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Revitalization and Initial Testing of a Blowdown Supersonic Wind Tunnel

West Cardman Ratliff

REVITALIZATION AND INITIAL TESTING OF A

BLOWDOWN SUPERSONIC WIND TUNNEL

By

West Cardman Ratliff

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REVITALIZATION AND INITIAL TESTING OF A BLOWDOWN

SUPERSONIC WIND TUNNEL

By

West Cardman Ratliff

Approved:

Keith Koenig
Professor of
Aerospace Engineering
(Thesis Director)

David H. Bridges
Associate Professor of
Aerospace Engineering
(Committee Member)

Thomas Hannigan
Instructor of
Aerospace Engineering
(Committee Member)

Pasquale Cinnella
Professor of
Aerospace Engineering
(Graduate Coordinator)

Sarah A. Rajala
Dean of the Bagley
College of Engineering

Name: West Cardman Ratliff

Date of Degree: December 12, 2008

Institution: Mississippi State University

Major Field: Aerospace Engineering

Major Professor: Dr. Keith Koenig

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Candidate for Degree of Master of Science

The Supersonic tunnel located in Patterson Labs at Mississippi State University has been thoroughly documented for future reference purposes. Data acquisition, physical components, shutdown devices, a control program, and the hydraulic system are all discussed in detail. Analysis is performed showing that the flow within the Mach 2 nozzle only reaches Mach 1.8 for a portion of the flow, but that this portion of the flow is relatively stable for a wide range of settling chamber pressures. It is concluded that the tunnel with the nozzle blocks used functions correctly.

Key words: supersonic tunnel

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NOMENCLATURE

A	Nozzle area
A^*	Throat Area
A/D	Analog to Digital
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BASIC	Beginners' All-purpose Symbolic Instruction Code
COFF	Cutoff
DAQ	Digital Acquisition
DMA	Direct Memory Access
HP	Hewlett-Packard Company
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
M	Mach number
NI	National Instruments

NI-MAX	National Instruments Measurement & Automation Explorer
P	Pressure
P_0	Stagnation Pressure
PCI	Peripheral Component Interconnect
SAE	Society of Automotive Engineers
SSM	Servo-System Module
SST	Supersonic Tunnel
SW	Switch for tunnel Fail/Safe System
WTCR	Wind Tunnel Control Room

CHAPTER 1

INTRODUCTION

The MSU supersonic wind tunnel in Patterson laboratory was built in 1954 for a NASA study of supersonic flutter in prototype airfoils and also for flow-visualization purposes. The tunnel was donated to the University in 1963 after NASA had finished its testing. The tunnel was used here at Mississippi State University in the early 1980s by students in the Aerospace Lab I class to predict and measure the Mach number within the nozzle. The tunnel has also been used in several Aerospace I Lab seminar projects (Ratliff, Ellis). The original tunnel consisted of a settling chamber, a series of sixteen inch diameter pipes, a vacuum tank, selectable nozzle blocks, and a butterfly valve. Over the years a number of control systems were used culminating in the Pegasus Servo System Module. Originally the tunnel was manually controlled, but later two central processing units were used to both control and take data. In 1990 a single program was written both to take data using Direct Memory Access (DMA) and to control the tunnel (Hannigan). The program used to control the tunnel has been updated periodically, and the latest revision was a version written for a two-CPU computer running two separate programs, one a compiled Turbo-BASIC program running in the foreground, with a background program written in Hewlett Packard BASIC running on an HP Measurement Co-processor. The revision from the compiled Turbo-BASIC and HP-BASIC programs was done in an effort to move to National Instruments LabView and compatible NI hardware as the most logical upgrade path for this facility (Okoro). All of the legacy systems for subsonic and supersonic tunnels continue to evolve to current generation hardware and software.

The supersonic wind tunnel has been inoperable for several years. The butterfly valve used for controlling the wind tunnel speed broke its seal and was not replaced until 2006. Additional problems arose from the wiring and the computer program. The wiring had been disconnected when the tunnel was disassembled due to a burst water main beneath the floor of the Patterson high bay. When the tunnel was reassembled the former test section was replaced with the much larger test section NASA had used. The reason for the change was because the small size of the previous test section had inhibited wind tunnel experiments. The reason the larger test section hadn't been used previously was because the amount of pressurized air available was insufficient to provide reasonably long run times in the large tunnel, and smaller test sections had been used successfully for some time in another facility with a smaller reservoir and a manual control system in another facility. Therefore, the test section settling chamber of the large tunnel was mated to a smaller diameter pipe that had the nozzle with a 3" x 3" test section from this smaller facility (Hannigan). This system was tested and the control system adapted for effective active computer control, but following the failure of the valve seat, another small facility that had been developed for routine testing and training on a small scale was adapted for use in the undergraduate lab class (Al'Habbash), (Cruse). Coinciding with repairs of this facility, it is hoped that a return to the larger nozzle block and test section will allow extended educational and research use of this facility.

Since the supersonic tunnel has been in Patterson no comprehensive description and manual have been created. Previous theses have focused on particular aspects such as the control program or test section sting, but none have exhaustively described the entire tunnel and its operation. One of the major goals of this project was to produce such a document so that in the future a single all-encompassing guide to the supersonic tunnel will be readily available to anyone. The other major goal of this project was to determine whether it is feasible to make use of the large test section. This is a valid concern since the larger test section has not previously been extensively used and documented by the university.

CHAPTER 2

DESCRIPTION OF THE SUPERSONIC TUNNEL

A great deal of confusion has occurred in working on the tunnel due to a lack of ready references and current documentation regarding the tunnel and its operation. A large part of this project was the correction of this problem by gathering together all pertinent information into one cohesive document. An accurate description of the tunnel's components and the ways in which they interact is a necessary first step in working on the tunnel.

Physical Systems

The supersonic tunnel located in Patterson Labs consists of a number of subsystems. The air compressor, pressure tank, butterfly valve, sixteen-inch pipes, settling chamber, 8 pair of nozzle blocks mounted in a test section, an expansion nozzle, a downstream butterfly valve, a gate valve for relief, three 4-way hydraulic valves used for emergency shutdown, an exit nozzle, a vacuum sphere, and vacuum pump are all components of the tunnel. The air compressor used for pressurization of the reservoir is a Lovejoy Twistair model TA-335B screw compressor rated for 335 ft^3/min (Koehring) to a maximum pressure of 125 psi. The compressor is located in the basement of the central heating and cooling plant. The compressor is connected to the air tank through a three-inch underground pipe. The 1200 ft^3 air tank (Al'Habbash) is located immediately behind

Patterson Labs and is rated to withstand pressures up to 150 psi; however, the tank is usually only pressurized to 125 psi since that is the maximum rated compressor pressure. A vacuum sphere is also located behind Patterson Labs, but is not currently used. The vacuum pump itself is a type DK-180 built by Consolidated Vacuum Corporation, but is currently inoperable due to a crack in the low pressure cooling jacket. The main part of the tunnel is located inside Patterson and can be seen in Figure 1.

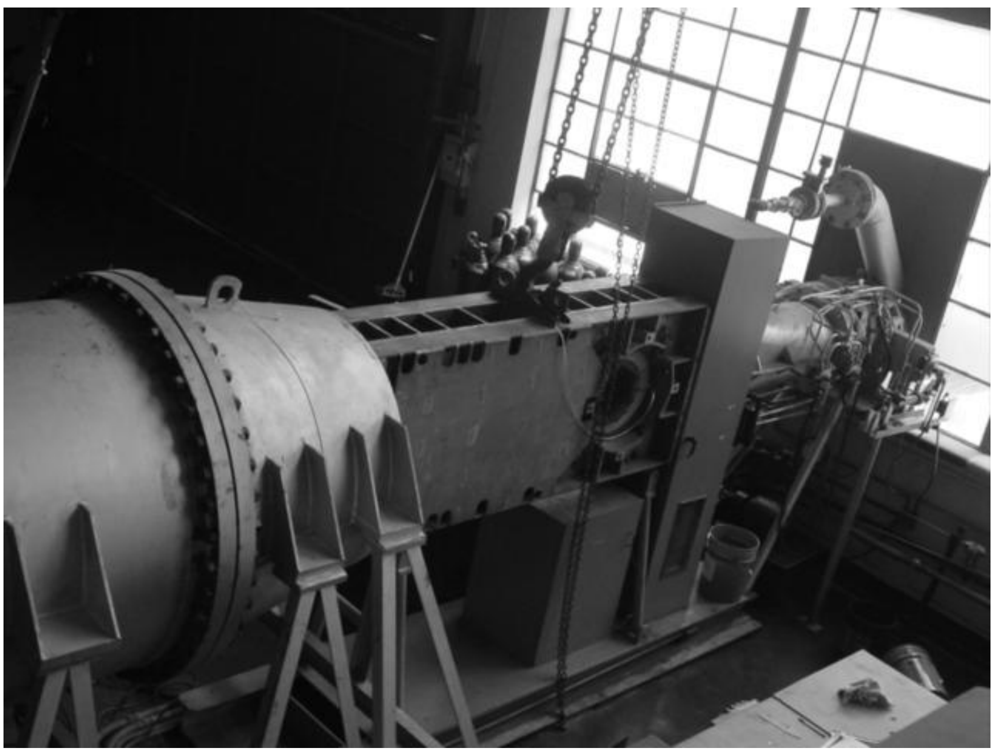

Figure 1 The Supersonic Tunnel Located in Patterson Labs

The butterfly valve used to control the tunnel is not the original; instead, a replacement was procured which had to be installed before the tunnel could become operational following the failure of the valve seat. This butterfly valve and its attendant hydraulic arm provide the only active means of control over the tunnel. When there is no hydraulic pressure the butterfly valve has a tendency to drift off the seat. The previous inlet butterfly had an off-center axis which insured the valve would remain closed when the upstream tank was pressurized. Now the valve must be restrained by the pin that was previously simply a guard to prevent unintentional opening. The pipe connecting the tank to the butterfly valve and settling chamber is sixteen inches in diameter, and runs approximately 48 ft from the butterfly valve to the settling chamber inlet. The settling chamber is 53 inches in diameter and is 12.5 feet long with tapered ends. The test section is comprised of four pieces: a matched pair of nozzle blocks and two sidewalls. The bolts holding the pipes, settling chamber, and test section together are usually based on the ASTM (American Society for Testing and Materials) standard which specifies 8 threads per inch for 1 1/8 inch bolts. The remaining bolts use the standard ASME and SAE bolts. The nozzle blocks range from Mach 1.3 to Mach 4 with some additional transonic nozzle blocks. One of the sidewalls possesses eight pressure taps, one every six inches along its length. The sidewalls also have a pair of hatches for access to the sting; each hatch also possesses three pressure taps with roughly six-inch spacing. The settling chamber and test section are shown in Figure 4. The test section itself is 17 inches high and 9.25 inches wide with a moveable sting. The sting was designed and built in 1972 (Overall). It is hydraulically operated and is capable of a change in the angle of attack. Once the flow has passed the sting it passes another butterfly valve and is currently vented to the atmosphere through a diffuser. The diffuser is required to raise the pressure until it is equal to that of the atmosphere.

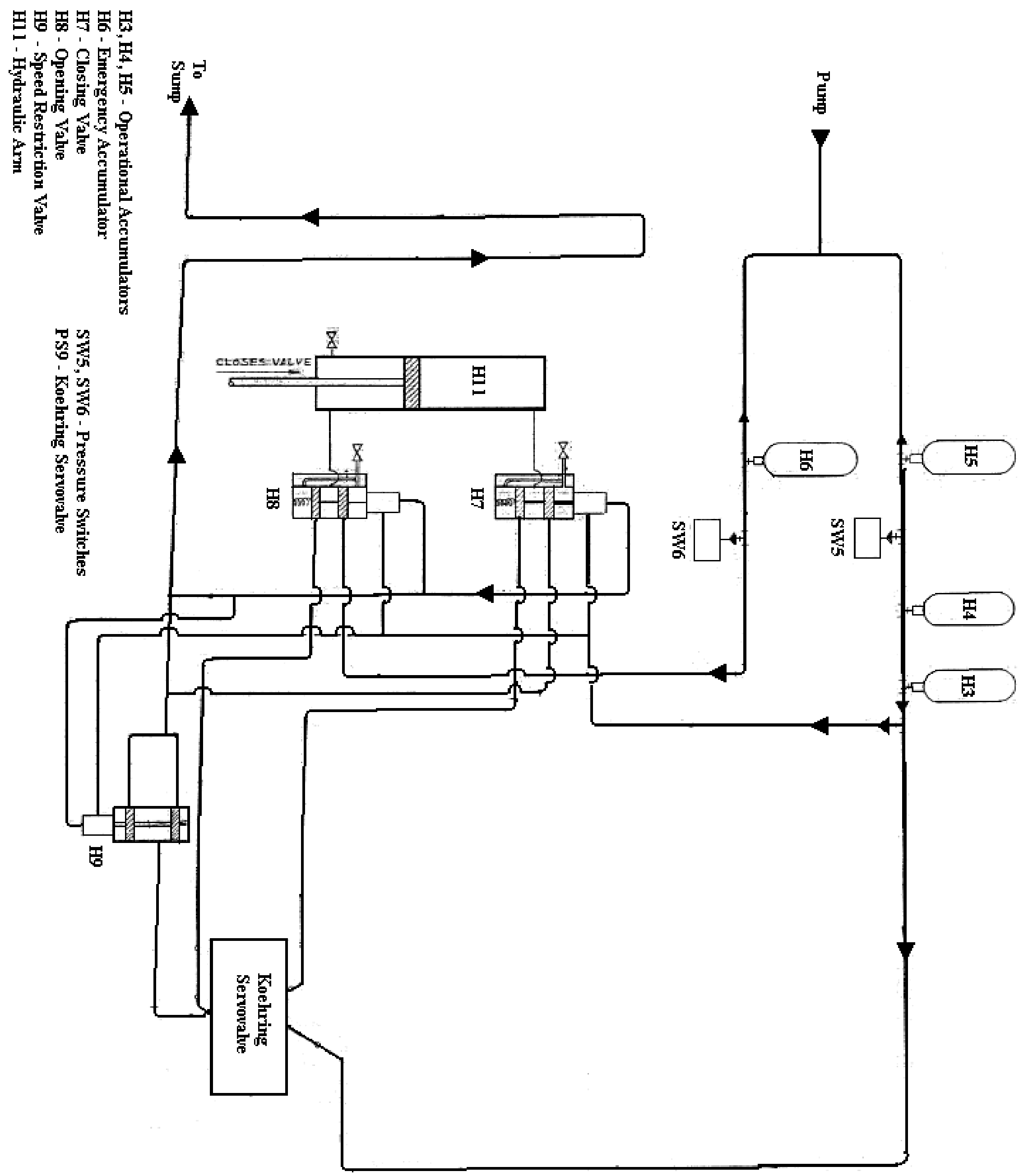

Figure 2 Hydraulic Piping Diagram

The hydraulic system that controls the valves is shown in Figure 2. The butterfly valves controlling the inlet and exit to the tunnel are controlled by hydraulic arms; there is an emergency gate valve upstream of the inlet valve which is operated by the same valve as the exhaust valve. The purpose of the emergency gate valve is to prevent accidental opening of the inlet valve to pressurize the tunnel. The hydraulic pump is a Racine model capable of pressurizing the system to 500 psi. There are two 10 gallon and three 5 gallon hydraulic accumulators. One of the five-gallon accumulator tanks is used for emergency shutdown, another five-gallon accumulator is used for the exhaust butterfly valve and emergency relief valve, and the remaining tanks are the normal operating tanks for the inlet butterfly valve.

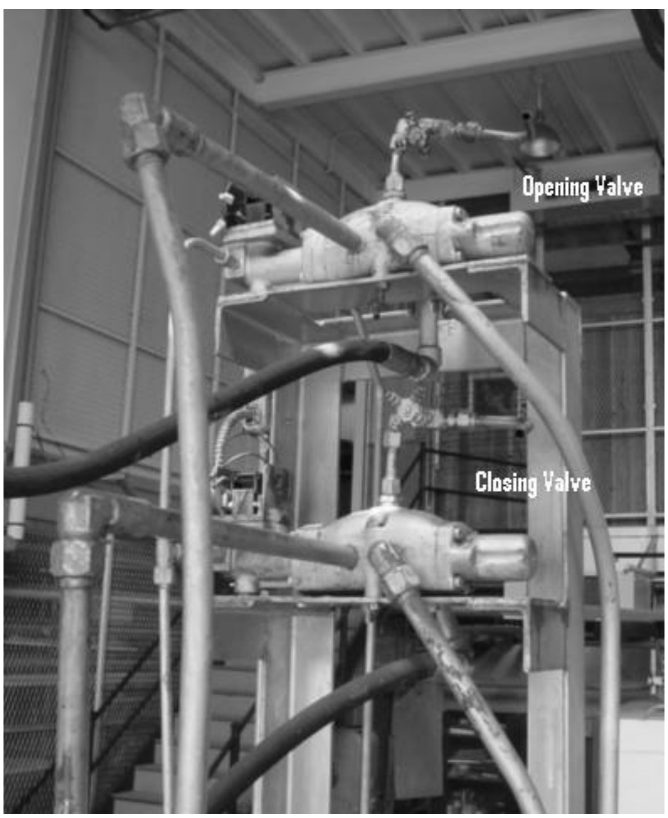

Figure 3 Tower with Opening and Closing Safety-Interlock Valves.

There is a tower located adjacent to the inlet butterfly valve with three Racine 4-way solenoid-activated hydraulic valves as shown in Figure 3. These valves are used to control the hydraulic arm that opens and closes the inlet butterfly valve. The bottom valve shown in Figure 4 is used to control the maximum operating speed of the butterfly valve by directing the return flow of hydraulic fluid through a smaller line that restricts the flow, or a larger drain line which does not. The restricting valve is automatically activated when the main power to the tunnel is turned on; should the main power be turned off the speed restriction valve will be unable to slow the closing speed of the butterfly valve. Currently, there is no way to prevent the inlet butterfly valve from closing at full speed if power is lost. This may have been a causal factor in the previous seat failure, and contributed to the failure of a collar on the shaft of the control valve in the current configuration.

Figure 4 Speed-Restriction Valve and Servovalve

During normal operation, when the butterfly is near the seat, the solenoid activates the restricting valve to limit the speed of the hydraulic arm controlling the butterfly valve. This is done to ensure that the butterfly valve does not close with such force that it damages the seat. Once the butterfly valve has been rotated a set amount the solenoid deactivates the valve and the hydraulic arm may move at its maximum speed of operation. The upper two valves shown in Figure 3 are activated by the safety-interlock system and their normal operation is simply to allow the hydraulic arm to move under control of the servo module. Should these two solenoids be deactivated either through power loss or by user command the butterfly valve will automatically shut as these solenoids direct the drain from the opening side of the hydraulic actuator, while simultaneously applying pressure and flow of fluid from the aforementioned accumulator to the closing side of the actuator. Shutting the butterfly valve in this manner can lead to eventual damage to the seat, however, since the lower valve will not inhibit the closing speed near the seat.

In summary, the operation of the tunnel from a physical standpoint is as follows. The desired set of nozzle blocks are placed in the test section and the hatches are bolted in place. The air tank is pressurized to approximately 125 psi by the compressor. The hydraulic pump is turned on and brings the pressure in the accumulator tanks to a pressure of between 425 psi and 475 psi and the sting is set at the desired angle of attack. The exhaust butterfly valve is opened while the gate valve is closed. The last preparatory step is to manually remove the metal pin preventing the butterfly valve from moving when the tunnel has no hydraulic pressure. At this point all the physical requirements to run the tunnel have been met. The butterfly valve will now be opened at the user’s command, slowly when in proximity to the seat then at normal speed. Once the run has been completed the butterfly valve will close, the metal pin will be reinserted, the exhaust valve will be closed and the relief valve opened, the hydraulic pump turned off, and the accumulator tanks drained.

Control System

There exist two major divisions within the control system: one actively controls and takes data and the other passively monitors the tunnel to keep it within operational parameters. The active portion of the control system consists of a computer, a Pegasus Servo System Module, a Koehring Pegasus Servovalve, a modified Statham PL131TC pressure transducer mounted on the settling chamber, a slide potentiometer, and a pair of PCI-6024E Digital Acquisition cards. Collectively the channels running from the computer in the Wind Tunnel Control Room (WTCR) to the Pegasus SSM and sensors are called signal lines. The passive branch of the control system consists of an HP 3495A scanner multiplexer, the computer, the supersonic tunnel control cabinet, various sensors throughout the tunnel, and the two uppermost 4-way hydraulic valves mounted on the tower. Figure 5 illustrates the safety interlock system of the tunnel.

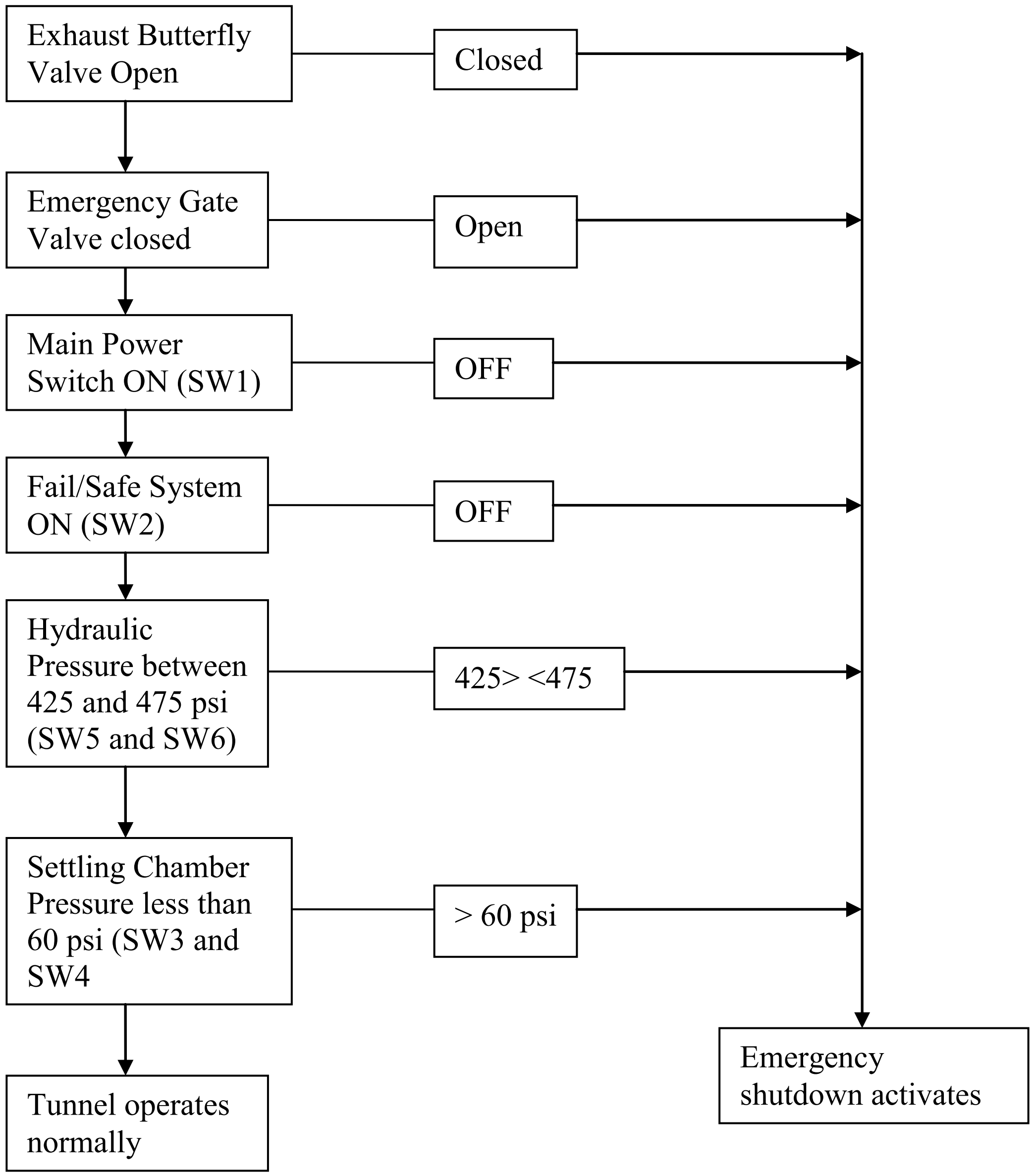

Figure 5 Flowchart of Tunnel Fail/Safe System.

The left column shows the required status of each element for tunnel operation. If, during the course of a run, any status changes to that indicated in the right column then the emergency shutdown activates.

Switches one and two can be activated either from the control cabinet or through the HP 3495A scanner. The scanner is used during normal operations of the tunnel by switching channels 0-3 of decade 5 closed or open. Decade refers to the multiple sets of ten wires within the HP 3495A scanner that can be open or closed. The lines used to control the interlock system are collectively called control lines. Cable E/I runs from the HP3495A scanner and must be connected to slot E in the WTCR to enable connectivity which can then be used to activate the interlocks. Channel 0 is SW1 on, channel 1 is SW2 on, channel 2 is SW1 off, and channel 3 is SW2 off. The wiring diagram for the terminal board mounted on the control cabinet is shown in Table 1.

Table 1 Wiring Table for the WTCR

Terminal Board IN

Row	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	Br	G	Sh	W	G	Sh			Bl	W	B	Y	B	Br	B	O	B	Bl	B	G	B	W	B	R
2	R	W	Sh	R	Bl	Sh	O	G	Sh	R	B	Sh	R	O	Sh	R	G	Sh	Br	B	Sh	Y	G	Sh
3	Br	R	Sh	Y	R	Sh	W	R	Sh	O	R	Sh	G	R	Sh	Bl	R	Sh	W	G	Sh	O	G	Sh
4	Bl	B	Sh	R	Br	Sh	Y	R	Sh	G	Bl	Sh	Bl	W	Sh	Y	B	Sh	O	B	Sh	G	B	Sh
5	Bl	G	Sh	Br	G	Sh			Bl	W														

Control Room OUT

Cable	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
H/M									O	B	Bl	B	Y	B	Br	B	W	B	W	R	B	R	G	R
B	R	G	R	B	R	W	B	W	B	Br	B	Y	B	Bl	B	O	B	G						
A	O	B	Sh	Y	B	Sh	G	B	Sh	Br	B	Sh	W	B	Sh	B	R	Sh	G	R	Sh	W	R	Sh
E/I	O	B	Sh	Y	B	Sh	G	B	Sh	Br	B	Sh	W	B	Sh	B	B	Sh	G	R	Sh	Sh	R	Sh

B-Black
Bl-Blue
Br-Brown
G-Green
O-Orange
R-Red
Sh-Shield
W-White
Y-Yellow

Row 3 = SST Signal Line
Row 4 = SST Control Line
Cable A = Connects to DAQ card
Cable E/I = Connects to HP3495A scanner for SST

Table 1 shows the wiring connections from the DAQ cards and 3495A scanner within the WTCR to the terminal board mounted on the side of the control cabinets. The lines labeled Control Room OUT are signal lines inside the WTCR while those lines labeled Terminal Board IN are for the lines running from the WTCR to the terminal board mounted on the control cabinet. The cables within the WTCR consist of eight shielded pairs with a 26-pin connector manufactured by Amphenol attached to one end. This connector corresponds to another 26-pin connector in slot of the WTCR which is hardwired to a terminal board, for the tunnel this is the terminal board mounted on the side of the control cabinets. Table 1 simply shows the changes in color of the different wires between the two terminal bodies which occurs at the connectors. From the control cabinet additional signal lines can be attached to run DMA, and the interlocks are connected to the computer.

The standard way of activating the interlock system is by commanding the scanner to close all four channels then releasing SW1 off and SW2 off. Closing these switches energizes the 4-way valves with 110V current. Functionally holding channels 0 and 1 closed is the same as holding the manual buttons down on the control cabinet. This proved problematic during one dry run when the interlock system tried to shut the tunnel down, but the computer was holding the switches shut. Switch one provides power to the relays while switch two powers the two uppermost hydraulic valves on the tower, which control the hydraulic arm and the inlet butterfly valve. The power to activate these valves must pass through a pair of Barksdale Valve 420E-20 pressure switches located at the settling chamber and a pair of Barksdale Valve 9612-2-H pressure switches that read the hydraulic pressure in the accumulator tanks. Should the pressure in the settling chamber rise over 60 psi or the hydraulic pressure in the tanks fall below 425 psi the power to the 4-way valves will be interrupted and the tunnel will automatically shut down as previously detailed in the system description. Should the interlock system shut the tunnel down it will do so by deactivating these two hydraulic valves which will automatically close the inlet butterfly valve. Switches three and four are located on the side of the settling chamber and will shut the tunnel down if the pressure is greater than 60 psi. Switches five and six are located at the accumulator tanks and determine whether the hydraulic pressure is within the acceptable limits of 425 psi and 475 psi. Additionally, the exhaust butterfly valve must be opened and the emergency relief valve shut in order to even start the tunnel. The final safety interlock is the valve pin removal. During dry run testing of the tunnel it was found that the hydraulic pump did not have to be on for the safety interlock system to activate provided sufficient hydraulic pressure is maintained by the accumulator. It was also found that the switches measuring the pressure in the accumulator tanks will not attempt to shut the tunnel down until the pressure in the hydraulic accumulator is 350 psi, or lower.

The program controlling the tunnel is written in LabView 8.2 and can be found in Appendix A. The control program has several sub-VIs which act as subroutines to perform several discrete functions. Among these is accepting the user-defined input variables (SSTInit.vi), stopping the tunnel (SST Stop Tunnel.vi), outputting the data obtained from DMA (SST Output.vi), releasing the interlocks (SST RELEASE INTERLOCKS.vi), and providing a checklist for start-up (SST CHECKLIST.vi). The control program as a whole performs four main tasks: specifying a command voltage to the Pegasus SSM, reading the feedback voltage from the settling chamber pressure transducer, performing Direct Memory Access on the eight signal lines, and controlling the activation of the interlock system. The LabView program reads the data by using a pair of PCI-6024E Digital Acquisition cards. The first DAQ card is tasked with DMA and specifying a command voltage to the Pegasus SSM. The second DAQ card is only tasked with reading the feedback voltage from the Pegasus SSM. The reason for this division of responsibilities between the two DAQ cards is because they must perform mutually exclusive tasks. A DAQ card cannot both take DMA data and use the same data in a foreground operation; likewise the same DAQ card cannot take active readings on an input voltage and specify a command voltage simultaneously. The DAQ cards are configured to measure differential voltages between the low and high side of particular channels. Analog signals are then converted to digital numbers for the computer to read.

Figure 6 WTCR Showing Connection slot, HP 3495A Scanner, and Netscanner

Figure 6 shows the WTCR with the connection slot mounted on the wall to the left, the computer, and the HP 3495A scanner. The signal lines connecting the DAQ cards to the tunnel run through cable A into slot A of the WTCR. From there the lines run to the terminal board mounted on the side of the control cabinet. The signal line channels, names, and functions are shown in Table 2.

Table 2 Signal Channels and a Description of Their Tasks

Signal Line	Input	Description
Channel 0	SSM IN	Pegasus SSM commanded voltage
Channel 1	SSM Meter	User-determined output from the Pegasus SSM; usually Error, but Compensated Error, Valve Current, Feedback, and others are also possible outputs.
Channel 2	Valve Position	Angle of the inlet butterfly valve as measured by the 4-inch slide potentiometer
Channel 3	SSM OUT	Pressure transducer voltage that has been amplified and calibrated to be a tenth of the settling chamber pressure
Channel 4	Tank Pressure	Measures the air tank pressure with a 500 psi pressure transducer
Channel 5	Available	Currently unused
Channel 6	Available	Currently unused
Channel 7	Servo Signal	Measures the AC signal sent to the inlet butterfly valve; this channel is generally unused and therefore disconnected

The LabView program as it is currently configured records whatever is connected to these eight channels at 1 kHz per channel for ten seconds regardless of the length of the tunnel's run time through a predefined task. This task can easily be modified using the NI-MAX.

The Pegasus SSM is the primary component of the active control system. The LabView program has little control over active operations other than to specify a command voltage for the Pegasus SSM. The Pegasus SSM compares the command voltage to the feedback voltage and adjusts the inlet butterfly valve accordingly. The Pegasus SSM's response can also be altered through adjustment of gain and rate stabilization. Gain affects the amplitude of the system response while rate stabilization affects the time of the response. With systems that have long run times it is possible to optimize the gain and rate stabilization values through traditional closed loop techniques. Since the tunnel has a short run time due to the limited amount of pressurized air available, closed loop optimization is not possible. Instead, useable values for the gain and rate stabilization are arrived at through a process of trial and error. The Pegasus SSM accepts user-defined inputs for the gain, rate stabilization, amplifier balance, zero suppression, transducer balance, dither frequency, dither amplitude, and various others through a series of 25-turn potentiometers on the front panel. The Pegasus SSM dithers the inlet butterfly valve signal in an attempt to ensure that the response time of the system is not affected by the static friction of the butterfly valve. The dither frequency can be measured by the servo signal line on channel 7 and is currently arbitrarily set to approximately 110 Hz.

The pressure transducer mounted on the side of the settling chamber is a Statham PL131-TC. It has been placed into the circuit shown at Figure 7 for zeroing purposes. The addition of the 20 kΩ potentiometer and 25 kΩ resistor as a voltage divider in the manner shown allows the transducer to be zeroed for atmospheric pressure.

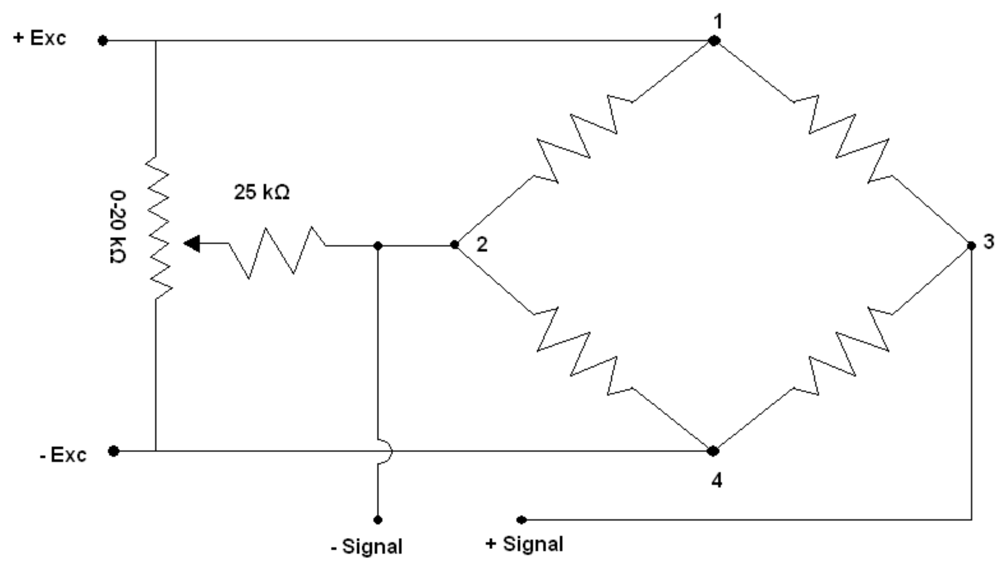

Figure 7 Modified Statham PL131TC Wiring Diagram.

The excitation voltage is determined from the following equation and Table 3 (Koehring).

Table 3 Figure 403 from the Pegasus Manual Tabulating Gain Values

Resistor Gain (Ω)	Gain
100	1000
200	500
500	200
1K	100
2K	50
5K	20
10K	10
20K	5
50K	2
100K	1

$$V_{out} = \frac{ML}{C} \cdot S \cdot V_{exc} \cdot Gain \tag{1}$$

where:

ML = maximum load in a specific test (psi)

C = rated capacity of the transducer (psi)

S = output at rated capacity (Volts)

Gain = feedback gain used to determine resistance

An initial excitation voltage is chosen and the resistor gain is determined and then figure 403 of the Pegasus SSM manual is used to provide the nearest resistor value to the calculated gain value. The same equation is then reused to find the excitation voltage necessary for a particular maximum desired output voltage using the desired precision gain resistor. As the system is currently set up the gain resistor has a value of 100 Ω and an excitation voltage of 6.54 V. When the transducer was recalibrated for this project the value of $V_{out}/psi/V_{exc}$ was found to be 0.000157 for a 7 V excitation and 0.000152 for a 5 V excitation. These values agree very well with the previous value of 0.000154 $V_{out}/psi/V_{exc}$ (Koehring).

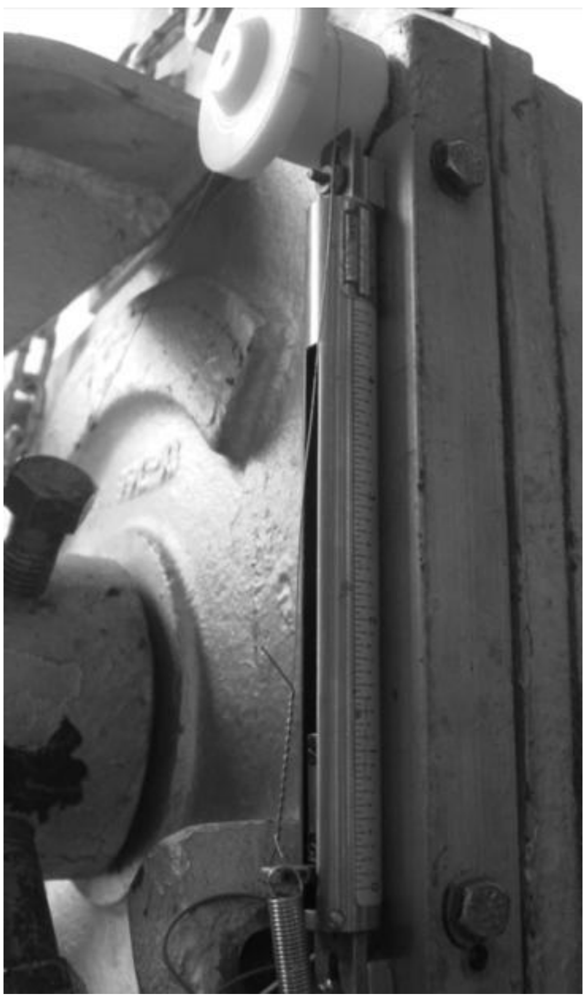

Figure 8 Potentiometer Used to Measure Valve Position

Valve position is now determined by the 4-inch slide potentiometer shown in Figure 8 which is connected to the shaft of the butterfly valve. The measurement of the valve position has no effect on the control system of the tunnel as it currently is, but this has not always been the case. When the tunnel was first constructed a user would read the settling chamber's pressure and manually control the angle of the inlet butterfly valve. Later the system was altered slightly; instead of a manual control, an analog computer would automatically adjust the butterfly valve angle through the use of a servomotor (Overall).

The active control system continuously monitors the settling chamber pressure while simultaneously providing the Pegasus SSM with a command voltage. The command, error, valve position, and feedback voltages are meanwhile being recorded with DMA. These are both done within the LabView 8.2 control program as a foreground process in the case of monitoring the feedback voltage and specifying the command voltage, and as a background process with regards to DMA. The entire process of actively controlling the tunnel is done while the various passive safety systems are powered and operating to ensure that the tunnel, its operators, and any bystanders are unharmed during testing.

CHAPTER 3

TEST METHODOLOGY

When first begun it was uncertain whether the tunnel would again be capable of operating using the large test section since the previous test section used in the current blowdown configuration had been much smaller. The former test section was a thirteen inch pipe connected to the end of the settling chamber which was connected to a nozzle only three inches wide and three inches tall. The larger test section was put in place in order to increase the utility of the tunnel. Part of this project was determining whether the desired velocity within the test section could even be achieved and maintained long enough to stabilize the flow. Additionally a set of procedures and parameters for start-up of the tunnel that maximized run-time also had to be found and implemented.

Start-up Parameters

In order for the tunnel to operate properly the flow must be choked in the nozzle throat. Tunnel run time can be extended if the flow can be choked relatively quickly. The original start-up procedure for the tunnel was to simply open the inlet butterfly valve to a set position then manually adjust the valve to achieve the desired settling chamber pressure. Later a “bang-bang” approach was used with the Pegasus SSM. This means that the Pegasus SSM is ordered to reach the maximum settling chamber pressure, then at a certain percentage of the desired settling chamber pressure the inlet butterfly valve is ordered shut. When the pressure within the settling chamber peaks the Pegasus SSM is given the command voltage corresponding to the desired settling chamber pressure. The fraction of the desired settling chamber pressure at which the Pegasus SSM is given a zero voltage is called the cutoff coefficient. The time between the Pegasus SSM receiving a zero command voltage and the desired settling chamber command voltage is referred to as the cutoff time. This method of starting the tunnel was used during this project, but other methods can be used. Previous start-up procedures attempted have included a ramp-up of the command voltage and elimination of a user-defined cutoff time. Eliminating the cutoff time requires that the computer instead actively track the rise and fall of the settling chamber pressure; once the pressure begins to fall the desired command voltage is sent to the Pegasus SSM. Ramping up the command voltage was found to work too slowly and was thus discarded as a start-up method (Hannigan). Allowing the computer to determine the cutoff time by monitoring for the peak pressure has merit, but spikes in the data caused by background noise might cause the system to react prematurely. Figure 10 shows the standard start-up procedure using the “on-off-on” approach.

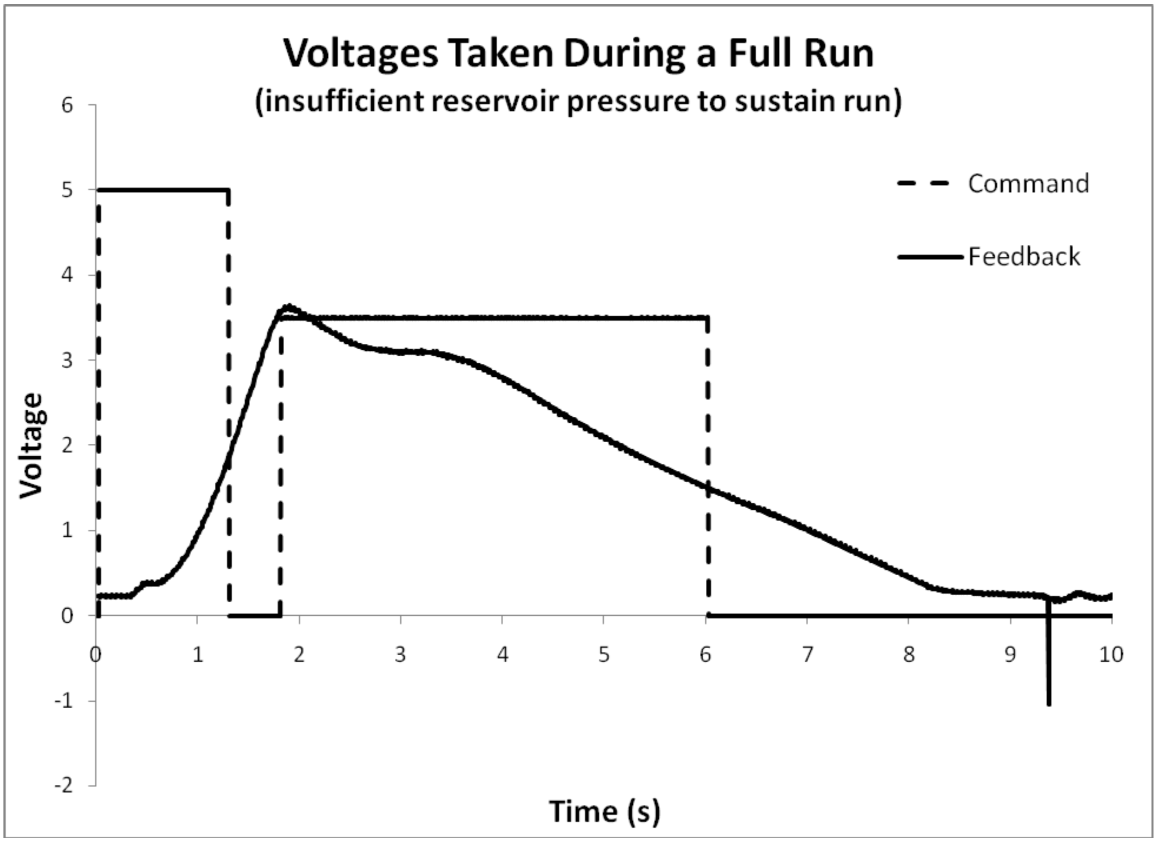

Figure 9 Voltages Corresponding to the Command and Feedback during Start-up

As can be seen in Figure 9, even with the cutoff command, the resulting peak pressure will still be much higher than the value at cutoff. Resuming the command at that peak pressure is an effort aimed at using the Pegasus SSM to maintain the peak value through its gain and rate stabilization functions. In this instance, there was insufficient reservoir capacity to sustain the run, and even though the Pegasus SSM commanded the valve to its fully-open position, the pressure continued to drop in a linear fashion as the reservoir emptied.

The process used to determine the cutoff coefficient and cutoff time is arrived at through a process of trial and error. A modified version of the control program (COFFcal.vi) was created to determine the cutoff time and cutoff coefficient. The sub-VI

SST INIT.vi accepts user-defined values for the cutoff times and coefficients. COFFcal.vi sends a 5 V command to the Pegasus SSM until the given cutoff coefficient is reached at which time a 0 V command is sent. Analysis of the recorded data shows a distinct peak in the settling chamber pressure. Figure 10 shows an example of the data taken using the COFFcal.vi program.

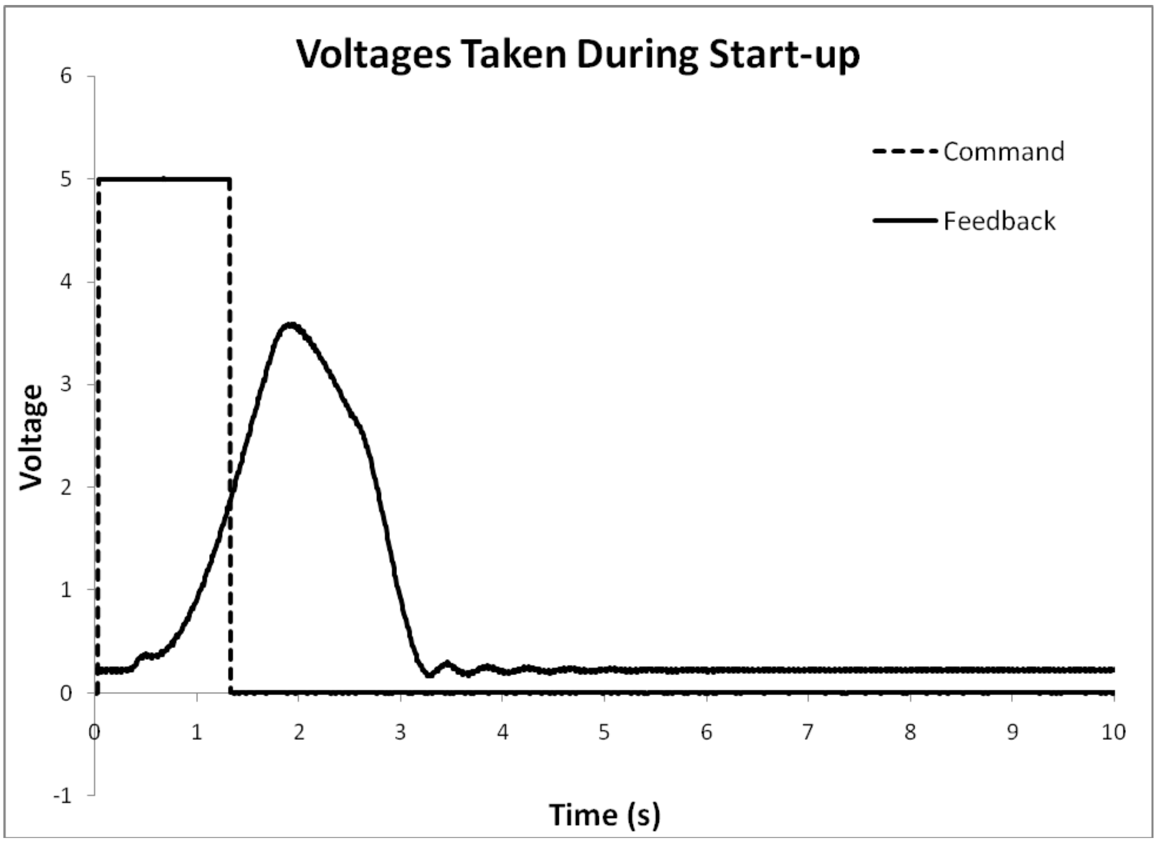

Figure 10 Command and Feedback Voltages Used to Determine Start-up Parameters

After examination of the data the cutoff coefficient is adjusted to either raise or lower the settling chamber pressure to the desired value. The cutoff time can be determined once the peak of the settling chamber pressure is approximately the same as the desired settling chamber pressure. The cutoff time is found by determining the difference in time between the 0 V command signal being sent and the time of peak response within the settling chamber. Currently the desired settling chamber pressure is 35 psi, to increase run-time, but higher pressures are quite feasible. Should the gain or rate stabilization of the system be adjusted, the entire process of determining the cutoff time and cutoff coefficient would have to be redone. Also, the system response varies greatly with changes in the reservoir pressure. This will have an immediate effect on the peak pressure for a given cutoff value, as well as determining the response as the pressure falls off. The tunnel can be brought to a desired settling chamber pressure of 35 psid within two seconds with the gain set to maximum, but previous reports mention the desired pressure being reached in approximately one second (Hannigan). However, the system used previously had a much smaller throat area which enabled the flow to be choked in much less time.

Nozzle and Test Section Characteristics

The Mach number throughout the nozzle can be verified experimentally through the use of pressure data. Pressures taken from the taps located in the sidewalls of the nozzle are used in the isentropic pressure equation, given as:

$$\frac{P_0}{P} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \qquad (2)$$

where:

P_0 = Settling chamber pressure

P = Measured pressure at a pressure tap

γ = Ratio of specific heats; for air γ=1.4

M = Mach number for a given pressure ratio

Within the test section the Rayleigh-Pitot formula must be used since the Pitot probe is behind a normal shock. The Rayleigh-Pitot formula is given here as Equation 3.

$$\frac{P_{0,2}}{P_1} = \left(\frac{(\gamma+1)^2 M^2}{4\gamma M^2 - 2(\gamma-1)} \right)^{\frac{\gamma}{\gamma-1}} \frac{1-\gamma+2\gamma M^2}{\gamma+1} \quad (3)$$

where:

$P_{0,2}$ = Stagnation pressure behind the normal shock

M = Mach number immediately before the normal shock

P_1 = Static pressure immediately before the normal shock

γ = Ratio of specific heats; for air γ=1.4

Within the test section Equation 3 is used because it can accurately predict the stagnation pressure behind a normal shock while the isentropic pressure equation cannot.

It is assumed that the nozzles were designed through the use of the method of characteristics, but for the purposes of this project a different method was used for analysis. A theoretical Mach profile for the nozzle can be found through the Area-Mach relationship shown here as Equation 3.

$$\left(\frac{A}{A^*} \right)^2 = \frac{1}{M^2} \left[\frac{2}{\gamma+1} \left(1 + \frac{\gamma-1}{2} M^2 \right) \right]^{\frac{\gamma+1}{\gamma-1}} \quad (4)$$

where:

A = Given cross-sectional area within the nozzle

A^* = Throat area for the nozzle

M = Mach number corresponding to a given area

The cross-sectional area for a location within the nozzle corresponding to a tap must now be determined. This can be done with several methods: the two used here are cubic spline interpolation and the direct method. The nozzle blocks are constructed by welding vertical pieces of aluminum with varying height to a sheet of steel that is molded to match the vertical members. A thin sheet of aluminum is then bonded to the top of the steel. It is this sheet of aluminum molded to the upper surface that forms the contours of the nozzle. Figure 11 illustrates the structure of a nozzle block.

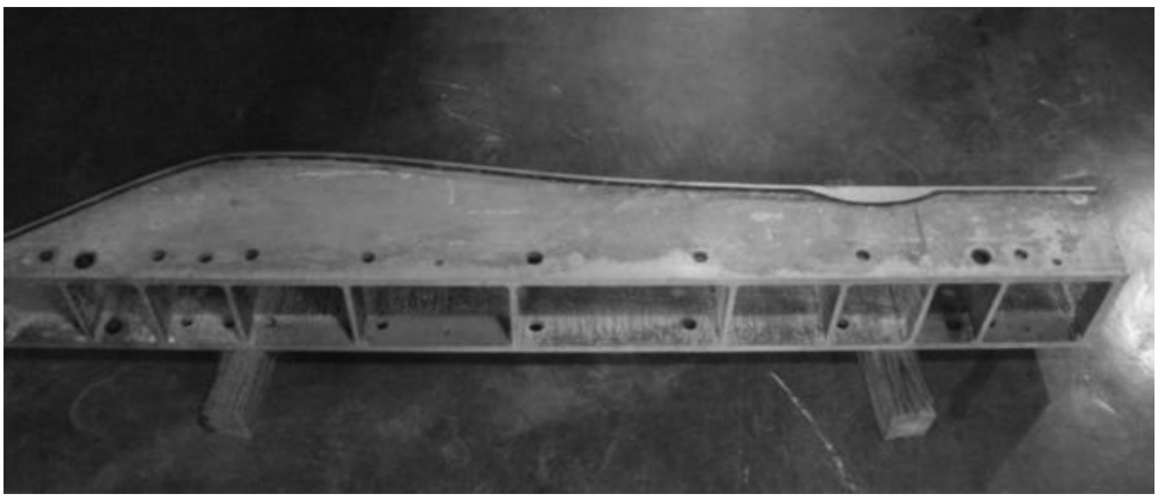

Figure 11 Nozzle Block Showing the Internal Structure

Cubic spline interpolation was performed using heights measured at one inch intervals along the nozzle block. The distance from the inlet to each pressure tap is measured. The nozzle height is then measured at the tap location. From there it is a simple matter to find the exact cross-sectional area of the nozzle and to use Equation 4 to determine the Mach number at the location of each pressure tap. Although the method of cubic splines is reasonably accurate and can give a solution for every point within the nozzle, only the ten locations corresponding to pressure taps are truly needed. A direct method does exist for determining the height of the nozzle at each pressure tap. Since the distances from the inlet to the pressure taps are known when the nozzle blocks are removed from the test section the nozzle block height is measured at those distances. It is an easy matter to then measure the height of the outline at the location corresponding to a pressure tap and use Equation 4 to determine a Mach number. Also, since the pressure taps located in the hatches are at a constant area section, the heights corresponding to their locations were not measured. Rather, it is assumed that both the Mach number and pressure ratios are the same as those measured at the tenth tap since it shares the same area ratio. The sole exception to this is using the Pitot-static probe within the test section, which requires the use of Equation 3. The cubic spline method's nozzle contour prediction was found and compared to the real vertical height at the pressure taps and is shown in Figure 12.

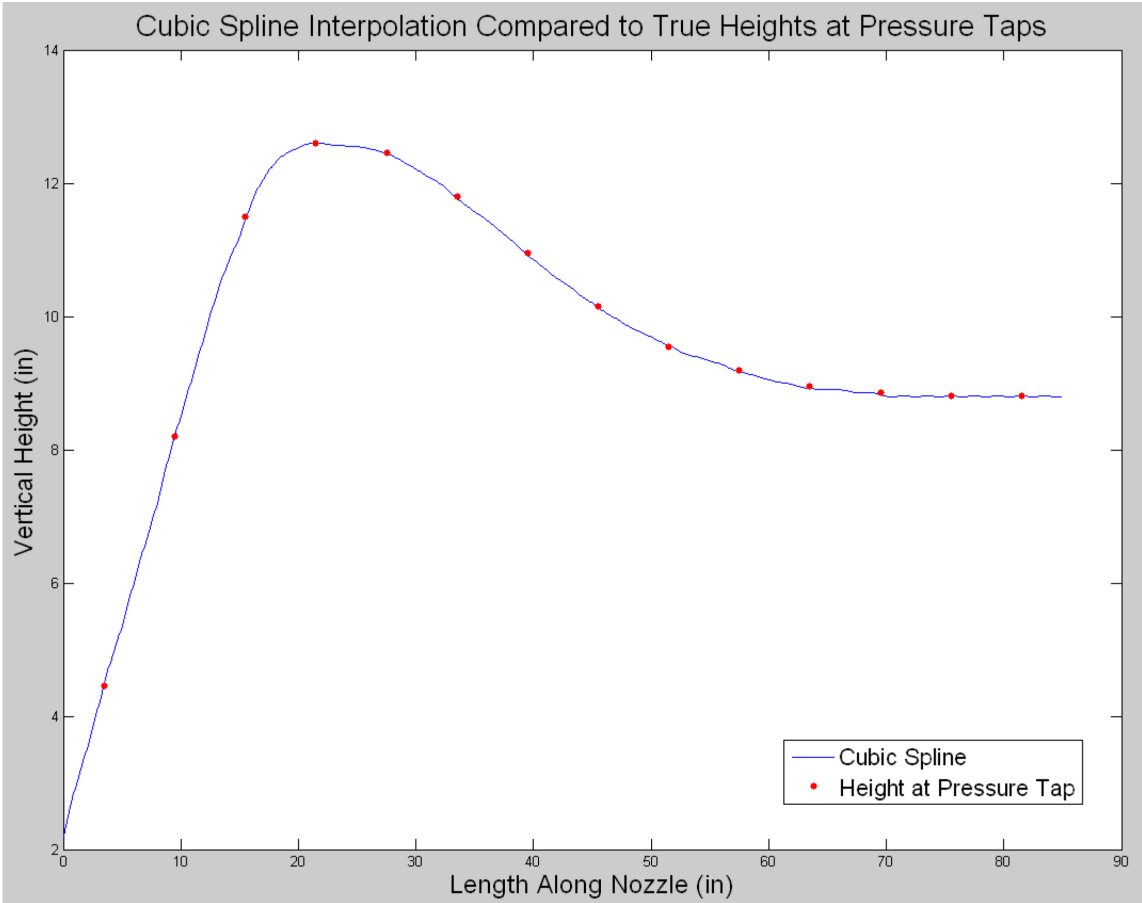

Figure 12 Comparison of Cubic Spline Interpolation to the Height at Pressure Taps

The largest relative error between cubic spline interpolation and the direct method was 0.8%. Using both the measured and the calculated heights the Mach numbers and pressure ratios at the pressure taps were calculated using Equations 2, 3 and 4. The results for the predicted pressure ratios are shown in Figure 13.

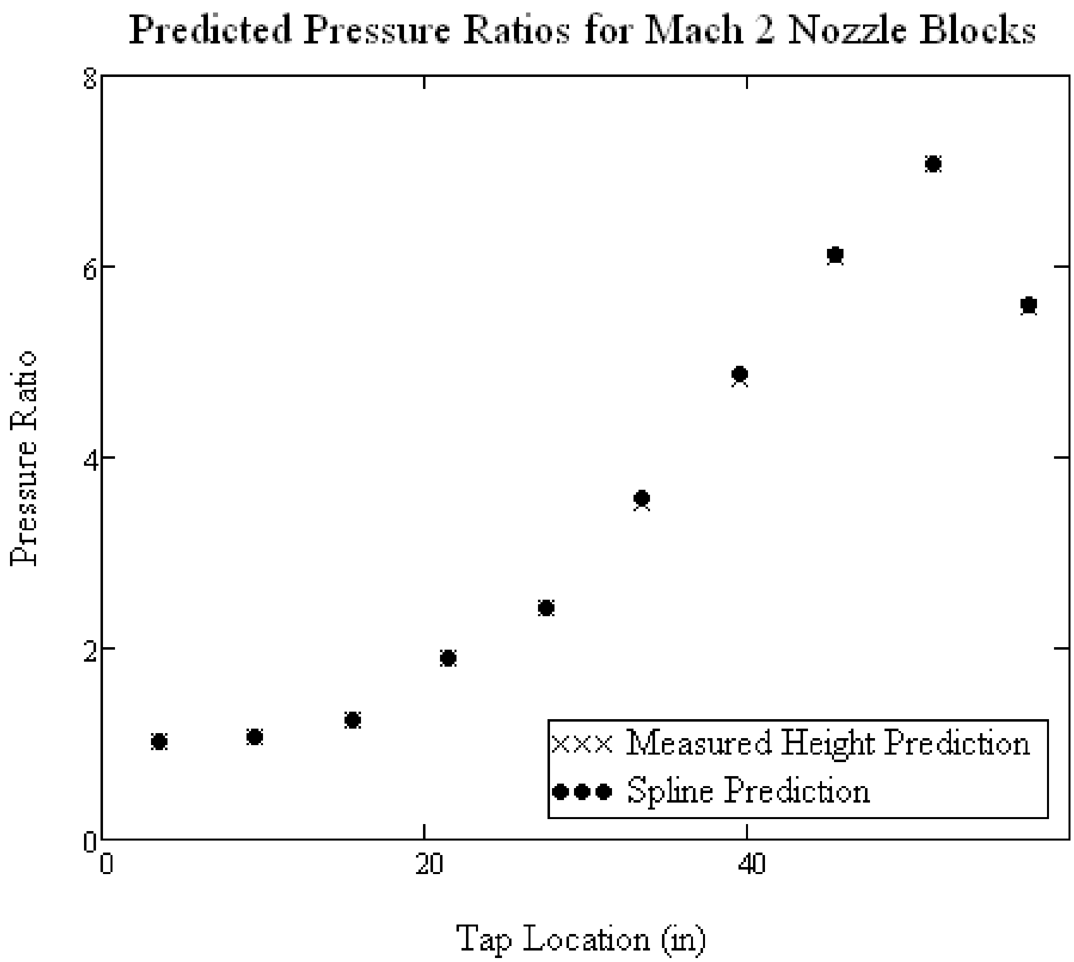

Figure 13 Predicted Pressure Ratios at each Pressure Tap

It should be noted that the last predicted pressure ratio in Figure 14 is for the pressure ratio using the stagnation pressure measured by the Pitot probe and the static pressure measured immediately upstream of the bow shock produced by the Pitot probe. Therefore, the last predicted pressure ratio uses the Rayleigh-Pitot formula given in Equation 3 to predict the pressure ratio instead of the isentropic pressure equation. The largest relative error between the direct method and cubic spline interpolation was 1.21%. Any measured pressure data can be expected to fall reasonably close to the predictions provided that the nozzle was functioning correctly. While cubic spline interpolation is not used for predicting the pressure values it can be used to determine a theoretical Mach number profile of the nozzle.

Two intelligent pressure scanners (so called because they measure pressure and convert to a digital signal) are used to read the pressures from the ten taps located in the sidewall of the test section, the four taps located in the hatches, the pitot probe mounted on the sting, and the settling chamber pressure. These two pressure scanners are connected to a Pressure Systems 9000 distribution box which provides the pressure scanners with power via Ethernet connectors. This distribution box is in turn connected to a hub to which the computer is also connected via Ethernet cable. Only one of the pressure scanners was used in the current set-up, but because the control program was modified to take data from two pressure scanners the second is also connected to prevent the computer from attempting to communicate with an unconnected device. One of the pressure scanners is capable of measuring up to 100 psi on its sixteen channels, but the other can only take pressure this high on eight of its channels. The other eight are only rated to measure up to 45 psi, but because this pressure scanner was not used to make actual measurements this did not affect the tests.

The control program had to be modified slightly from that described in chapter 2. In addition to performing DMA on eight channels, actively monitoring the feedback voltage, and providing a command voltage, the program must also take pressure samples with the pressure scanners. With the current manufacturer supplied library of device driver libraries (sub-VI’s) for LabView 8.2 the pressure scanners cannot be addressed in a background process; therefore, DMA cannot be used with them. Instead, the pressures must be taken in a foreground process which necessarily slows the active control of the tunnel. Fortunately, it is not enough to slow the active control of the tunnel to a point at which it is dangerous to operate. Another feature of being unable to perform DMA with the pressure scanners is a great decrease in the sampling rate. Recall that for DMA the sampling rate can be arbitrarily set for A/D channels, and is currently set for 1 kHz. With regards to the pressure scanners dry runs of the tunnel show that data is only retrieved from the pressure scanners on average once every 0.12 seconds; however, this is still sufficient to determine whether the nozzle is performing as desired. The pressure scanners are actually capable of throughput rates of 500 Hz with a buffer defaulted to the previous eight samples (Esterline). It is the values within this buffer that are read to the computer. These values are then used with Equation 2 to determine whether the nozzle is functioning as it should.

CHAPTER 4

TESTING RESULTS

Although many problems arose in the process of gathering usable pressure data, enough exists to determine whether the tunnel was performing as designed. The problems as currently known are given along with their respective solutions. The method used to validate the tunnel with the rather limited amount of pressure data available is also explained along with the conclusions drawn from it.

Problems Acquiring Data

Once the tunnel was made operational in 2008 it was assumed that extensive amounts of pressure data would be gathered to determine whether the tunnel was performing as it should. Unfortunately, this did not occur. Almost immediately after the tunnel was made operational the compressor experienced a broken diaphragm valve. After the valve was replaced it was found the pipeline connecting the compressor to the air tank was leaking. This prevented the pressure within the tank from rising above 70 psi, and sometimes even that figure was not obtainable. Although this did not prevent the tunnel from being tested, it did prevent long, sustained runs. Even a six-second run with the Mach 2 nozzle would drop the pressure in the tank to less than 10 psi. The delay caused by replacing the pipeline was used to track down the various sources of signal noise and reduce their effect upon the data. A large spike in the voltages measured was visible when the butterfly valve passed through a point near the seat. This spike is shown in Figure 14.

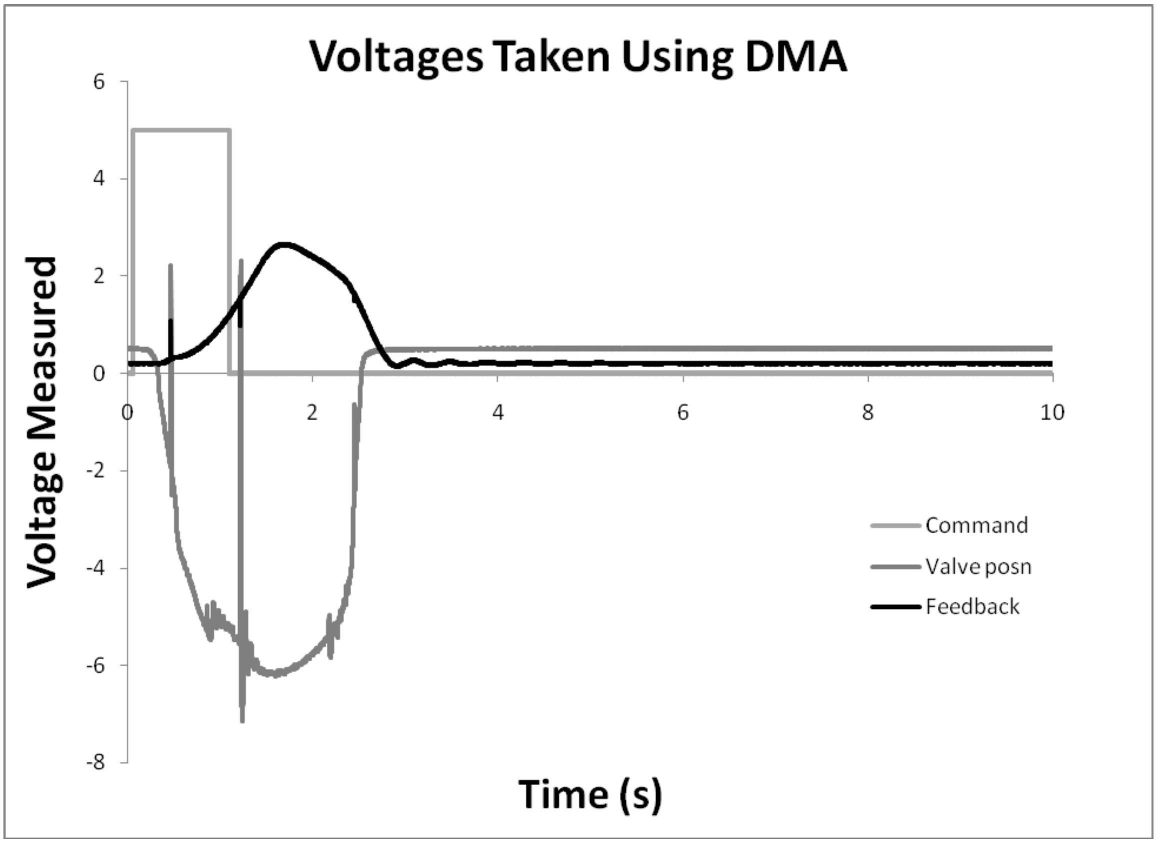

Figure 14 Data Taken during Tunnel Dry Run Illustrating the Spike near the Butterfly Valve Seat

It was originally assumed that the spike was caused by the switch deactivating the speed restriction valve since the spike occurred when the inlet butterfly valve was near the seat and the 110V switch controlling the valve was mounted near the signal lines used to transmit valve position data. Numerous attempts to eliminate the spike from the data were made at the butterfly valve, and these eventually culminated in replacing the Linear-Variable Differential Transformer with a slide potentiometer. Unfortunately, this step failed to eliminate the signal noise. The majority of the noise was finally eliminated by firmly grounding the control cabinets to the tunnel. This step eliminated the noise from dry runs, but during actual runs when the pressure within the settling chamber was rising, spikes within the various channels of A/D data were occurring. The problem was eventually found to be caused by intermittent power interruption emanating from the emergency settling chamber pressure switches. This was remedied by recalibrating and increasing their cutoff pressure. The delay caused by the leaking pipe was also used to replace the Mach 2 nozzle blocks with the Mach 4 nozzle blocks to increase runtime. The throat area for the Mach 2 nozzle blocks is approximately 93 in^2 whereas the throat area for the Mach 4 nozzle blocks is approximately 9.5 in^2. It was hoped that the large decrease in throat area would correspond to an increase in the tunnel run time. The only drawback to using the new nozzle blocks was the higher settling chamber pressure necessary to achieve Mach 4 flow.

As events proceeded it did not matter how much the run time was extended since on the first trial run the tunnel was rendered inoperable for a significant period of time. Within the linkage connecting the hydraulic arm to the inlet butterfly valve is a collar connecting two shafts. This collar is a machined cylinder with a keyway and four set-screws. At the corner of the keyway a crack had developed which eventually broke the collar on the maiden run of the Mach 4 nozzle blocks. This crack meant that the inlet butterfly valve was incapable of being closed fully since the collar could not transmit the necessary torque to shut the inlet completely. Currently a new design for the collar is being implemented which will minimize the chance of cracking within the collar.

It was intended to use the Mach 4 nozzle blocks to determine the gain and rate stabilization of the Pegasus SSM necessary to stabilize the tunnel for long runtimes. It was also intended to use pressure data from the Mach 4 runs to determine whether the tunnel was performing as desired. Since the tunnel did not function long enough to determine and implement the new start-up parameters, no pressure data were taken and no gain and rate stabilization values were found. This lack of pressure data meant that analysis had to be performed using pressure data taken from a series of Mach 2 test runs. Only two of these runs were made with pressure data taken from the taps within the nozzle itself; the rest were used when the tunnel was first made operational to verify the test section Mach number.

Nozzle Analysis

During the initial runs of the tunnel pressures were taken within the exit area of the nozzle by mounting a Pitot tube on the sting. Five runs were made in all before this configuration was changed. The Mach number was found using Equation 3 with the stagnation pressure being measured by the Pitot probe and the static pressure being measured by a pressure tap in the hatch which is immediately upstream of the Pitot probe. The Mach numbers calculated using the pressure ratios from this data are shown in Figure 15.

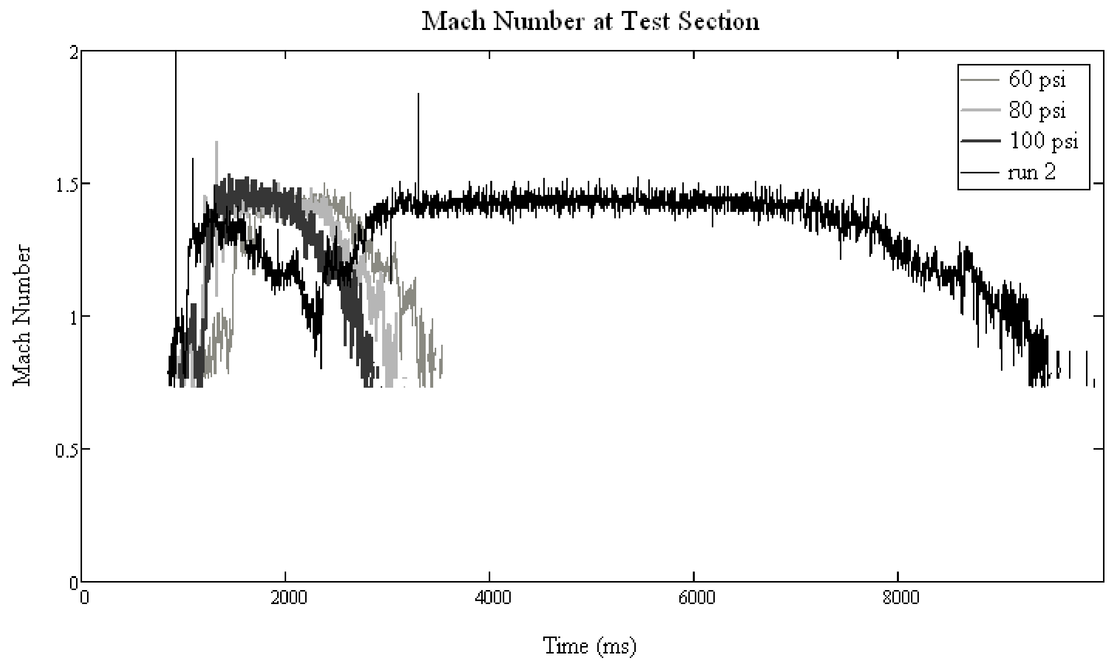

Figure 15 Mach Numbers Found During Early Runs

Regardless of the pressure within the air tank, all runs managed to achieve a test section Mach number of roughly 1.4 despite irregularities.

The pressure distribution along the nozzle was measured with the intelligent pressure scanner. The stable portion of the run was identified and the average pressure values were determined for each pressure tap within the nozzle, the settling chamber pressure, and the stagnation pressure measured by the Pitot tube mounted in the test section. The 9016 intelligent pressure scanners have an error as low as ±0.05% if properly zeroed and calibrated. Using this value along with the analysis shown in Appendix C the average error for the Mach number distribution is 2% if the percent variation of the ratio of specific heats is assumed to be 0.1%. If the uncertainty in the ratio of specific heats is neglected the general uncertainty is only 0.026%. It should be noted that these figures represent the lower bound of the error since the intelligent pressure scanners were not zeroed before use. The ratio of settling chamber pressure to static pressure for the nozzle has been plotted and is shown here as Figure 16.

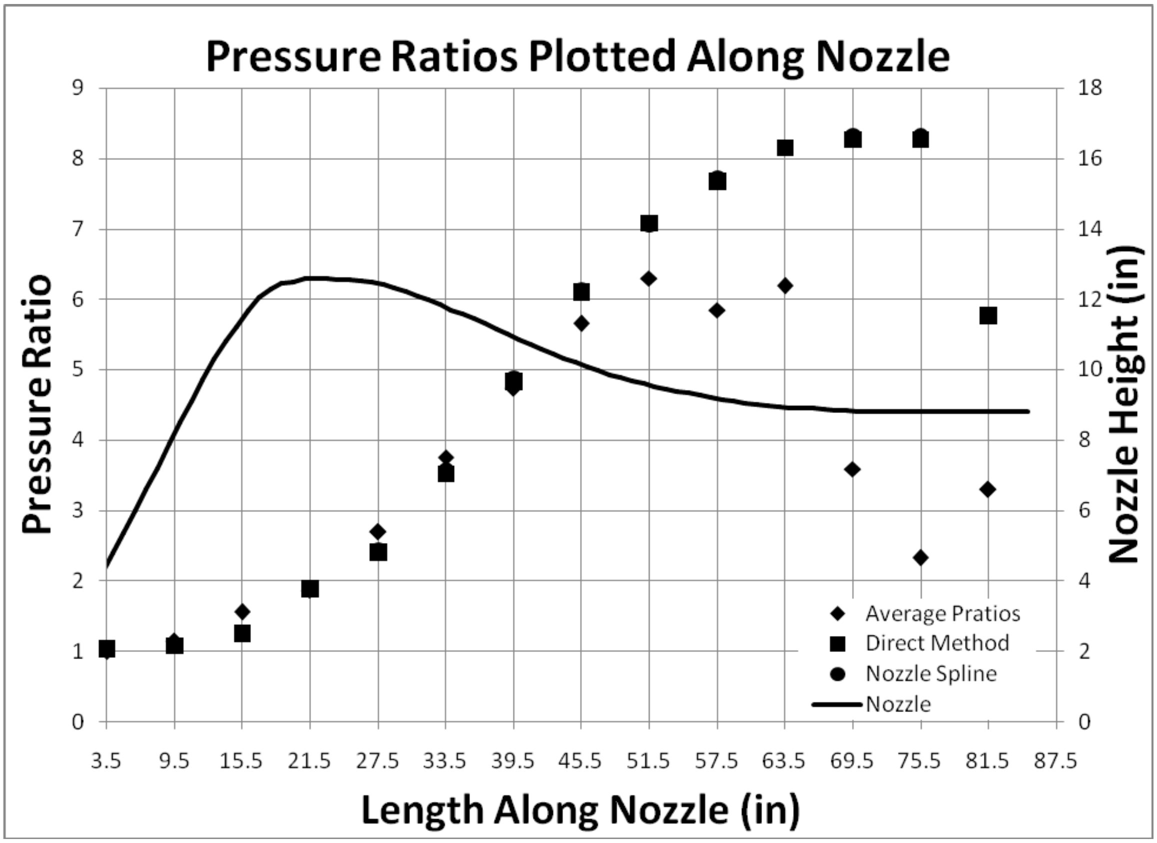

Figure 16 Pressure Ratio Distribution along Nozzle

As can be seen in Figure 16 the direct method of measuring the height of the nozzle and using Equation 2 and Equation 3 to predict the response differs little from the pressure ratios predicted using the heights provided by the nozzle spline analysis. The largest relative error for both methods was 148% at the pitot probe. The average relative error for the direct method was 41.1% and 41.3% for the nozzle spline method. Using the settling chamber pressure as the stagnation pressure Equation 2 was used to determine the Mach number at all tap locations except the pressure tap located immediately upstream of the Pitot probe. There Equation 3 was used with the stagnation pressure measured by the Pitot tube to calculate the Mach number in the test section. The Mach number distribution along the nozzle is shown in Figure 17.

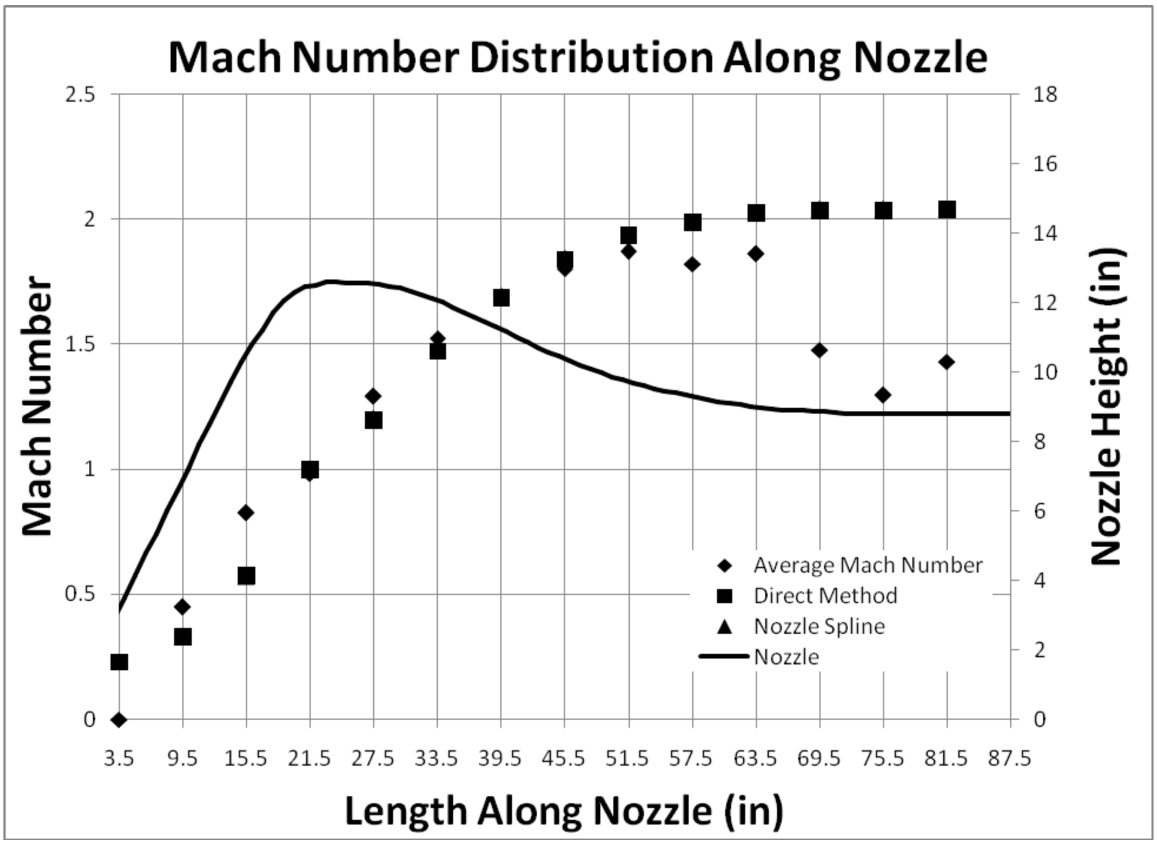

Figure 17 Mach Number Distribution along Nozzle

Within the nozzle there is a noticeable drop in the Mach number corresponding to the area between pressure taps 10 and 11, or from 63.5 to 69.5 inches from the inlet. This corresponds to the area between the first and second pressure taps located in the hatches.

The Mach number of flow exiting the nozzle was determined to be 1.4 instead of the design value of 2.0. Two runs made which captured the pressures at the various tap locations were used to determine the Mach numbers within the nozzle. A noticeable jump in pressure was found between taps 10 and 11. These taps are respectively the first and second taps located in the hatches. This sudden rise in static pressure was thought to be due to an oblique shock possibly caused by the hatch protruding into the flow. Using Equation 2 with the stagnation pressure measured from the settling chamber and the static pressure measured at tap 10 a Mach number of approximately 1.88 was found during the steady portions of both runs. The normal shock pressure equation given as Equation 5 is then used to find the incoming Mach number normal to the shock.

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma + 1}\left(M_1^2 - 1\right) \tag{5}$$

where:

P_2 = Pressure after the shock

P_1 = Pressure before the shock

M_1 = Mach number before the shock

Using the pressure measured from tap 11 as the pressure after the shock and that from tap 10 as the pressure before the shock the normal Mach number across the oblique shock was found. The inverse sine of the normal component of the Mach number over the total Mach number yields the shock wave angle β. The θ-β-Mach relationship given as Equation 6 can then be used to find the flow deflection angle θ.

$$\tan\theta = 2\cot\beta\left[\frac{M_1^2 \sin^2\beta - 1}{M_1^2\left(\gamma + \cos 2\beta\right) + 2}\right] \tag{6}$$

where:

θ = flow deflection angle

β = shock wave angle

M_1 = Mach number before the shock

Use of the normal Mach number in the normal shock equation for Mach numbers given by Equation 7 yields the normal component of the Mach number immediately after the oblique shockwave.

$$M_{n2}^2 = \frac{1 + \frac{\gamma - 1}{2} M_{n1}^2}{\gamma M_{n1}^2 - \frac{\gamma - 1}{2}} \tag{7}$$

where:

M_{n2} = normal component of the Mach number after the shock

M_{n1} = normal component of the Mach number before the shock

Equation 8 given below can then be used to find the Mach number after the shock.

$$M_2 = \frac{M_{n2}}{\sin(\beta - \theta)} \tag{8}$$

Finally, with Equation 3 this will yield the stagnation pressure behind the bow shock of the Pitot probe. A figure that graphically illustrates the flow geometry assumed for the analysis given above is shown in Figure 18.

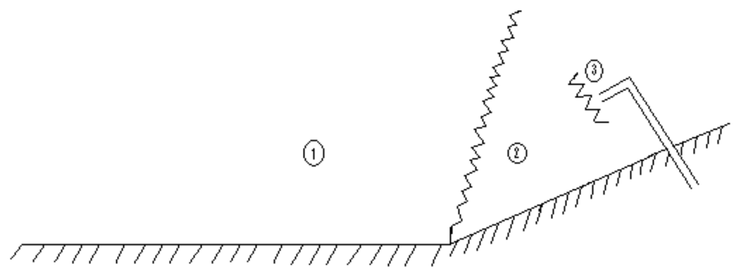

Figure 18 Graphic Representation of the Analysis Performed

The values found using the steps described above are listed in Tables 4 and 5.

Table 4 Values Found for Flow Properties Using Prun061608_001 Data

M1	Mn1	β (deg)	θ (deg)	Mn2	M2	P03 (psi)	Pitot (psi)	P03/Pitot
1.83	1.24	43.0	9.7	0.82	1.49	32.8	33.3	0.99
1.83	1.26	43.3	10.1	0.81	1.48	36.0	35.7	1.01
1.83	1.19	40.8	7.9	0.85	1.55	38.0	34.7	1.10
1.85	1.28	43.7	10.8	0.80	1.47	42.2	37.0	1.14
1.87	1.27	42.7	10.4	0.80	1.50	44.2	38.1	1.16
1.85	1.24	42.1	9.5	0.82	1.52	44.8	47.7	0.94
1.84	1.26	43.1	10.2	0.81	1.49	44.6	49.4	0.90
1.85	1.26	43.0	10.2	0.81	1.49	43.0	46.4	0.93
1.86	1.32	45.5	12.4	0.77	1.41	42.2	43.5	0.97
1.86	1.25	42.2	9.7	0.82	1.52	39.7	41.6	0.95
1.86	1.26	42.8	10.3	0.81	1.50	37.8	40.3	0.94
1.86	1.32	45.1	12.2	0.78	1.43	37.9	39.1	0.97
1.86	1.32	45.4	12.3	0.78	1.42	36.7	38.4	0.96

Table 5 Values Found for Flow Properties Using Ptest061708_002 Data

M1	Mn1	β (deg)	θ (deg)	Mn2	M2	P03 (psi)	Pitot (psi)	P03/Pitot
1.84	1.10	36.9	4.3	0.91	1.69	36.3	36.1	0.99
1.85	1.22	41.0	8.6	0.83	1.55	41.0	40.6	0.99
1.86	1.27	43.0	10.6	0.80	1.49	43.8	38.8	0.89
1.85	1.26	42.9	10.2	0.81	1.49	45.1	48.0	1.06
1.85	1.26	42.8	10.2	0.81	1.50	45.0	47.6	1.06
1.85	1.24	42.3	9.6	0.82	1.51	43.7	45.2	1.04
1.85	1.27	43.2	10.5	0.80	1.48	42.5	43.9	1.03
1.85	1.30	44.3	11.4	0.79	1.45	41.3	42.8	1.04
1.86	1.29	43.8	11.2	0.79	1.47	40.5	44.2	1.09
1.86	1.24	41.7	9.4	0.82	1.53	39.2	41.5	1.06
1.86	1.28	43.3	10.8	0.80	1.48	39.0	40.5	1.04
1.86	1.27	43.2	10.6	0.80	1.48	38.2	40.3	1.06
1.86	1.28	43.3	10.7	0.80	1.48	37.3	39.6	1.06

Examination of Tables 4 and 5 show that within each run there is a period of relatively stable flow which possesses the maximum Mach number of 1.85 within the nozzle on average for the two sets of data. The maximum relative error within the steady portion of the run is 7.19% between measured and theoretical stagnation pressure at the exit. The exit Mach number is approximately 1.47 for the relatively stable period of the flow. The average values for the β and θ angles are 43.8° and 10.8° respectively. Figure 19 shows the oblique shock wave and its position relative to the hatch and pressure taps assuming that the hatch is the cause of the shockwave.

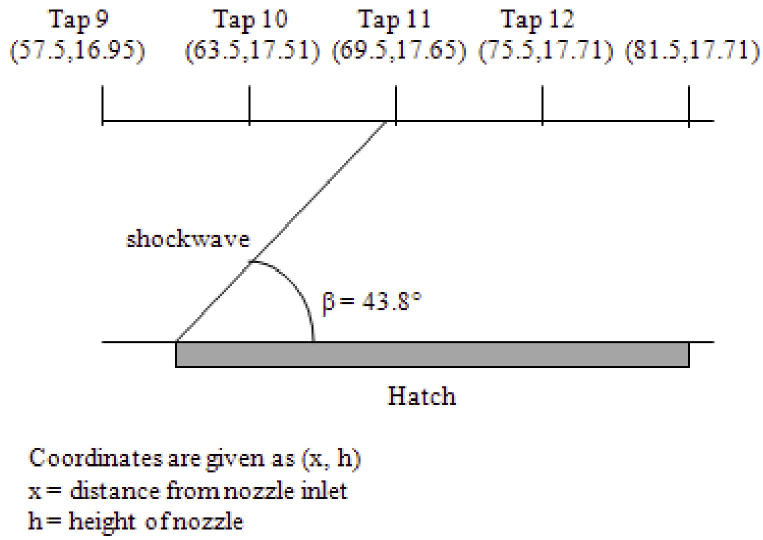

Figure 19 Positions of the Hatch, Pressure Taps, and Shockwave in Relation to each Other

Figure 20 shows the comparison of the measured pressures to the predicted pressures.

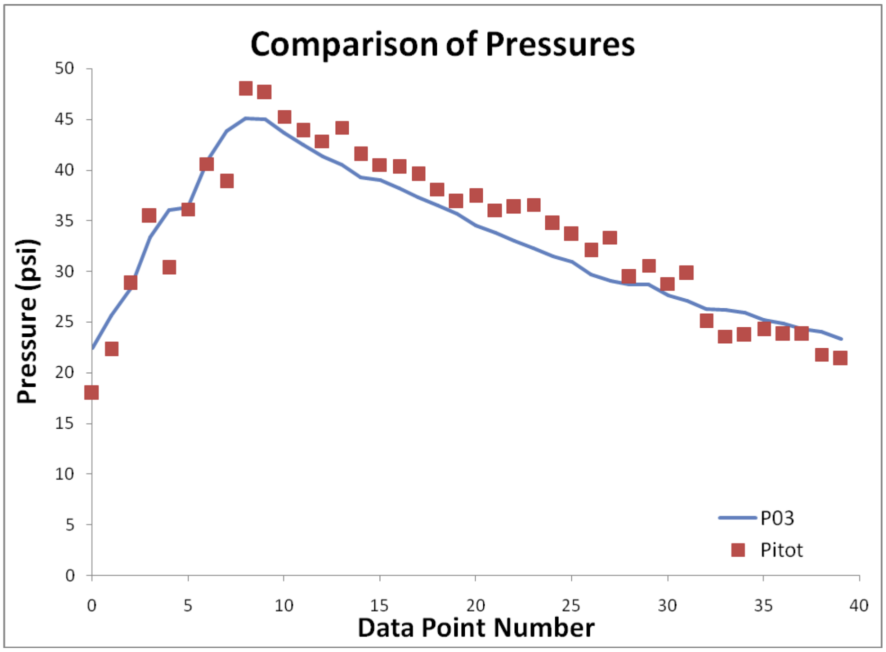

Figure 20 Comparison of Predicted Stagnation Pressure to those Measured for Ptest061708_002

The maximum relative difference found in the comparison between the two pressures within the stable portion of the run is 19%; however the average of the relative difference is only 6.27%.

The Mach numbers calculated throughout the nozzle show that for a wide range of settling chamber pressures the flow is stable. This Mach number behavior within the nozzle indicates that the nozzle is choked until the settling chamber pressure has dropped to approximately 30 psi. This is illustrated in Figure 20 as well as Figure 21.

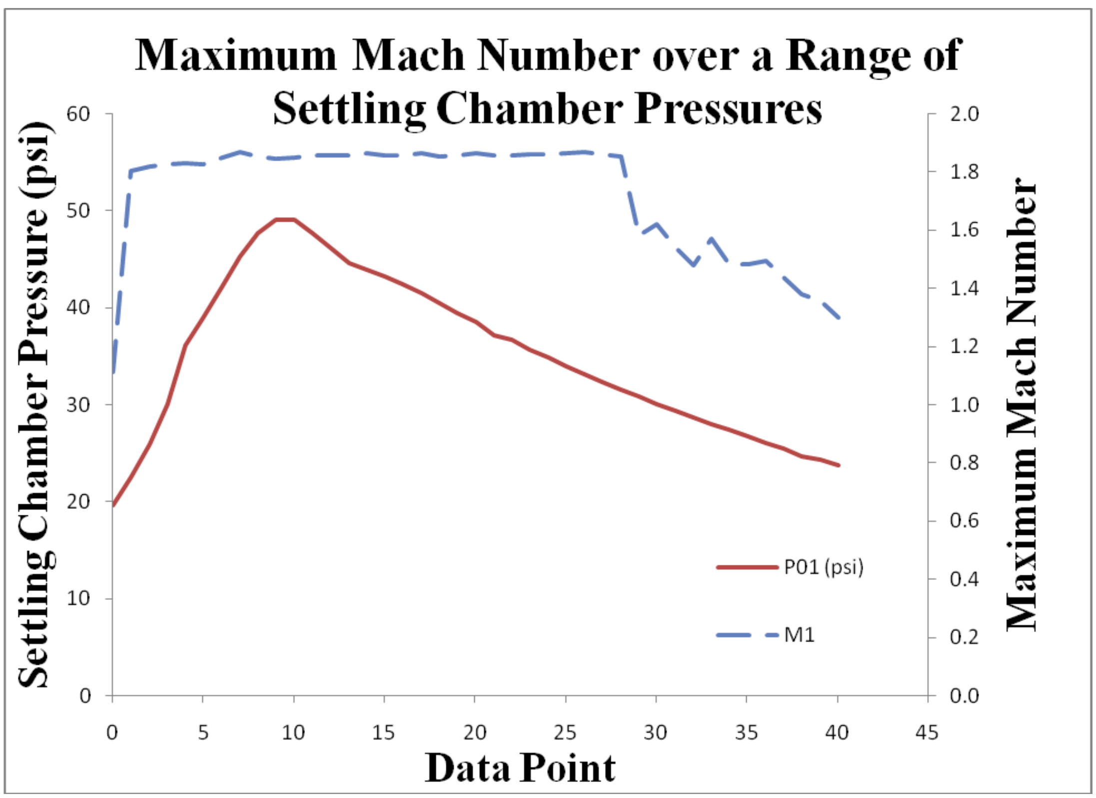

Figure 21 The Maximum Mach Number within the Nozzle for Ptest061708_002

Figure 21 shows that with a settling chamber pressure greater than approximately 30 psi the nozzle will achieve Mach 1.88 flow. This is larger than the calculated settling chamber pressure of 25 psi necessary to achieve the design Mach number. Figures 20 and 21 illustrate that the pressure ratios and maximum Mach number within the nozzle remain effectively constant over a wide range of settling chamber pressures. Figures 22 and 23 show the predicted stagnation pressure for the Pitot probe using the analysis already described with Equations 2, 3, 5, 6, 7, and 8 along with Figure 18.

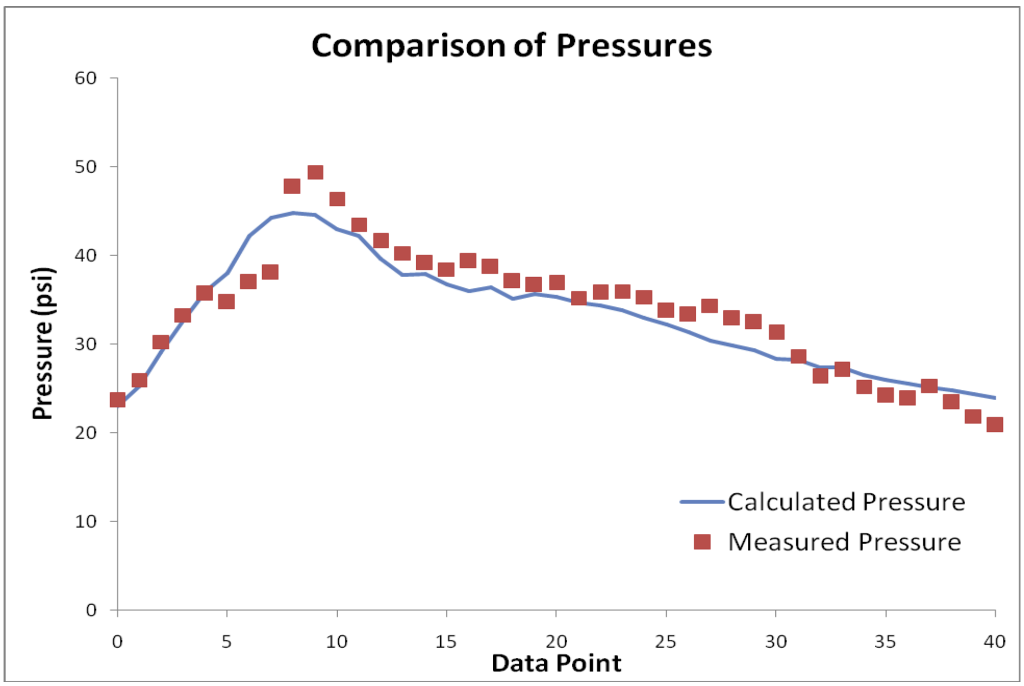

Figure 22 Comparison of Predicted Stagnation Pressure to those Measured for Prun061608_001

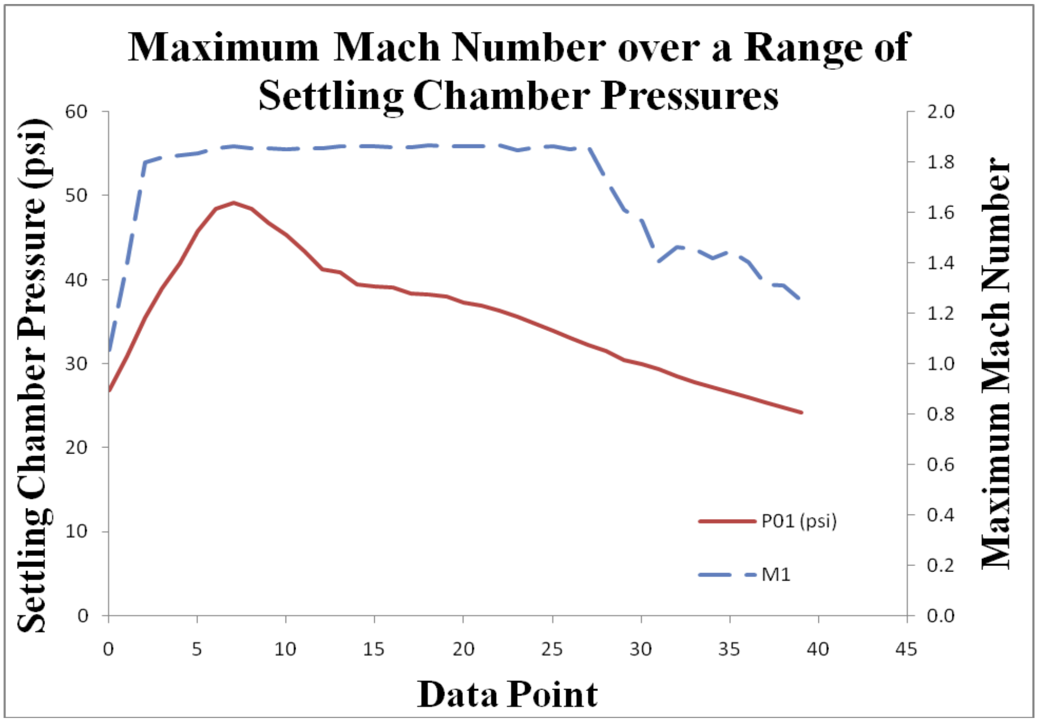

Figure 23 The Maximum Mach Number within the Nozzle for Prun061608_001

The combination of the data from these two runs which show a steady Mach number for a most of the run despite a steadily declining settling chamber pressure strongly indicates that the tunnel is stable for the majority of a given run. The run-times for the tunnel compare favorably to those found using the analysis shown in Appendix B. The predicted run-time for the tunnel with 70 psi in the supply air tank and the Mach 2 nozzle blocks is 1.81s compared to the approximately 2s of stable flow that was actually achieved.

CHAPTER 5

CONCLUSIONS

Overall the tunnel does perform as desired and predicted. There is definitely a stable region of the flow during the course of the runtime. With greater tank pressure this stable portion of the flow can be extended. It is quite likely that the Mach 1.8 region of the flow can also be extended through the nozzle by rigorously smoothing the sidewalls and nozzle blocks. As shown in Appendix D the predicted run times for the Mach 2 nozzle gives a run-time of 1.81s for the Mach 2 nozzle block with an initial tank pressure of 70 psi. Observation of the tunnel data shows that the tunnel was able to achieve Mach 1.4 flow downstream of an oblique shock for approximately 2s. Calculations show that for the Mach 2 nozzle blocks there is a run-time of 3.32s for an initial tank pressure of 125 psi. The analysis shown in Appendix B finds that if the smaller Mach 4 throat area is used the run-time increases to 32.5s. These numbers are not unreasonable, although the analysis does not account for the start-up or the actual settling chamber pressure required. Therefore, it is safe to assume that since the pipeline has been replaced and pressures within the supply air tank can reach 125 psi that runtimes approaching ten seconds are possible.

The revitalization process of this project did achieve its purpose of making the tunnel operational again. Except for the broken collar connecting the hydraulic arm to the inlet butterfly valve all components are currently functional. A new design for the collar is being implemented which will ensure that in the future a crack is not allowed to form and propagate until failure occurs. In the future it is also hoped that a safer method of emergency shut-down will be devised which does not cause the inlet butterfly valve to shut at full force. This will require that the speed-restriction valve be powered even in the event of power loss. Another area of improvement lies within the control cabinet wiring. The tunnel was originally run entirely from the cabinet, but was later modified to be controlled entirely by computer with the cabinet only retaining the ability to cause emergency shut-down. This rewiring has caused the tunnel to lose manual control capability which, although not serious, does lessen its usefulness to some degree. A bonus to rewiring the control cabinet for manual control lies in its wiring. The current wiring schematics are outdated, and have not been addressed properly in this project. It is recommended that in the future a systematic effort should be made to properly document and rewire the control cabinet in a more straightforward manner.

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APPENDIX A

LABVIEW CONTROL PROGRAM

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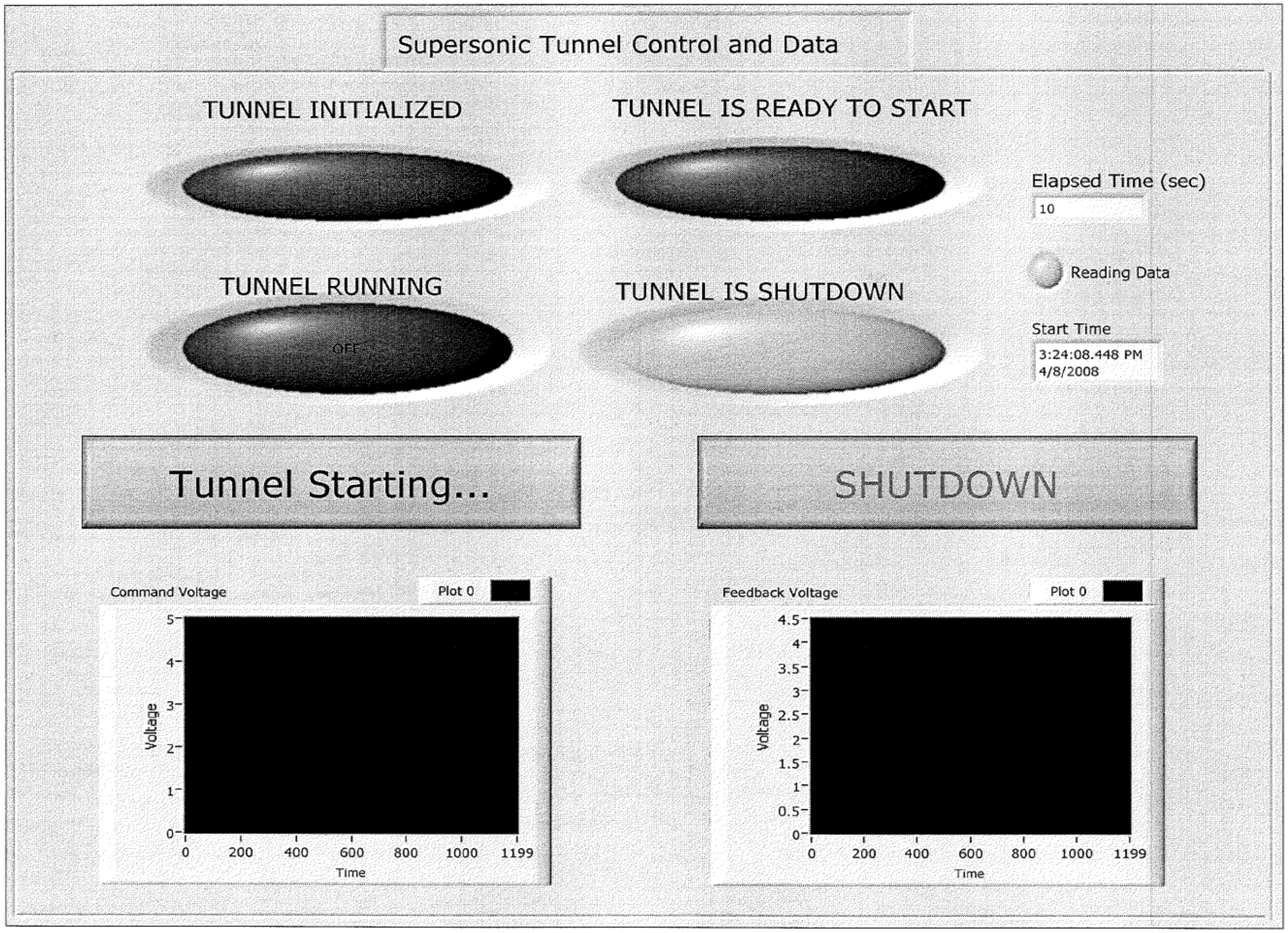

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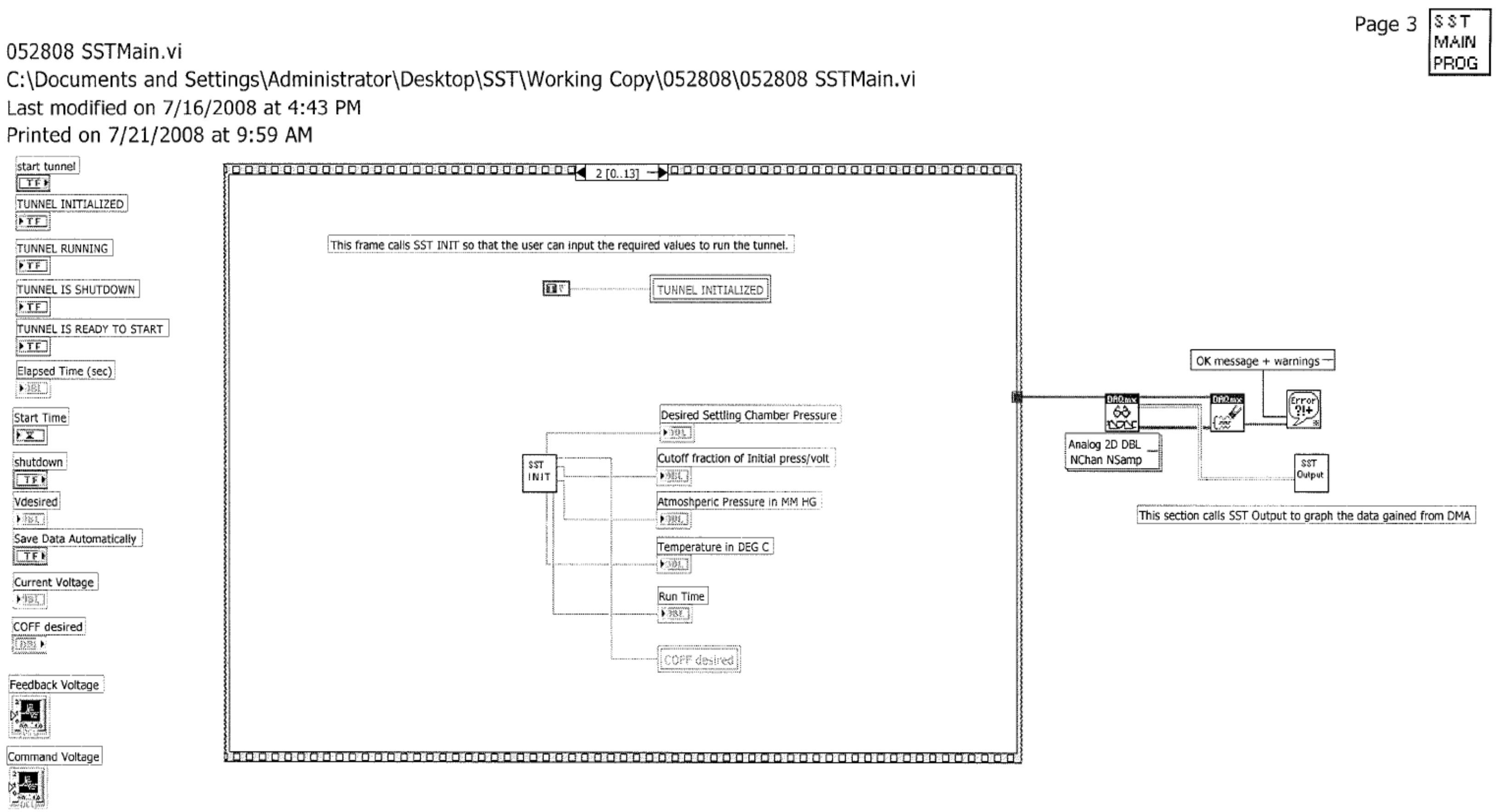

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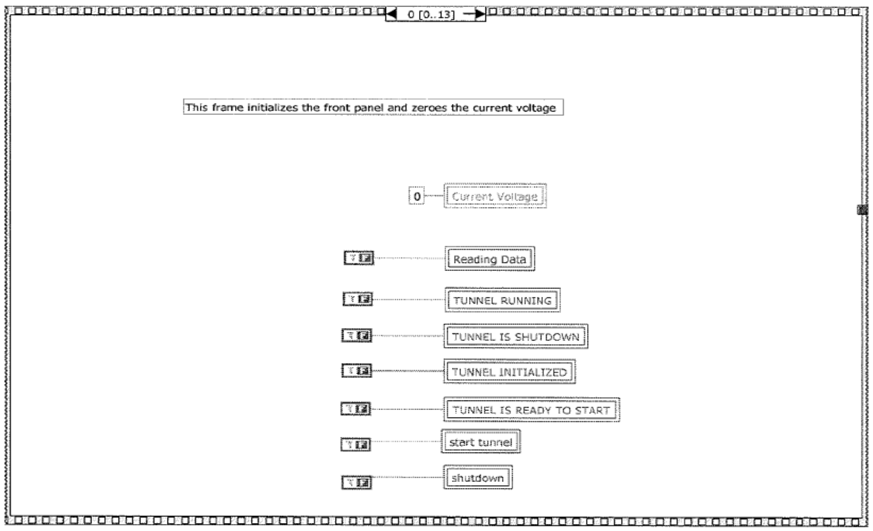

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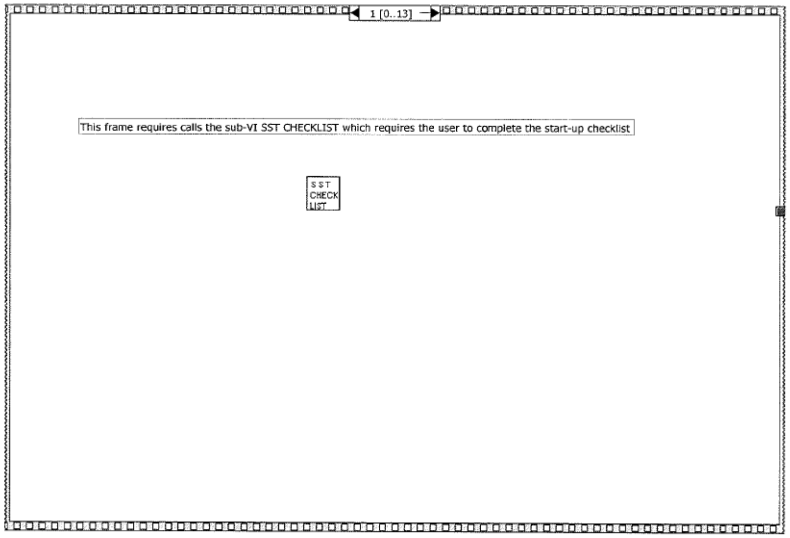

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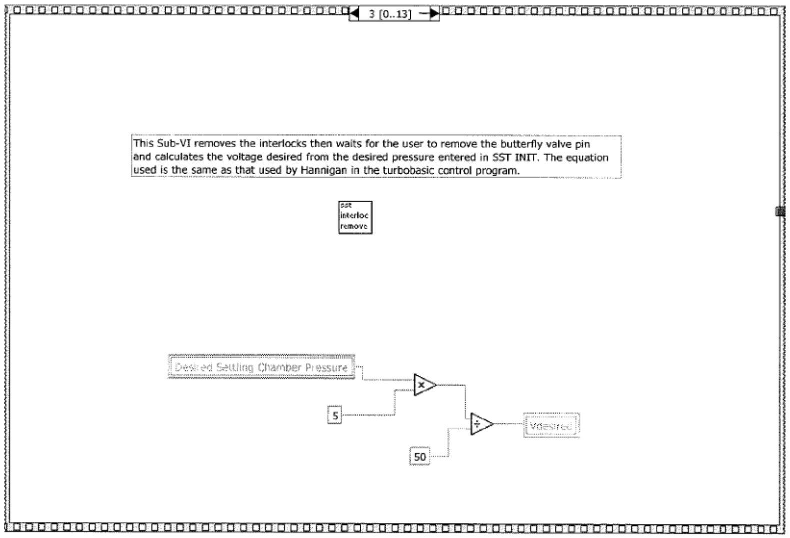

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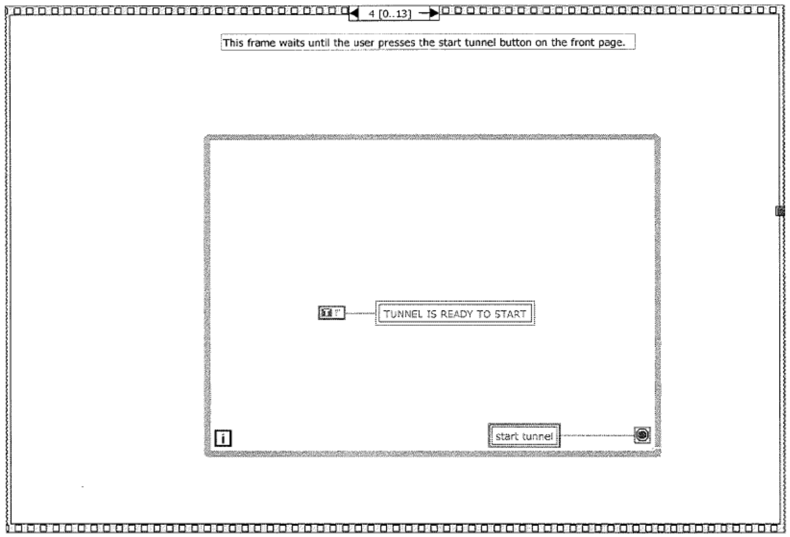

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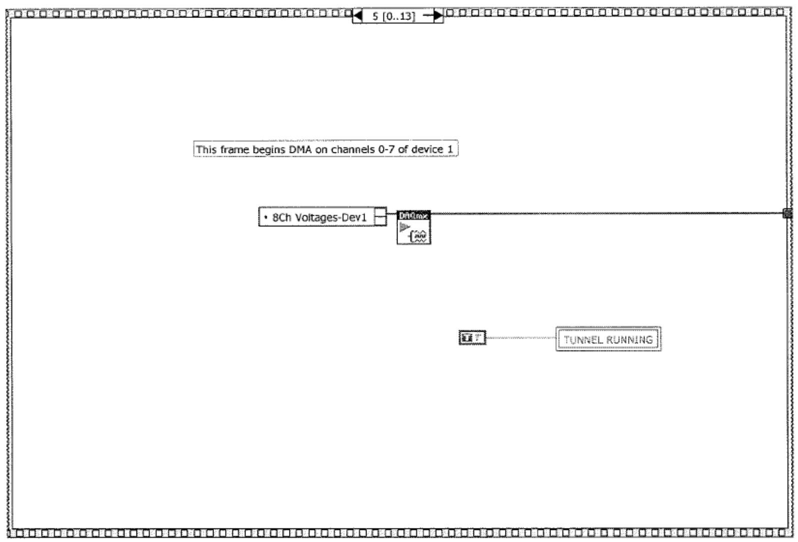

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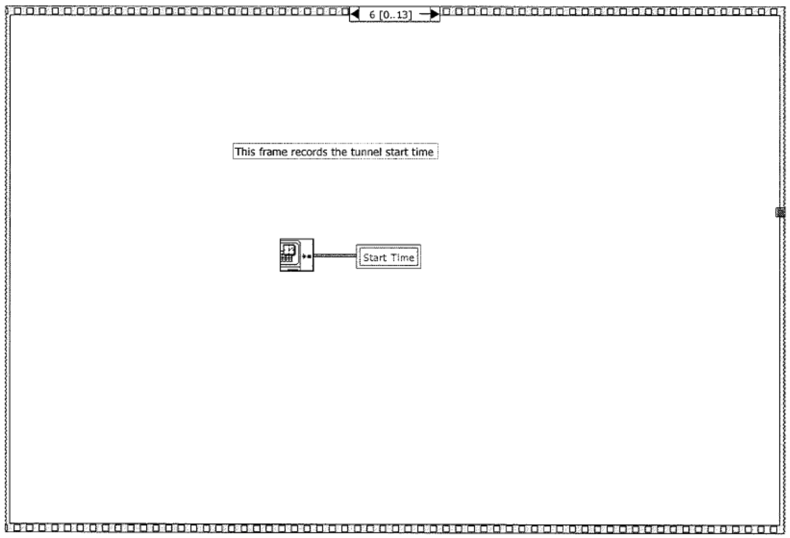

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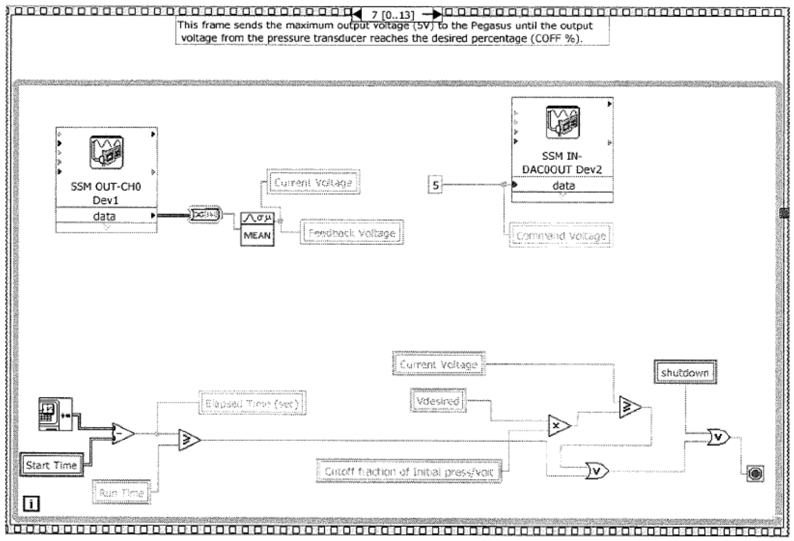

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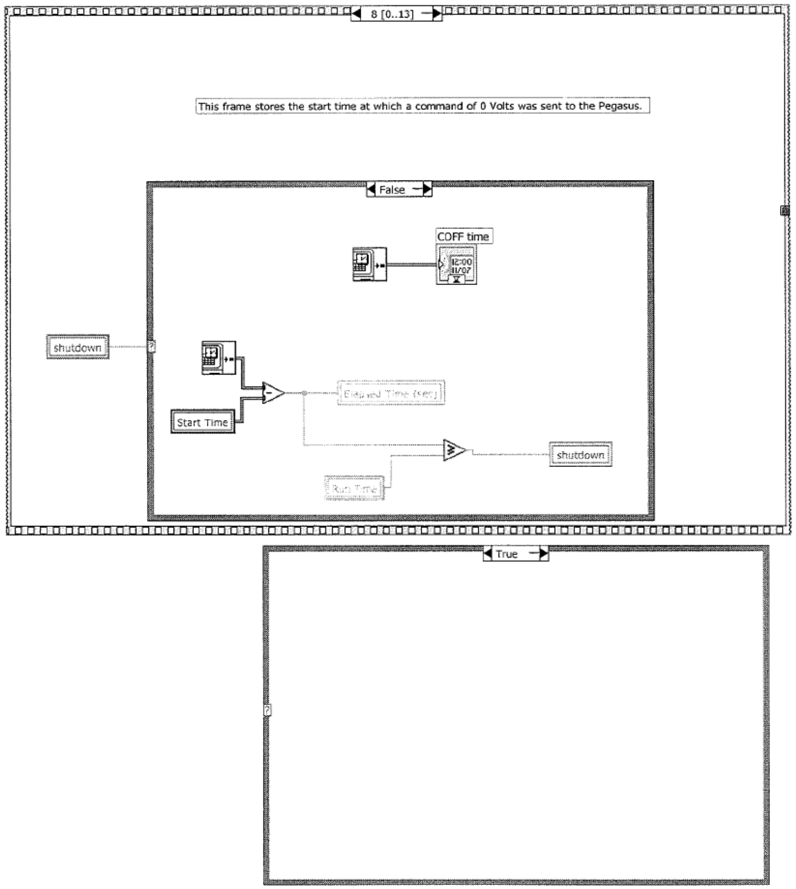

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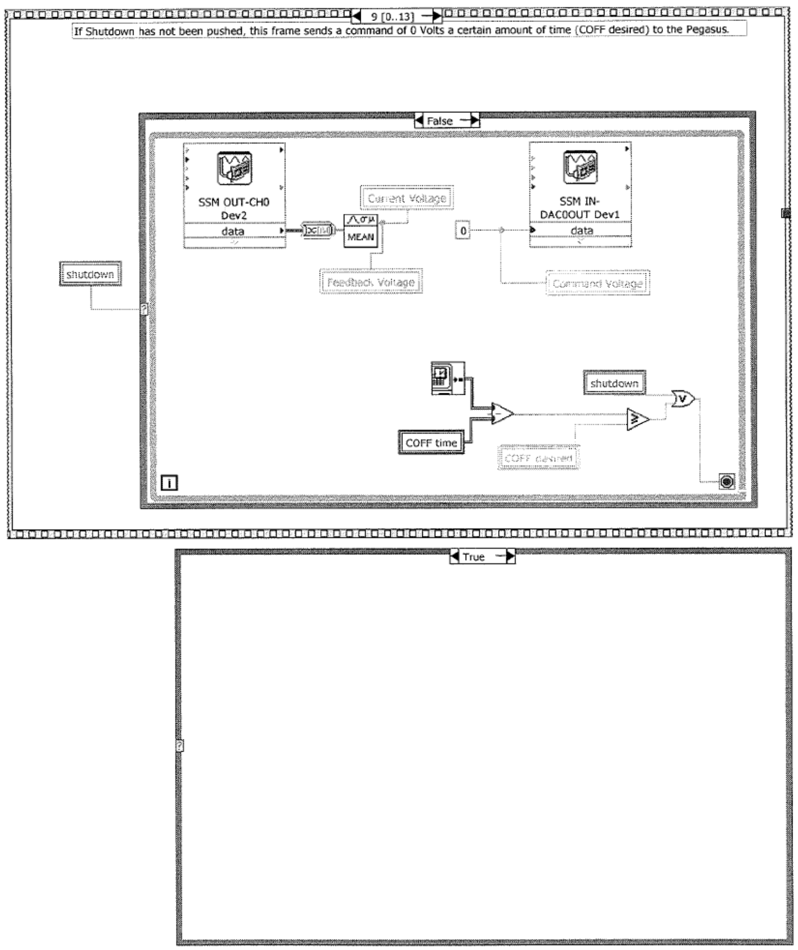

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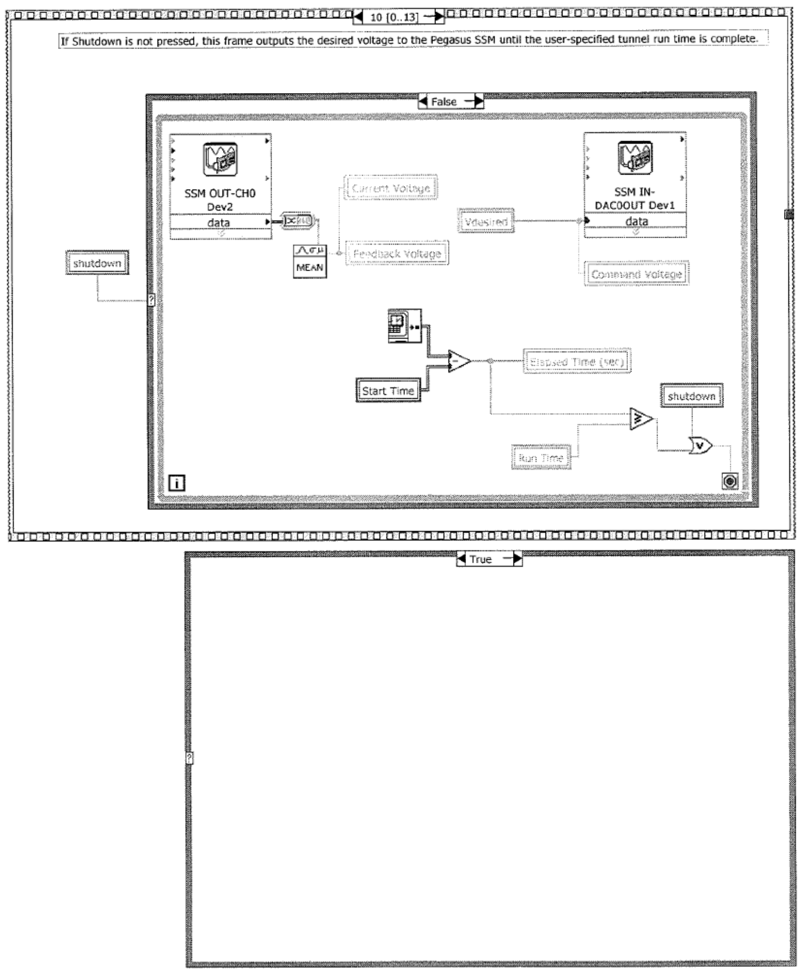

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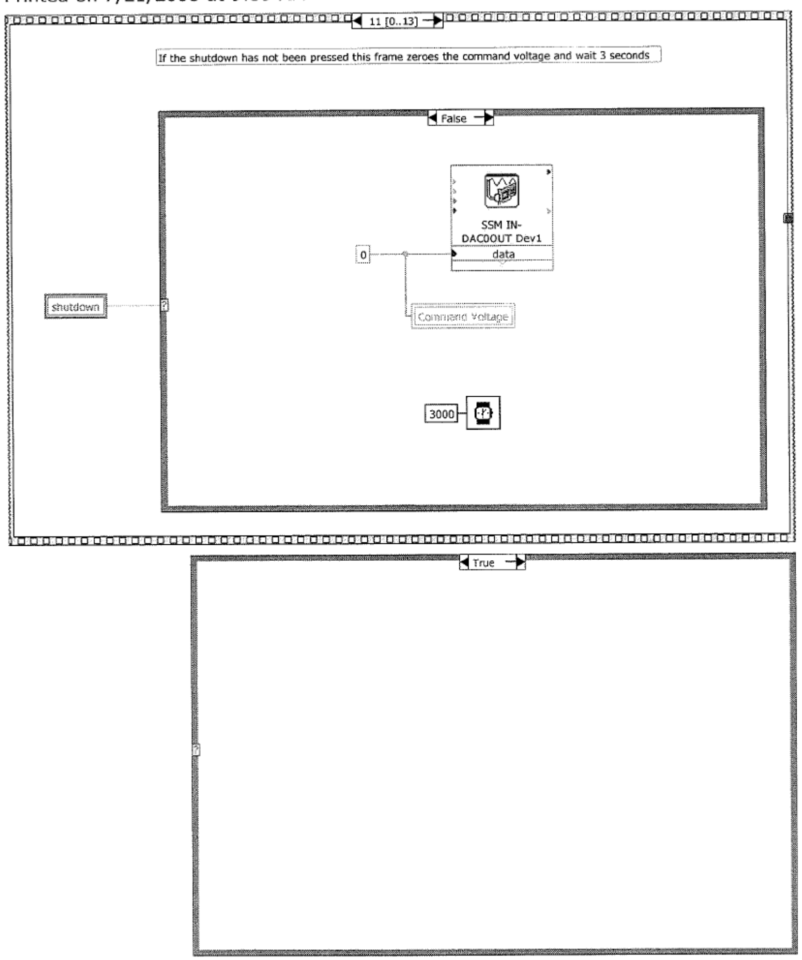

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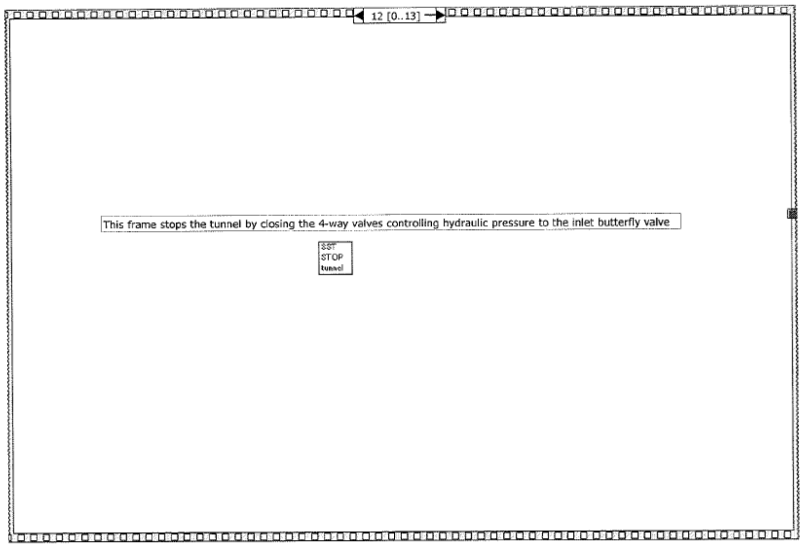

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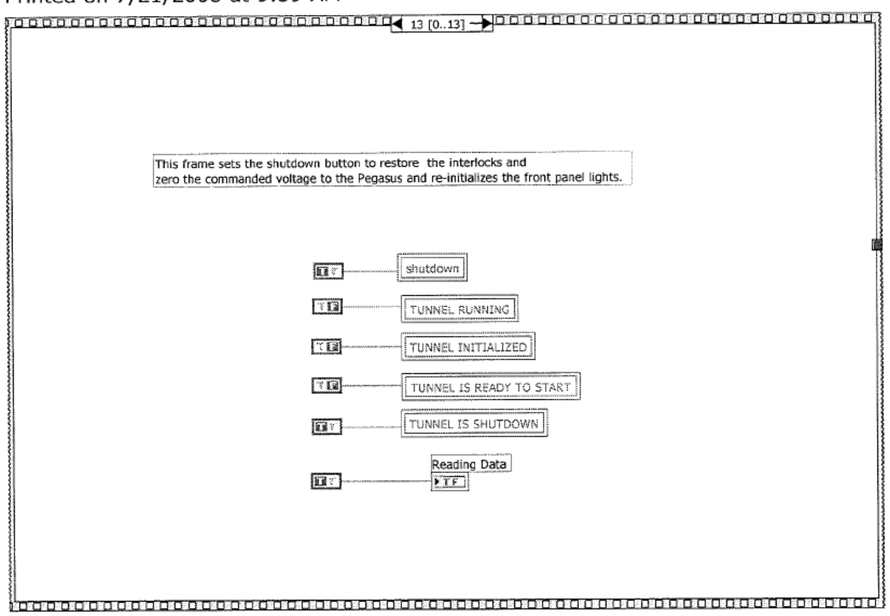

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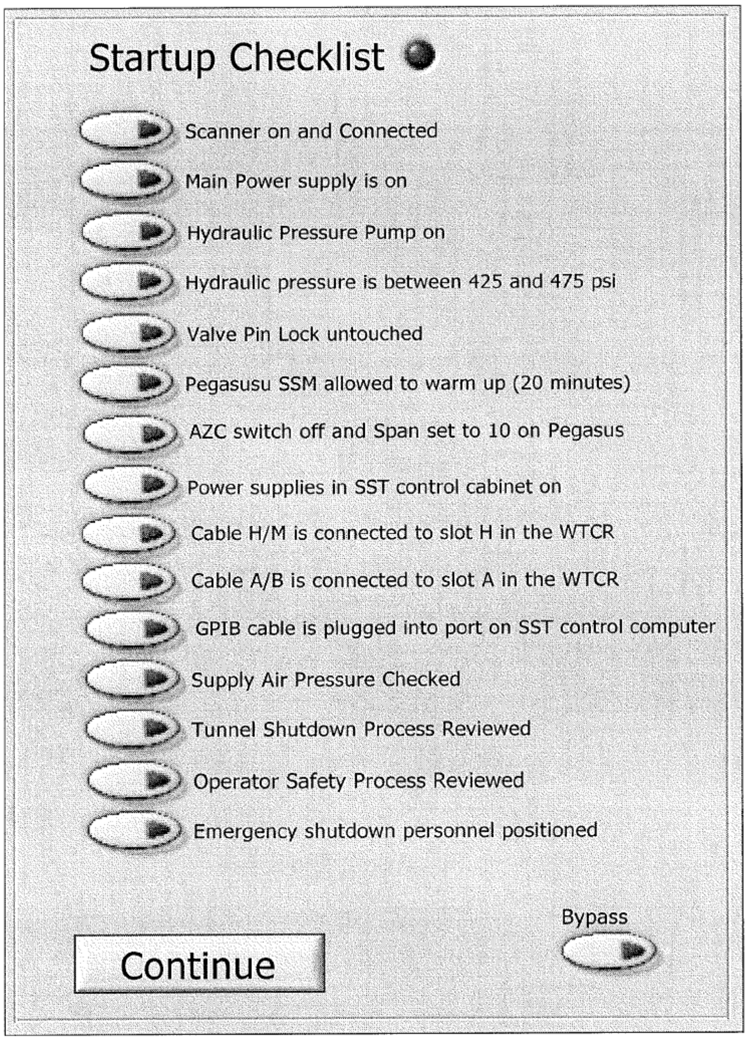

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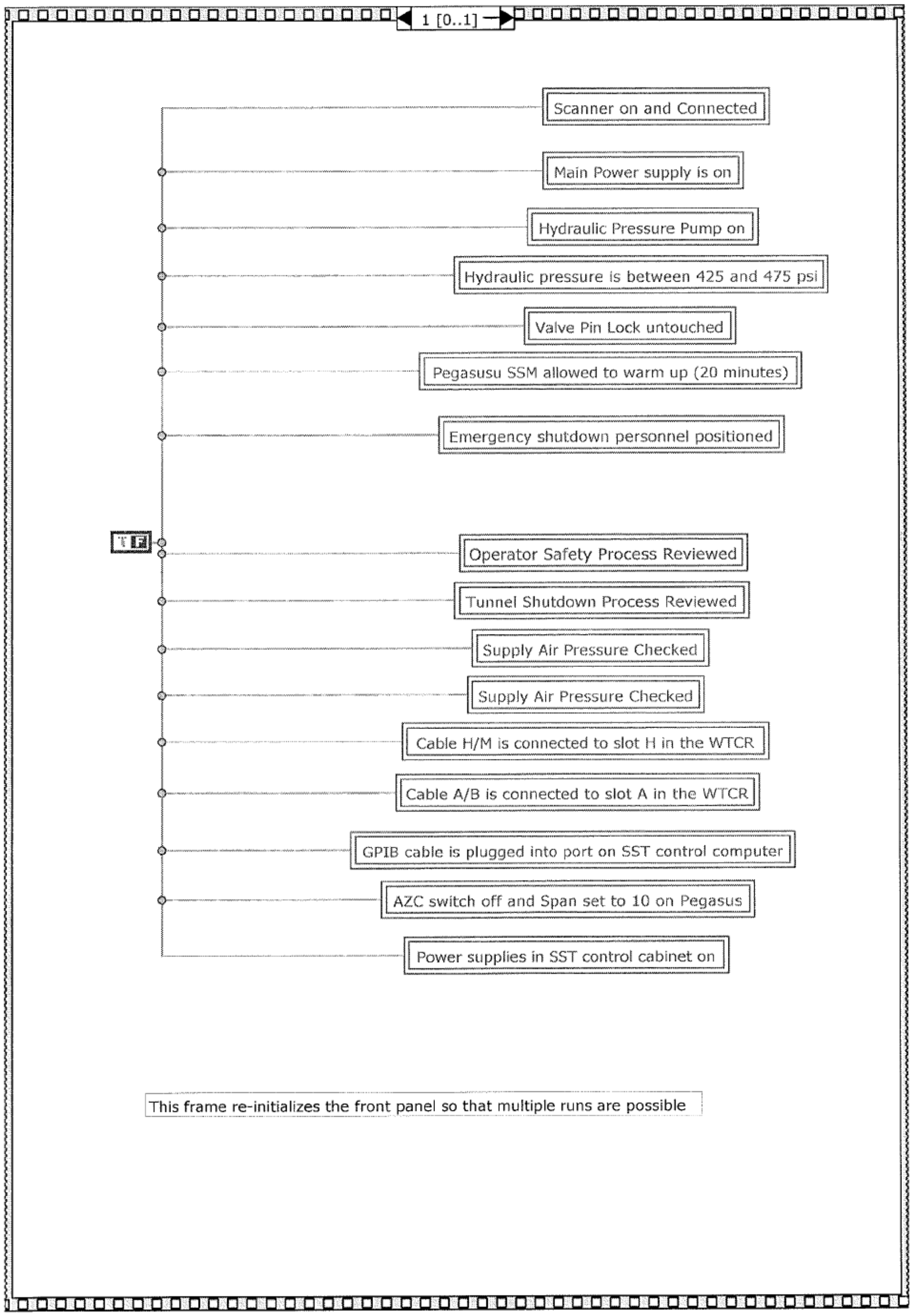

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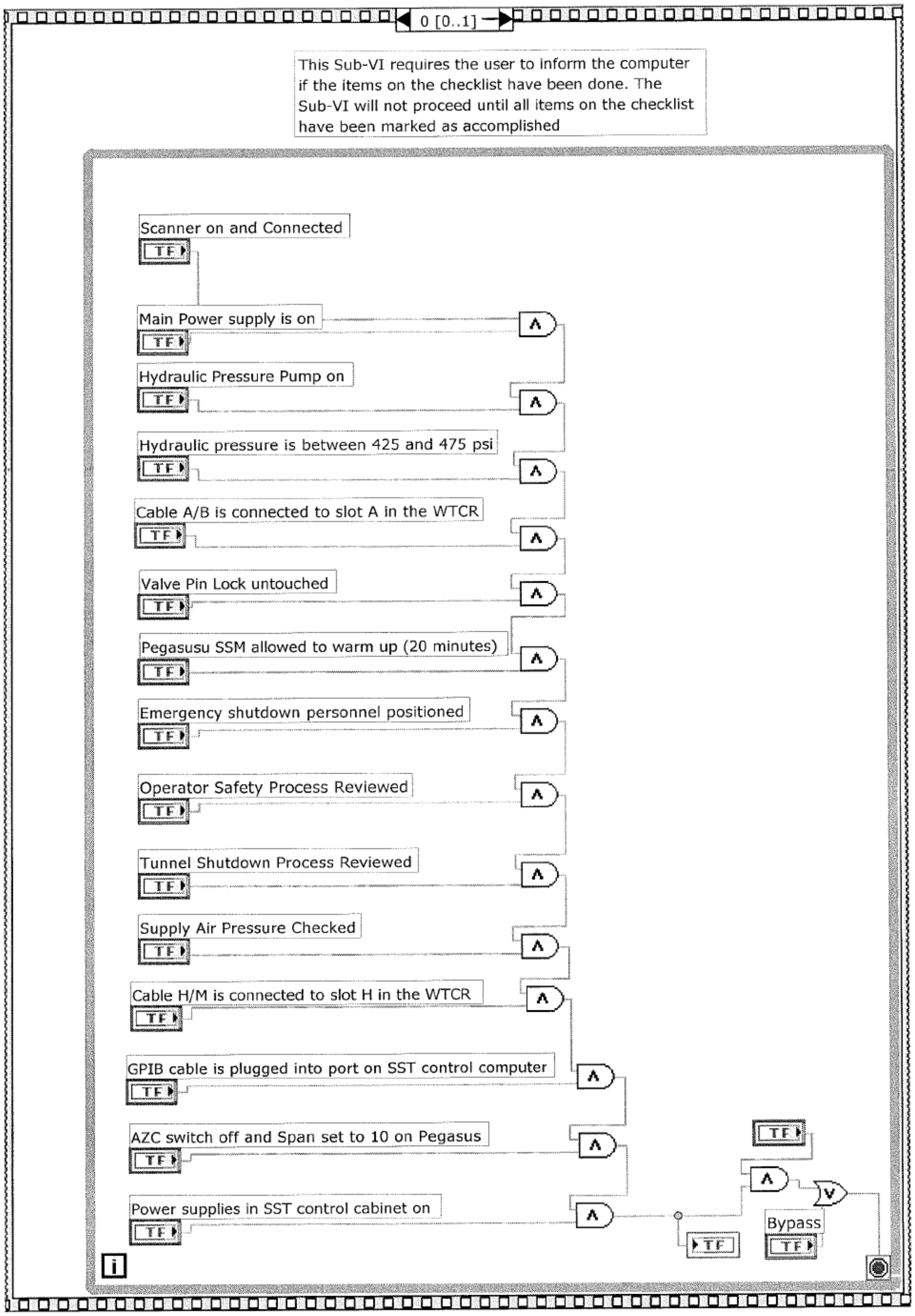

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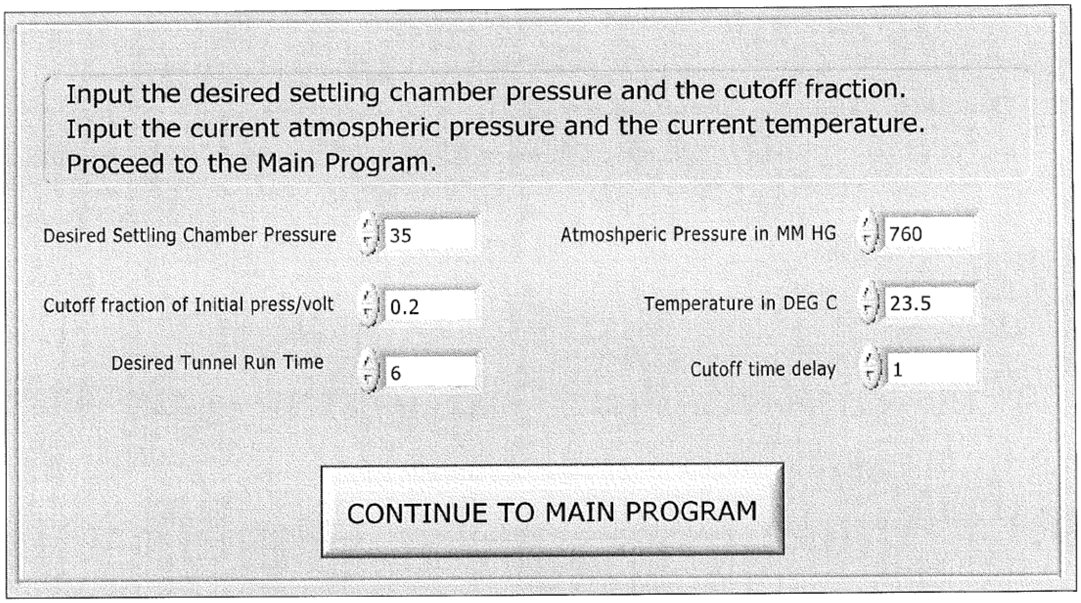

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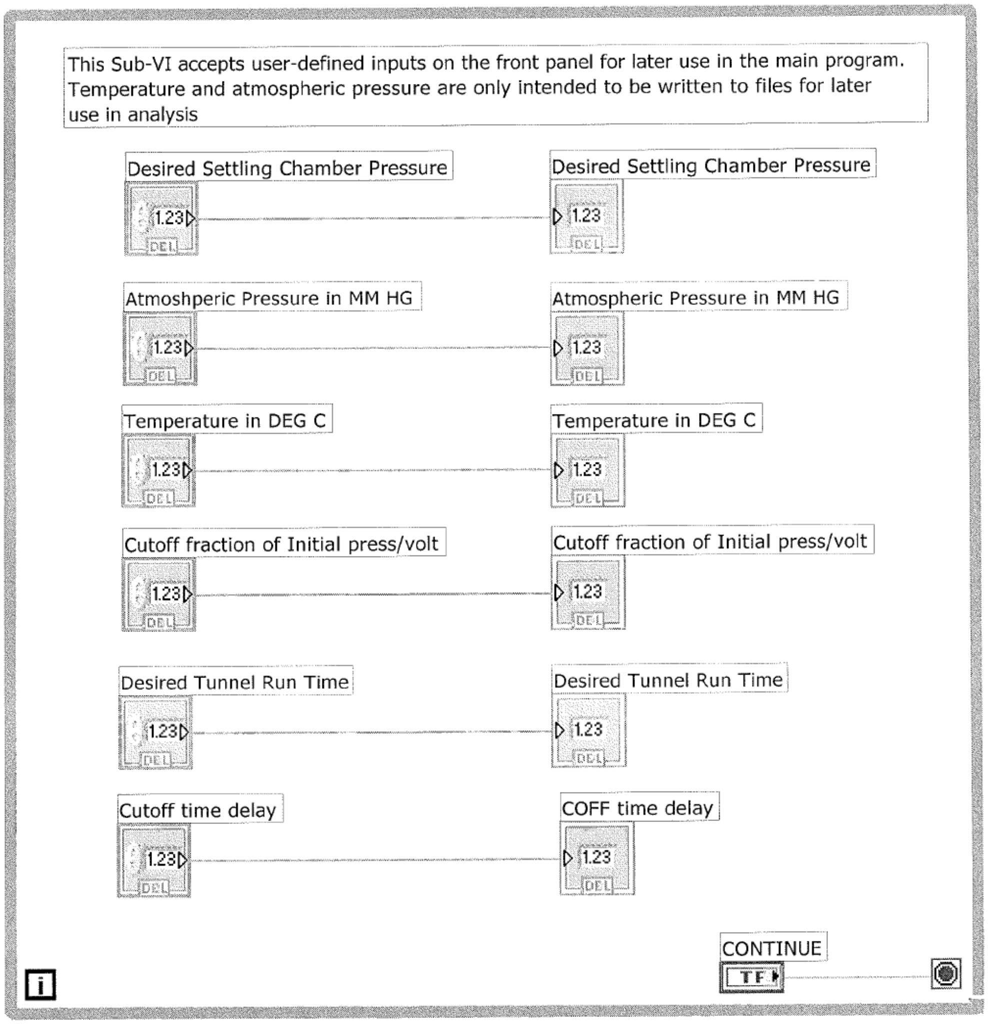

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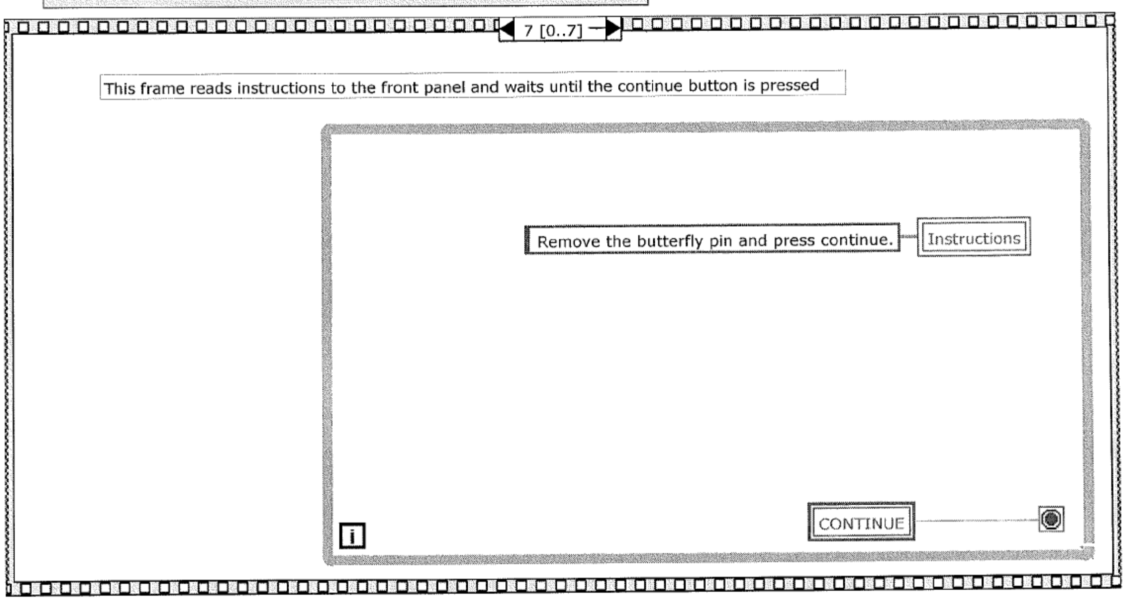

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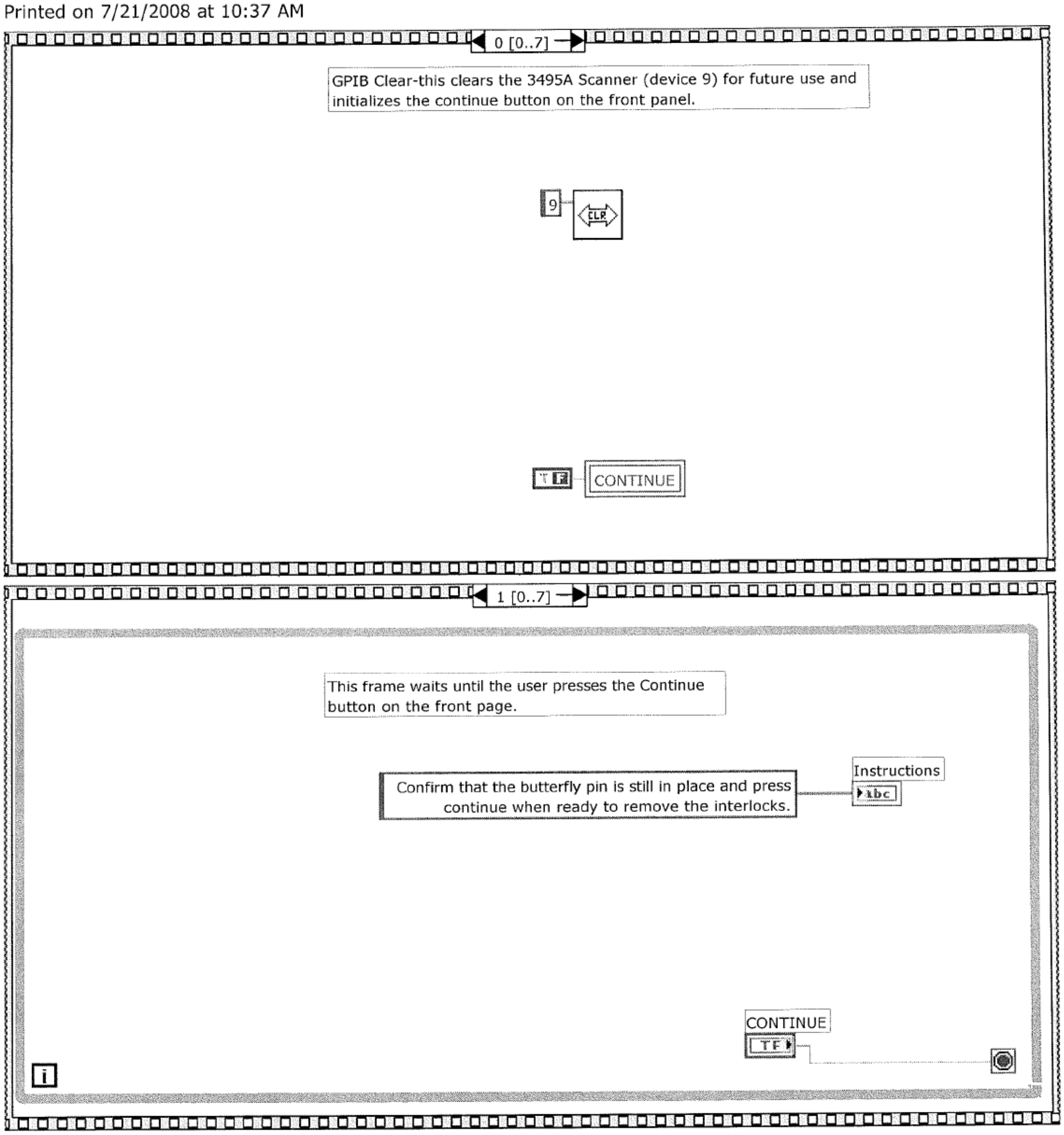

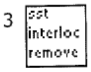

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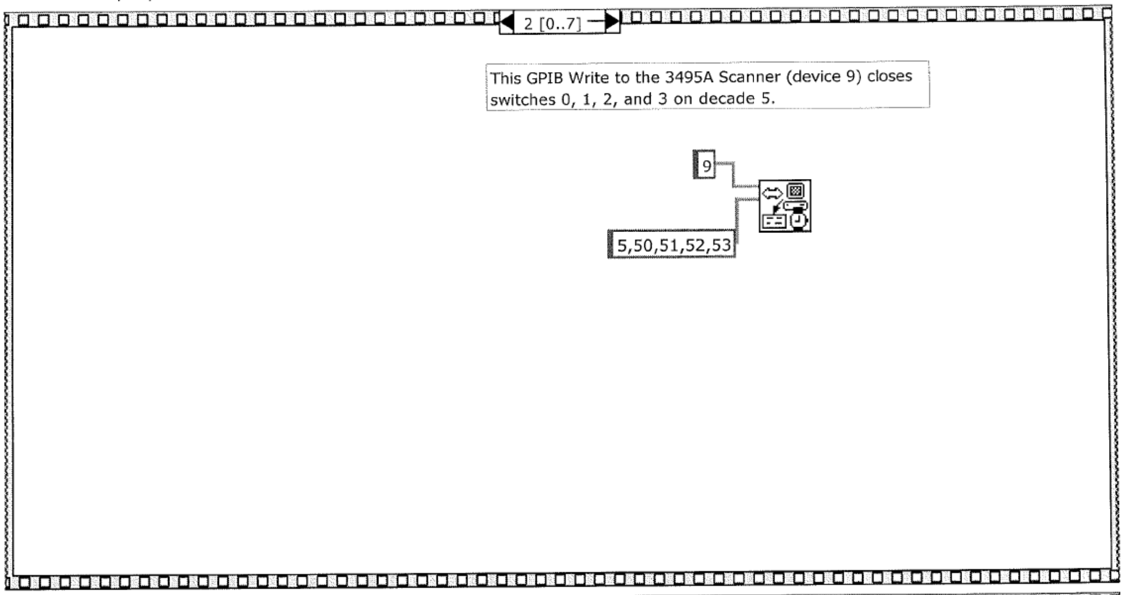

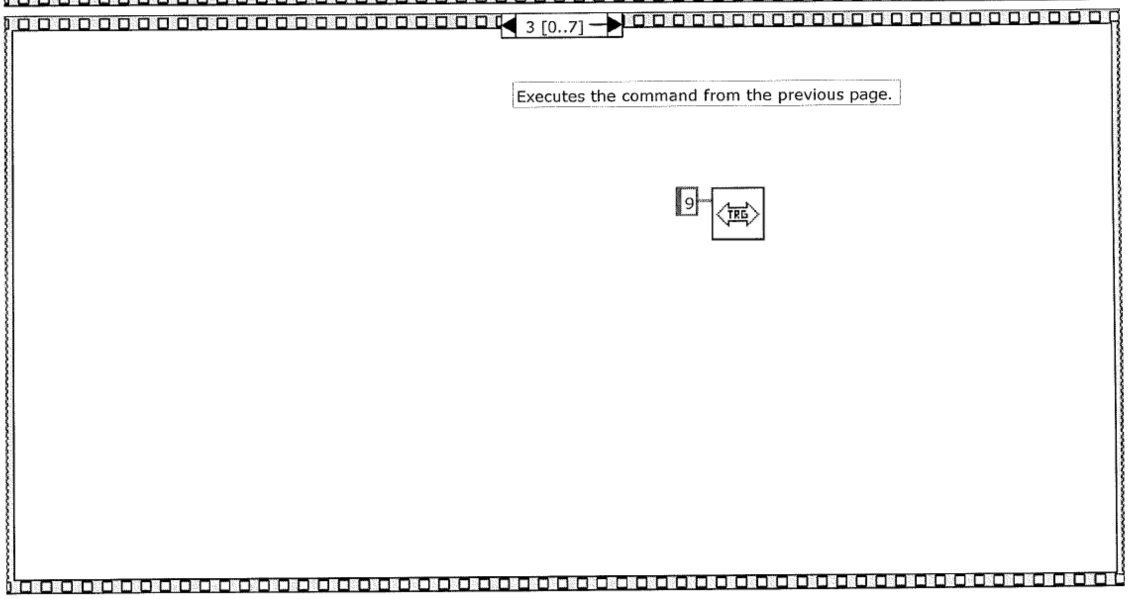

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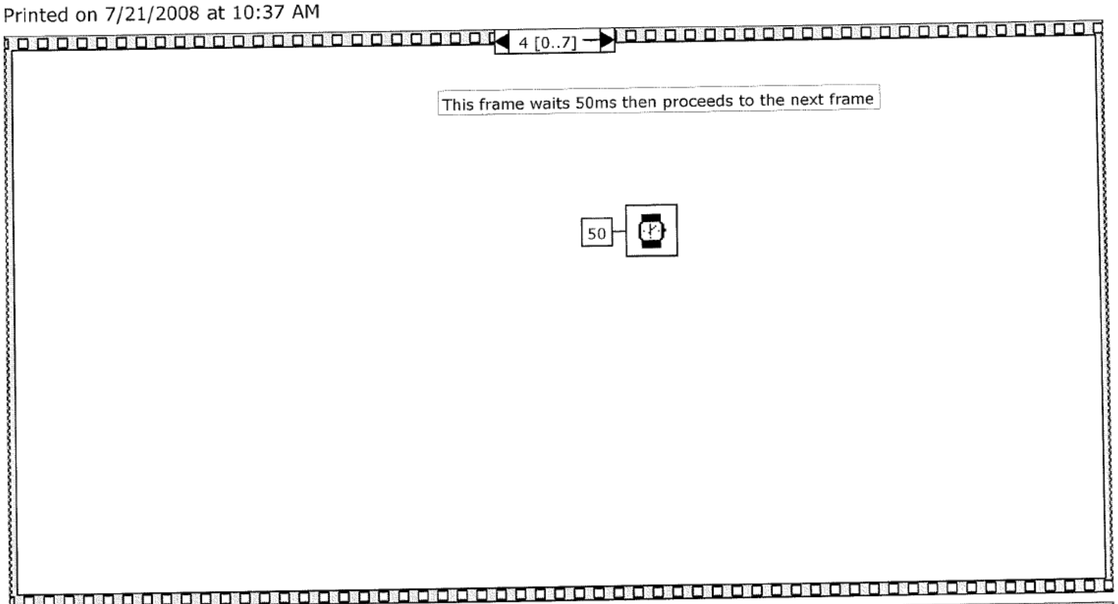

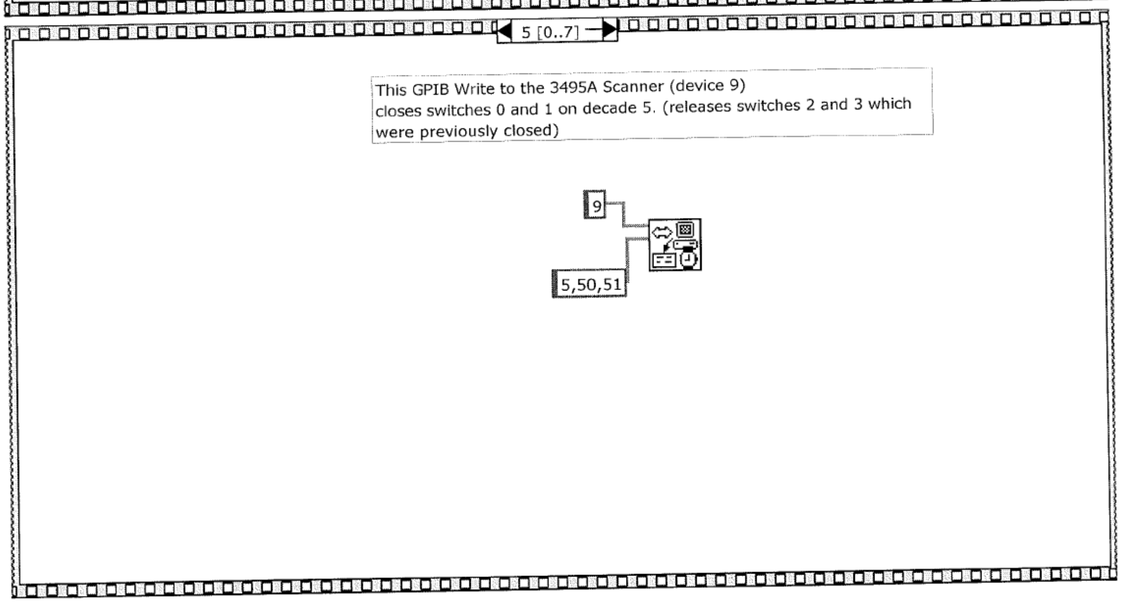

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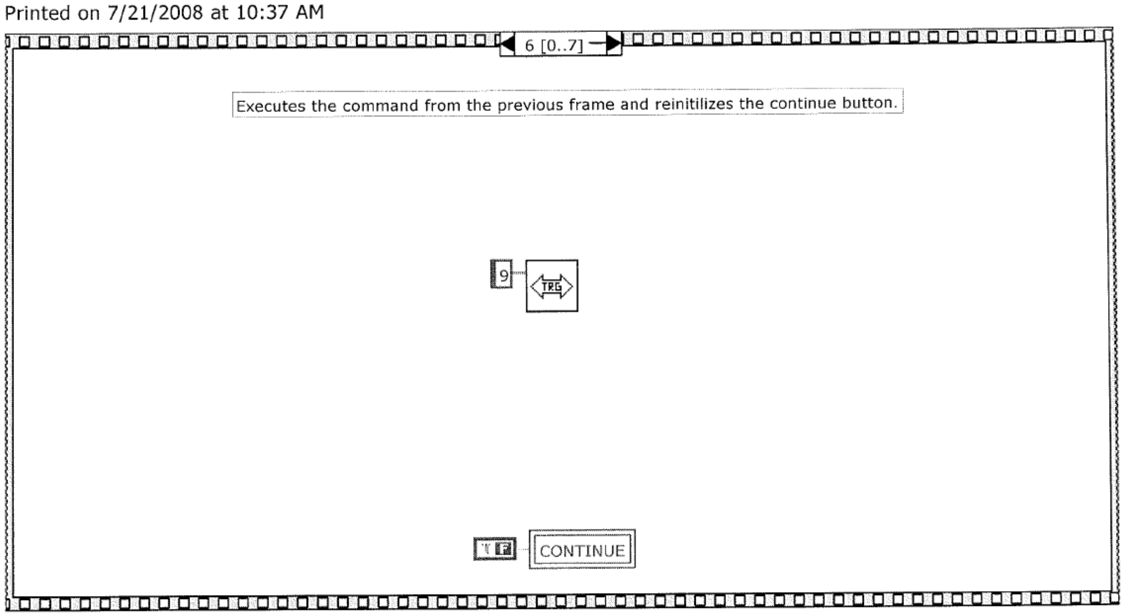

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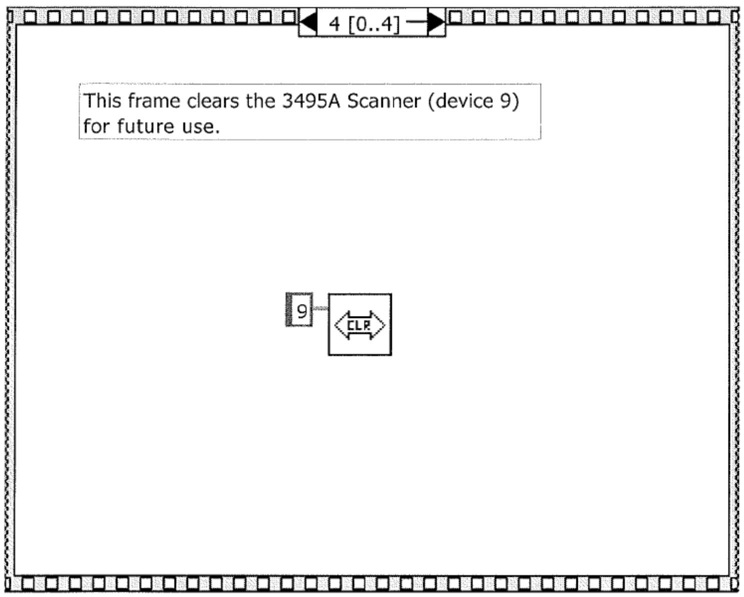

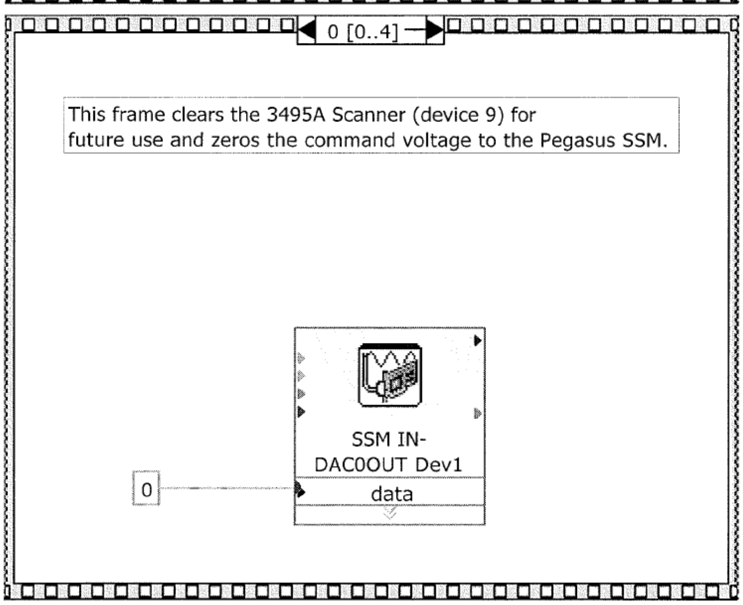

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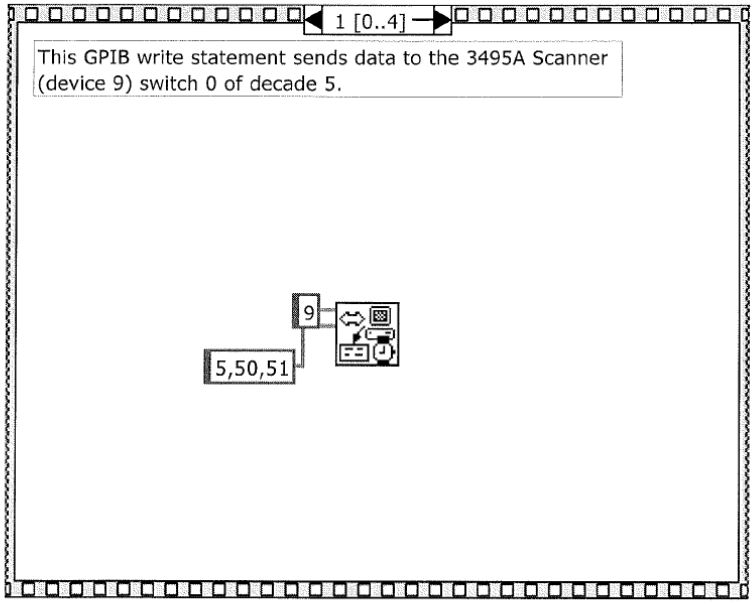

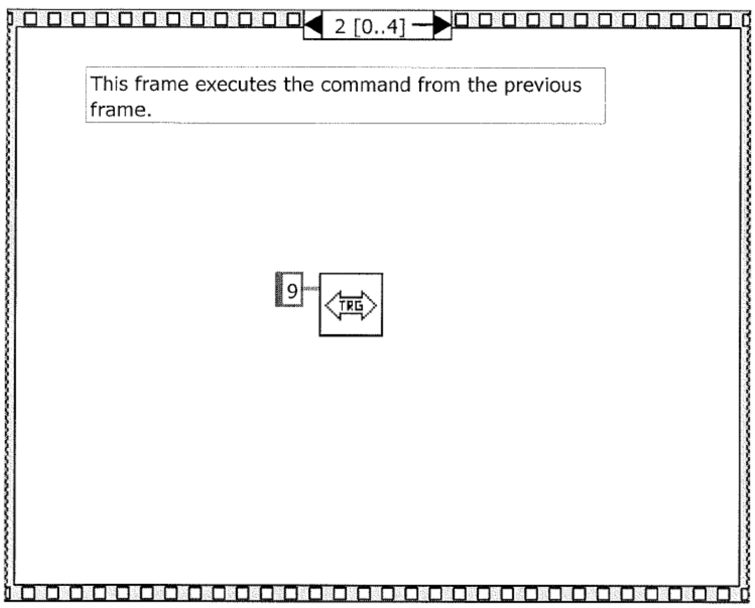

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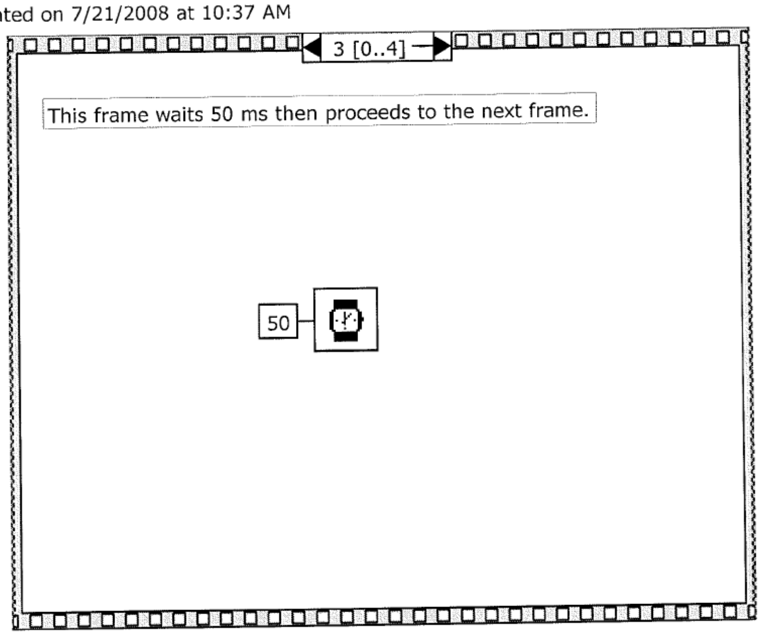

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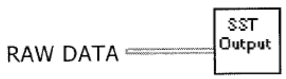

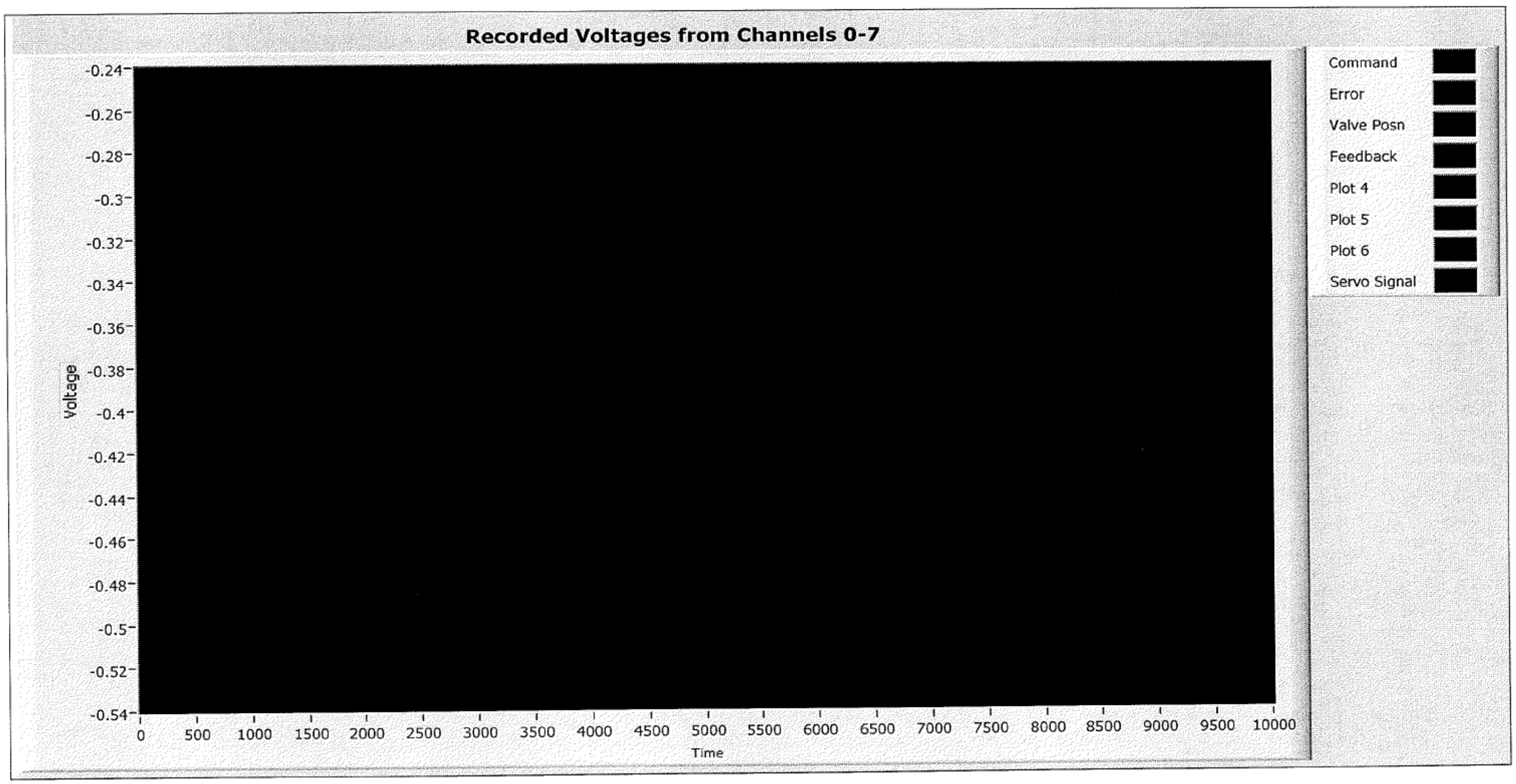

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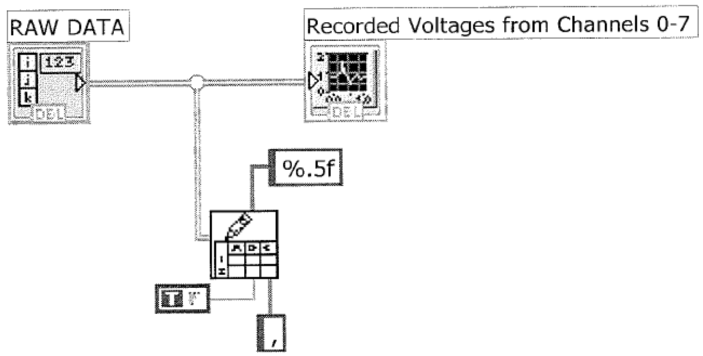

APPENDIX B

INITIAL RUN-TIME ANALYSIS

Initial estimates for the tunnel run-times with both the Mach 2 and the Mach 4 nozzles was found using Equation 1.

$$\frac{Vol}{RT_0}\frac{dP_0}{dt}+\frac{\left(\frac{P}{P_0}\right)^*}{RT^*}\sqrt{\gamma RT^*}A^*=0 \tag{1}$$

The tank volume is 1200 ft^3 with a stagnation temperature of 20°C and a ratio of specific heats of 1.4. The pressure at Mach 1 is equal to 0.5283 P_0 while the temperature at the same point is 0.8333 T_0. The throat area for the Mach 2 nozzle blocks is 93 in^2 while the throat area for the Mach 4 nozzle blocks is 9.5 in^2. Solving Equation 1 for time and using these values the Mach 2 nozzle blocks will drop the pressure in the air tank from 125 psi to 35 psi in 3.23s; however, with a starting tank pressure of only 70 psi the run-time is 1.81s. This value corresponds with the observed duration of stable flow within the wind tunnel. Lastly, with the smaller throat area for the Mach 4 nozzle blocks and a starting tank pressure of 125 psi a run-time of 32.53s is calculated.

APPENDIX C

TUNNEL FIGURES

Figure C.1 Linkage System for Inlet Butterfly Valve Showing Hydraulic Arm

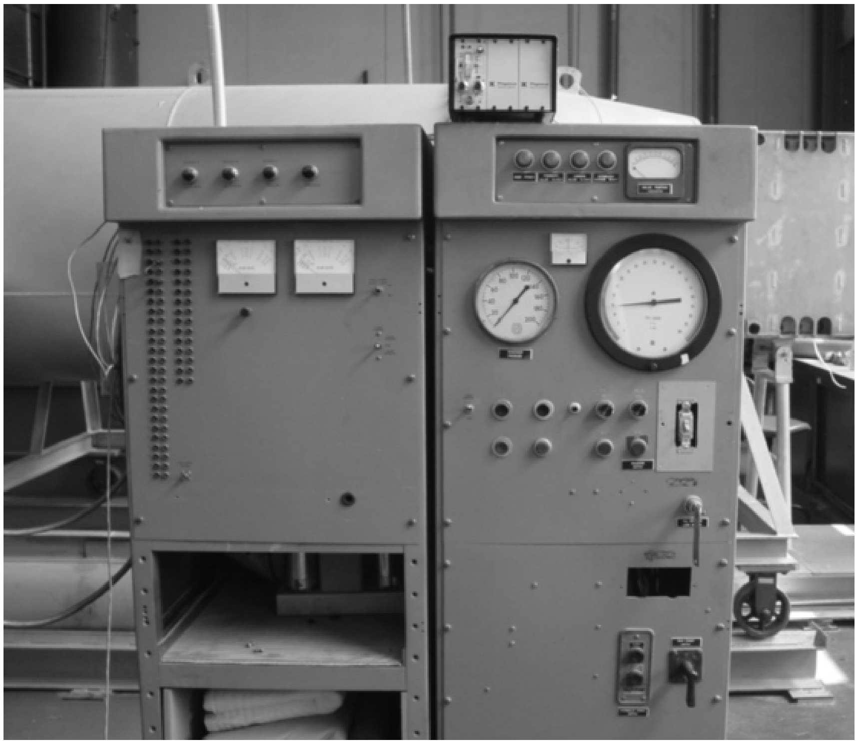

Figure C.2 Tunnel Control Cabinet

Figure C.3 Hydraulic Pump and Reservoir

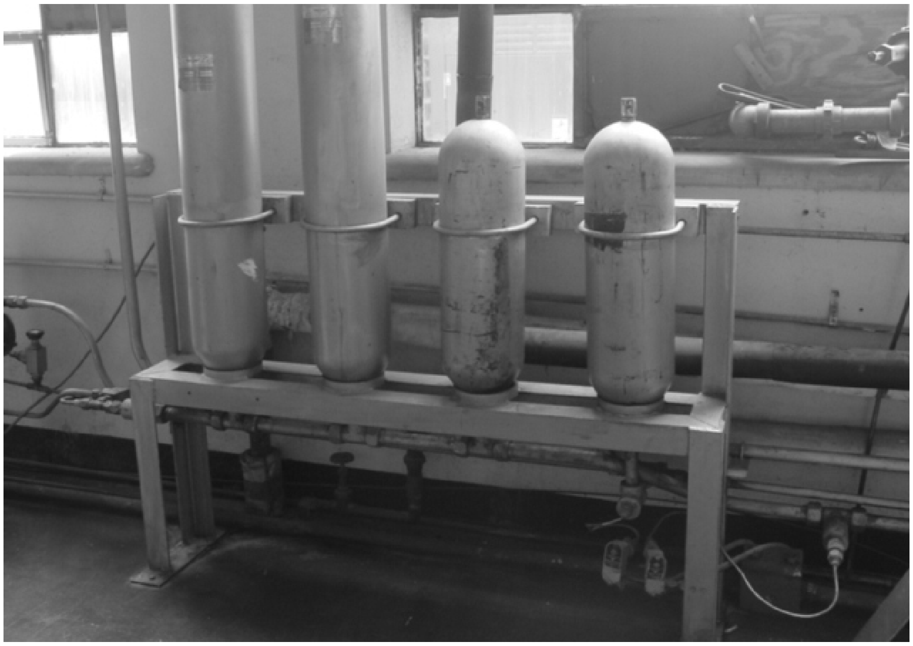

Figure C.4 Hydraulic Accumulators with Pressure Switches Below

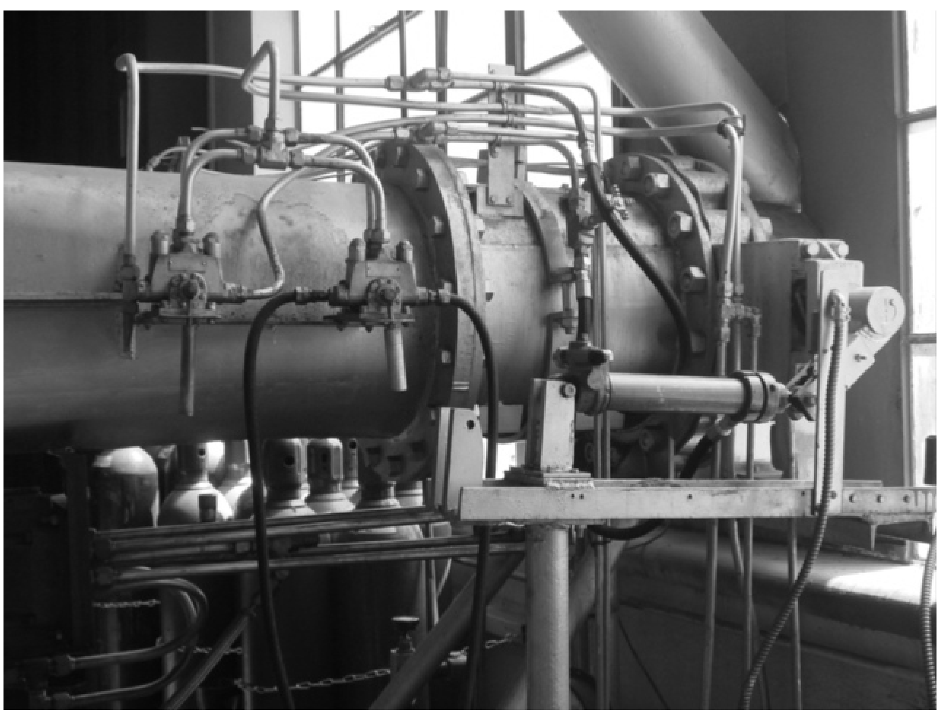

Figure C.5 Exhaust Butterfly Valve

Figure C.6 Emergency Gate Release Valve with Inlet Butterfly Valve Above

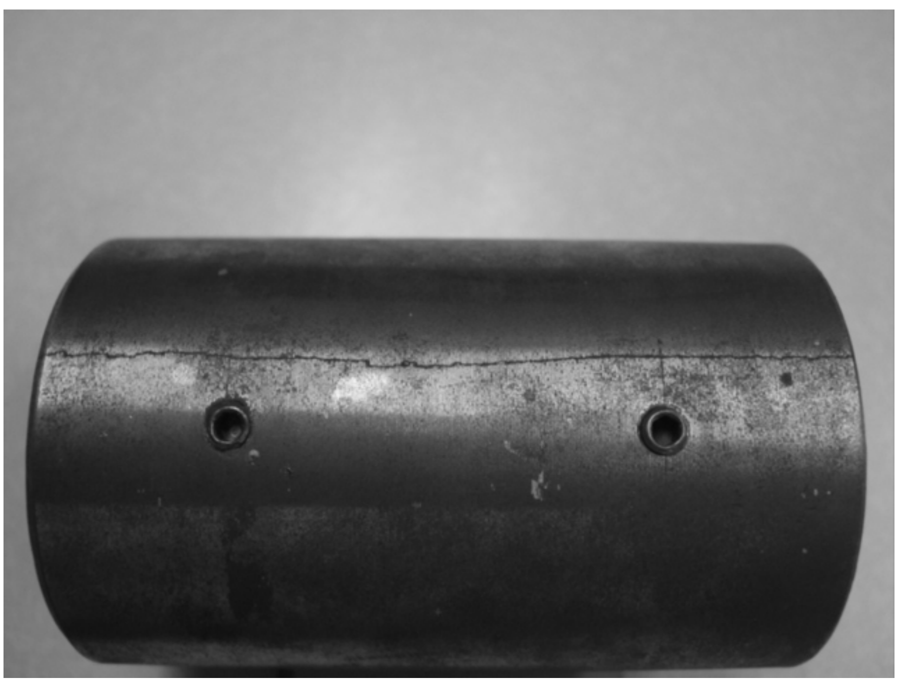

Figure C.7 Cracked Collar for Inlet Butterfly Valve

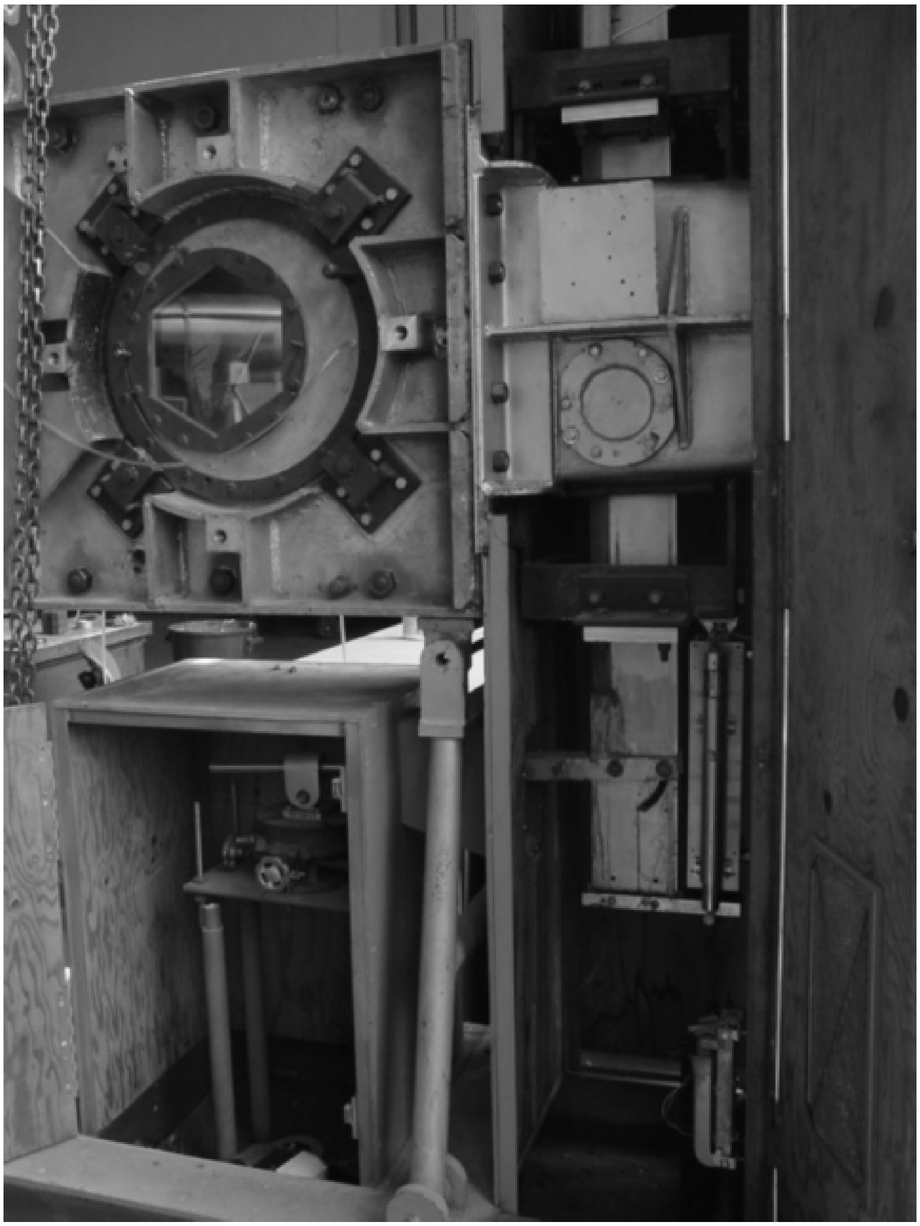

Figure C.8 Sting System for Tunnel

APPENDIX D

UNCERTAINTY ANALYSIS

We desire to determine the uncertainty in computed values of Mach number that are determined from measured pressures in the wind tunnel. The starting point is the isentropic pressure ratio.

$$\frac{p_0}{p} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

Solving this equation for M gives

$$M = \left[\frac{2}{\gamma-1}\left(\left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)\right]^{1/2} \tag{2}$$

This is the data reduction equation. The uncertainty in *M* is

$$\left(\frac{U_M}{M}\right)^2 = \left(\frac{p_0}{M}\frac{\partial M}{\partial p_0}\right)^2\left(\frac{U_{p_0}}{p_0}\right)^2 + \left(\frac{p}{M}\frac{\partial M}{\partial p}\right)^2\left(\frac{U_p}{p}\right)^2 + \left(\frac{\gamma}{M}\frac{\partial M}{\partial \gamma}\right)^2\left(\frac{U_\gamma}{\gamma}\right)^2 \tag{3}$$

To aid in the determination of the derivatives let us define the following intermediate variables.

$$r = \frac{p_0}{p} \tag{4}$$

$$g_1 = \frac{\gamma-1}{2} \tag{5}$$

$$g_2 = \frac{\gamma}{\gamma-1} \tag{6}$$

$$c_1 = \frac{1}{g_1} \tag{7}$$

$$c_2 = \frac{1}{g_2} \tag{8}$$

Expressing *M* in terms of the intermediate variables gives the intermediate form of the data reduction equation.

$$M = [c_1(r^{c_2} - 1)]^{1/2} \tag{9}$$

The required uncertainty derivatives are found using the chain rule.

$$\frac{\partial M}{\partial p_0} = \frac{\partial M}{\partial r}\frac{\partial r}{\partial p_0} \tag{10}$$

$$\frac{\partial M}{\partial p} = \frac{\partial M}{\partial r}\frac{\partial r}{\partial p} \tag{11}$$

$$\frac{\partial M}{\partial \gamma} = \frac{\partial M}{\partial c_1}\frac{dc_1}{d\gamma} + \frac{\partial M}{\partial c_2}\frac{dc_2}{d\gamma} \tag{12}$$

Evaluating the derivatives and expressing them in terms of the physical variables *M*, γ and the pressure ratio *r*, yields

$$\frac{\partial M}{\partial r} = \frac{c_2}{2\,g_1}\frac{r^{c_2-1}}{M} = \frac{r^{-\frac{1}{\gamma}}}{\gamma M} \tag{13}$$

$$\frac{\partial M}{\partial c_1} = \frac{1}{2M} \tag{14}$$

$$\frac{\partial M}{\partial c_2} = \frac{1}{2M}\, c_1 r^{c_2} \ln r = \frac{r^{\frac{\gamma-1}{\gamma}} \ln r}{(\gamma-1)M} \tag{15}$$

$$\frac{\partial r}{\partial p_0} = \frac{1}{p} \tag{16}$$

$$\frac{\partial r}{\partial p} = -\frac{r}{p} \tag{17}$$

$$\frac{dc_1}{d\gamma} = \frac{1}{\gamma^2} \tag{18}$$

$$\frac{dc_2}{d\gamma} = -\frac{1}{(\gamma-1)^2} \tag{19}$$

These all go in the uncertainty equation. The percent uncertainty in *M* is $100\,\frac{U_M}{M}$. The pressure uncertainties, U_{p0} and U_p , are based on the manufacturer's specifications for the pressure transducers. Uncertainty in the ratio of specific heats, γ, is based on the assumption that changes in local atmospheric conditions, particularly humidity can cause the specific heat ratio to change by up to 0.1% from the nominal value of 1.4. The intelligent pressure scanners used have accuracies of up to 0.05%. Neglecting the uncertainty caused by the change in the ratio of specific heats gives a general uncertainty of 0.026%. If the change in the ratio of specific heats is taken into account the general uncertainty is found to be 1.93%.