNE  LOOP2
    RTS

*****
* Subroutine PROMWAIT
*
*   Loop for timing the 10ms memory array erase
*
*****
PROMWAIT:
    STX  TEMPX
    LDX  #$0D05        * 20000 x 0.5us =10ms, so 20000/6clks= 3333 = $D05

PROMLOOP
    DEX
    BNE  PROMLOOP
    LDAA PORTA
    ANDA #$BF          * Clears high voltage after TWC time
    STAA PORTA
    LDX  TEMPX
    RTS

```

```

*****
* Subroutine XMIT
*
*   Transmits the data string to the RFID memory array.
*
*****
XMIT:
    CLR    LOCHECKSUM    * Zeros out checksum bytes
    CLR    HICHECKSUM
    CLR    CHAR          * Zeros out xmitted character count

    LDAA   #$80          * Turn on RFID chip for programming
    STAA   PORTA
    JSR    WRT_WAIT

    LDAA   #$D0          * The programming sequence is started by pulsing
    STAA   PORTA          *   the high voltage and the CLK at the same time
                        *   while maintaining Vdd

    JSR    ONEMILLI
    LDAA   #$80          * After the first CLK and hi volt pulse, turn them
                        *   off

    STAA   PORTA
    JSR    ONEMILLI

    LDAA   #$75          * The first 8 bits of 355 programming mode for
    JSR    SENDBYTE      *   erase code, all ten being 0111010100
    LDAA   #$80          * Now send 9th and 10th bits by
    STAA   PORTA          *   clearing out port word, sending CLK twice
    JSR    ONEMILLI
    LDAA   #$90
    STAA   PORTA
    JSR    WRT_WAIT
    LDAA   #$90
    STAA   PORTA
    JSR    WRT_WAIT
    LDAA   #$C0
    STAA   PORTA          * After the EE erase code is given, a high voltage
                        *   is applied for > 10 ms to clear the array

    JSR    PROMWAIT
    LDAA   #$80
    STAA   PORTA          * Turn off high voltage
    JSR    ONEMILLI
    LDAA   #$D0          * The programming sequence is finished by pulsing
    STAA   PORTA          *   the high voltage and the CLK at the same time
    JSR    ONEMILLI
    LDAA   #$80          * After the first CLK and hi volt pulse, turn it
                        *   off

    STAA   PORTA
    LDAA   #$00          * Must turn off 355 before can place in program EE
                        *   mode

    STAA   PORTA
    JSR    WRT_WAIT      * Give RFID time to power down

    LDAA   #$80          * Turn back on VDD
    STAA   PORTA
    JSR    WRT_WAIT      * Wait for stabilize

```

LDAA #\$D0	* The programming sequence is started by pulsing
STAA PORTA	* the high voltage and the CLK at the same time
JSR ONEMILLI	
LDAA #\$80	* After the first CLK and hi volt pulse, turn it
	* off
STAA PORTA	
JSR ONEMILLI	
LDAA #\$74	* The first 8 bits of 355 program EE mode code
JSR SENDBYTE	* Program EE code is 0111010010
LDAA #\$A0	* Now send 9th and 10th bits, first is a 1
STAA PORTA	
JSR ONEMILLI	
LDAA #\$B0	* Need short delay before CLK so VPRG can be
	* registered by RFID
STAA PORTA	
JSR WRT_WAIT	
LDAA #\$80	* 10th bit, a 0
STAA PORTA	
JSR ONEMILLI	
LDAA #\$90	
STAA PORTA	
JSR WRT_WAIT	
LDX #\$0008	* Sets up countdown for header bits
HEAD_WRI	
LDAA #\$90	* Since header is nine ones, and reset of EEPROM
STAA PORTA	* sets array to all ones, need only index memory
	* array pointer 8 times since SPACE subroutine
JSR WRT_WAIT	* adds a CLK pulse at its beginning
DEX	* Counts down header bit loop counter
BNE HEAD_WRI	* Sees if loop is done
JSR SPACE	* Call sub to write space between header and bytes
LDX #SENSNUM	* Set X pointer to xmission array
NEXTCHAR	
LDAA 0,X	
JSR WRITEBYTE	* Call sub to send next byte to RFID chip
JSR SPACE	* Call sub to set space between characters in
	* EEPROM memory array
LDAA CHAR	
CMPA #\$0E	* Sees if all but checksum has been
BHS DN_CHECK	* xmitted - if so, stop checksum calc
LDAA 0,X	* Calculate the 2 byte checksum
ADDA LOCHECKSUM	* First add to low byte
STAA LOCHECKSUM	
LDAA HICHECKSUM	* Then add to high byte
ADCA #\$00	* with carry from low byte sum
STAA HICHECKSUM	
DN_CHECK	
INX	
INC CHAR	* Increment pointer for bytes
LDAA CHAR	
CMPA #\$10	
BNE NEXTCHAR	* Check if done with bytes + checksum
NOP	

```

        LDAA #$D0          * The programming sequence is ended by pulsing
        STAA PORTA        *   the high voltage and the CLK at the same time
        JSR  ONEMILLI
        LDAA #$80          * After the first CLK and hi volt pulse, turn it
                           *   off

        STAA PORTA
        JSR  ONEMILLI
        LDAA #$00          * Turn off 355 Vdd
        STAA PORTA

RTS

*****
* Subroutine SENDBYTE
*
* For sending command words to RFID chip at TTL voltage levels
*
*****

SENDBYTE:
        STAA TEMP_BYTE    * Grab byte to be xmitted
        LDAA #$08         * Set number of bits in byte for counter
        STAA BIT_POINTER  * Assign to variable

NXTBIT LDAA TEMP_BYTE
        LSLA              ** Kick MSB out into carry flag
        STAA TEMP_BYTE    ** Store shifted byte in variable
        BCC  LWBIT        ** Check if kicked out bit was low

        LDAA #$A0
        STAA PORTA        ** If carry flag was high, set xmit bit high
        JMP  BITFIN       ** Jump over LWBIT code

LWBIT  LDAA #$80          ** If carry flag was LOW, set xmit bit LOW
        STAA PORTA        ** Apply LOW xmit bit

BITFIN
        JSR  ONEMILLI
        LDAA PORTA
        ORAA #$10         ** Set CLK mask
        STAA PORTA        ** Apply CLK mask
        JSR  WRT_WAIT     ** Call writing delay subroutine
        DEC  BIT_POINTER  ** Decrement loop for xmit of byte
        BNE  NXTBIT       ** Check if done with byte
        RTS

```

```

*****
* Subroutine WRITEBYTE
*
* Writes bytes of data to the RFID chip by triggering high voltage pulses
* to set EEPROM memory array position to zero
*
*****

WRITEBYTE:
    STAA TEMP_BYTE      * Grab byte to be xmitted
    LDAA #$08           * Set number of bits in byte for counter
    STAA BIT_POINTER    * Assign to variable

NEXTBIT
    LDAA #$90
    STAA PORTA          * Index RFID EEPROM memory array pointer to next
                        * position in byte

    JSR ONEMILLI
    LDAA #$80
    STAA PORTA          * Clear CLK pulse
    JSR ONEMILLI

    LSL TEMP_BYTE       * Kick MSB out into carry flag
    BCC ZEROBIT         * If kicked out bit was low, clear EEPROM position
    JMP BIT_FINISH

ZEROBIT
    LDAA #$C0
    STAA PORTA          * Set high volt xmit write bit high
    JSR PROMWAIT        * Call writing delay subroutine, turn off writing
                        * voltage when done

BIT_FINISH
    JSR WRT_WAIT        * If carry flag was high, do not want to clear
                        * this EEPROM position
    DEC BIT_POINTER     * Decrement loop for xmit of byte
    BNE NEXTBIT        * Check if done with byte

    RTS

```

```

*****
* Subroutine SPACE
*
* Sets a single bit in the RFID EEPROM array to 0
*
*****

SPACE: LDAA #$90
      STAA PORTA          * Index RFID EEPROM memory array pointer to next
                          *   position in memory

      JSR  ONEMILLI
      LDAA #$80
      STAA PORTA          * Clear CLK pulse
      JSR  ONEMILLI
      LDAA #$C0
      STAA PORTA          * Sets currently pointed to RFID EEPROM memory
                          *   array bit to 0
      JSR  PROMWAIT       * Calls eeprom writing wait subroutine, turns off
                          *   high voltage when done

      NOP
      RTS

*****
* Subroutine COLLECT
*
* Waits on the STI to fire and then collects the timer values
* for all edges of the PWM. Since three timer values are necessary to find
* temperature from the PWM, two full PWM cycles are needed to calculate
* temperature. T1 and T2 are defined as the high and low period times.
*
*****

COLLECT:
      LDAA #$00          * Clear out working variables
      LDX  #$0000
      STX  CPTRNOW
      STX  CPTRLAST

* This code finds the first edge of the PWM signal

      LDAA #$01          * Sets config for IC3 capture
      STAA TCTL2          *   to trigger at rise edge
      CLI                * Clear interrupt disable
      WAI                * Wait for interrupt to occur

      LDX  CPTRNOW
      STX  FIRSTPOS

* This code finds the second edge of the PWM, completing T1

      LDAA #$02          * Sets config for IC3 capture
      STAA TCTL2          *   to trigger at next falling edge
      CLI                * Clear interrupt disable
      WAI                * Wait for interrupt to occur

```

```

NOP

* This code finds the last edge of the PWM, completing T2

    LDAA #$01          * Sets config for IC3 capture
    STAA TCTL2         *   to trigger at rise edge
    CLI                * Clear interrupt disable
    WAI                * Wait for interrupt to occur

* Can now find T2 from last two edges

    LDX  CPTRNOW        * Compare current positive edge capture with
    CPX  CPTRLAST       *   the timer value for the previous neg edge
    BCS  SECNDROLL      * Branch if result negative (rollover)
    BRA  SECNDCOMP      * If not negative, branch to difference finding

SECNDROLL
    LDD  $FFFF          * First subtract the previous edge time from $FFFF
    SUBD CPTRLAST
    ADDD CPTRNOW
    STAB LSBTWO
    STAA MSBTWO
    BRA  DNEG_TWO       * Branch to pulse width finish

SECNDCOMP
    LDX  #CPTRNOW
    LDAA 1,X
    LDX  #CPTRLAST
    SUBA 1,X            * Subtracts LS byte of previous value from LS byte
                        *   of current
    STAA LSBTWO         * Stores LSbyte of T2 width
    LDX  #CPTRNOW
    BCC  SECWIDGRTR     * branch if plus
    LDAA 0,X
    DECA
    STAA 0,X

SECWIDGRTR
    LDAA 0,X
    LDX  #CPTRLAST
    SUBA 0,X
    STAA MSBTWO

DNEG_TWO
    NOP

*From the first two edges, can find T1

    LDX  CPTRLAST       * Determine if the new captured value is less or
                        *   greater than the timer value for the previous
                        *   positive edge
    CPX  FIRSTPOS
    BCS  FRSTROLL       * Branch if rollover
    BRA  FRSTCOMP       * If not negative, branch to difference finding

```

```

FRSTROLL
    LDD    $FFFF          * First subtract the previous edge time from $FFFF
    SUBD   FIRSTPOS
    ADDD   CPTRLAST
    STAB   LSBONE         * Store least sig byte of T1
    STAA   MSBONE         * Store most sig byte of T1

    BRA    DNEG_ONE       * Branch to pulse width finish

```

```

FRSTCOMP
    LDX    #CPTRLAST
    LDAA   1,X
    LDX    #FIRSTPOS
    SUBA   1,X            * Subtracts LS byte of previous value from LS byte
                           * of current
    STAA   LSBONE         * Stores LSbyte of T1
    LDX    #CPTRLAST
    BCC    FRSTWIDGRTR    * branch if plus
    LDAA   0,X
    DECA
    STAA   0,X

```

```

FRSTWIDGRTR
    LDAA   0,X
    LDX    #FIRSTPOS
    SUBA   0,X
    STAA   MSBONE

```

\*Can now find the temperature from T1 and T2

```

DNEG_ONE
    JSR    FINDTEMP       * Call sub to calculate temperature from T1 and T2

    RTS

```

```

*****
* Subroutine FINDTEMP
*
* The ratio between T1 and T2 is proportional to the temperature measured by
* the thermometer, and is found from the equation from Analog Devices:
*      235 - 400 *(T1/T2)
* To get 0.1 deg C resolution, will use 2350 and 4000.
*
*****

```

```

FINDTEMP:
    CLR    ACCUM3
    CLR    ACCUM2
    CLR    ACCUM1
    CLR    ACCUM0

```



```

LDX    #$0FA0      * Need to load 4000 ($FA0) into multiplicand so
                    * will have 0.1 resolution

STX     MPD1
LDAA    MSBONE      * Load T1 high and low words
STAA    ACCUM1      *   into the multiplier subroutine memory accum;
LDAA    LSBONE      *   will be changed to FFFF - hlll format in
STAA    ACCUM0      *   subroutine to generate correct answer
JSR     MPY32        * Call multiply subroutine, places product in 4
                    *   accum bytes

LDAA    MSBTWO      * Load T2
STAA    DVSOR1      *   high and low words into divisor variables of
LDAA    LSBTWO      *   DIV32 subroutine, numerator already present
STAA    DVSOR0      *   from mult
JSR     DIV32        * Call division subroutine
LDAA    #$34         * Subtract the above result from 2350 - 250 = 2100
                    *   ( $0834 ) so that the desired range
                    *   (24.5-50.0 degC) will fit in one byte

SUBA    QUOT0
STAA    QUOT0
LDAA    #$08
SBCA    QUOT1
STAA    QUOT1

LDD     QUOT1
SUBD    #$000F
STD     QUOT1

LDAA    QUOT1
BNE     DONETEMP

LDD     QUOT1
CLR     ACCUM3
STAA    ACCUM2
STAB    ACCUM1
CLR     ACCUM0
LDD     #$00E5      * Scale slope to 256/229, gained from
                    *   calibration data

STD     DVSOR1
JSR     DIV32

LDAA    QUOT0
STAA    BYTES
RTS

ORG     $FB20      * Debug, reminds compiler of where it is

DONETEMP
LDAA    #$FF
STAA    BYTES
RTS

```

```

*****
* Interrupt service routine CAPTURE
*
* This subroutine address is listed as the IC3 interrupt response sub.
* It is the TIC3 timer value capture subroutine when the thermometer PWM
* signal has edge transitions, used by the COLLECT sub to find temperature.
*
*****

```

#### CAPTURE:

```

    SEI                      * Sets interrupt disable
    LDX  CPTRNOW             * Moves stored timer value
    STX  CPTRLAST           *   from last capture
    LDX  TIC3                * Loads current interrupt value
    STX  CPTRNOW            * Saves timer value
    LDAA #$01
    STAA TFLG1
    RTI

```

```

PROG1 EQU      *           * Program code address marker

```

```

=====
*
*           1 6   B I T   M A T H   P A C K A G E
*       for the Motorola 6805 family of microprocessors.
*
*           D G Weiss
*           Motorola Inc
*           Microprocessor Group
*           Midrange Strategic Engineering
*           13 Nov 1985
*
* This package features maximum simplicity, with each routine accepting
* operands and leaving results in fixed memory locations.
*
=====

```

```

* Multiply 16 by 16 bit unsigned integer routine

```

```

*   Accepts:
*       Multiplier:    Accum[1..0]
*       Multiplicand:  Mpd[1..0]
*   Yields:
*       Product:       Accum[3..0]
* -----

```

```

    ORG  RAM1
ACCUM3   RMB  1      * Accumulator byte 3 (high order)
ACCUM2   RMB  1
ACCUM1   RMB  1
ACCUM0   RMB  1      * Accumulator byte 0 (low order)
CTR      RMB  1      * Iteration counter
*
PROD3    EQU  #ACCUM3 * Product byte 3 (high order)
PROD2    EQU  #ACCUM2
PROD1    EQU  #ACCUM1
PROD0    EQU  #ACCUM0 * Product byte 0 (low order)

```

```

MPR1      RMB      1      * Multiplier byte 1 (high order)
MPR0      RMB      1      * Multiplier byte 0 (low order)
MPD1      RMB      1      * Multiplicand byte 1 (high order)
MPD0      RMB      1      * Multiplicand byte 0 (low order)
*
RAM2      EQU      *      * RAM marker for later RMBs
*
          ORG      PROG1      * Address to end of last program area in EEPROM

MPY32:
    LDAA  PROD0      * Mpr[1..0] := Prod[1..0]
    COMA
    STAA  MPR0
    LDAA  PROD1
    COMA
    STAA  MPR1
    CLR   PROD0      * Prod[1..0] := 0
    CLR   PROD1
    LDAA  #16         * For ctr := 16 Downto 1 Do
    STAA  CTR

MPY32A
    LDAA  MPR1      * <
    BITA  #$80      * < These lines are additions by ECH,
    BMI   MPY32C    * < BRCLR not a command for HC11

*      BRCLR 7,MPR1,MPY32C * Same function is done in above three lines

    LDAA  PROD0      * Then prod += mpd
    ADDA  MPD0
    STAA  PROD0
    LDAA  PROD1
    ADCA  MPD1
    STAA  PROD1
    LDAA  PROD2
    ADCA  #0
    STAA  PROD2

MPY32C
    DEC   CTR      * If (ctr -= 1) = 0 Then Exit
    BEQ   MPY32E
    ASL   PROD0      * shift prod left
    ROL   PROD1
    ROL   PROD2
    ROL   PROD3
    ASL   MPR0      * shift mpr left
    ROL   MPR1
    BRA   MPY32A

MPY32E  RTS

PROG2  EQU  *      * Marker for future code

```

```

*-----
* Subroutine DIV32
*
* Divide 32 by 16 bit unsigned integer routine
*
*           D G Weiss
*           Motorola Inc
*           Microprocessor Group
*           Midrange Strategic Engineering
*           13 Nov 1985
*
* Accepts:
*   Dividend:      Accum[3..0]
*   Divisor:       Dvsor[1..0]
* Yields:
*   Quotient:      Accum[1..0]
*   Remainder:     Accum[3..2]
*-----
                ORG   RAM2          * get back to RAM area

DVDND3 EQU    #ACCUM3          * Dividend byte 3 (high order)
DVDND2 EQU    #ACCUM2
DVDND1 EQU    #ACCUM1
DVDND0 EQU    #ACCUM0          * Dividend byte 0 (low order)
RMNDR1 EQU    #ACCUM3          * Remainder byte 1 (high order)
RMNDR0 EQU    #ACCUM2          * Remainder byte 0 (low order)
QUOT1 EQU     #ACCUM1          * Quotient byte 1 (high order)
QUOT0 EQU     #ACCUM0          * Quotient byte 0 (low order)
DVSOR1 RMB    1                * Divisor byte 1 (high order)
DVSOR0 RMB    1                * Divisor byte 0 (low order)
*
                ORG   PROG2

DIV32: LDAA   #16                * For Ctr := 16 Downto 1 do
      STA    CTR

DIV32A LDAA   DVDND3            * shift dividend left one place
      ROLA
      ROL    DVDND0
      ROL    DVDND1
      ROL    DVDND2
      ROL    DVDND3

      LDAA   DVDND2            * subtract divisor from remainder
      SUBA   DVSOR0
      STAA   DVDND2
      LDAA   DVDND3
      SBCA   DVSOR1
      STAA   DVDND3
      LDAA   DVDND0            * {dividend low bit holds subtract carry}
      SBCA   #0
      STAA   DVDND0

      LDAA   DVDND0            *< Lines added by ECH
      ANDA   #$01              *< as replacement for BRCLR
      BEQ    DIV32C            *< below

```

```

*      BRCLR 0,DVDND0,DIV32C    *if subtract carry = 1

      LDAA DVDND2                * Then add divisor back in
      ADDA DVSOR0
      STAA DVDND2
      LDAA DVDND3
      ADCA DVSOR1
      STAA DVDND3
      LDAA DVDND0
      ADCA #0
      STAA DVDND0
      BRA  DIV32D

DIV32C
*      BSET  0,DVDND0            * Else set hi bit := 1

      LDAA DVDND0                *< Added by ECH as replacement for BSET above
      ORAA #$01                  *<
      STAA DVDND0                *<

DIV32D DEC   CTR
      BNE   DIV32A
      RTS

*****
* Interrupt subroutine WRONG_INT
*
* If non-planned interrupt fires, this sub handles it
*
*****

WRONG_INT:
      LDAA #$00
      STAA SCCR2 * Disable any SCI interrupts
      STAA SPSR  * Disable any SPI interrupts
      STAA TCTL1 * Turn off output compare
      LDAA #$FF
      STAA TFLG2 * Clear pulse accum interrupts, RTI, timer overflow

      RTI

ENDHERE                * End of code if things go wacky
      NOP
      END

```

```

*****
* Interrupt vectors, most are set to the erroneous interrupt subroutine,
*   WRONG_INT
*****

```

```

                                ORG      $FFD6

FDB    WRONG_INT    * SCI serial interrupts
FDB    WRONG_INT    * SPI serial xfer complete
FDB    WRONG_INT    * Pulse Accum input edge
FDB    WRONG_INT    * Pulse Accum Overflow
FDB    WRONG_INT    * Timer Overflow
FDB    WRONG_INT    * Timer input capture 4 / output cmp 5
FDB    WRONG_INT    * Timer output cmp 4
FDB    WRONG_INT    * Timer output cmp 3
FDB    WRONG_INT    * Timer output cmp 2
FDB    WRONG_INT    * Timer output cmp 1
FDB    CAPTURE      * Timer input capture 3
FDB    WRONG_INT    * Timer input capture 2
FDB    WRONG_INT    * Timer input capture 1
FDB    WRONG_INT    * Real Time interrupt
FDB    WRONG_INT    * External IRQ pin
FDB    WRONG_INT    * External XIRQ pin, sets X in CCR
FDB    WRONG_INT    * Software interrupt
FDB    WRONG_INT    * Illegal Opcode trap
FDB    MAIN          * COP watchdog
FDB    WRONG_INT    * Clock monitor fail
FDB    MAIN          * External RESET pin or POR

```

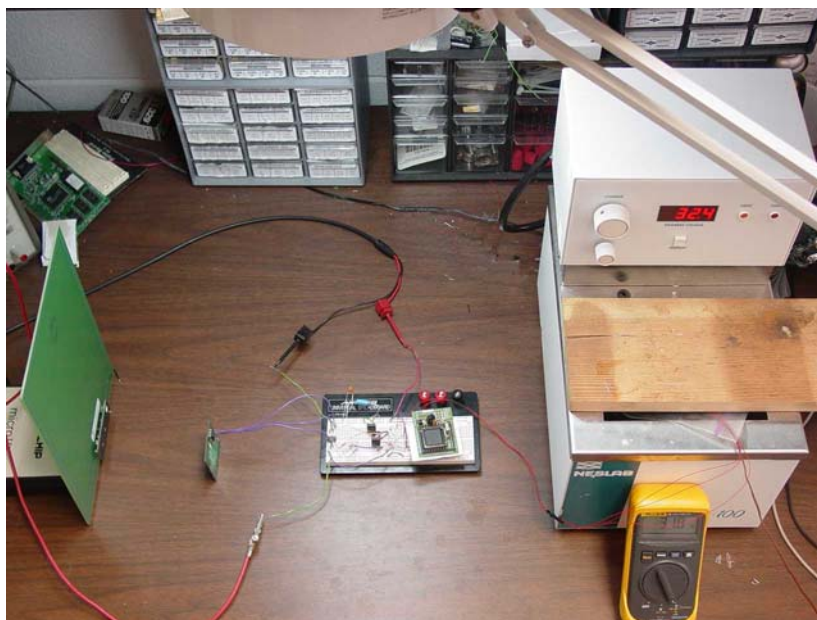


Figure A.2: Photograph of Benchtop Setup Overview - from left to right, interrogator, sensor antenna, breadboard with microcontroller, temperature controlled water bath with thermometer submerged in protective bag.

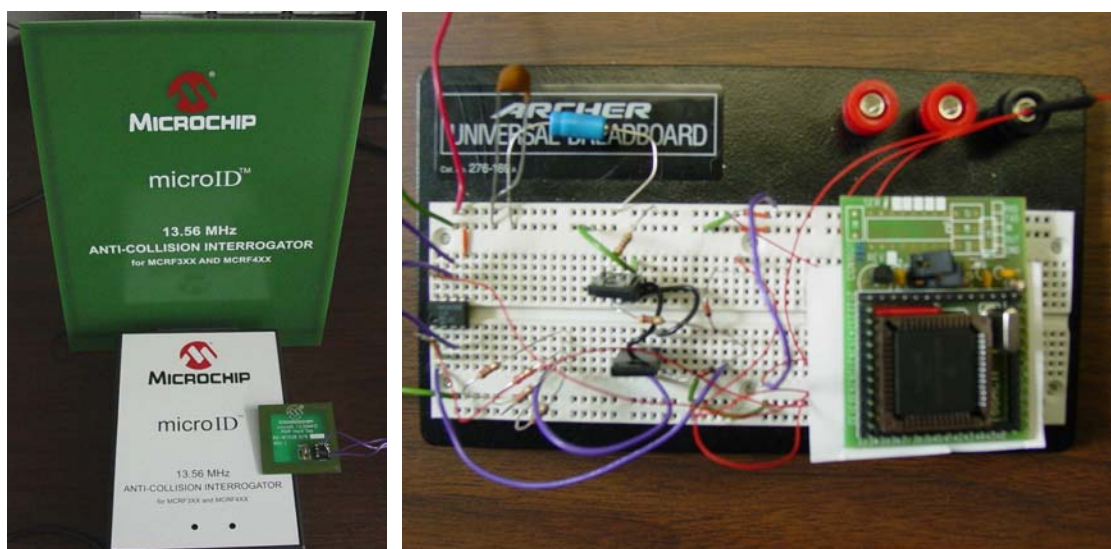


Figure A.3: Photographs of Close-up Views. Left to right - Interrogator and sensor antenna, breadboard with sensor components.

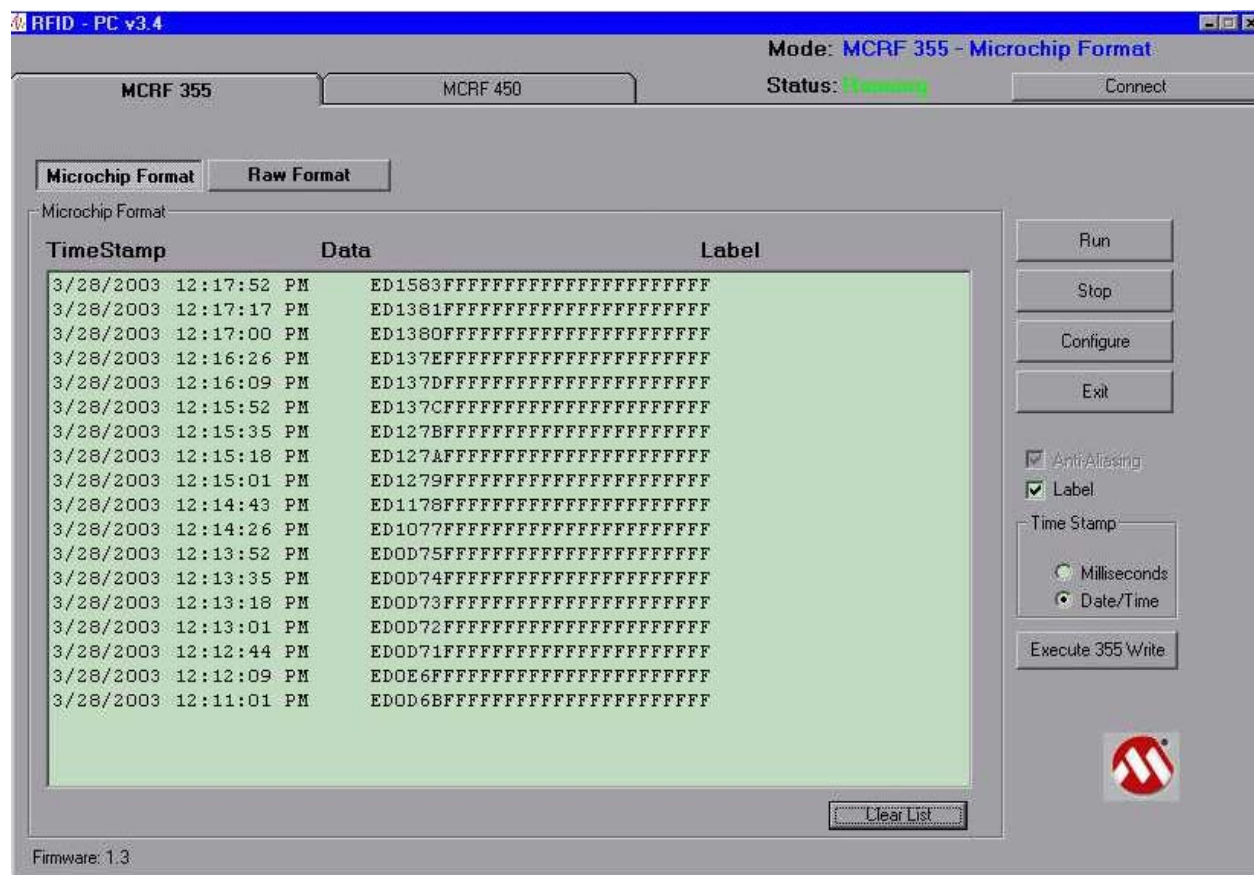


Figure A.4: Screen Capture of MicroChip© RFID Interrogator PC Communication Software



## APPENDIX B

### PLC Ladder Diagrams

- PLC Program for May 4, May7, May 10, and May 13
- PLC Program for May 16
- PLC Program for May 19 and May 31

PLC Program for May 4 - May 13

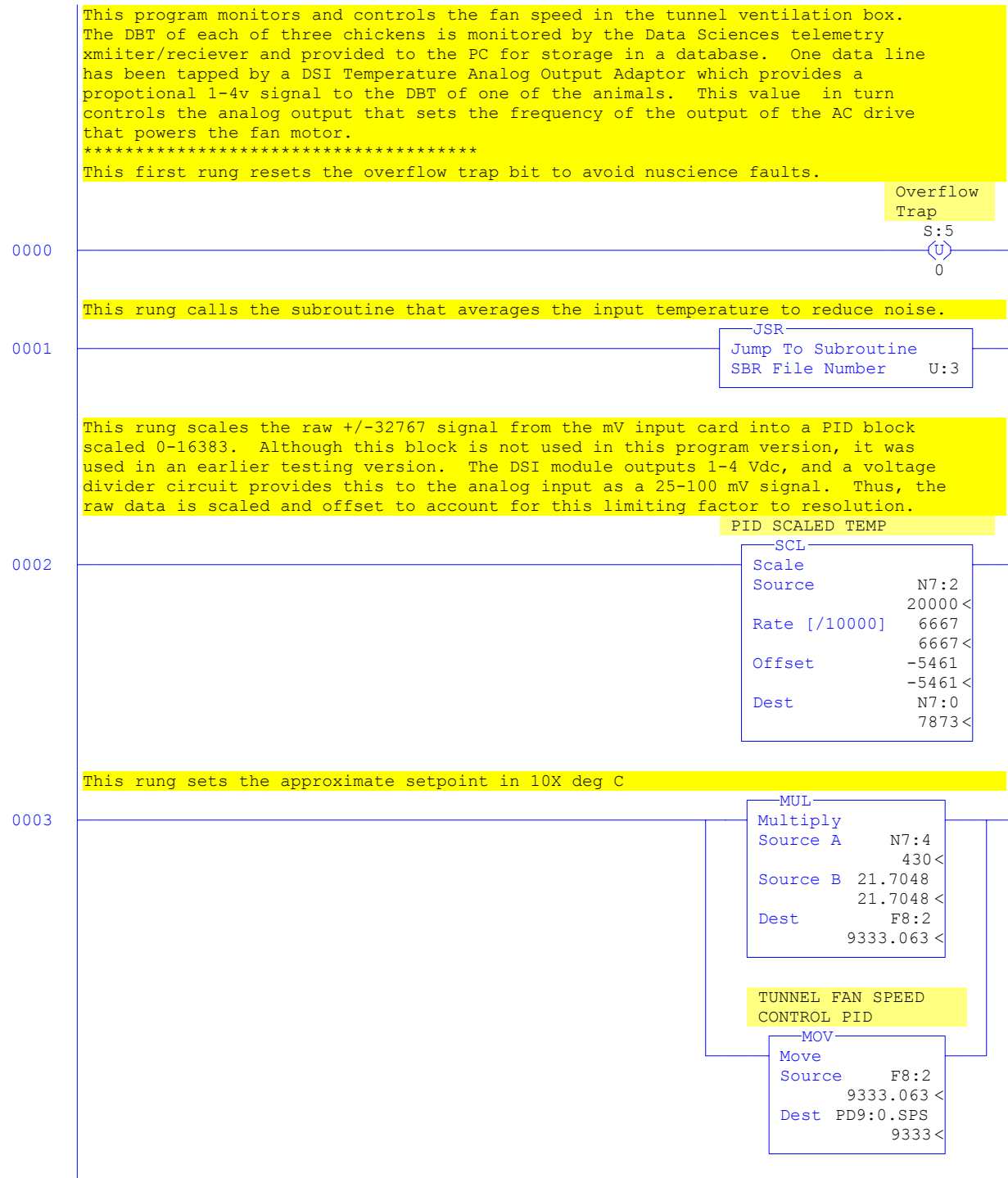
Program File List

---

Name	Number	Type	Rungs	Debug	Bytes
[SYSTEM]	0	SYS	0	No	0
	1	SYS	0	No	0
MAIN_PROG	2	LADDER	10	No	552
INPUT_INT	3	LADDER	7	No	659

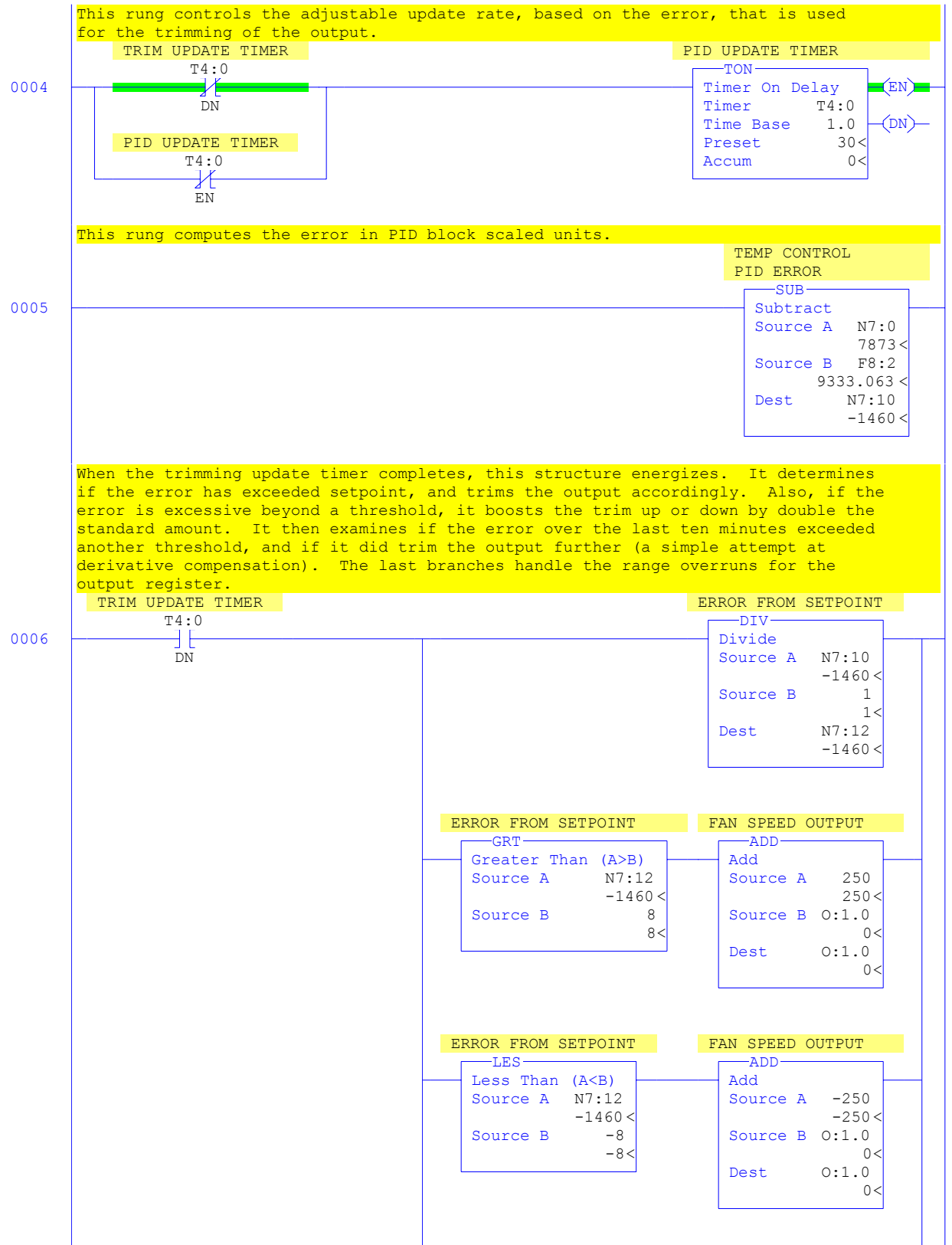
## PLC Program for May 4 - May 13

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10



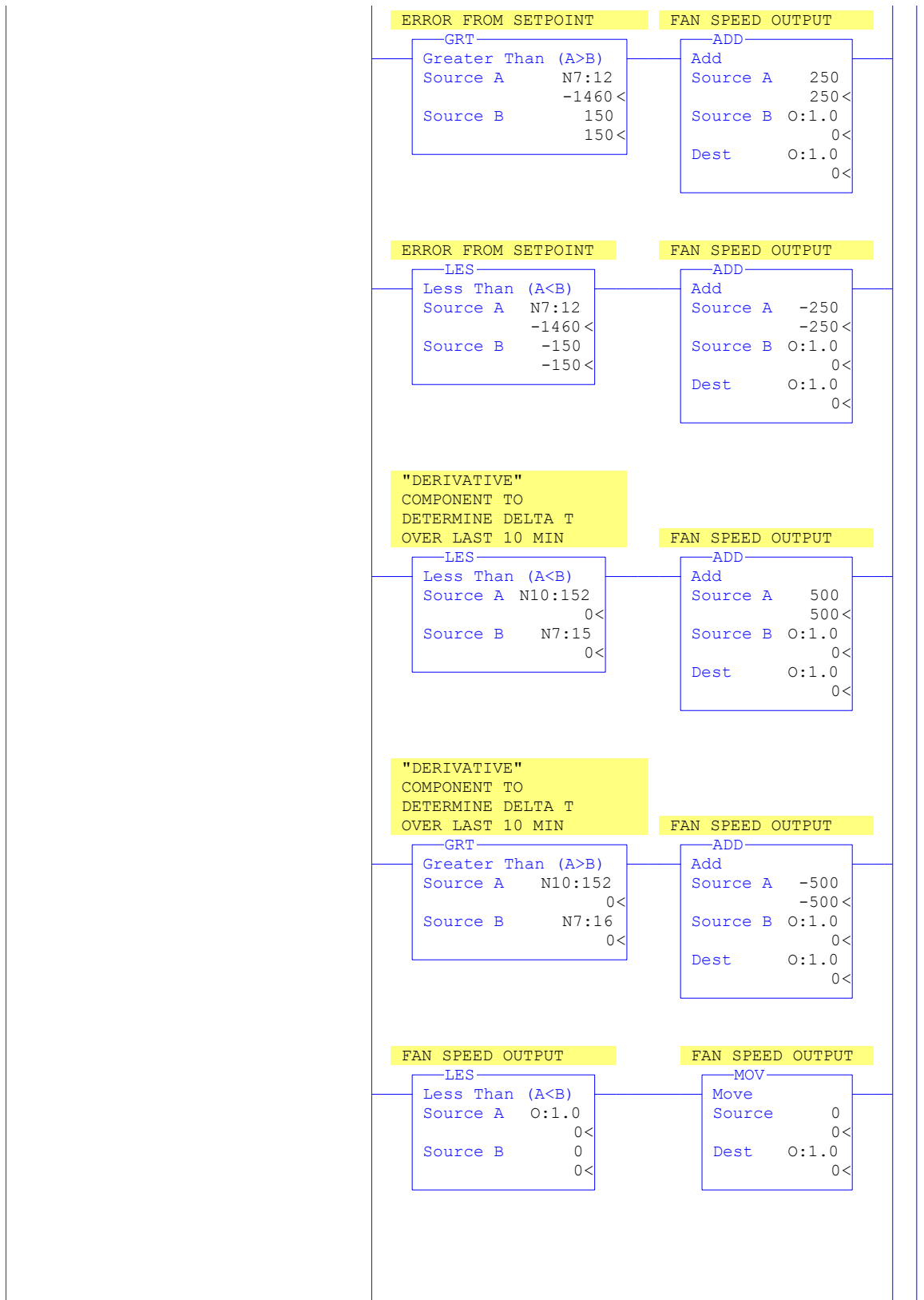
# PLC Program for May 4 - May 13

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10



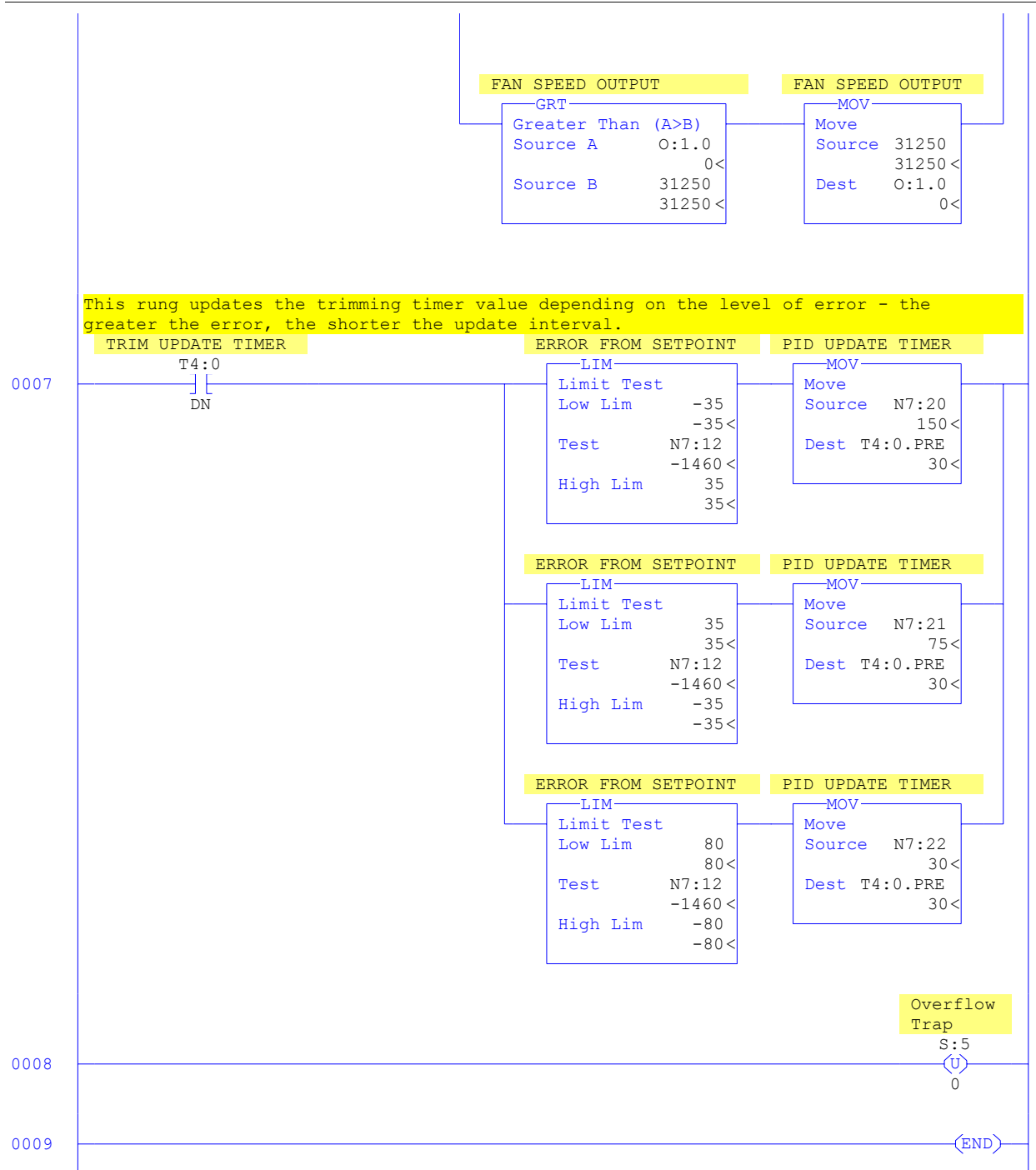
# PLC Program for May 4 - May 13

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10



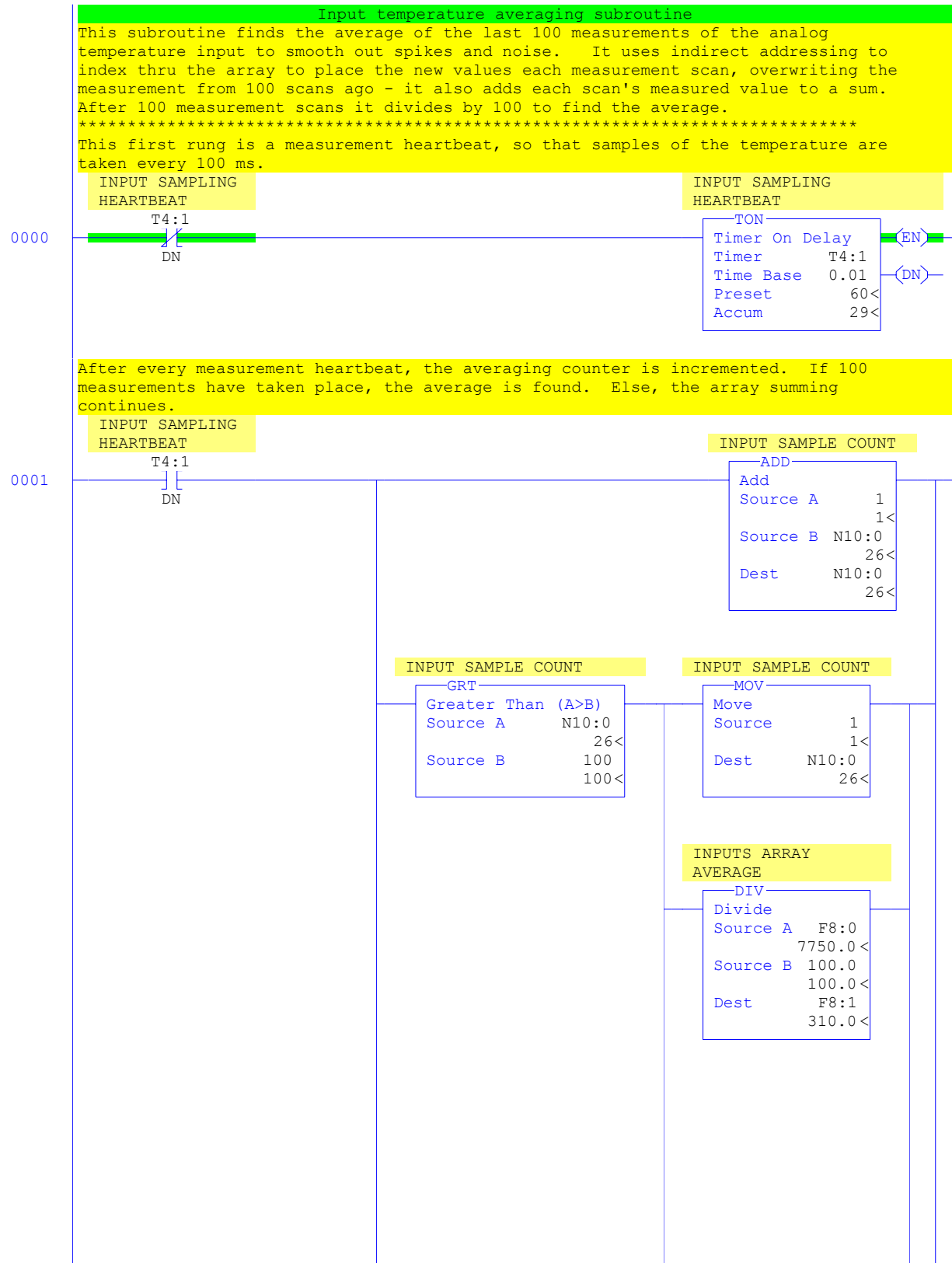
# PLC Program for May 4 - May 13

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10



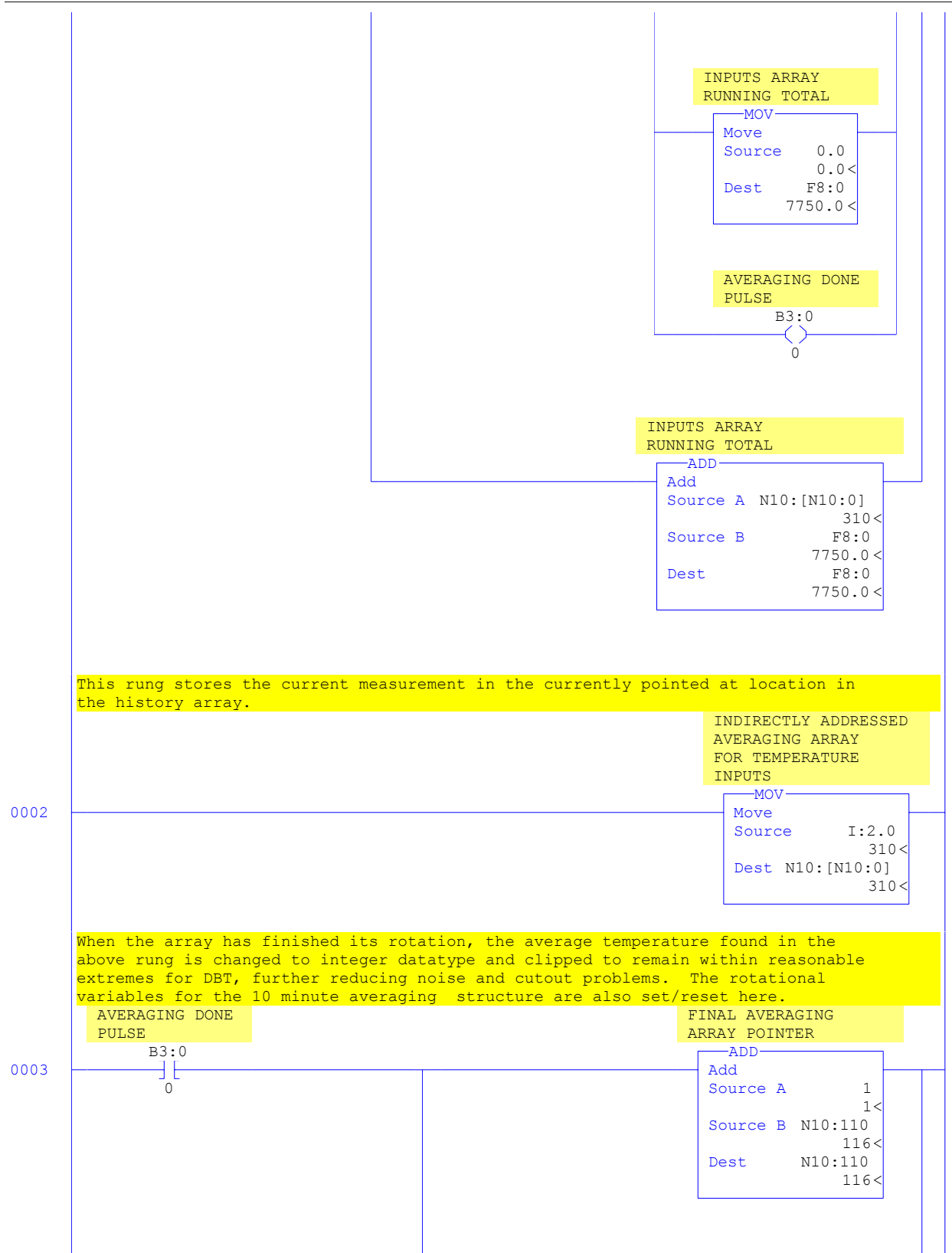
# PLC Program for May 4 - May 13

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



# PLC Program for May 4 - May 13

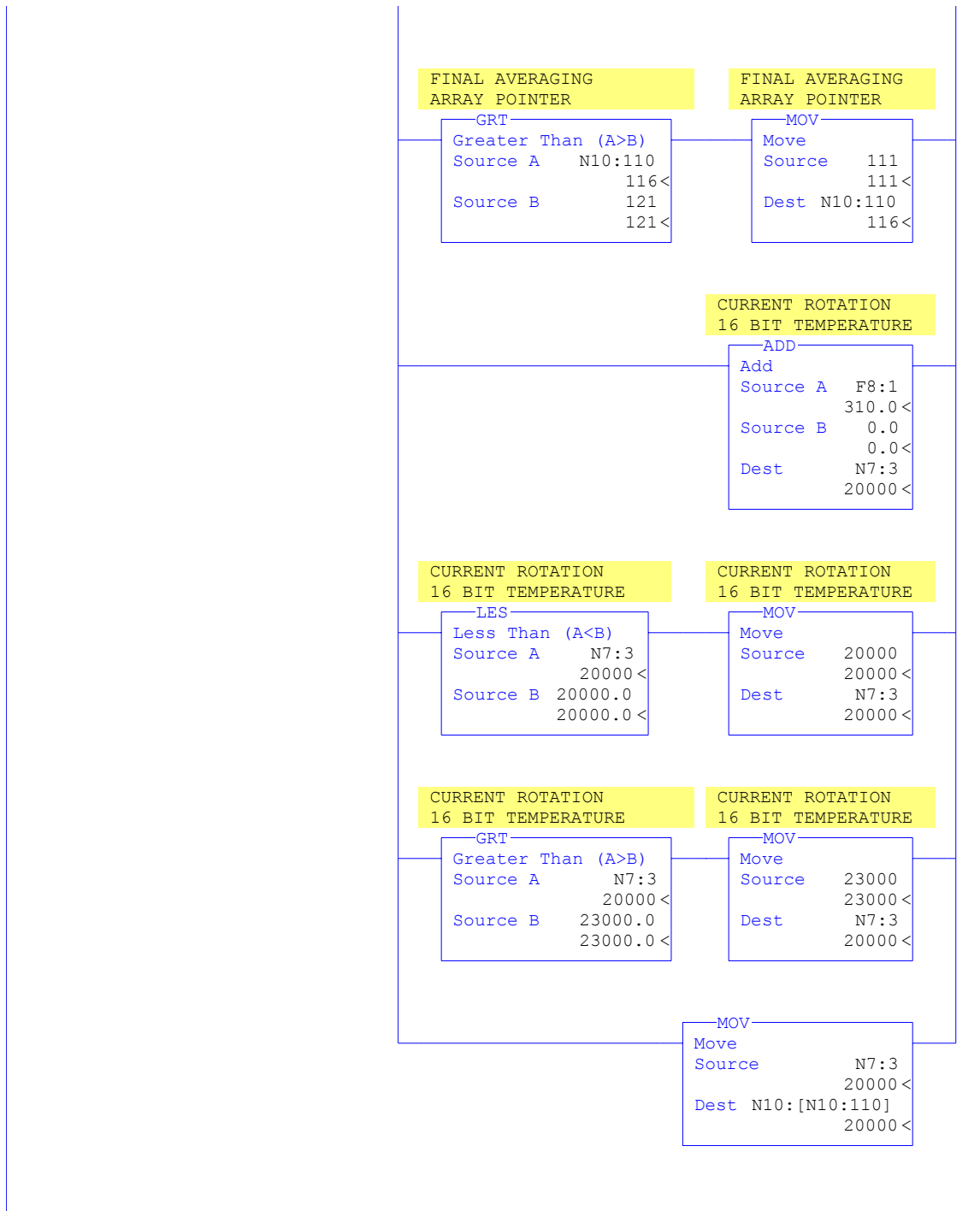
LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7





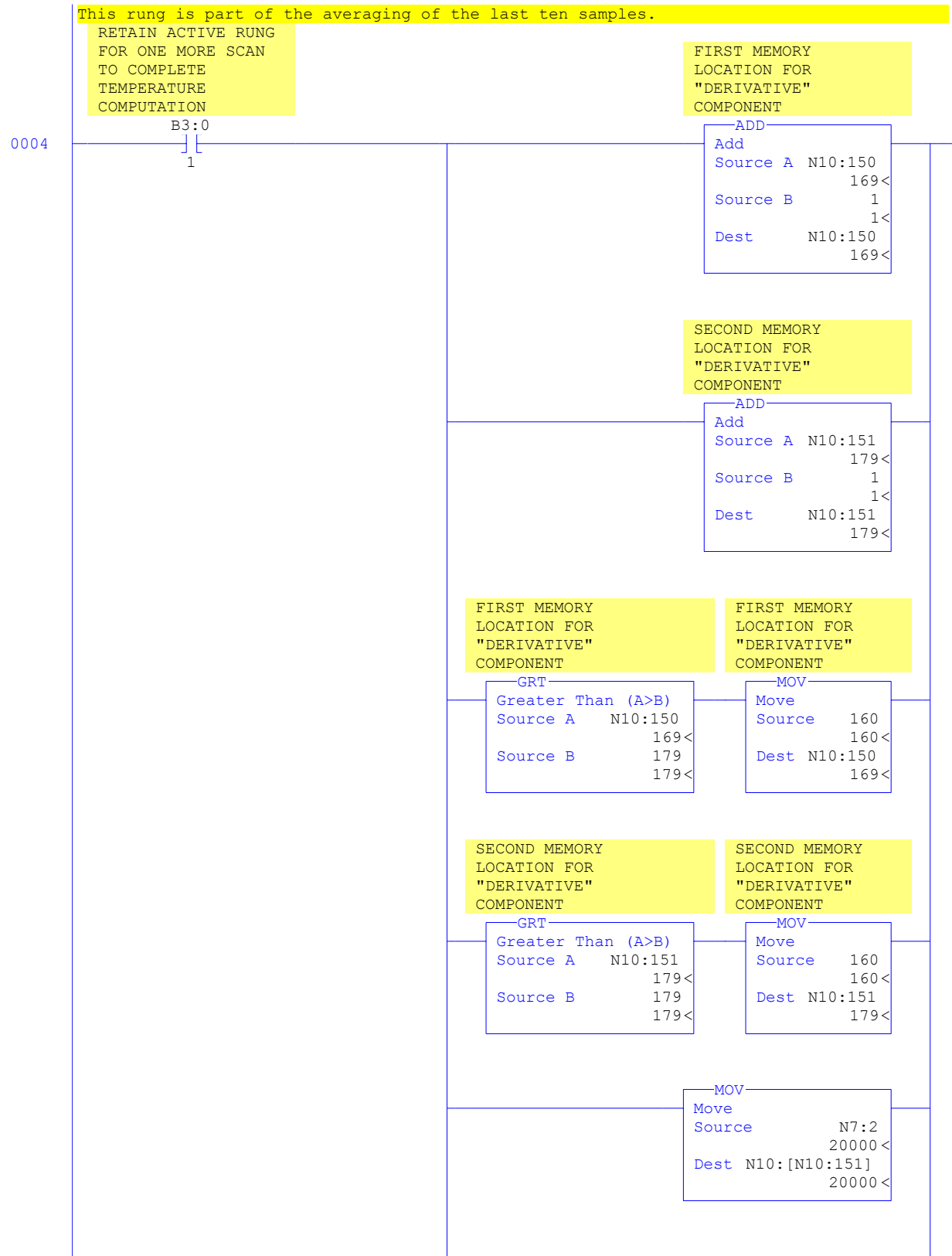
# PLC Program for May 4 - May 13

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



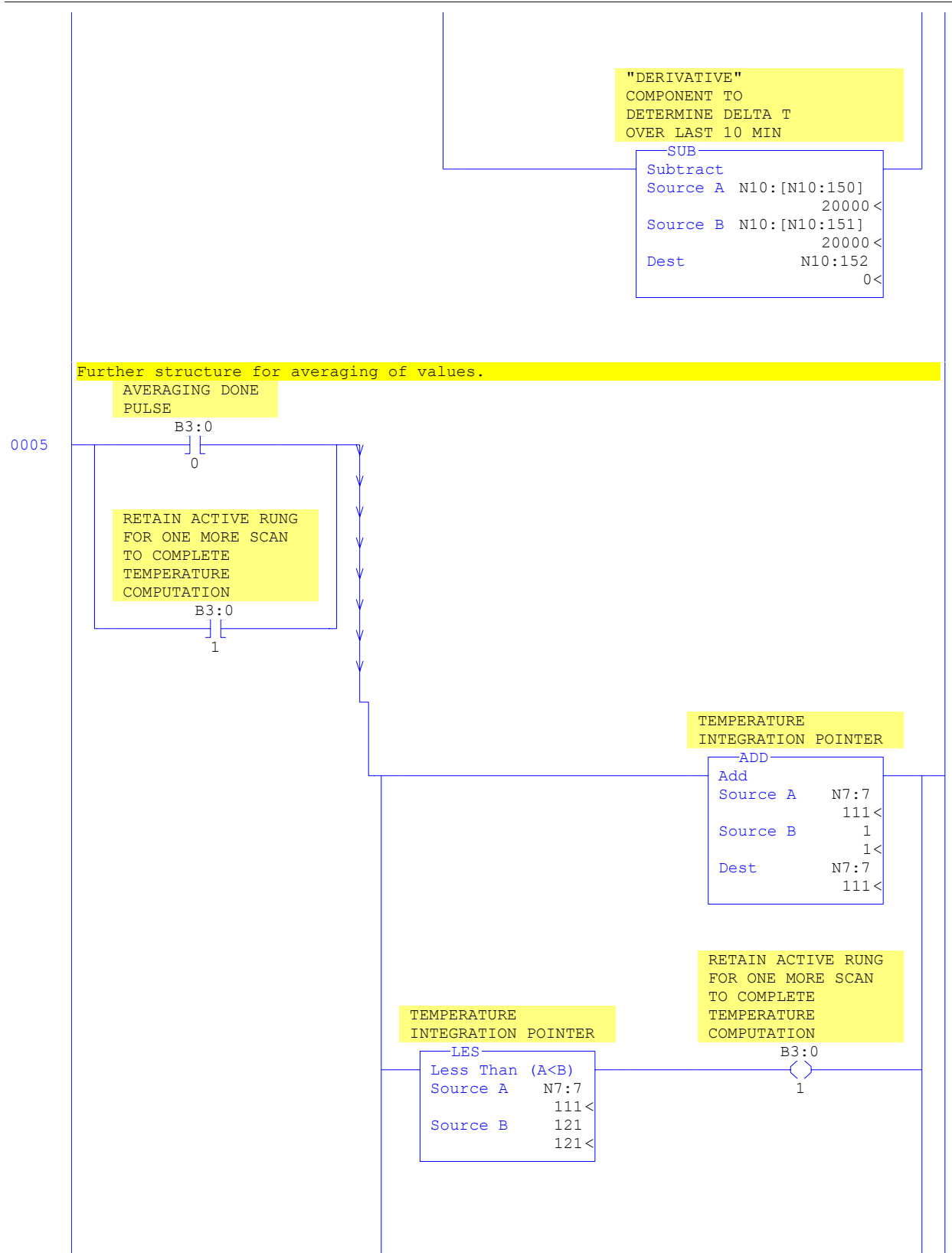
# PLC Program for May 4 - May 13

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



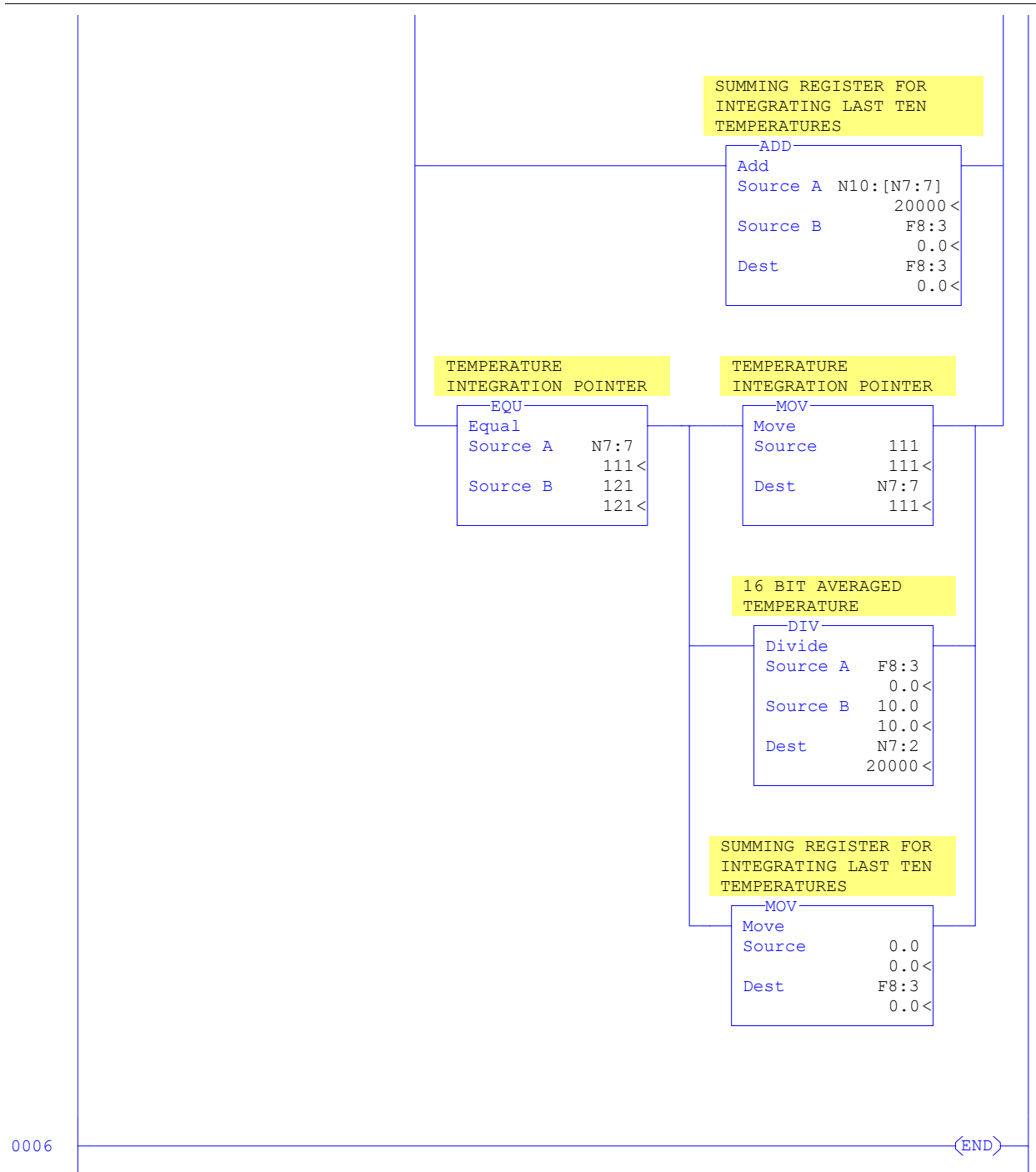
# PLC Program for May 4 - May 13

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



# PLC Program for May 4 - May 13

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



PLC Program for May 16

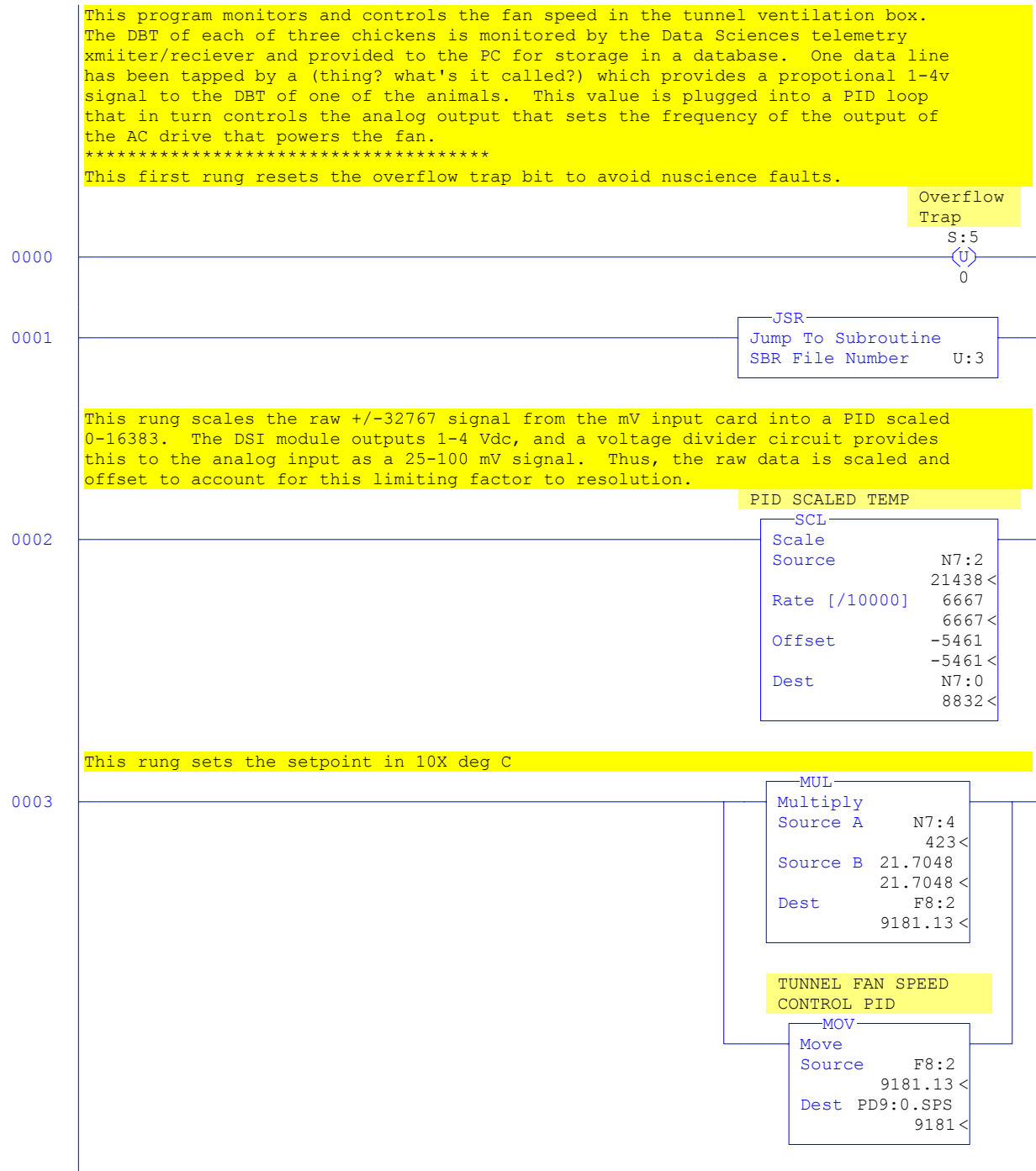
Program File List

---

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	1	SYS	0	No	0
MAIN_PROG	2	LADDER	10	No	668
INPUT_INT	3	LADDER	7	No	659

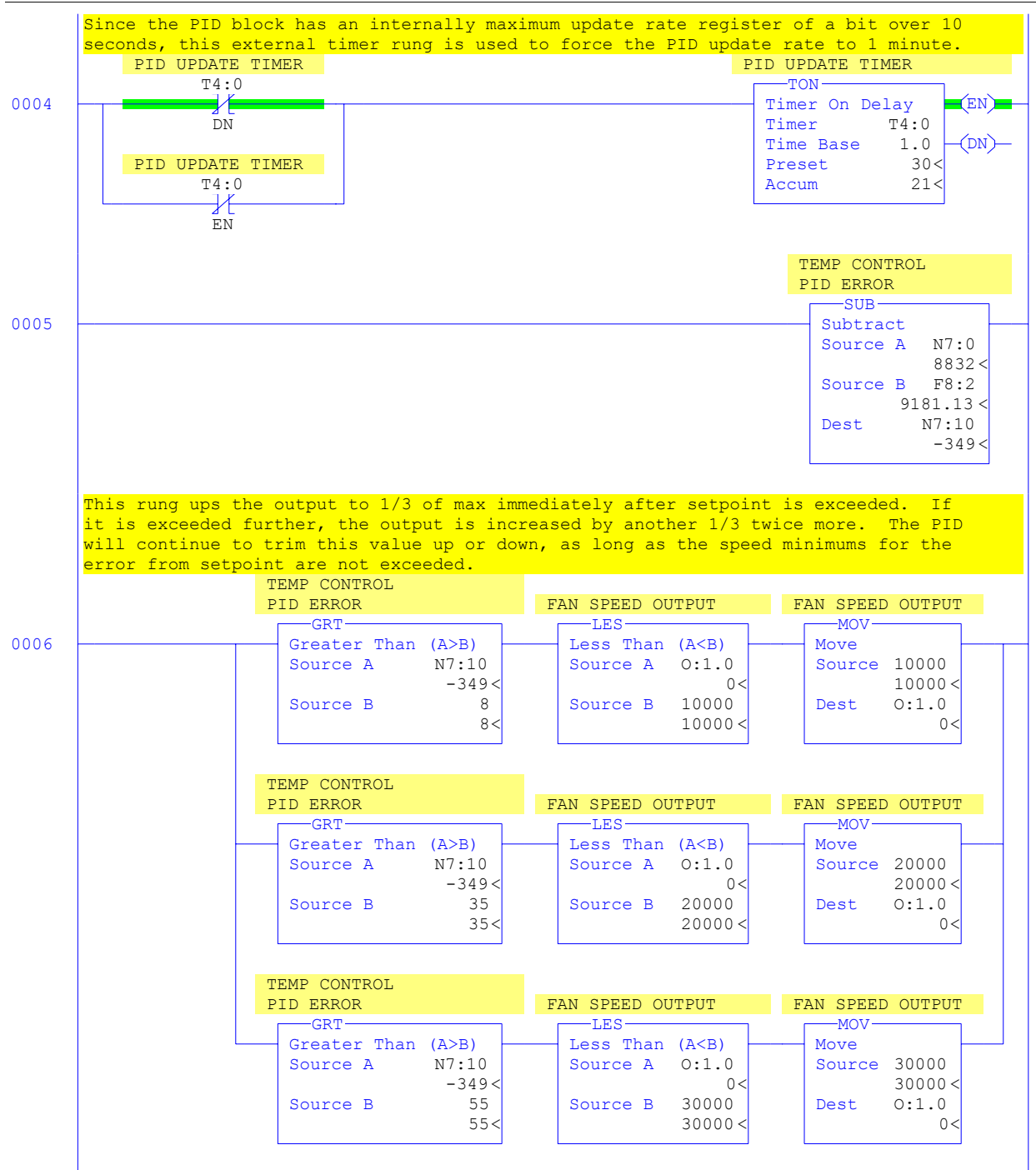
# PLC Program for May 16

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10



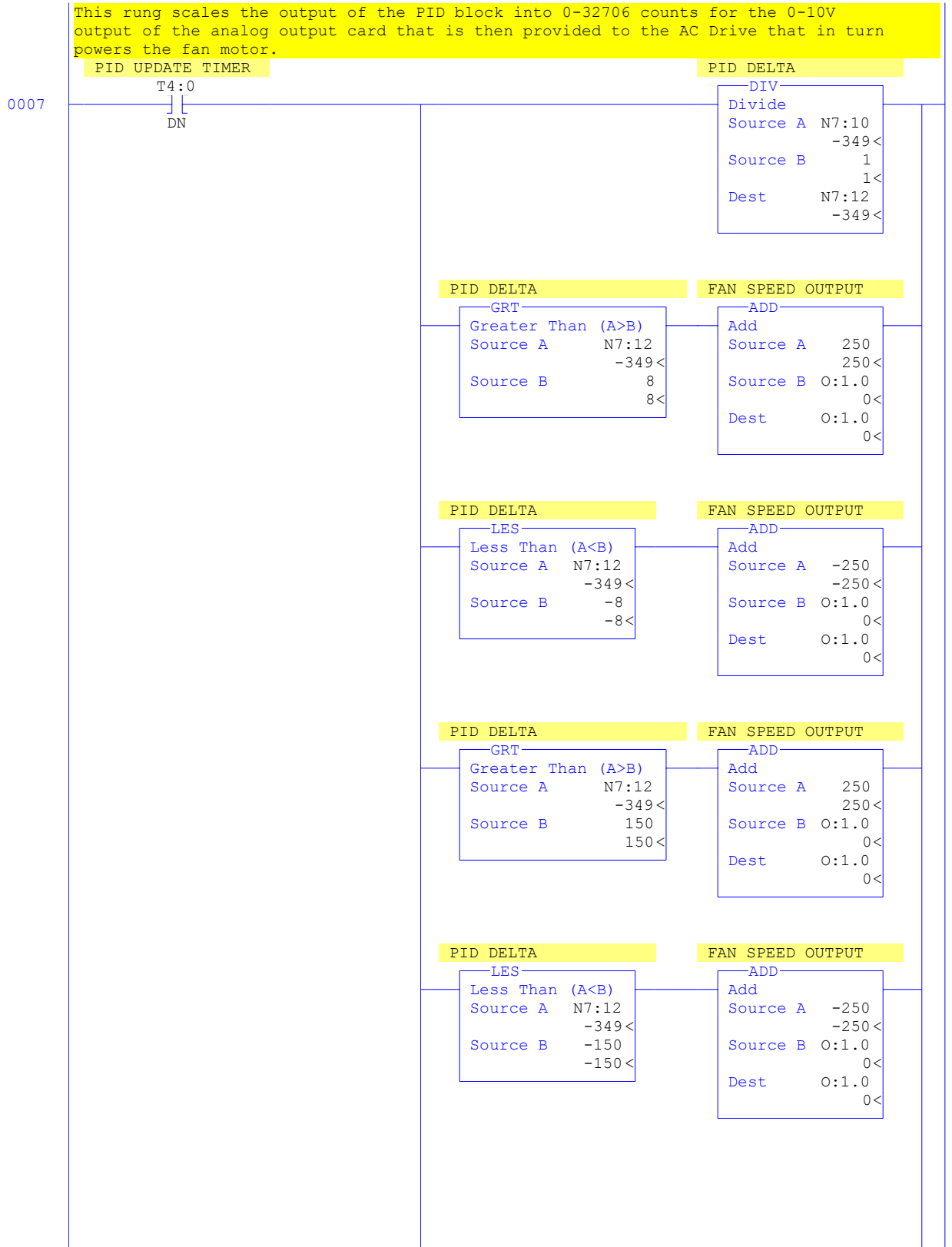
# PLC Program for May 16

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10



# PLC Program for May 16

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10





# PLC Program for May 16

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10

"DERIVATIVE"  
COMPONENT TO  
DETERMINE DELTA T  
OVER LAST 10 MIN

LES  
Less Than (A<B)  
Source A N10:152  
-144<  
Source B N7:15  
-20<

FAN SPEED OUTPUT

ADD  
Add  
Source A 500  
500<  
Source B O:1.0  
0<  
Dest O:1.0  
0<

"DERIVATIVE"  
COMPONENT TO  
DETERMINE DELTA T  
OVER LAST 10 MIN

GRT  
Greater Than (A>B)  
Source A N10:152  
-144<  
Source B N7:16  
20<

FAN SPEED OUTPUT

ADD  
Add  
Source A -500  
-500<  
Source B O:1.0  
0<  
Dest O:1.0  
0<

PID DELTA

LIM  
Limit Test  
Low Lim -35  
-35<  
Test N7:12  
-349<  
High Lim 35  
35<

PID UPDATE TIMER

MOV  
Move  
Source N7:20  
150<  
Dest T4:0.PRE  
30<

PID DELTA

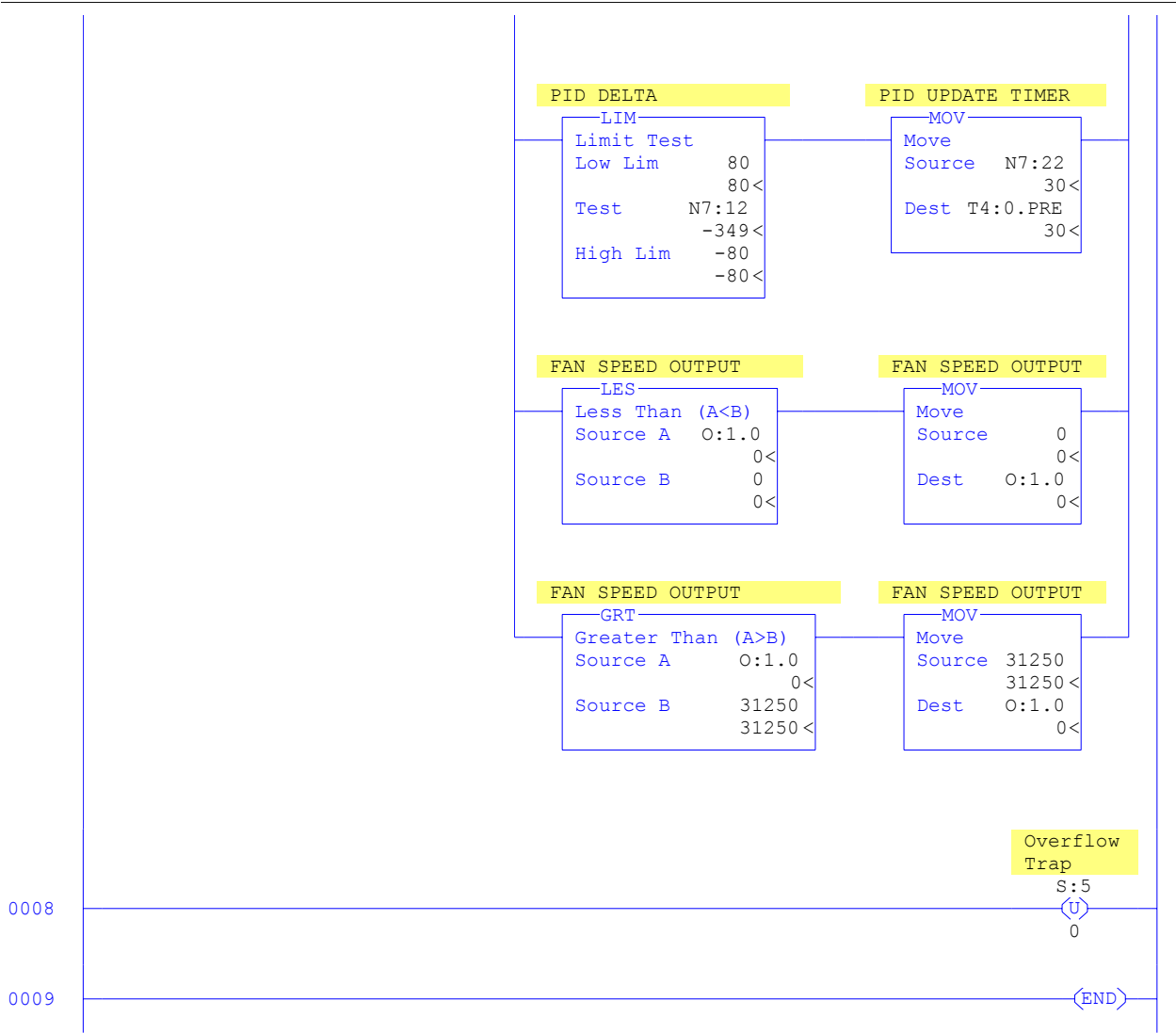
LIM  
Limit Test  
Low Lim 55  
55<  
Test N7:12  
-349<  
High Lim -55  
-55<

PID UPDATE TIMER

MOV  
Move  
Source N7:21  
75<  
Dest T4:0.PRE  
30<

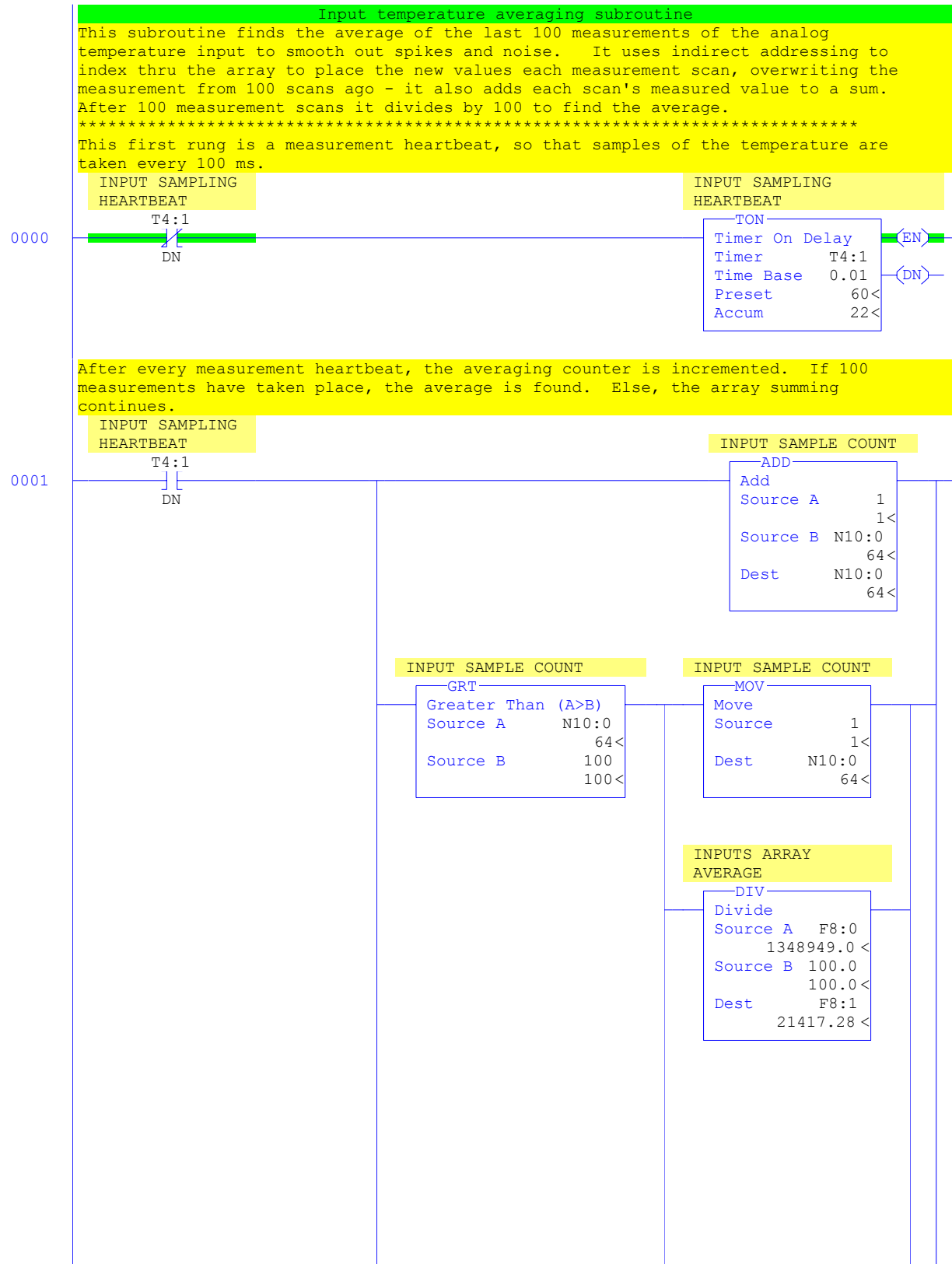
PLC Program for May 16

LAD 2 - MAIN\_PROG --- Total Rungs in File = 10



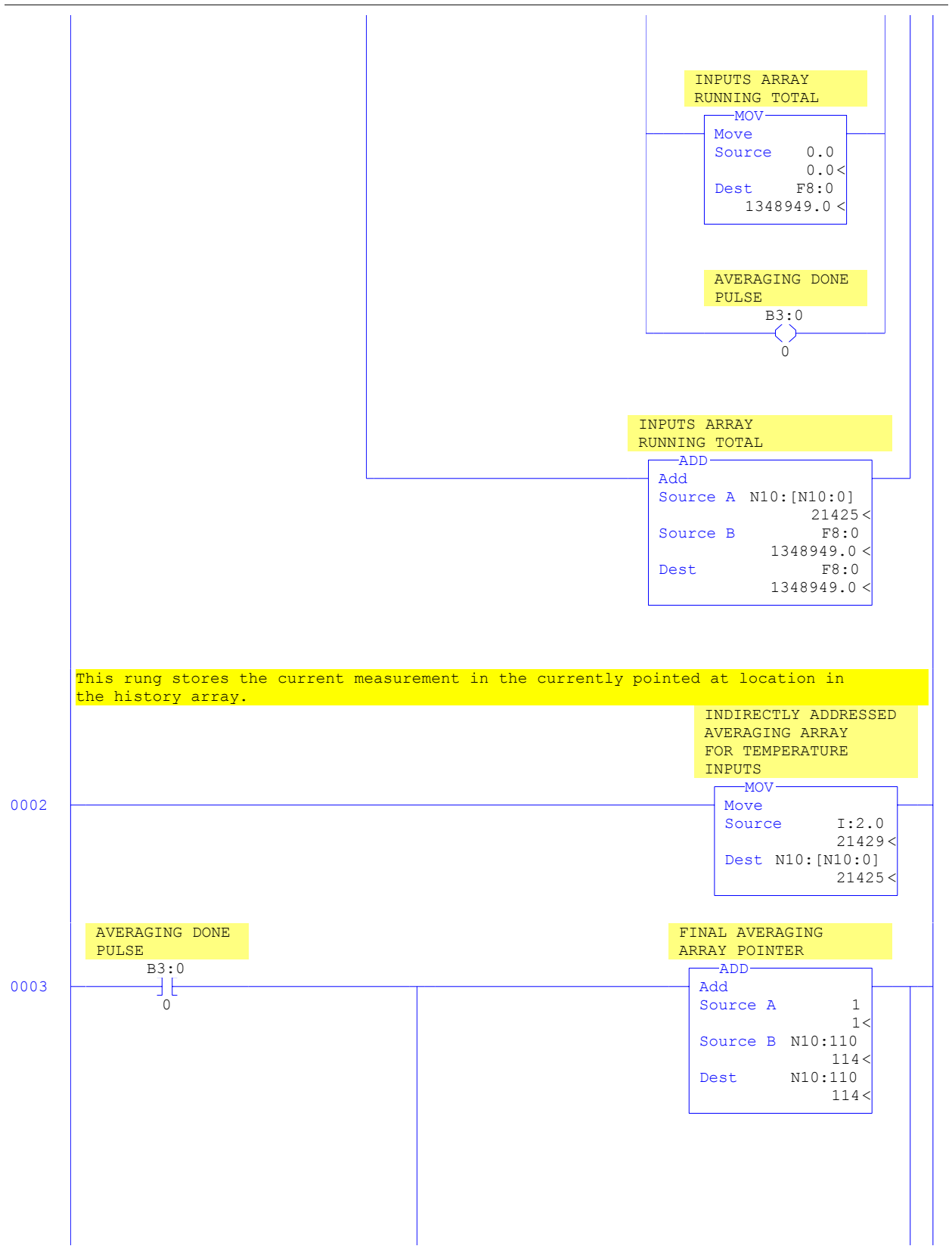
## PLC Program for May 16

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



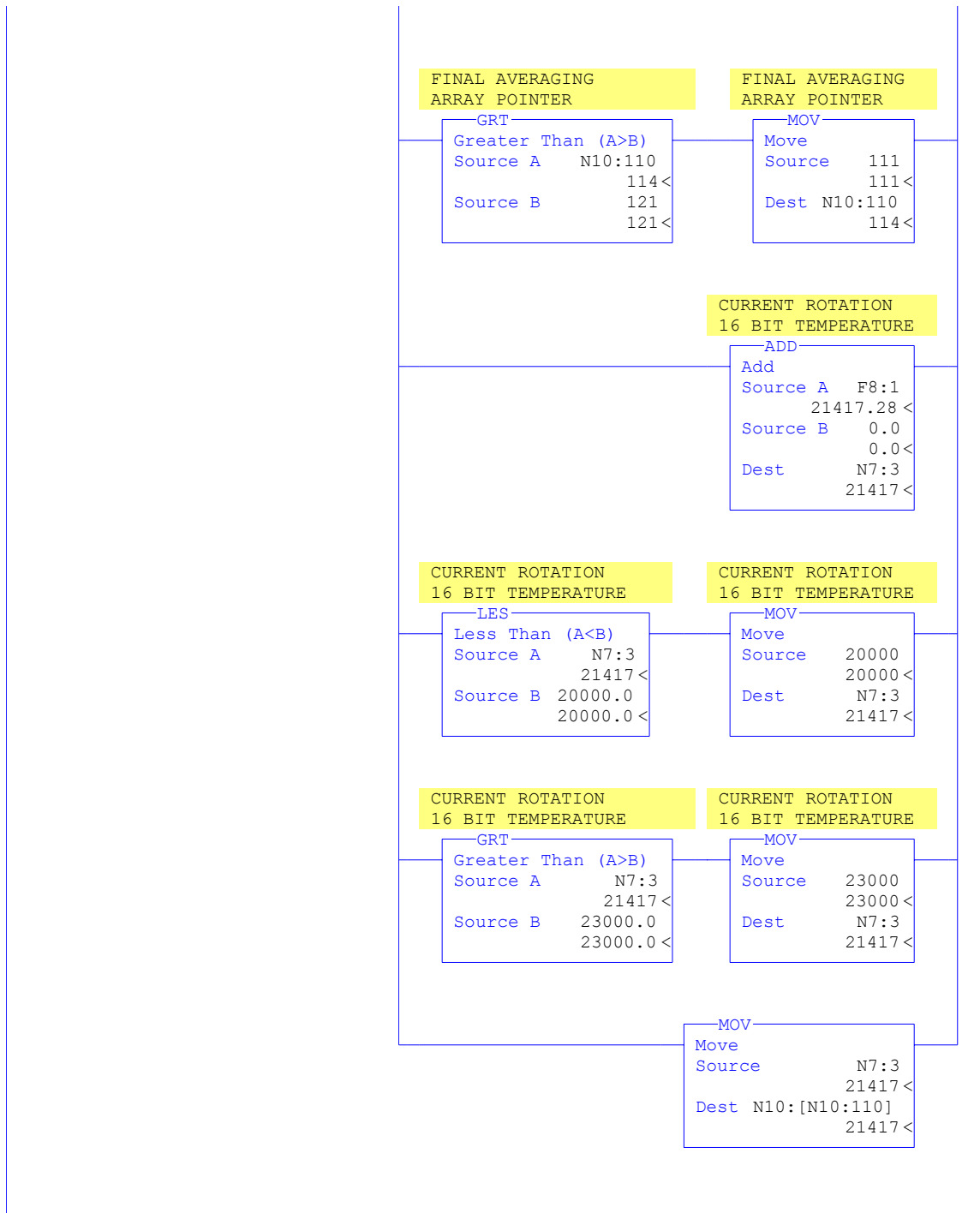
PLC Program for May 16

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



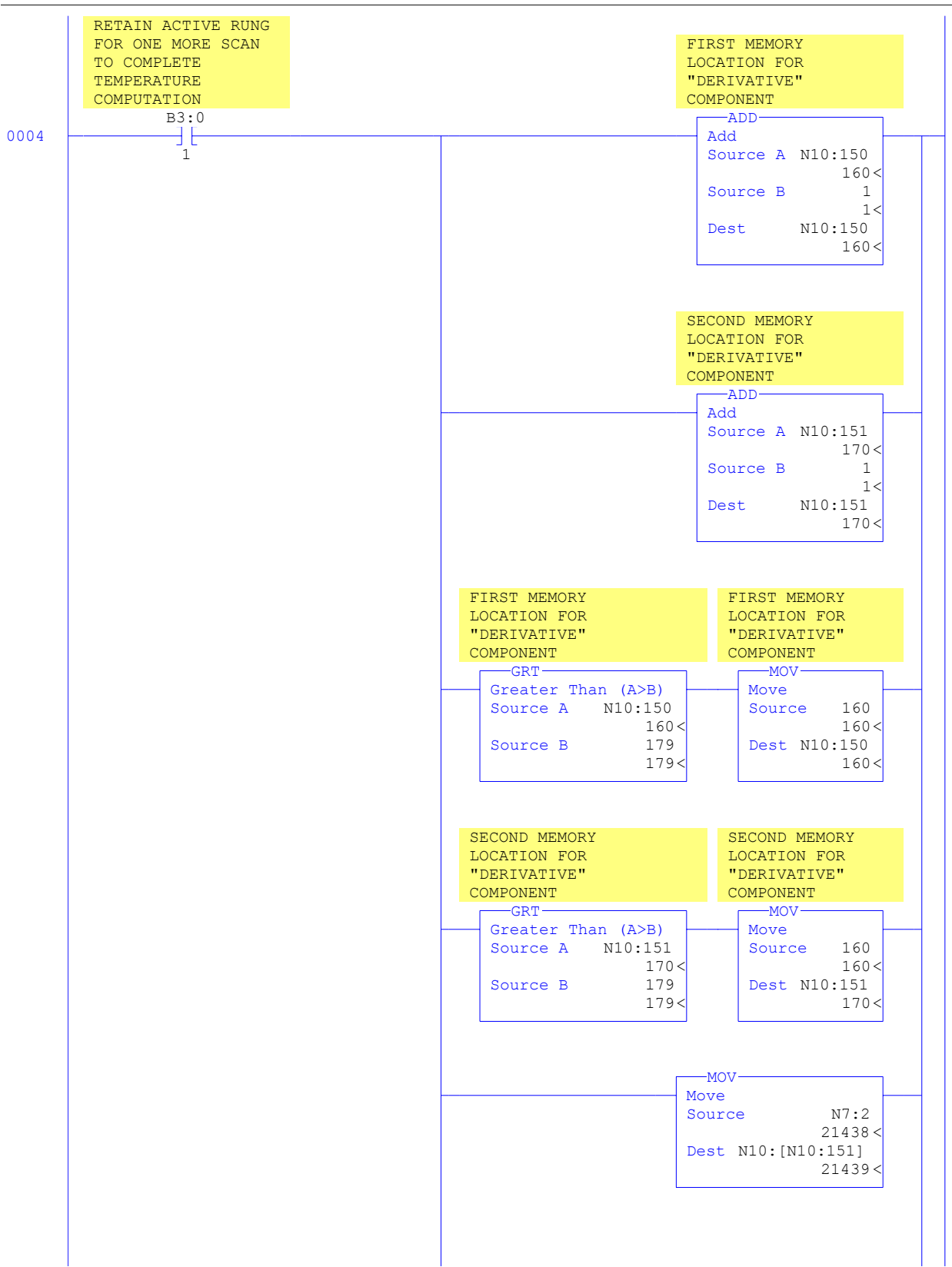
## PLC Program for May 16

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



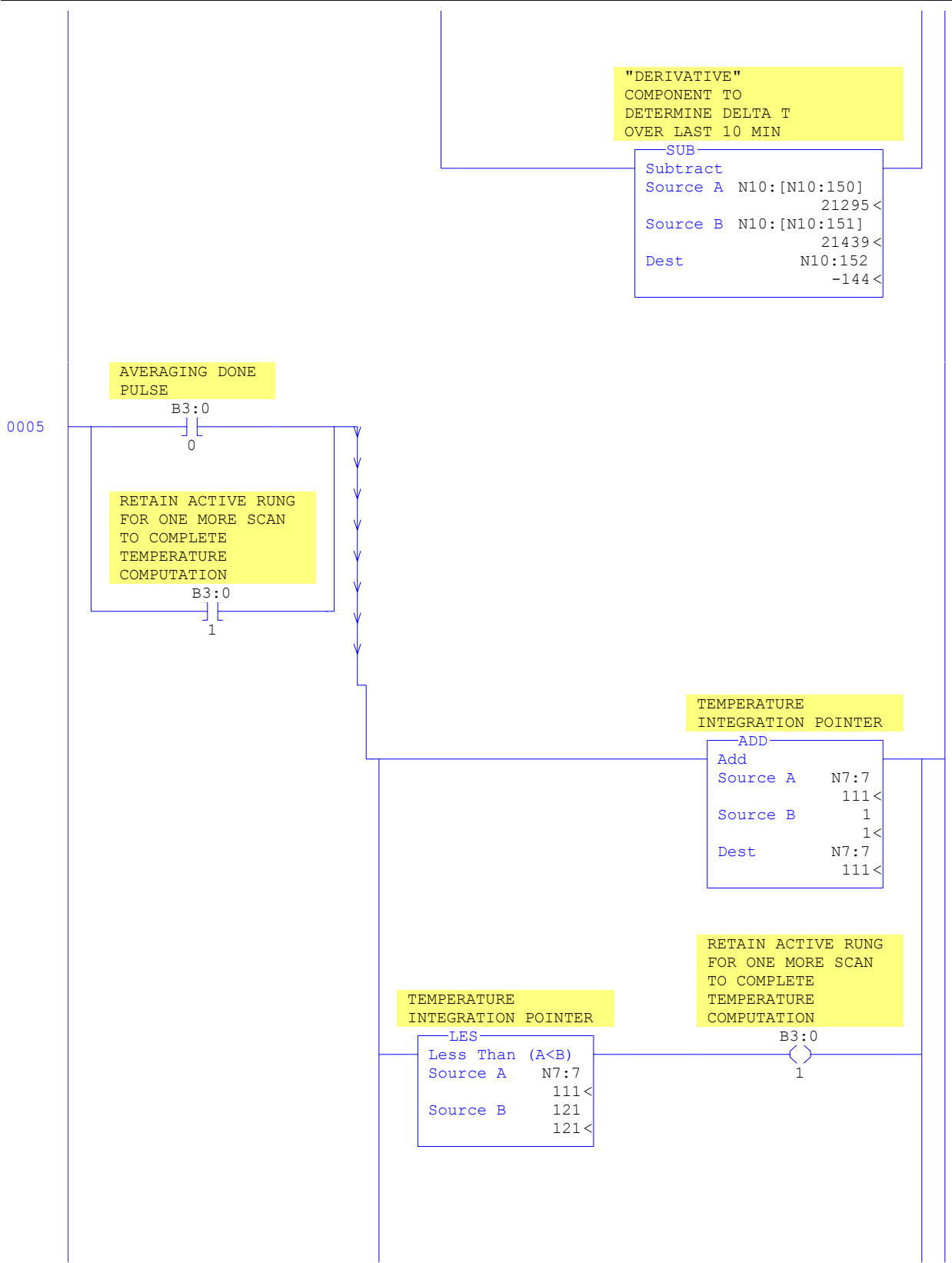
PLC Program for May 16

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



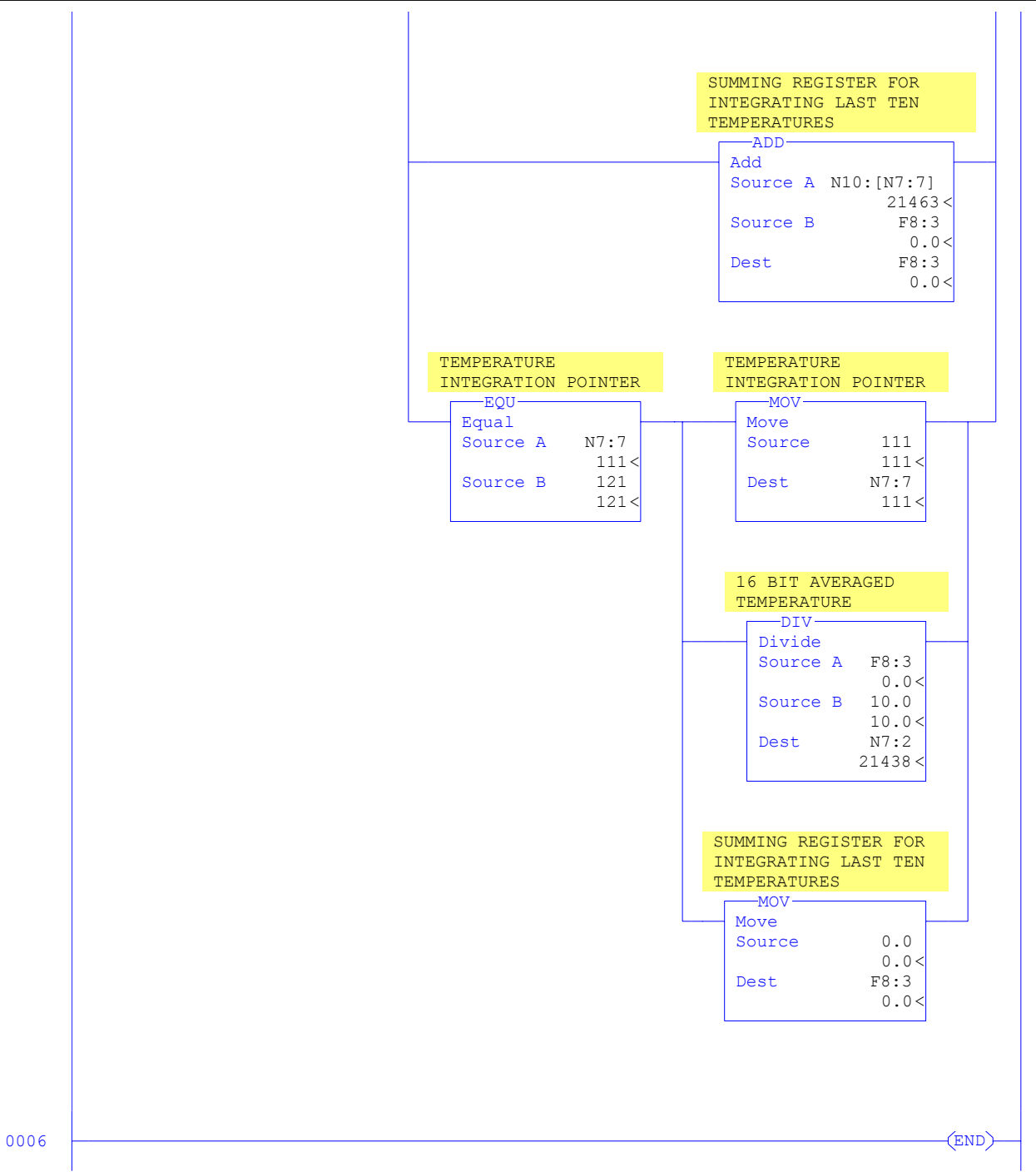
PLC Program for May 16

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



PLC Program for May 16

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7





PLC Program for May 19 and May 31

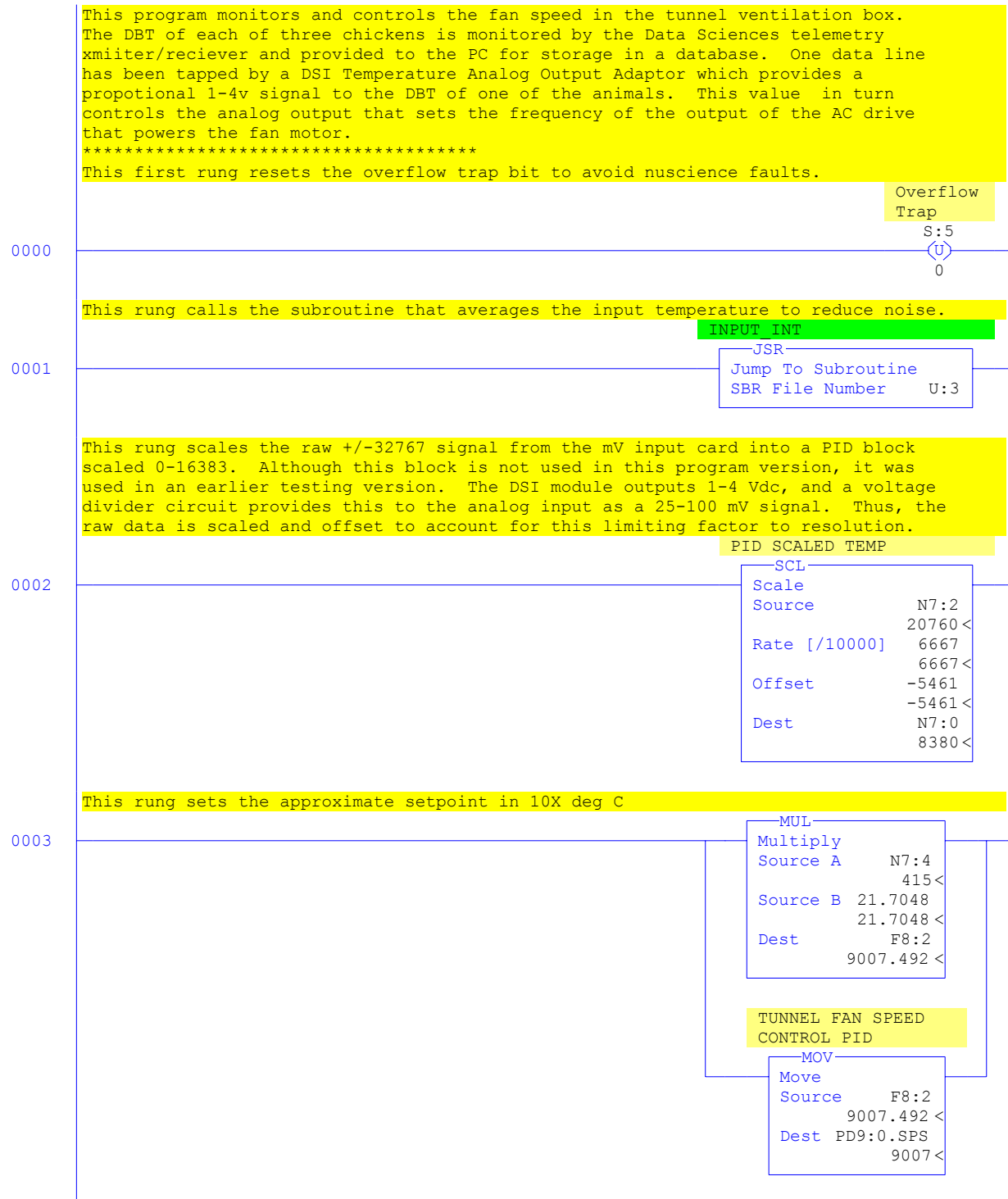
Program File List

---

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	1	SYS	0	No	0
MAIN_PROG	2	LADDER	11	No	745
INPUT_INT	3	LADDER	7	No	659

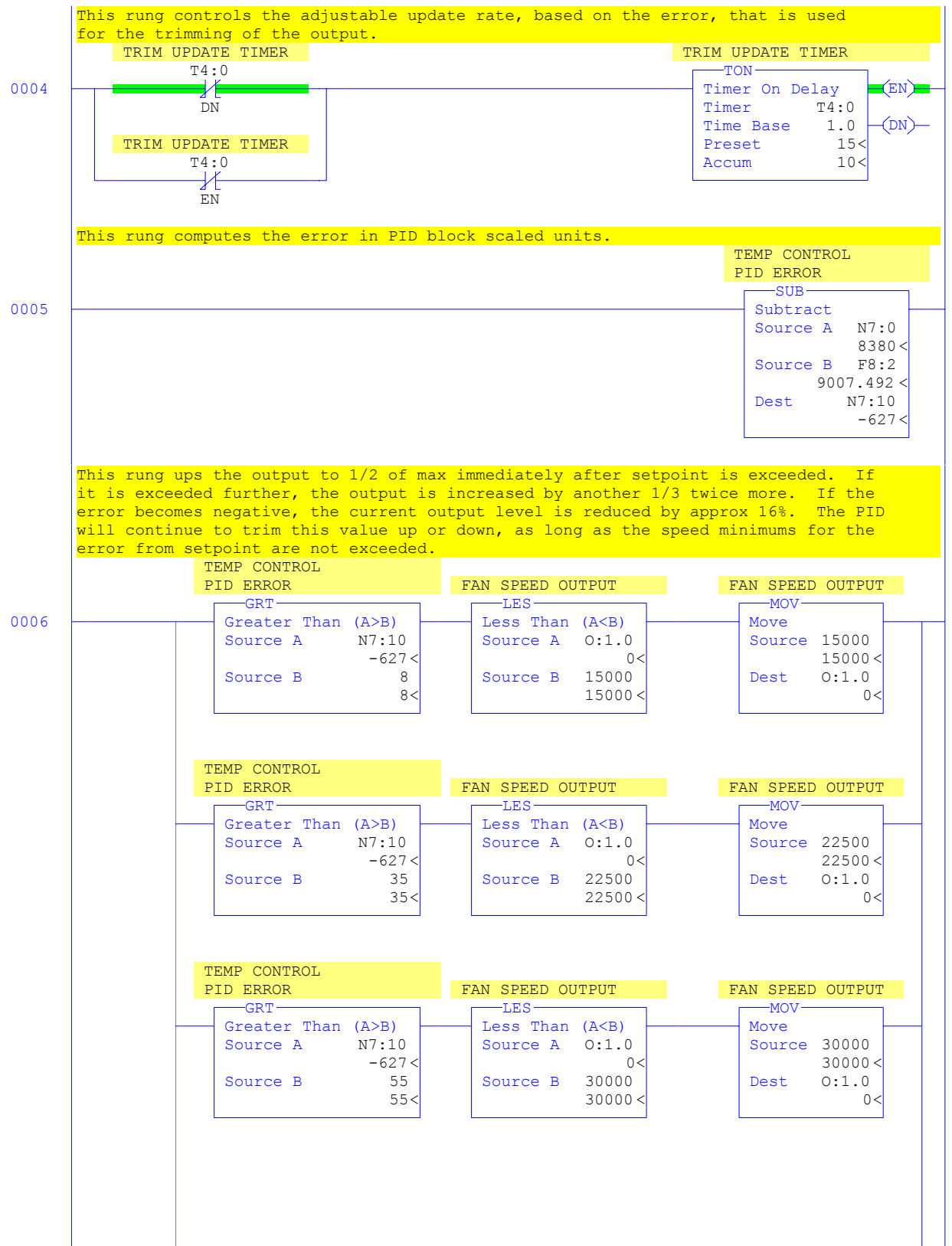
# PLC Program for May 19 and May 31

LAD 2 - MAIN\_PROG --- Total Rungs in File = 11



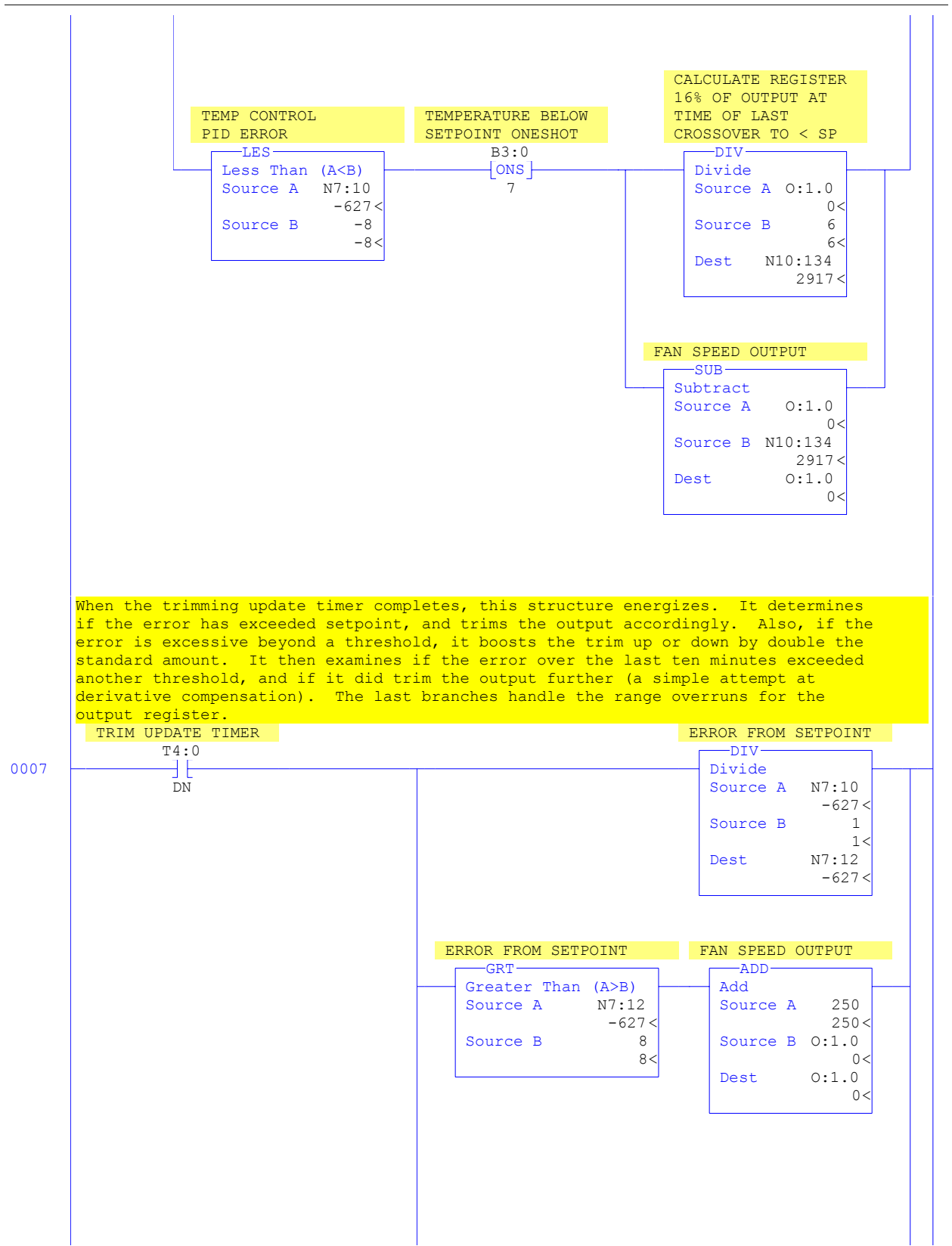
# PLC Program for May 19 and May 31

LAD 2 - MAIN\_PROG --- Total Rungs in File = 11



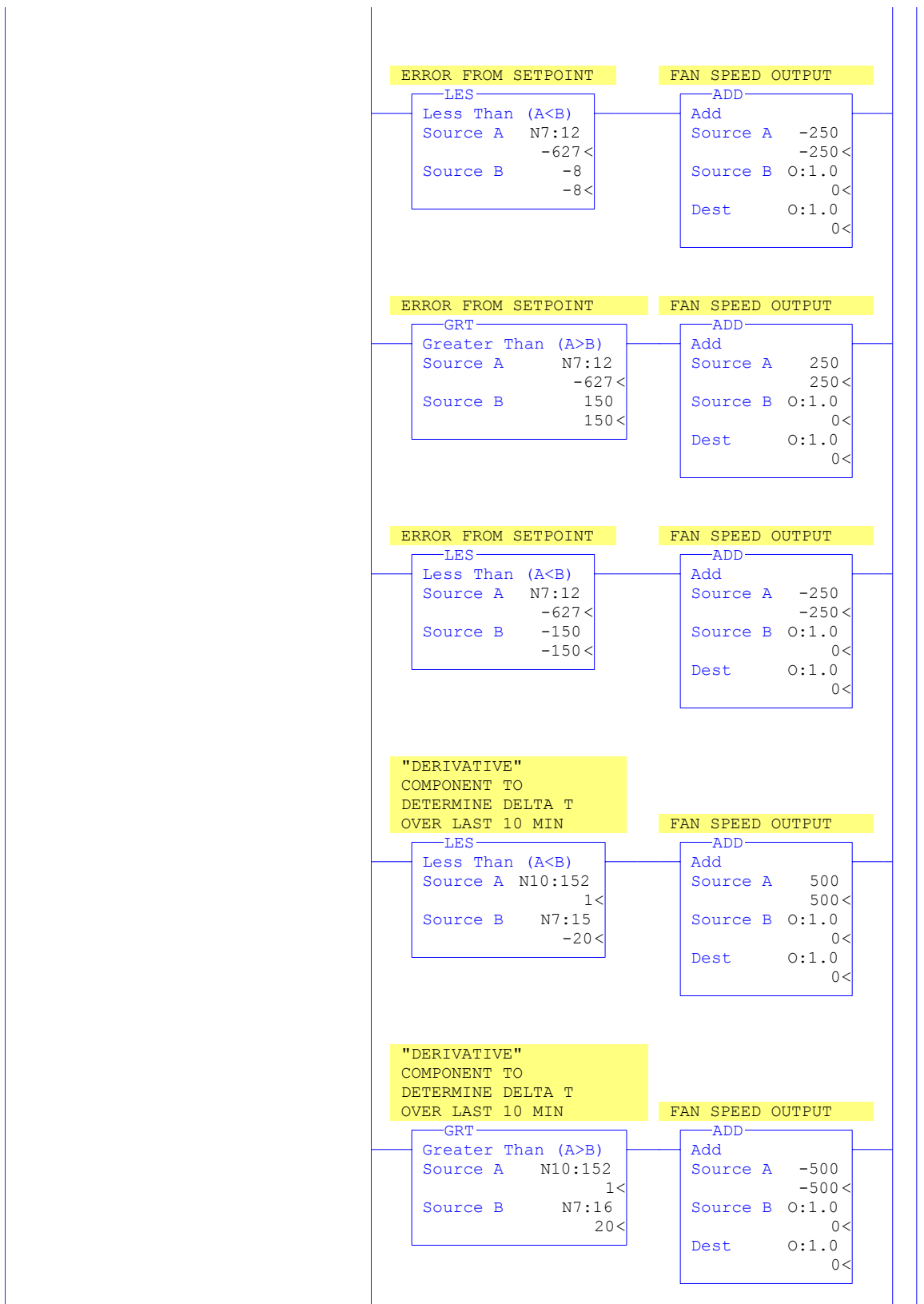
PLC Program for May 19 and May 31

LAD 2 - MAIN\_PROG --- Total Rungs in File = 11



# PLC Program for May 19 and May 31

LAD 2 - MAIN\_PROG --- Total Rungs in File = 11

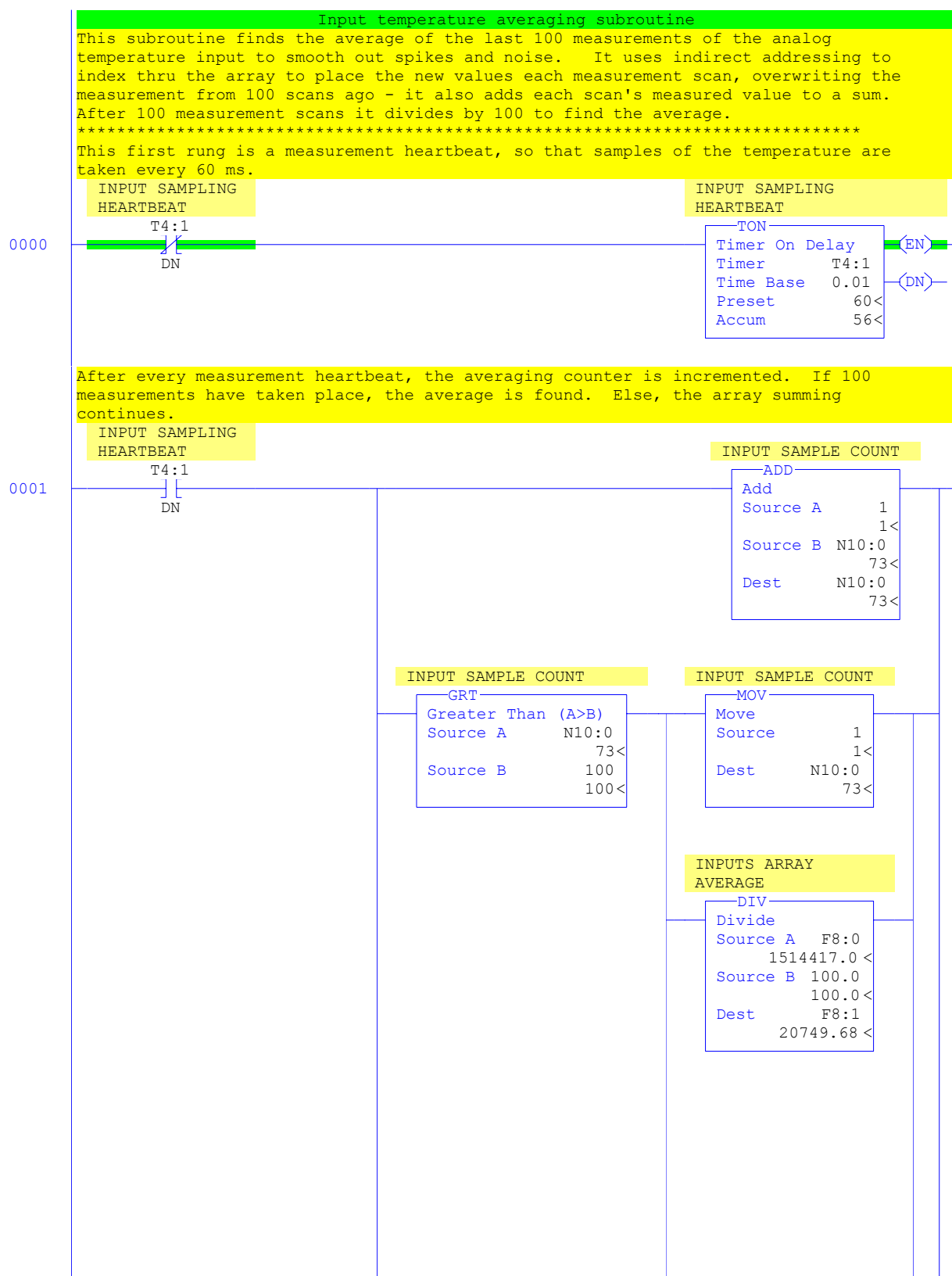


LAD 2 - MAIN\_PROG --- Total Rungs in File = 11



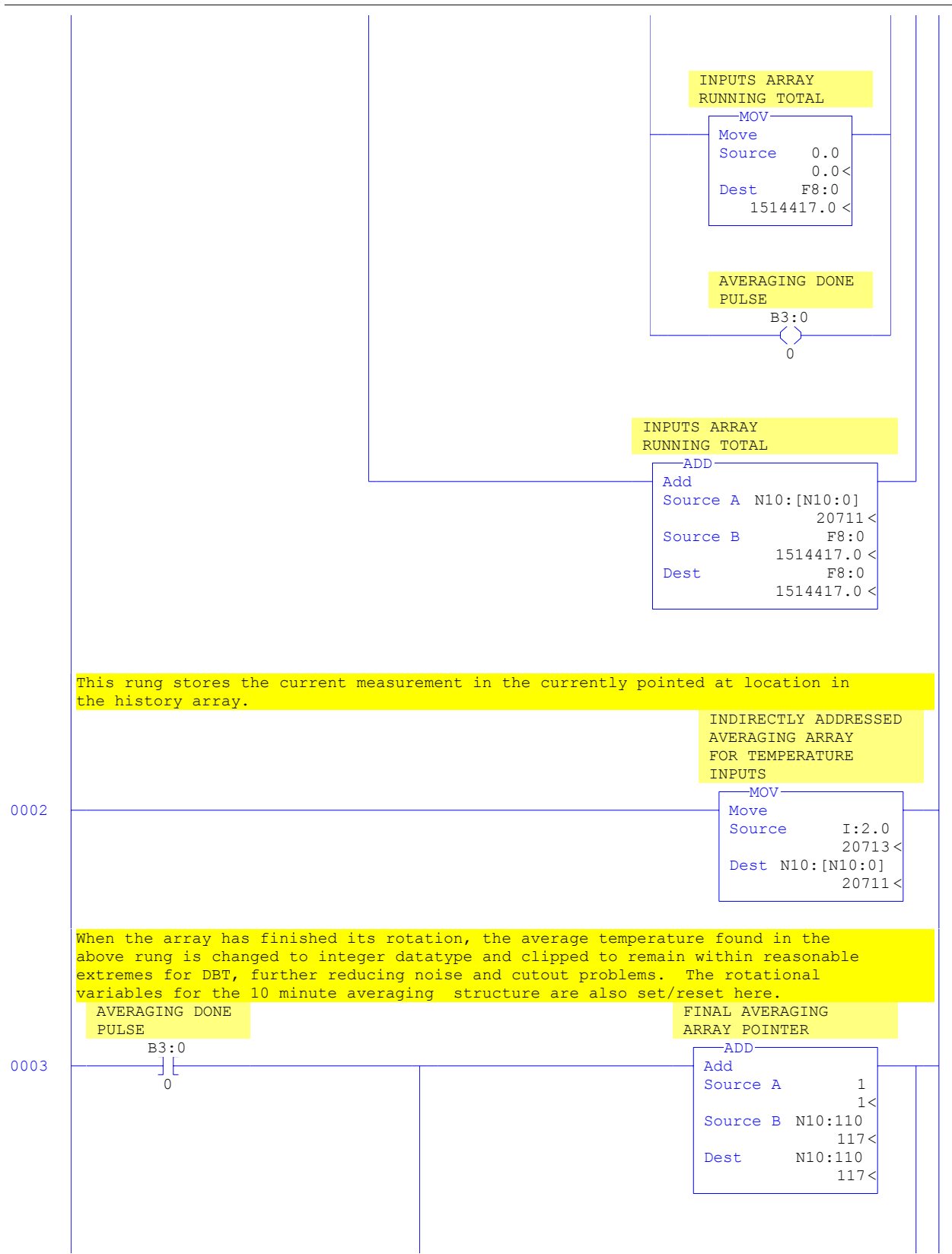
# PLC Program for May 19 and May 31

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



PLC Program for May 19 and May 31

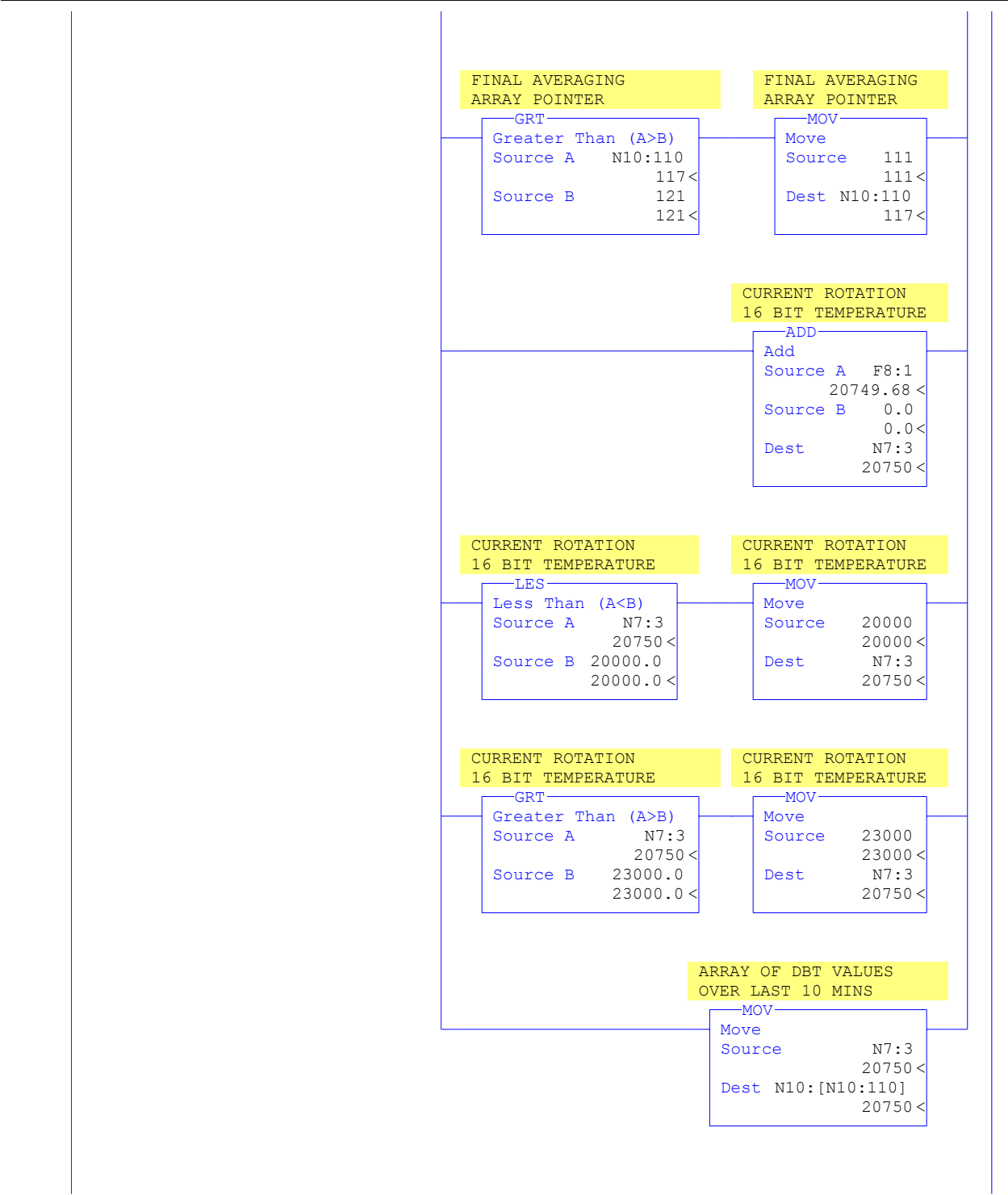
LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7





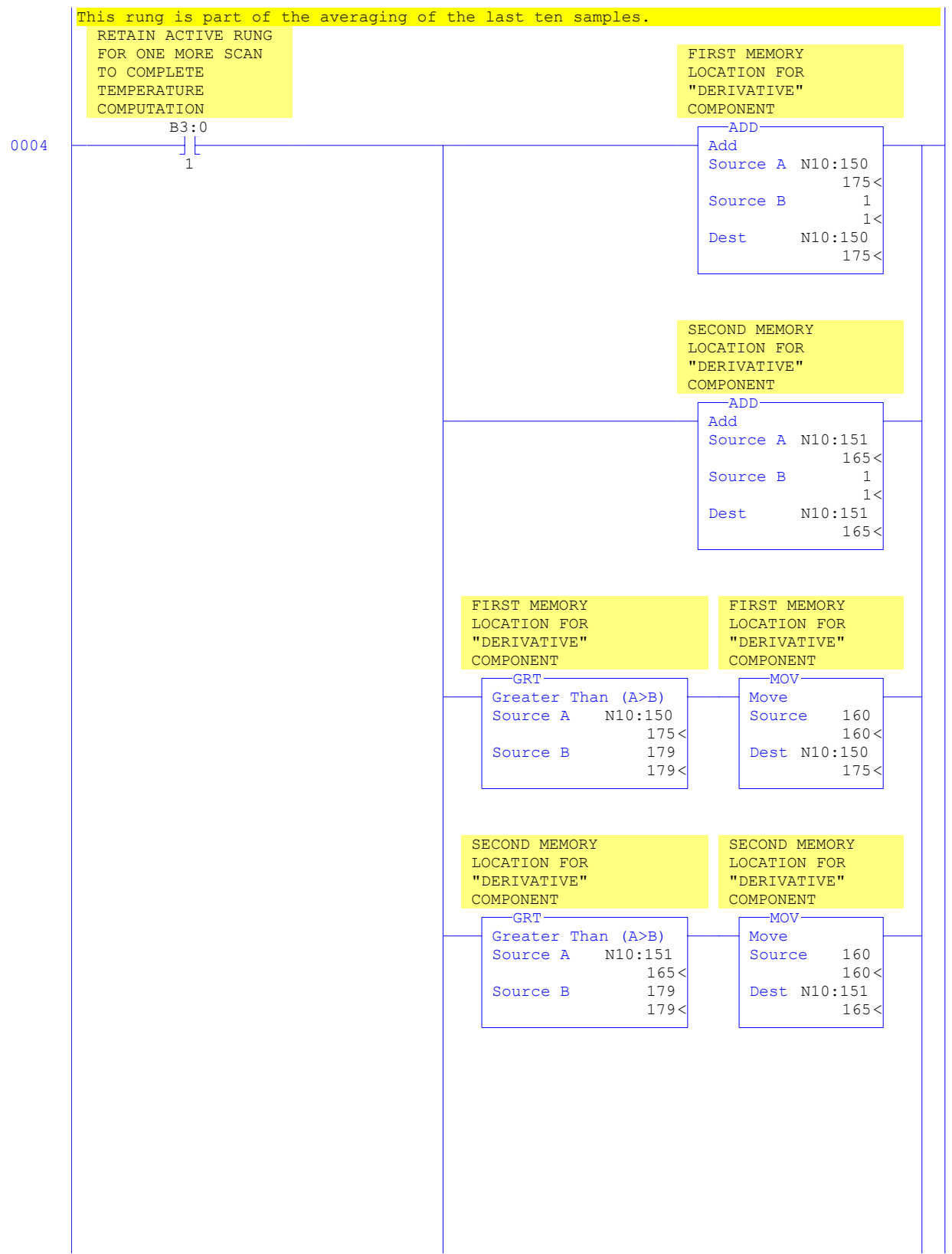
PLC Program for May 19 and May 31

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



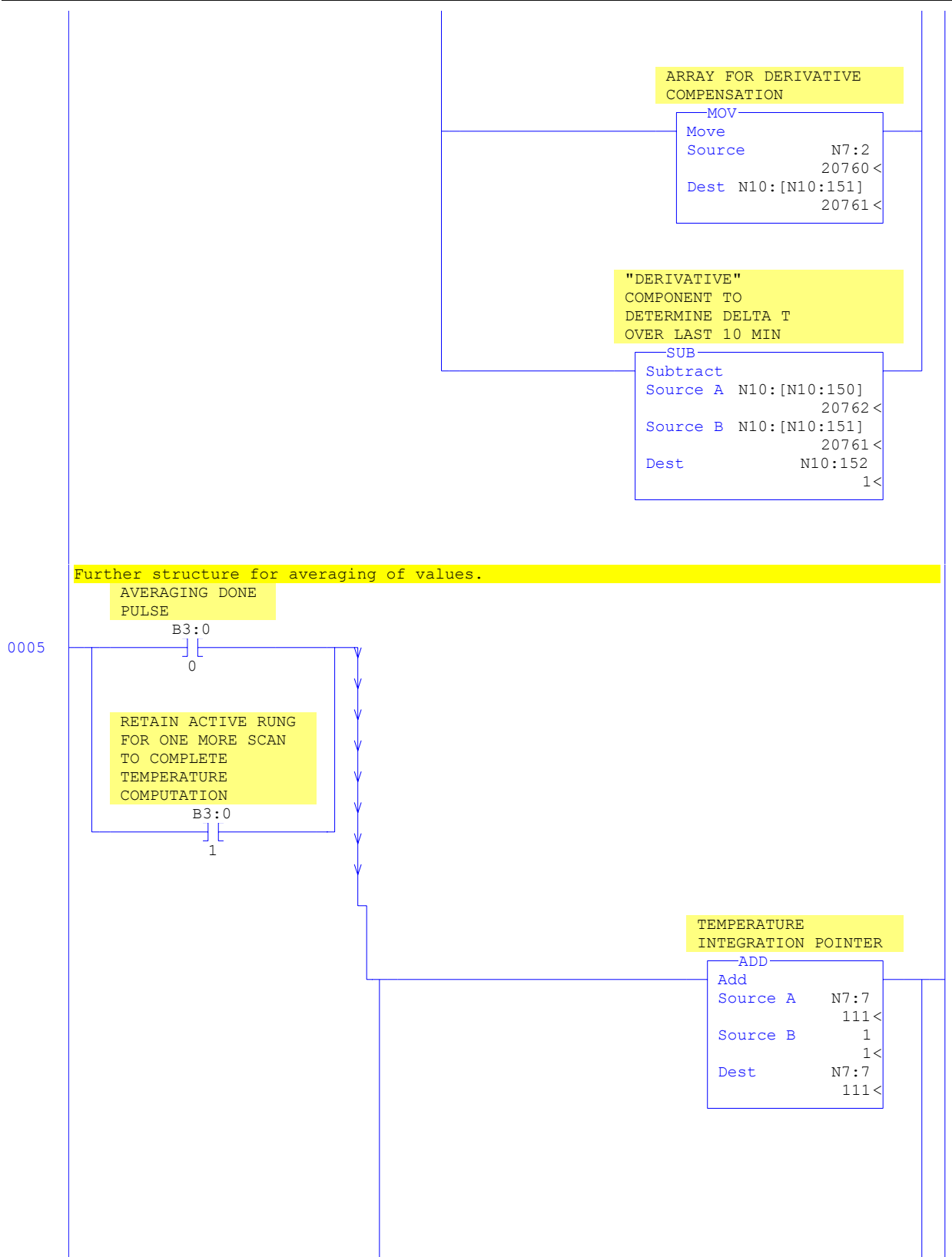
PLC Program for May 19 and May 31

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



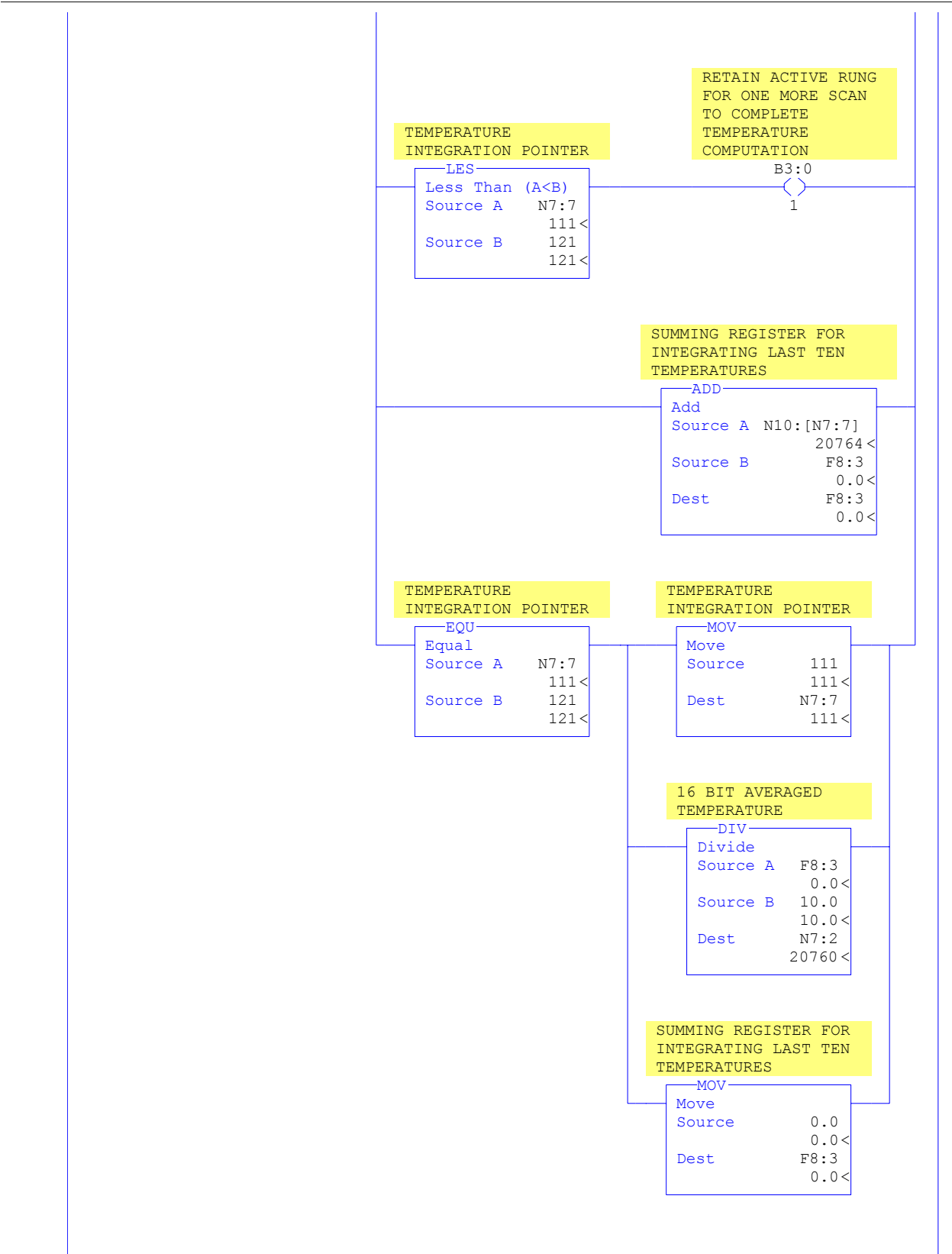
PLC Program for May 19 and May 31

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



PLC Program for May 19 and May 31

LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7



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LAD 3 - INPUT\_INT - Analog input integration --- Total Rungs in File = 7

