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Pacer Comet 4: Automated Jet Engine Testing of a TF33-P100 Pratt & Whitney Engine

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Abstract

Pacer Comet 4 found its life out of necessity to replace an obsolescent Pacer Comet 3 engine test system at Tinker AFB in Oklahoma City, OK. Pacer Comet 3 (PC3) was created and installed in the early 1980's to test jet engines from a wide range of planes. PC3 had several problems from a maintenance standpoint: contractors designed and installed the system but the contract did not include the OEM data package. Without drawings or design knowledge, fixing the smallest of problems could turn into a multi-day project. In addition to high cost, as the OEM companies of proprietary parts went out of business, it became impossible to find a replacement for a failed part. These issues set the framework for the Pacer Comet 4 (PC4) system.

PC4 was created as an organic AF and Department of Defense collaboration to fix the issues with PC3. PC4 provides the customer with a complete data package including multiple drawing sets and data sheets for all parts used, as well as design files for all PCBs created in house. PC4 has a standard to use commercially available off the shelf parts (COTS). The reason for this is sustainability in maintenance. If a part is to fail, it should be able to be purchased from any manufacturer that meets the specs of the original product. No proprietary parts are used, except as directed by the engine's OEM.

This thesis will focus on the design and installation of the on-frame data acquisition PC4 system for the Pratt & Whitney TF33-P100A-QEC engine that is currently in use on the E3 Sentry. This thesis will show efficiency improvements for maintenance sustainability (70% cabling reduction) as well as discuss performance improvements in both test and production environments.

Acknowledgements

I would like to acknowledge several individuals for their continued support and effort in making this thesis possible. First and foremost, I would like to thank my beautiful wife, Ashley, for the encouragement, motivation, and love that she has shown me from the early days of my undergraduate career to the final steps of graduate school. Without her, I would not be the engineer, friend, husband, and most importantly, man that I am today. I would also like to thank my coworkers on the PC4 team, with specific respects to Neil Taylor, without whom this thesis may have been nonexistent, and Blake Cunningham for hiring me into this amazing project and for being a great mentor and friend. I would like to thank Dr. Patrick Parkerson of the University of Arkansas' College of Engineering for being my thesis advisor and helping me complete this degree long distance.

Dedication

I would like to dedicate this thesis to my wonderful, amazing, beautiful wife, Ashley, for her hard work in helping me achieve all my goals and for making me who I am today. Without her, life would not be as amazing as it is today. I would also like to dedicate this thesis to our son, due July 20th 2015, for inspiring me to better myself in all aspects; I cannot wait to meet you!

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Introduction

Pacer Comet 4 (PC4) is a joint venture between the Department of Defense and the United States Air Force to create an in-house replacement for an aging and obsolescent engine test system, Pacer Comet 3 (PC3). PC4 is comprised of engineers from the 76th SMXG 555 SXMS/MXDEC at Tinker AFB. The test system is installed at Tinker AFB, Oklahoma City Air Logistics Center (OC-ALC) in Oklahoma City, OK. OC-ALC is one of three Air Force depots that can handle tip to tail maintenance for aircraft [1].

Currently, PC4 is operating in ten cells across the base; when complete, PC4 will be operational in twelve test cells. This PC4 operation at Tinker AFB is designated as a depot activation. PC4 also operates at Edwards AFB in California, Whiteman AFB in Missouri, and Naval Air Station Joint Reserve Base in New Orleans, LA. PC4 is currently pacing to become the standard for jet engine testing across the Air Force. This standardization would mean that PC4 will be installed anywhere the Air Force tests rebuilt engines across the world. At the time of this writing, PC4 is also in talks with OEM providers outside of the Air Force to handle specific engine tests in their own facilities. The PC4 project is at the forefront of DoD and USAF enterprising projects, set to show that in-house programs can succeed at a lower cost than contractor bids. Typically, PC4 works with outside companies ATEC and Vital Link to complete test cell contracts. ATEC and Vital Link manufacture the test cell and engine frames while PC4 designs and installs the electrical and software components that make up the testing equipment. By designing and building in-house, PC4 provides a more advanced system and far superior support from a maintenance standpoint than PC3.

The work done for this thesis involves the design and construction of the on-frame PC4 system for the Pratt & Whitney TF33-PW-100A engine, as well as the software design of the Safety Parameter LABVIEW code that is ran on the PXI system specifically for this engine test. This thesis will show efficiency improvements for maintenance sustainability as well as discuss performance improvements in both test and production environments.

Background

PC4 Background

PC3 was created in the mid-1980s as a replacement for the previous test system, Pacer Comet 2. Like most government projects at the time, a group of outside contractors for the USAF created PC3. While a fully functioning system, PC3 had its drawbacks: as with most contracts, the fee for the OEM schematics and data packages was exorbitantly high and not worked into the original contract. The cost of maintenance and support from the OEM was also significantly high.

The Air Force has several in-house groups, known as flights, in charge of the maintenance of PC3: 555th SMXS/MXDEF, MAD (Maintenance Assembly-Disassembly), and PMEL (Precision Measurement Equipment Laboratory). Designated the 555th SMXS/MXDEF, this 76th Software Maintenance Group flight is in charge of the software that runs the PC3 system. This flight will also serve as the software maintenance for the new PC4 system. MAD, also known as Plant Services handles the test cell equipment that facilitates engine test, such as the fuel and preservation oil system, as well as the equipment used to load and store engines for test. PMEL is the calibration arm of the depot and maintains the hardware that makes up the PC4 test system. However, these flights only take over once the PC4 team has finished a test cell and transfers ownership to the customer, the 76th PMXG at OC-ALC.

The three flights combined to support PC3 for over 20 years [2] and still continue to maintain two test cells at Tinker AFB. However, because the Air Force did not purchase documentation for the PC3 system, the engineers at Tinker AFB had to create their own schematics as they were troubleshooting. This caused the maintenance process to take significantly longer than it should. Lack of documentation was only one part of the drawbacks to PC3. Another significant hurdle that has developed over the years is the lack of availability of proprietary parts used in PC3. Several parts have gone obsolete without a replacement part offered, even by different manufacturers. As such, Tinker AFB has seen a number of test cells condemned. At that point, the condemned test cells were cannibalized to maintain operational capabilities in the remaining cells. This fixed the problem of obsolescent equipment only for a while. A final concern with the PC3 system is that it required highly knowledgeable operators to run engine tests. It is quite easy to damage these engines under the PC3 system. Due to this, the majority of the operators, while now civilian employees have had previous experience working on these engines as they served in the Air Force. PC4's primary goal is to eliminate, or minimize, the drawbacks that PC3 has created.

Another benefit of PC4 over PC3 is that the maintenance is much easier on PC4. Under PC4 configuration, there is a 70% reduction in cable runs. By using the PowerDNA (Distributed Networked Automation), the majority of cables can be terminated inside the JBOX and don't have to be wired back to the facility. Specifically for the P100, there are 176 different connections that would have to be wired back to the facility in PC3, as illustrated in Figure 1. With PC4, only 52 connections have to be connected back to facility, as illustrated in Figure 2. Eight of these connections are the wiring for the Ethernet signal. Some of these connections are power supplies; however there are a select group of signals that have to be read by the facility, in case communication to the frame is severed. These signals are call the Safety Parameters and consist of signals such as exhaust gas temp (EGT), oil pressure, fan speed (both inlet fan and core fans), and vibrations.

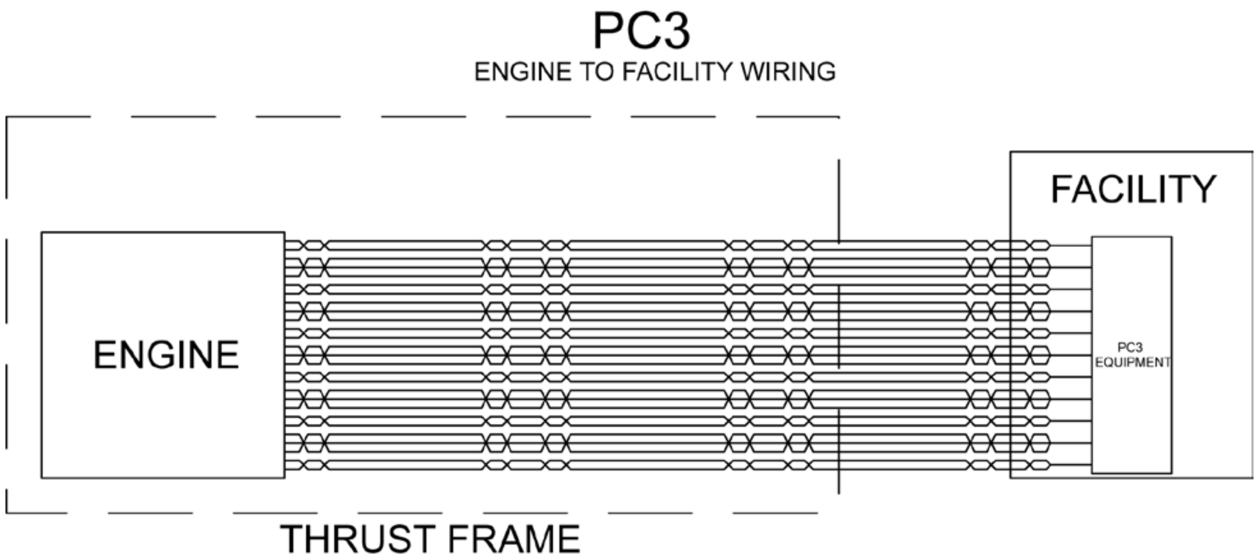

Figure 1 - PC3 Wiring Overview

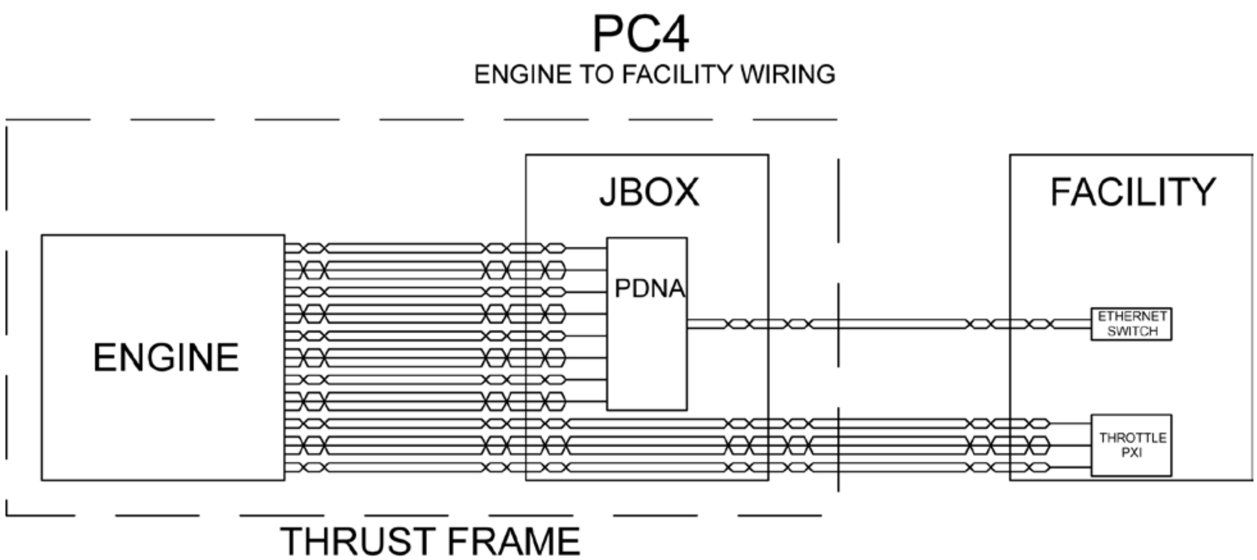

Figure 2 - PC4 Wiring Overview

TF33-P100 Background

The TF33-P100 is a high-bypass turbo fan engine manufactured by Pratt & Whitney, a UTC company. It is designed for military use on the USAF E-3 AWACS sentry. The TF33-P100 has a max thrust at takeoff of 21,000 lbs. The TF33 family has been in service since 1958, most visibly on the B52 bomber (which runs the –P103 variant). The E3 has been in service since 1977 and uses four of the P100 engines. The E3 is used as an airborne early warning and control (AEW&C) vehicle for the Air Force. It houses the 30 foot wide airborne warning and control system (AWACS) radar dome on top of the fuselage, giving the E3 its distinct profile. The E3 and its crew are based out of Tinker AFB.

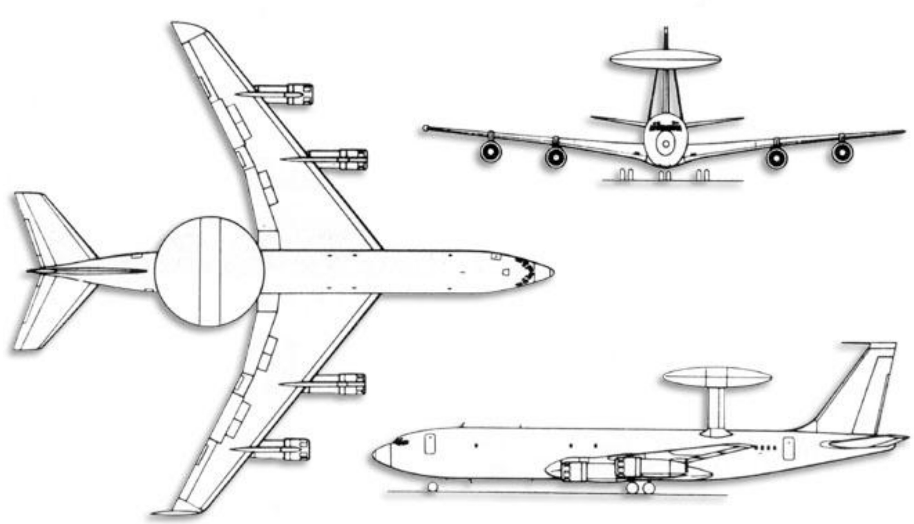

Figure 3 - E3 Line Drawing [3]

The mechanics behind a turbo fan engine are fundamentally simple, as explained by the familiar colloquialism "suck, squeeze, bang, blow" and shown in Figure 4. The inlet fan pulls in air from the environment (suck), and then a series of smaller fans compresses the air, raising the pressure (squeeze). Fuel is then injected into the engine and ignited (bang), and finally the air is pushed out the exhaust nozzle creating thrust (blow). The bypass air, air that does not travel through the engine to be ignited, creates most of the thrust generated by a turbofan. The ratio of the amount of flow of the bypass air to the air that is ignited is called the bypass ration (BPR). For a TF33, the BPR is typically around 1.4:1; this means that the bypass air creates about 40% more thrust than the air that is ignited.

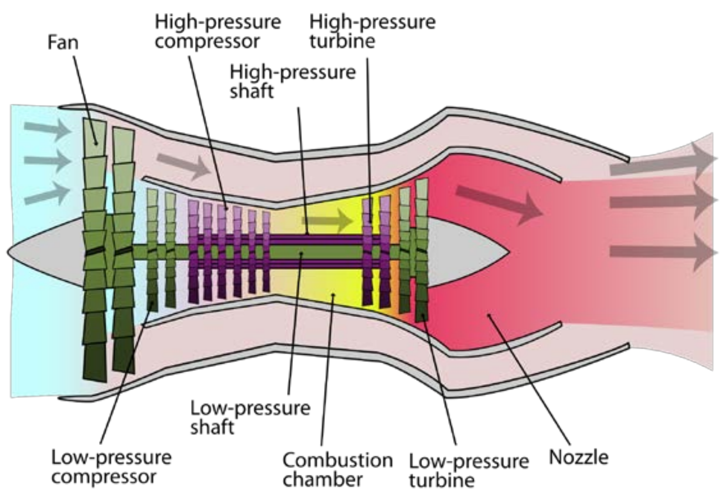

Figure 4 - Simple Jet Engine Operation [4]

It appears that the fan is the driving force for the compressor and turbine blades, but in reality, the high and low pressure turbines create the power that then turns the fan and compressor sections [5]. This is why the bypass air creates more thrust than the ignited air; the energy of the ignited air is used to power the fan and compressors, rather than to propel the engine (or aircraft). In starting an engine, compressed air from the facility is applied to start the spinning of all blades in the engine. Fuel is then added, and as the RPM of the core is sufficiently high enough, ignited. At this point the turbines are turning fast enough to produce enough power to turn the fan and compressors so that the engine can be self-propelled; that is, the combustion of the fuel in the air creates enough energy to power the fan and compressors to pull in more air that can then be combusted. Now, the engine will continue to run as long as fuel is continually supplied and the throttle is in the run position. Figure 5 shows a more in-depth look into the inner workings of the

P100 engine. There are typically four general sections of an engine: the compressor section, combustion chamber section, the turbine section, and the exhaust section. The P100's front compressor is made of eight stages; a stage is a single set of blades attached in a circle. The rear compressor has seven stages while the turbine is a four-stage section.

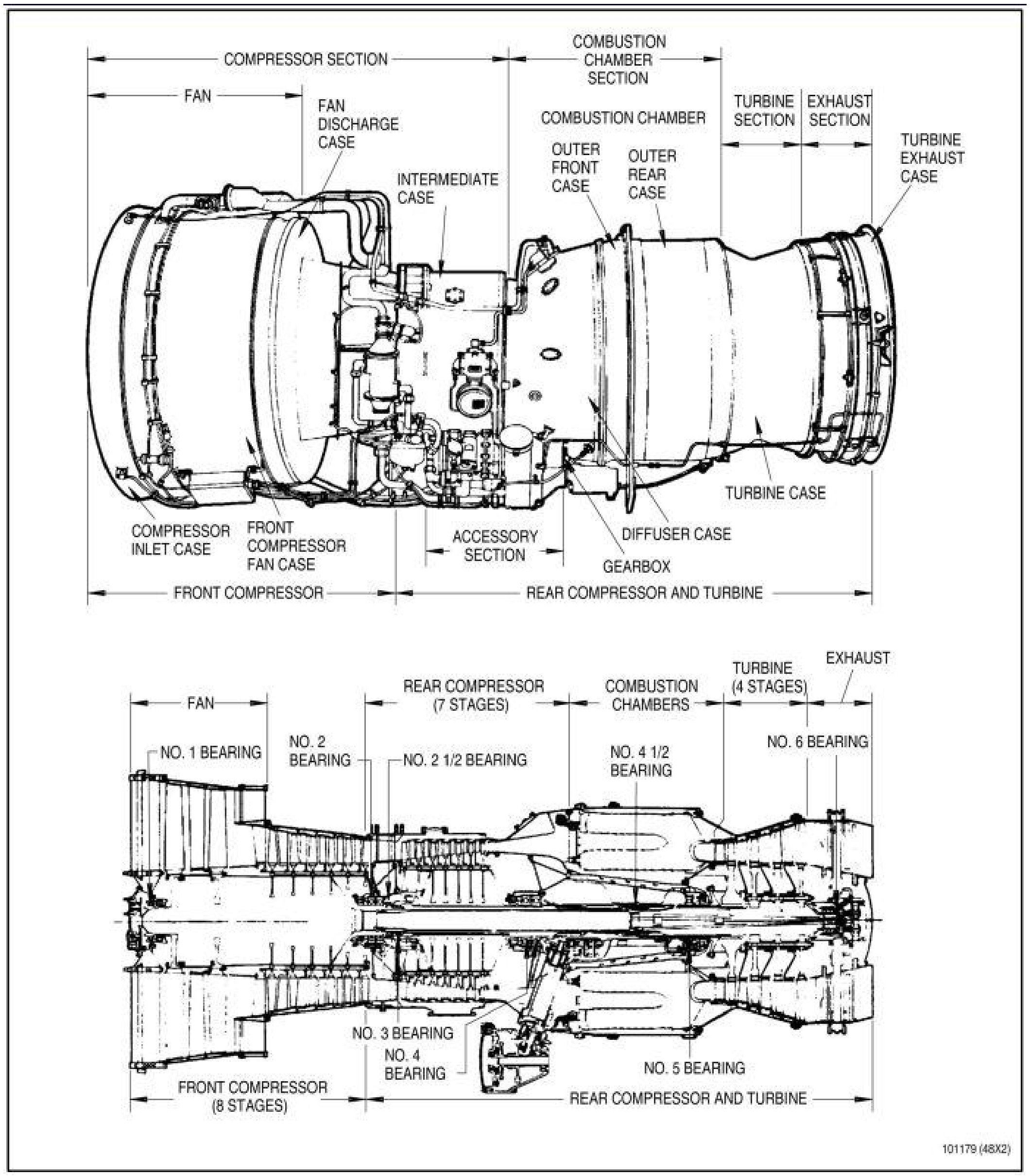

Figure 5 - TF33-P100 Engine Sections and Components [6]

To power all the electronics on the aircraft, the E3 has access to two generators on each of the four P100 engines. These generators provide standardized 26 VAC 400 HZ three phase power to aircraft electronics including the AWAC system. The aircraft can also rectify the signals to provide the standardized 28 VDC to control the engine and electronics on-board. In addition to the generators, the P100 also contains the sophisticated fire detection and suppression system that gives the aircrew the ability to extinguish the engine fires mid-flight. The P100 variant is also able to remotely monitor the status of the oil system, including temperature, pressure, and the amount of oil in the engine. It is PC4's responsibility to replace the PC3 system with respect to these three signals specifically. There are several other components, to be discussed later, that can simply be integrated into the PC4 system.

PC4 Design Requirements

PC4 set out to eliminate the flaws in PC3 through several main design goals: provide OEM (in this case, PC4) drawings and schematics, as well as operational software and proprietary equipment; design the PC4 system using as many commercially off-the-shelf (COTS) parts as possible; and automate the test process, all the while providing safety lockouts and operational ease.

PC4 System Components

PC4 is made up of several key components divided into two categories: the Facility and the Frame. This thesis will focus on the design and development of the frame, specifically in respect to the TF33-P100 engine. However, for completeness, the facility system will be discussed throughout the document.

PC4 Facility Design

The PC4 Facility design is focused on the following pieces of equipment: the National Instrument PXI's (of which there are two), the PC4 racks, the PC4 Host (which runs the National Instruments LabVIEW software), and the facility autoconnector. The PXI's are the backbone of the PC4 facility design and provide communication to the PC4 racks and the host. The PXI's, one for facility monitoring and switching and the other for the throttle control and safety parameter monitoring, each run on a dedicated processor with real-time operating systems to provide guaranteed timed response [7]. The PXI's will run independently from the host should communication failure occur, allowing safe control of the engine for shutdown. The whole PC4 system is run through an APC UPS with battery backup to prevent shutdown due to power loss. The autoconnector is a group of connectors that mate with the engine frames for quick connect to the facility for test. While each cell has the same configuration of connectors, each frame uses only a select subset for test; having the larger configuration in the test cell allows any frame to be run in any cell.

PC4 Frame Design

The PC4 frame design is centered on the on-frame data acquisition (DAQ) capabilities of PC4. As the facility has the PXI's, the frame has the United Electronic Industries' PowerDNA (PDNA) chassis. This small form data acquisition device houses modular input/output (I/O) cards that can be specially configured for each individual frame. The PDNA then converts the signals into an Ethernet protocol for transmission through the autoconnector, back to the host computer for monitoring and control, as illustrated in Figure 2. The PDNA is housed inside a junction box (JBOX) that is mounted to the frame.

The JBOX is a NEMA-4 rated housing to provide a degree of protection from hazardous materials such as dust and water, which could harm the PDNA and devices inside [8]. In addition to the PDNA, the JBOX contains pressure transducers, a cold-junction-compensation (CJC) board for thermocouple transmission, regulated power supplies, any specific engine module required, and the PCB's to interface with the PDNA. Specifics relating to the TF33-P100 engine will be discussed more in depth later.

PC4 Automation Capabilities

PC4 has the ability to run engine tests without the direction of an engine operator. Obviously, for safety purposes, operators are still required during the test. Every time an engine is ran, an operator and an inspector are to be present. In order to ensure operator awareness, in automated mode, PC4 still requires the operator to acknowledge certain items during a test, such as a specific engine reading pertaining to the test, or to simply "okay" a procedure has occurred. PC4 however, has the ability to control engine states, throttle positioning, and engine controls signals automatically. This functionality allows the operator to be more efficient at selling off an engine while training on the specific engine type for certification. An example of the benefits of running in automatic mode is seen in an excerpt of the break-in test run in Table 1.

N2 Target (RPM)	Time (sec)	Total Time (sec)
At Idle	2400	2400
Accel to 8450	5	2405
At 8450	10	2415
Decel to Idle	5	2420
At Idle	40	2460
Accel to 9200	5	2465
At 9200	10	2475
Decel to Idle	5	2480
At Idle	90	2570

Table 1 - Excerpt of P100 Break-in Run [9]

This is but a small sample of a very long break-in run. If running in automation mode can save only several seconds per step by eliminating operator reaction time, over the course of every test step and every engine run, significant time savings can add up.

Air Force Technical Orders

Steps in the testing process are derived from Air Force Technical Orders (TO's). These TOs direct, step by step, how to test an engine, including parameter limits at each step. It is directed that the PC4 system adheres to the TO completely for use in a production environment. A specific group manages each TO across the Air Force. The TF33-P100 engine is tested under the TO 2J-TF33-53-10. This TO is written for all TF33 variants, but has sections for each specific variant. In addition to test steps the TOs include directions for building up the engine for test and build down steps for after test. Operators are required to follow the TO for every process.

In addition to the test TO, there are TO's that cover depot maintenance, as well as a TO that describe individual parts of the test stand, down to the nuts and bolts. The 53-10 is the maintenance test TO. Related to the TF33, there is a 53-1, which is a depot maintenance TO that describes repair of the engine (Figure 6).

c. Install permanent shims and torque slave socket head capscrews to 580-640 FT LB.

d. Verify proper fit for each cell with permanent shims installed.

e. Remove bolts individually and replace with self-locking nylon insert bolts. Step torque to 300-500 FT LB and final torque to 580-640 FT LB.

f. Drill spiral roll pin holes to final dimension of 0.500-inch diameter through support arms (Figure 3-1, 3, 9), shims (11), and machined support arm mounting surfaces of thrust frame adapter assembly (1).

g. Drive 0.500- by 3.00-inch spiral roll pins in place.

3.2.6 Disconnect Lugs Installation.

WARNING

Use correct lifting equipment and techniques. Stay out from under suspended loads to prevent injury.

Lower thrust frame adapter to floor. Install two disconnect lugs (Figure 3-1, 2) to thrust frame adapter (1) as follows:

a. Position disconnect lugs (2) directly forward of aft support arms (3) on either side of thrust frame adapter (1).

WARNING

Molybdenum disulfide, DOD-L-25681, is an eye irritant. Pressure application involves hazardous airborne particles that could be harmful to eyes. Eye protection is required.

b. Attach each disconnect lug with two each MS90726-166 hex-head grade No. five capscrews (0.625-18 UNF by 2.500 inches long). Lubricate threads and friction surfaces with molybdenum disulfide, DOD-L-25681, or equivalent.

c. Install AN960-1016L washer (0.625-inch nominal ID) under bolt head, and steel hex nut to bolt threads on inside of thrust frame adapter sidewall.

d. Torque nuts evenly to 70-78 FT LB.

3.2.7 Coupling Plate Adjustment. The two halves of the Coupling Plate (Figure 3-1, 4) are independently adjustable vertically, horizontally, tilt, and spacing from thrust frame adapter body. The following procedure assumes thrust frame adapter is in thrust bed of primary test cell.

WARNING

To prevent injury or death from crushing or falling, two people should work together in thrust bed-catwalk area of test cell. Do not overextend reach or operate equipment without coordination. Ensure safe footing.

a. Loosen locknut on adjustable stop pads (5).

b. Turn stop pad (5) CCW until approximately two inches of space is measured between adapter (1) and inner face of stop pad.

c. Temporarily tighten locknut.

d. Check leveling screws.

(1) Screws should be completely engaged with no space under heads and no threads showing.

(2) Locking screws shall be loose enough to turn by hand.

e. Loosen nuts two turns on adjustment bar bolts.

WARNING

To prevent injury or death, keep fingers and other body parts clear of Coupling Plate during operation.

NOTE

An experienced cell operator should be present for assistance in operating facility Coupling Plate controls, and determining proper engagement with thrust frame adapter.

f. Operate control with caution. Make a practice run to observe alignment pin and hole accuracy. Stop pads (5) should prevent complete mating of connectors until final adjustments are made.

g. Adjust thrust Coupling Plate (4) as necessary.

(1) Adjust Coupling Plate (4) horizontally or vertically, and tighten adjustment bar nuts.

Figure 6 - Maintenance TO Example

Specific to the TF33-P100 at Tinker AFB, there is another frame TO that contains the Illustrated Parts Breakdown, or IPB; this TO is numbered 33D4-6-609-4. Depending on the scope of the contract, PC4 will update frame TO's as required. For the TF33-P100, the IPB will not be updated for use with the PC4.

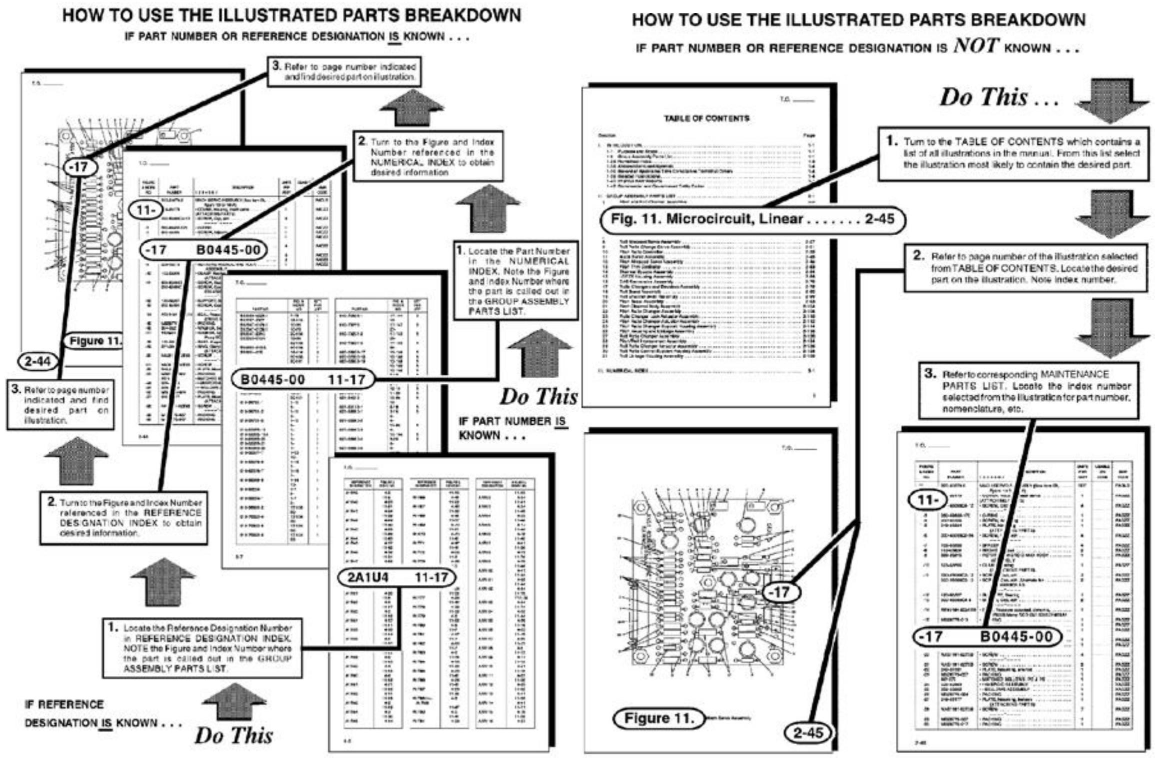

Figure 7 - IPB TO Example

Therein lies a problem with the TO's: due to the age of the engines and the multiple generations of airmen and operators who have worked on the engines, changes may have been made to frames or other procedures that are not reflected in the TO. This provides issues when developing new systems, such as PC4. Often PC4 engineers will design the system based off the TO only to find that the documentation was incorrect once integration occurs. Then redesign has to take place, directly impacting the project's schedule. It is a major goal of PC4 to provide accurate documentation for the system for future use.

TF33-P100 Design

Systems of the P100

The P100 has several key engine components at require monitoring by PC4:

- Oil System
- Fire Detection
- Generators
- Anti-Icing
- Engine Control Signals
- PC4 Designed PCBs
- Engine Pressures

Oil System

PC4 has the requirement to replace the PC3 indication system for the three oil signals: pressure, temperature, and quantity. With PC3, rack mounted indicators were used to monitor these signals. However with PC4, all readings are sent through the PDNA to the PC4 Host. Given only the TO for each indicator, PC4 engineers reversed engineered the ability to read and convert the signal to a simple voltage. Due to the scope of the project, the pressure signal is deemed a critical parameter and is passed through the autoconnector back to the Throttle PXI.

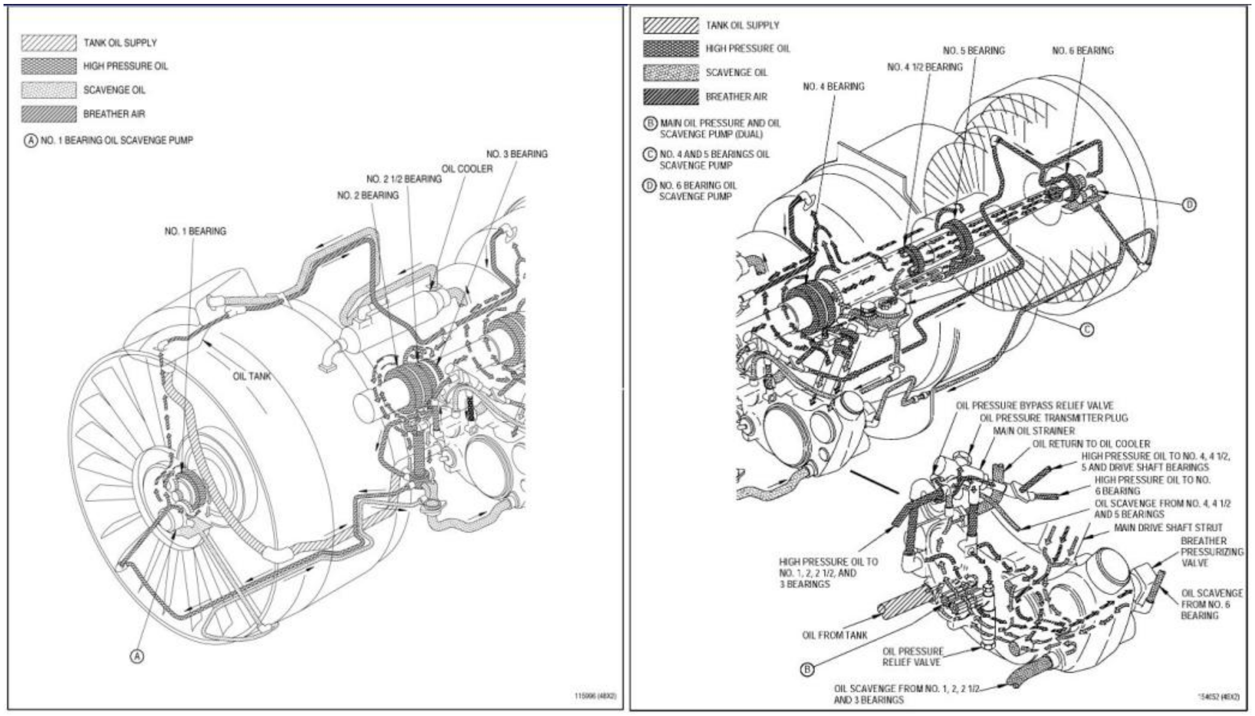

Figure 8 - TF33-P100 Oil System Model [6]

Oil Temperature Transmitted

The engine uses a thermobulb to generate the temperature signal and is displayed in PC3. The PC3 (Figure 9) indicator must be replaced by PC4. This indicator has an indicating range of -70° to +300° Celsius. Table 2 shows the relationship of the resistance of the bulb to the temperature of the indicator reading.

Temperature v Resistance			
Temp. °C	Ω	Temp. °C	Ω
-70	68.27	20	97.31
-50	74.24	40	104.60
-41	77.39	50	108.39
-20	83.77	100	128.85
0	90.38	150	151.91

Table 2 - Oil Temp Indicator Set Points [10]

Using the data in Table 2, a suitable PC4 design was created. Since the thermobulb is a simple RTD, the circuitry in PC4 is a simple voltage divider. The engine provides the connection points to the thermobulb; PC4 uses those points to read across the bulb and record the voltage through the PDNA. With the addition of another resistor, PC4 regulates the current flowing through the circuit to negate the change of current based on the resistance of the bulb. Using a resistance of 2000Ω for the control resistor, the following expected results were obtained, as shown in Table 3. The 2000Ω resistor provides for minimal current change while maintaining a sufficient voltage swing. The PDNA uses the DNA-AI-207 card to read the voltage; this card has an input accuracy of ±287.59 µV with a ±10 V input range [11]. The supply voltage for the circuit will be the standardized engine power +28 VDC.

Ra (Ω)	Rtemp (Ω)	Itemp (A)	VRtemp (V)		Voltage Range
2000	77.39	0.01271	2.583491785		1.052037888
	90.38	0.01263	2.741434572		
	104.6	0.01254	2.912097311		
	120.36	0.01245	3.098568168		
	137.78	0.01235	3.301480976		
	151.91	0.01227	3.463657867		
	167.09	0.01218	3.635529673		

Table 3 – Oil Temp Circuit Measurements

Using the measured voltage across the bulb (V_{Rtemp}), and the known supply voltage (28 VDC) and resistor (R_A = 2000Ω), the current through the circuitry (I_{temp}) can be substituted for an equation with the measure voltage, and the resistance of the bulb (R_{temp}) can be calculated via the following equation:

$$R_{temp} = {V_{R_{temp}}}/{I_{temp}} \quad ; \quad I_{temp} = {\left(28 - V_{R_{temp}}\right)}/{R_A}$$

$$R_{temp} = {(V_{R_{temp}} \times R_A)}/{(28 - V_{R_{temp}})}$$

With this equation, the software can take the measured voltage, V_{Rtemp}, and immediately calculate the resistance of the bulb. The software then will interpolate the resistor's value across the values in Table 2 to come up with a corrected temperature of the oil in the engine. The oil temperature limits depends on the temperature of the fuel (which is measured in the facility); this is important because the P100 uses a fuel cooled oil cooler. At 70°F fuel temp, the oil temperature should be below 195°F at takeoff thrust and 270°F at all other operating conditions. If oil temperature measures higher than that, additional steps are taken to measure oil flow between the oil cooler and oil tank inlet.

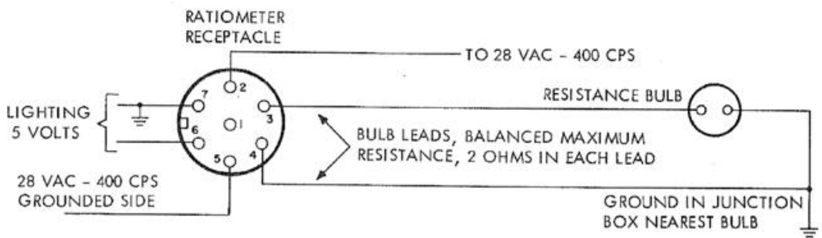

Figure 9 - PC3 Oil Temperature Indicator Wiring [10]

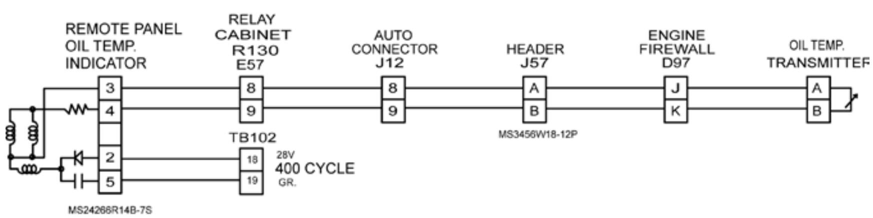

Figure 10 - PC3 Oil Temperature System Wiring

Oil Quantity Transmitted

An on-engine transducer generates the oil quantity transmitted signal. The oil quantity transmitted works in the same manner as oil temperature transmitted in that they both use a resistance value to correspond to the end unit. However, the oil quantity transmitted uses two resistors on the engine, instead of one. Similarly, the circuitry will use a 2000Ω resistor to regulate current to a safe level. The PC3 indicator (Figure 11) must be replaced by PC4. This indicator has an indicating range of 0 to +6 gallons of oil contained in the engine. Table 4 shows the relationship of the resistance of the bulb to the quantity of the indicator reading.

Test Points	Tolerance	Input Signal	
	Signal Reading	Engine Resistors	
		RA	RB
Gallons	Gallons	Ω	Ω
0	± 0.15	300.0	0.0
1	± 0.15	237.2	62.8
2	± 0.15	193.5	106.5
3	± 0.15	157.2	142.8
4	± 0.15	124.0	176.0
5	± 0.15	85.4	214.6
6	± 0.15	34.3	265.7
FS	- 0.15	0.0	300.0

Table 4 - Oil Quantity Indicator Set Points [10]

R1=R2	R_AΩ	R_BΩ	V Range	IA	IB		VRA	VRB
2000	300.00	0.00	3.6521	0.0121	0.014		3.6521	0
	237.50	32.75		0.0125	0.0137		2.9720	0.4511
	193.55	106.45		0.0127	0.0132		2.4706	1.4149
	157.25	142.75		0.0129	0.0130		2.0410	1.8653
	124.06	175.94		0.0131	0.0128		1.6353	2.2639
	85.39	214.61		0.0134	0.0126		1.1465	2.7133
	34.26	265.74		0.0137	0.0123		0.4715	3.2840
	0.00	300.00		0.014	0.0121		0	3.6521

Table 5 - Oil Quantity Circuit Measurements

Using the measured voltage across the engine resistors (V_{RA}, V_{RB}), and the known supply voltage (28 VDC) and resistor ($R_1 = R_2 = 2000\Omega$), the resistance of the bulb (R_A and R_B) can be measured via the following equation:

$$R_A = {V_{R_A}}/{I_A} \quad ; \quad I_A = {(28 - V_{R_A})}/{R_1}$$

$$R_A = \frac{(V_{R_A} \times R_1)}{(28 - V_{R_A})}$$

$$R_B = \frac{V_{R_B}}{I_B} \quad ; \quad I_B = \frac{(28 - V_{R_B})}{R_2}$$

$$R_B = \frac{(V_{R_B} \times R_2)}{(28 - V_{R_B})}$$

With this equation, the software can take the measured voltage, V_{RA} and V_{RB}, and immediately calculate the resistances R_A and R_B. Then, similar to the oil temperature transmitted, the software can interpolate the values of R_A and R_B across the values in Table 3 to calculate the value of the oil quantity in the engine.

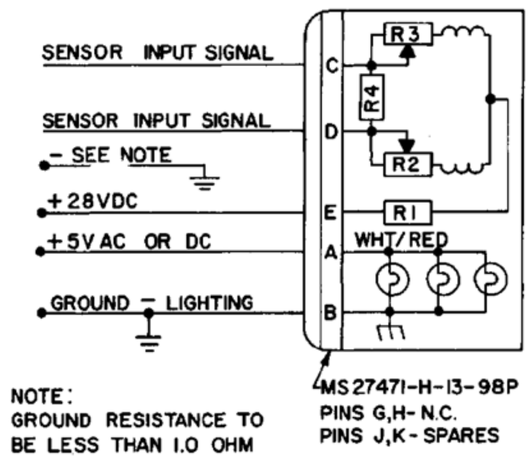

Figure 11 - PC3 Oil Quantity Indicator Wiring [10]

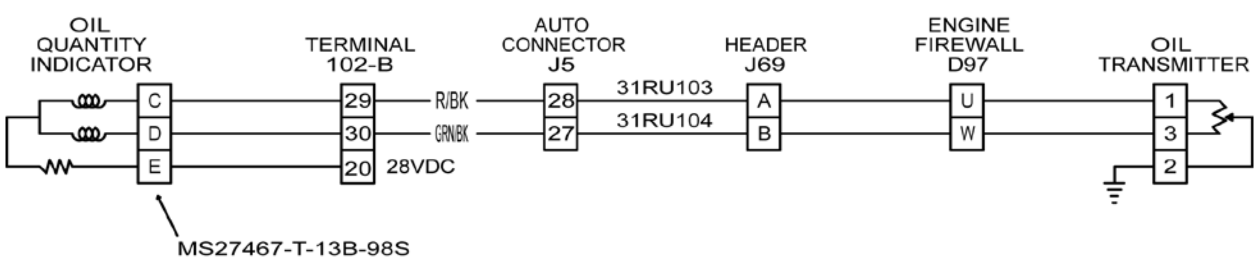

Figure 12 - PC3 Oil Quantity System Wiring

Oil Pressure Transmitted

A TRU-66/A oil pressure transmitter generates the oil pressure transmitted signal. The TRU-66/A is a ratiometric transmitter with an operating range of 0 to 100 PSI. The transmitter can withstand 100% over-pressurization for up to 10 minutes should the situation arise. This allows sufficient time for the operator to recognize that the oil pressure is significantly over safe limits and allows safe shut down procedures to occur. Recording the supply voltage and the transmitter's output voltage and dividing them determines the calculated pressure. Oil Pressure is a safety parameter; therefore it is handled by the facility in the Throttle PXI.

Fire Detection System

The P100 engine is equipped with a fire detection system [12]. The engine is contained in cowl doors that could conceal a fire without much indication on the outside. To detect a fire, the engine has metal loops installed that, when exposed to fire, short together. The aircraft, or in this case the test cell, is equipped with a Boeing Fire Detection Module (PN 204-53097) with internal cards 204-53173-4 and 204-70091-3. There is no requirement of PC4 to replace this module, but rather incorporate it into the system. The module is relatively small at 4.5”x4.8”x1.5”; due to the small footprint, the module is incorporated into the JBOX design. By including the module in the JBOX, the need for additional autoconnector runs specifically for this module only (which only the P100 engine uses) was eliminated. PC4 interfaces with the module via the PDNA and a PC4 designed and built relay PCB. The Fire Detection system is designed around this module, as seen in the wiring schematic for PC3 (Figure 13).

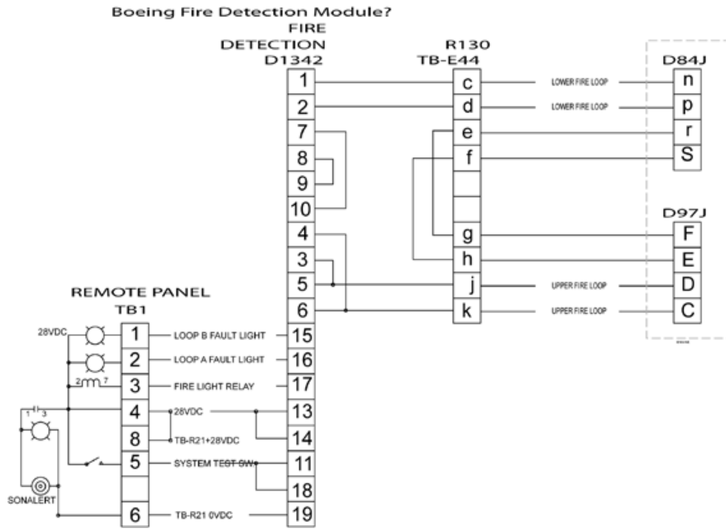

Figure 13 - Boeing Fire Detection Module Schematic (PC3)

The symbols on the left of Remote Panel TB1 show the switches and indicators for this module. This PC3 schematic shows how to incorporate the module into PC4. Positions 1 and 2 on TB1 short to ground whenever there is a fault detected on either loop. Under normal operation, if there is a fire, position 3 will also short to ground, activating the coils of the Fire Light Relay which will then light a lamp and enable an audible alert in the test cell. The system also has a test switch to ensure that the module is working correctly. Instead of having the relays, lights, and alarms in the facility, in PC4, the PDNA interfaces with this module and the software is responsible for alerting the operator. A single terminal block group inside the JBOX replaces both TB-E44 and TB1.

Generators

There are two generators on the TF33-P100 engine. Each generator produces [12] a 3-phase 26VAC, 75KVA, 400HZ signal. The 26VAC 400HZ signal is a standard aircraft power voltage used for aircraft equipment, like indicators, and for signals such as AC ignition. For testing purposes, only one generator is on at a time; there is a relay inside the JBOX to switch between the two generators. Each phase has its voltage and frequency measured and monitored through the PDNA simultaneously. Each phase runs through two signal conditioners to change the amplitude and frequency of the signal to a 0-10VDC linear voltage. Current is not a consideration for the test of the generators since there isn't a sufficient load available to test.

In addition to the signal characteristic measurements, there is also a Generator Control Unit (GCU) associated with each of the P100's generators. In PC3, this GCU was stored in the facility and required a specific set of cabling in the autoconnector, just as the fire detection module did. In PC4, both GCUs are located on frame in a box mounted across from the JBOX. This box is called the GCU Box. By putting the GCU on frame, along with the Fire Detection Module, the P100 can now be tested in any cell at Tinker AFB.

Anti-Icing System

The TF33-P100 engine is equipped with an anti-ice system to prevent ice buildup during flight. The anti-ice system targets three core areas of the P100: the fuel inlet, the nose cowl, and the core of the engine. The engine opens one of the three valves to route preheated air from the hot sections of the compressor to the unheated forward compressor sections. This provides thermal protection for the fuel coming into the engine to ensure proper viscosity to achieve correct fuel flow. Equally important is the protection against ice buildup on the nose cowl of the engine; the nose cowl is the section of fairing located forward of the inlet fan. The nose cowl is important for reducing drag by correcting airflow into the engine. Having proper airflow through the engine is critical to the efficient operation, as well as to the durability of the engine. The nose cowl reduces the drag and corrects airflow by creating a smaller surface area to achieve more laminar airflow (Figure 14). The beveled shaped of the nose cowl helps facilitate the airflow patterns into the engine (Figure 15).

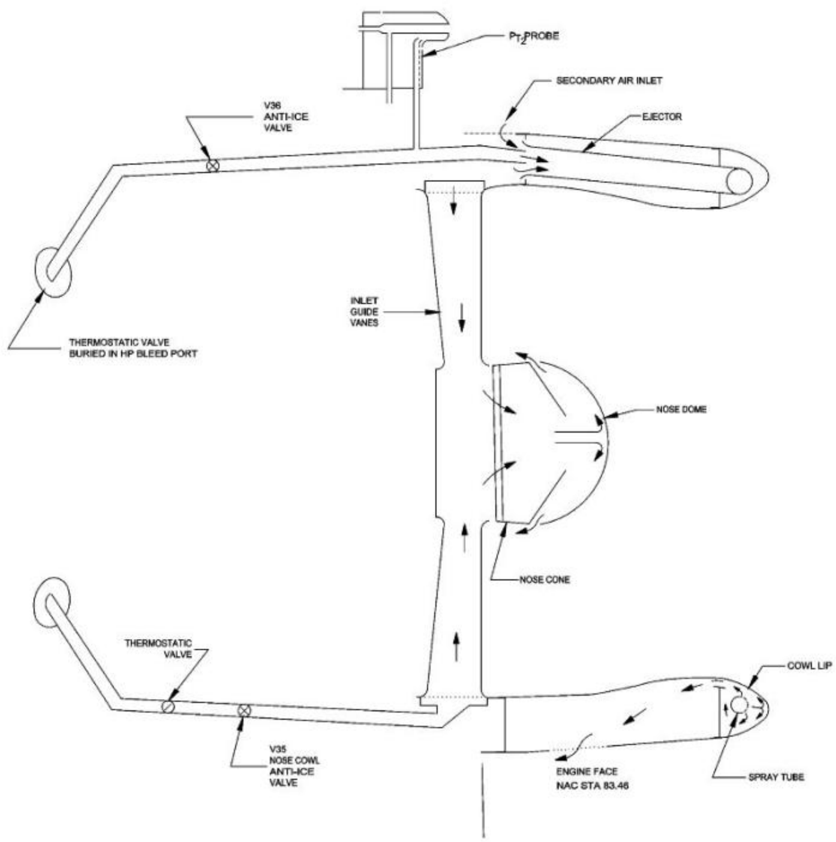

Figure 14 - TF33-P100 Nose Cowl Anti-Ice Airflow Diagram [13]

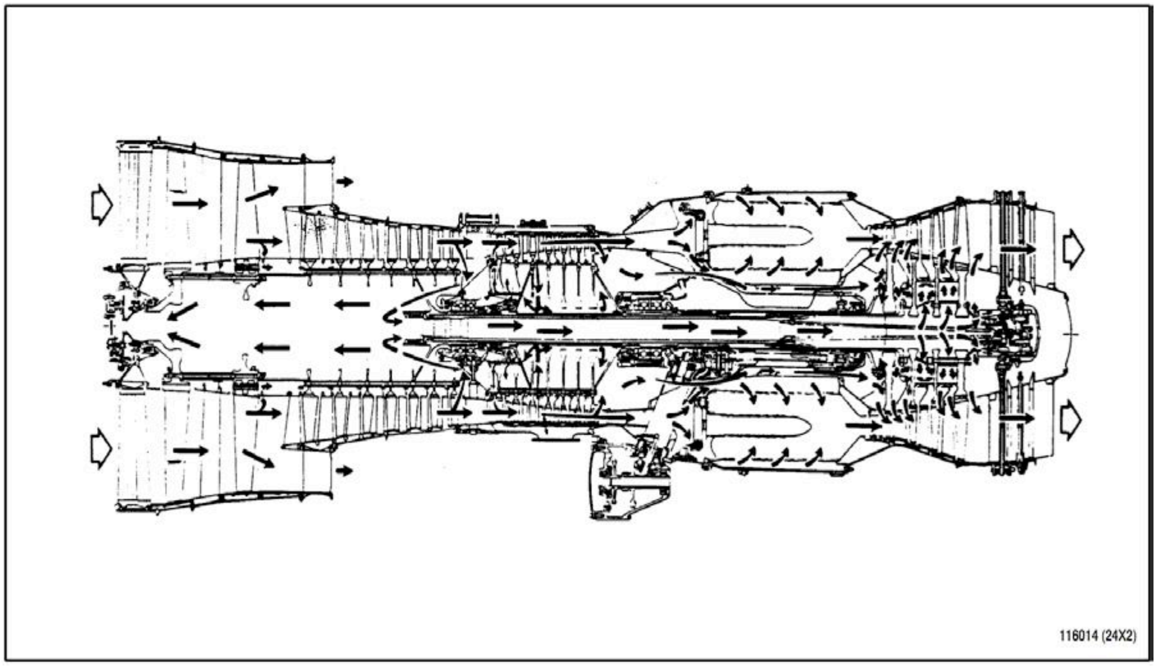

Figure 15 - TF33-P100 Airflow Diagram [6]

At the operator’s (or pilot’s) behest, the system will send a 28VDC signal to the valve actuator to open the valve to bypass the hot air. When the valve is fully engaged, the engine will send back a ground signal to the system to indicate correct operation. When anti-ice air is no longer needed, the system sends the 28VDC signal again to close the valve. Actuation is through the use of a double-pole-double-throw (DPDT) relay. The valve close signal is tied to the normally closed contact on the relay in order to set the default state of the engine. The valve open signal is tied to the normally open contact on the relay. If so desired, the system can be set up to default to the normally open position by energizing the relay on start-up. By using a DPDT relay, the JBOX can provide a feedback signal to the PowerDNA indicating when the relay has been energized. Using DPDT relays in this manner provide an additional tool in troubleshooting this complex system. Every switch from PC4 also has a dedicated feedback (Figure 16) that gives the operator a visual indication that the signal was sent to the engine successfully.

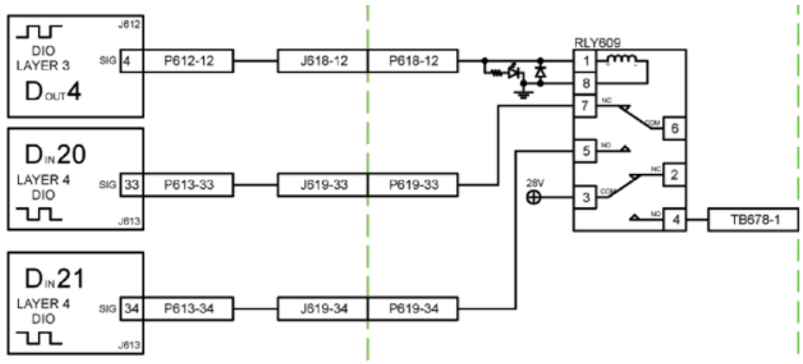

Figure 16 - Relay Feedback Logic

To aid in testing the anti-ice valve operation, PC4 uses two thermocouple probes to check air temp at the vents. Positioned on the top and right side of the engine, these probes allow the operators to see a physical response to the opening of the anti-ice valves. PC4 uses a J-type thermocouple probe for this purpose; the J-type thermocouple provides an operating range of 32°F to 1382°F with an accuracy of approximately 4°F or 0.75% [14] of the reading (whichever is greater).

Engine Control Signals

The P100 has several engine control signals that don't fit into any specific categories, but are still crucial to engine operation and test. These signals are:

- Ignition (AC and DC)
- Exhaust Gas Temperature
- Halon Bottle Control (Fire Supression)
- Oil Pressure Warning Light
- Fuel Filter-Delta Pressure Light
- Bleed Air Valves
- Cold Fuel Enrichment

- Electrical Depress Valve
- Starter Manifold Pressure Switch

Engine Ignition

The P100 engine is equipped with both an AC and DC ignition system. The AC ignition system utilizes 26VAC at 400HZ, while the DC system uses the 28VDC that is found in the engine control systems. In PC4, the facility controls the feeds for both of the ignitions; however, there is an additional relay inside the JBOX for the AC line for additional safety.

At the operator's direction, PC4 will enable either ignition, depending on the engine test. There is also a duty cycle limitation to the use of the ignition system to prevent engine damage [9]: two minutes on, three minutes off, two minutes on, twenty-three minutes off. Exceeding this duty cycle may cause damage to the ignition system and the engine; PC4 tracks this timing and will prevent incorrect operation. While different situations may arise for the pilot to use DC ignition, and even though PC4 verifies proper operation of DC ignition, the Air Force test TO designates use of AC ignition in the final acceptance run of the engine.

Exhaust Gas Temperatures

One of the most important parameters that PC4 monitors is the exhaust gas temperature (EGT). Singlehandedly, EGT has indicated more engine problems than any other parameter. At a quick glance, the operator can see that there is a problem with the engine and shut it down without damage to the engine. A high EGT reading can indicate a lean fuel condition, a dangerous condition that results in excessive engine operating temps. Just as with automobile engines, running at too high of an EGT for a prolonged period can result in significant damage to the jet engine.

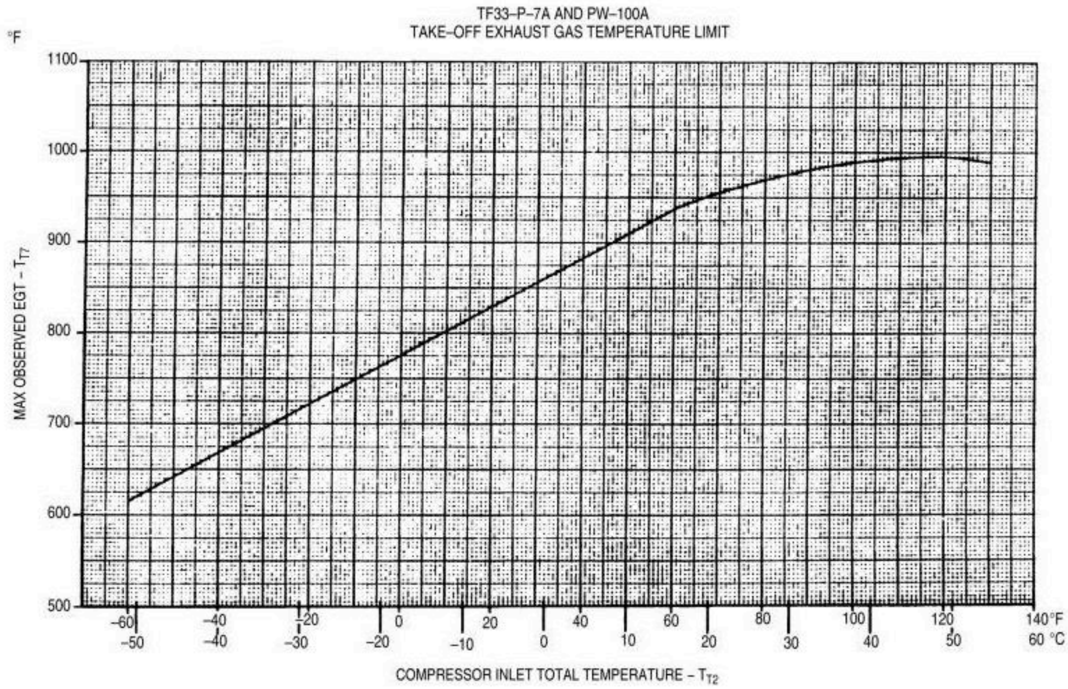

Figure 17 - TF33-P100 Take-off EGT Limits [9]

Due to the importance of this parameter, PC4 reads the thermocouple signal as a safety parameter in the Throttle PXI. However, the P100 also has an array of thermocouple probes around the exhaust nozzle to check against the single EGT (average) reading. This unique array of thermocouples uses six probes that all share a common ground. Using this configuration reduces the amount of cabling and connections required. A COTS cable is produced that contains the six chromel and single alumel wires.

Halon Bottle Control

Supporting the Fire Detection system is the on-frame Halon-1211/1301 bottle. This pressurized bottle contains the halomethane-derived chemical used to extinguish fires. Should a fire in the engine occur, halon floods the engine compartment via a pipe feeding from the bottle into the cowling. This will immediately extinguish a fire, hopefully preventing serious damage to the engine. However, the only check for this system is to visually verify that the bottle is charged, in much the same way one checks a fire extinguisher. No actual test on this bottle is performed. Up until 2012, the test cells were fitted with their own Halon extinguishing system. However, due to the environmental and personnel risks involved using this chemical, the test cells were updated to a water-fog system. Updating to this system not only eliminates an environmentally damaging chemical, it also allows the test cell engineers the ability to test the fire extinguishing system in cell to ensure proper operation. They don't have to wait for a fire to test the system!

Oil Pressure Warning Light

The P100 engine also has a built-in mechanism to alert the operator (or pilot) if it senses the oil pressure is too high. Inside the oil system on the engine is a pressure switch that monitors the pressure. If the oil pressure exceeds the threshold, a signal is sent back to the monitoring system. PC4 uses this signal from the engine to activate the coils of a relay on the relay PCB; a 24VDC signal is then fed back to the DIO card in the PowerDNA which will transfer back to the host system for indication display.

Fuel Filter-Delta Pressure Light

The P100 engine has a differential pressure switch (Figure 18) to detect when to change the fuel filter. This switch monitors both the up-stream (influent) and down-stream (effluent) fuel pressure surrounding the fuel filter. The fuel filter removes impediments from the fuel line. If the pressure differential is too great, the switch engages, providing a ground to an indicator relay coil on the relay PCB.

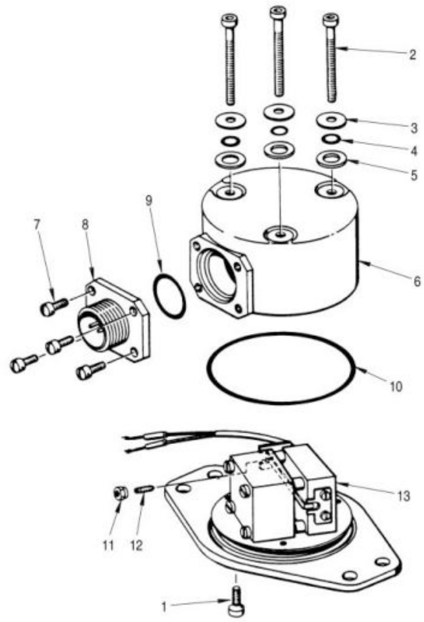

Figure 18 - TF33-P100 Differential Fuel Press Switch Assembly [15]

Bleed Air Valves

In order to prevent engine failures, the P100 is equipped with bleed valves. When pressure in the compressor is too high, the valve will automatically open, venting air to decrease the pressure. In addition to the safety aspect, the bleed valves help to prevent compressor stalls by directing air flow with the help of the inlet guide vanes. Large forward bleed air valves "unload" the forward compressor stages to start the engine and operate it at low speeds or low altitude (or both) where there is lots of air, otherwise there isn't enough torque from the turbines to turn the last stages of compressor needed to support combustion. Essentially, compressors stall because they are trying to get more air than is available to them; each individual blade is a wing and if enough of them can't “fly”, that is to say if they can't maintain attached flow, the compressor stalls. This usually happens when trying to spin the engine up (increase rotational speed), but inlet angle of attack, high altitude or "wrong" airspeed or compressibility effects can do it. Some engines are more susceptible to stalls than others and some engines tolerate it better than others. Large fan engines are particularly sensitive and sometimes suffer part failures from stall effects. The TF33 family is generally pretty stall tolerant due to its "small" fan size and robust construction.

The bleed valves have a pressure regulator that requires a 28VDC power supply (which comes from the JBOX). This regulator helps determine at what pressure to open the valve. In addition to the automatic opening by the engine, PC4 can also operate the valve for test purposes by sending out a 28VDC signal to the engine. The engine has an active feedback for the valve; when the valve is closed, 28VDC feeds back to an indicator relay coil to communicate to PC4 that the valve is closed. When the valve is open, this 28VDC signals disappears and the indicator relay goes to the normally closed state.

Cold Fuel Enrichment Valve

Either at high altitudes (greater than 15000 feet) or at cold temperatures (below freezing), starting the P100 requires additional fuel flow to properly run. This valve, when activated, will increase the amount of fuel flow to over 1400 pounds-per-hour at start [16]. The engine will also spin faster as seen by an increase in the core speed (N2); an increase in exhaust gas temperature (EGT) will also occur. For test purposes, this system is only used during start and will automatically turn off once fuel flow goes above 1500 pounds-per-hour.

Electrical Depress Valve

The electrical depress valve is similar to the bleed air valves on the engine, but located further into the engine and serve a much different purpose. Later stage bleed valves provide air for de-icing, cabin pressurization and other aircraft specific uses. In the case of the P100, it comes off at high temps at the final and 16th stage compressor through multiple valves. PC4 provides the ability to actuate the valve manually; the engine will respond with an increase in RPM’s.

Starter Manifold Pressure Switch

Of all the engines that Pacer Comet 4 tests at Tinker AFB, about half have on-frame starter air valve controllers. Those frames that don’t have controllers typically have some sort of engine feedback to indicate the engine is getting starter air; the P100 falls into this category. The Starter Manifold Pressure Switch provides a ground to an indicator relay coil on the relay PCB whenever the pressure is high enough to start the engine. The test cells at TAFB use 100 PSI shop air to start the engines.

Engine Pressures

The TF33-P100 engine provides measurements for six different pressure parameters.

- Oil Scavenge Pressure
- Breather Pressure
- PT7: Turbine Discharge Pressure
- PCP: Turbine Cooler Air Pressure
- PS4: Bleed Annulus Static Pressure
- PS3: Intercompressor Static Discharge Pressure

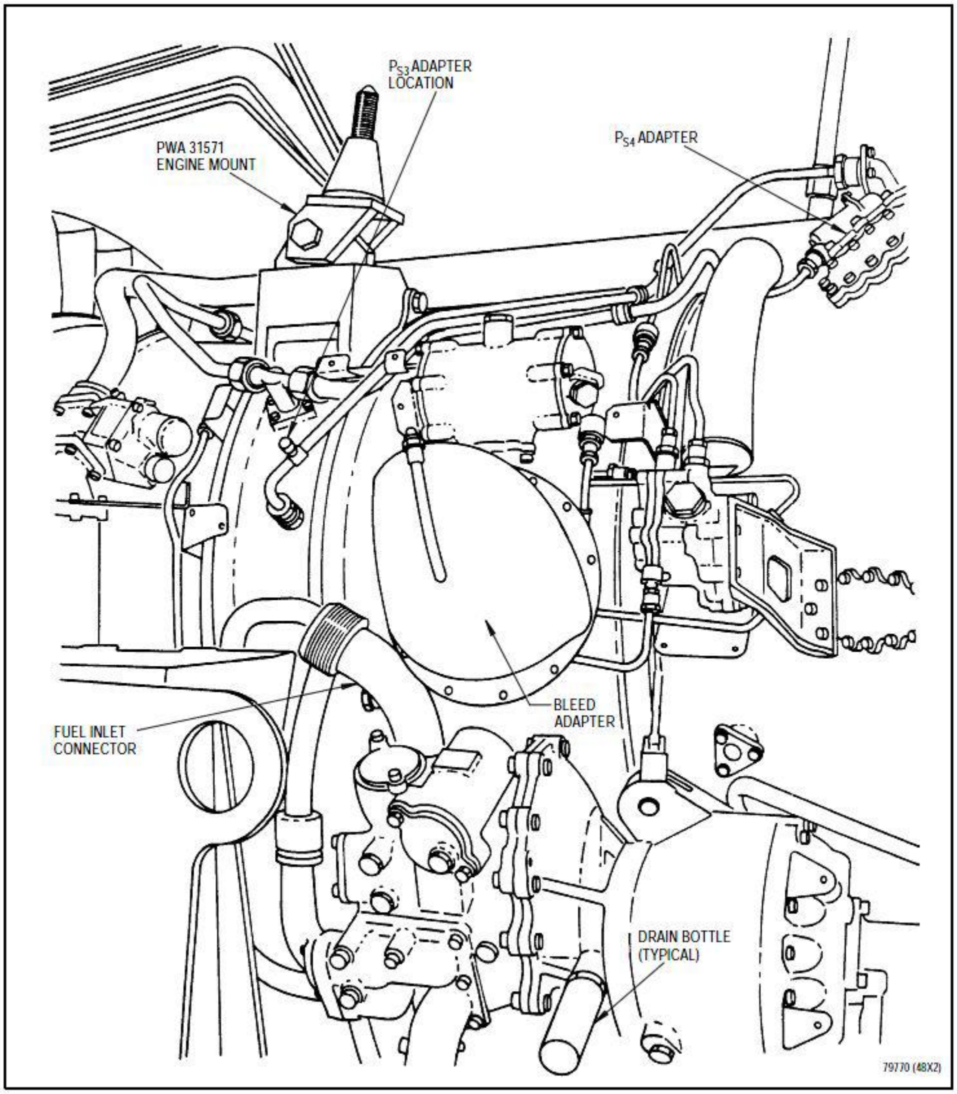

Figure 19 - TF33-P100 Pressure Ports (1 of 2) [16]

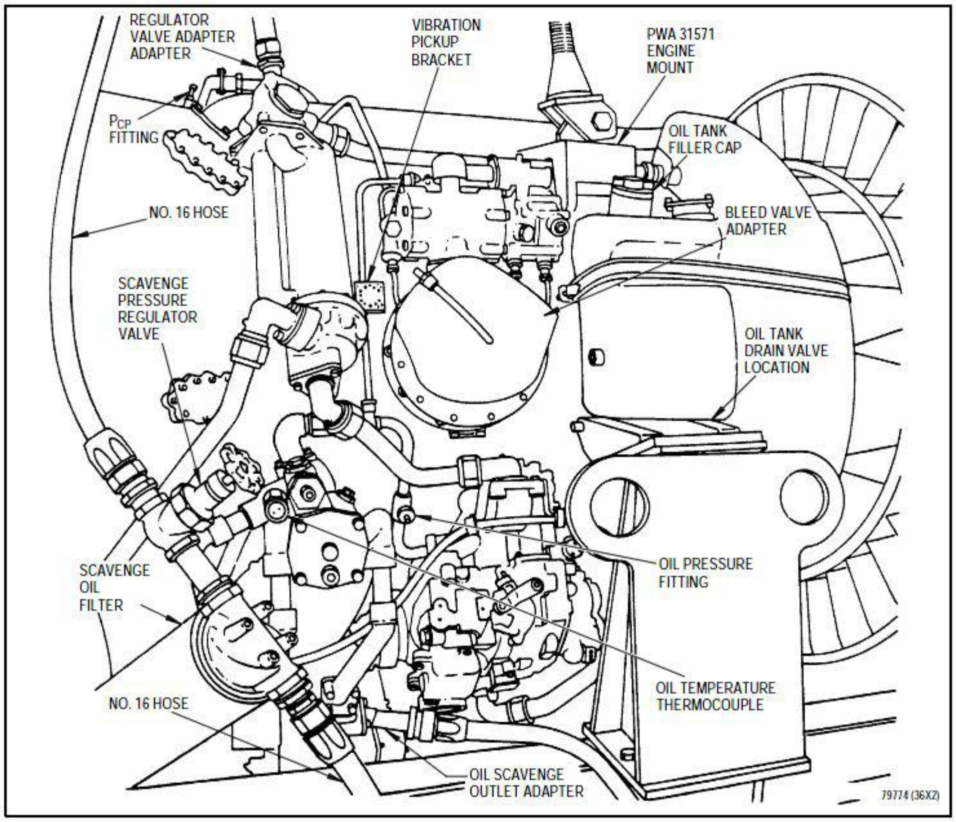

Figure 20 - TF33-P100 Pressure Ports (2 of 2) [16]

The calibration group, PMEL, has certified two different brands for transducer use: Honeywell and Tecsis, formerly Delta Metrics. As with all government purchases, both companies have the opportunity to bid for the contract to provide the transducers. For the P100, Tecsis won the contract due to cost advantages; however, all model information given is in Honeywell configuration (Tecsis takes this information and derives their own part numbers).

The first step in specifying a transducer is to determine an appropriate operating range. While the TO limits have been given above for each transducer, it is important to ensure that if the pressure goes out of limits, PC4 can read this increase. There are also standard pressure ranges that each manufacturer makes; therefore it is common practice to pick the next higher standard practice range available.

Signal	TO Limit Range [9]	Transducer Operating Range
Oil Scavenge Pressure	0-100 PSIG	150 PSIA
Breather Pressure	0-15 inHg	25 PSIA
PT7	0-60 inHg	50 PSIA
PCP	0-125 PSIG	150 PSIA
PS4	0-220 PSIG	300 PSIA
PS3	0-50 PSIG	75 PSIA

Table 6 - P100 Pressure Transducer Ranges

The next step is to determine accuracy requirements for the transducer. Both companies make two different transducer models for accuracy requirements: TJE and STJE. The TJE has an accuracy of 0.1% [17], while the STJE has a significantly tighter accuracy of 0.05% [18]. The STJE also has a smaller temperature effect than the TJE, although at 0.0015%/°F and 0.0025%/°F respectively, the difference in the effect due to temperature is negligent. However, the price of the STJE is normally about 25% higher than the TJE models.

Signal	TO Accuracy	Transducer Model
Oil Scavenge Pressure	± 1.0 PSIG	TJE
Breather Pressure	± 0.1 inHg	STJE
PT7	± 0.1 inHg	STJE
PCP	± 0.5 PSIG	TJE
PS4	± 0.5 PSIG	STJE
PS3	± 0.5 PSIG	TJE

Table 7 - Pressure Transducer Accuracy Requirements

Oil Scavenge Pressure

The TF33 uses a dry-sump oil system: oil is used to cool and lubricate the engine. The scavenge pump is used to recirculate used oil in the engine. After circulating, a significant amount of oil finds it way to the bottom of the engine components (sumps) and is recovered by the oil pump and collected in an external oil tank. The oil scavenge pressure transducer is used to measure the pressure of the oil flowing out of the scavenge pump.

In order to ensure correct oil system operation in all flight conditions, including severe turbulence, the scavenge pumps are designed with excess capacity to prevent oil from pooling in the engine. However, this causes a significant amount of air to enter the oil, causing the oil to become frothy. A de-aerator must be used to remove this air before the oil is returned to the oil tank. This process not only removes excess air, but also cools the scavenged oil by transferring the heat to the soon-to-be consumed fuel. This is important because the while the oil must be cooled, the fuel must also be heated. The de-aerator accomplishes both of these tasks in a single unit.

Other P100 Pressures

PC4 also monitors several other pressures in the engine: Breather, PT7, PCP, PS3, and PS4. These pressures measure the pressure at different stages in the engine. PT7 is the turbine discharge pressure; this is the pressure of the air in the engine right before it exits through the exhaust nozzle. PCP is the turbine cooler air pressure and is measured in the middle of the engine. PS3 is the intercompressor static discharge pressure, and the PS4 is the bleed annulus static pressure. Pressures are either total or static pressures (PT or PS respectively). Static pressure is typically read at a single point on the engine, whereas the total pressures are mechanically averaged in a manifold to represent a total section pressure.

PC4 Designed PCBs

The PC4 configured TF33-P100 uses three custom PC4 designed printed circuit boards to monitor and control the engine: a “generic” analog input board, a specific analog input board, and a relay board. Typically, all PC4 engine frames use the generic analog input board for communicating to the pressure transducers. The other two PCBs, the specific analog input board and the relay board are specifically designed for the P100 engine.

Transducer Analog Input PCB

All PC4 frames use at least one of the generic analog input boards for powering and measuring pressure transducers. The P100 engine only requires the use of six pressure transducers; the generic pressure transducer analog board has a maximum of twelve channels. The limit is set by the amount of channels on the PowerDNA 207 board. All transducers produce a 0-10VDC analog signal based off a linear conversion of the input pressure.

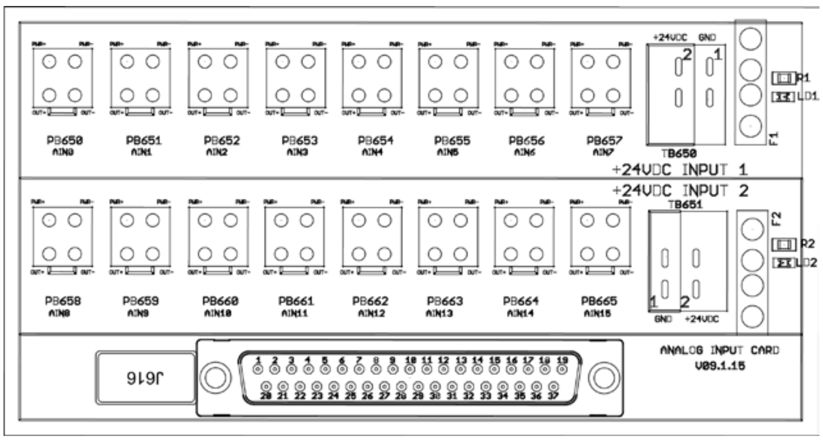

Figure 21 - PC4 Transducer PCB, flatshot

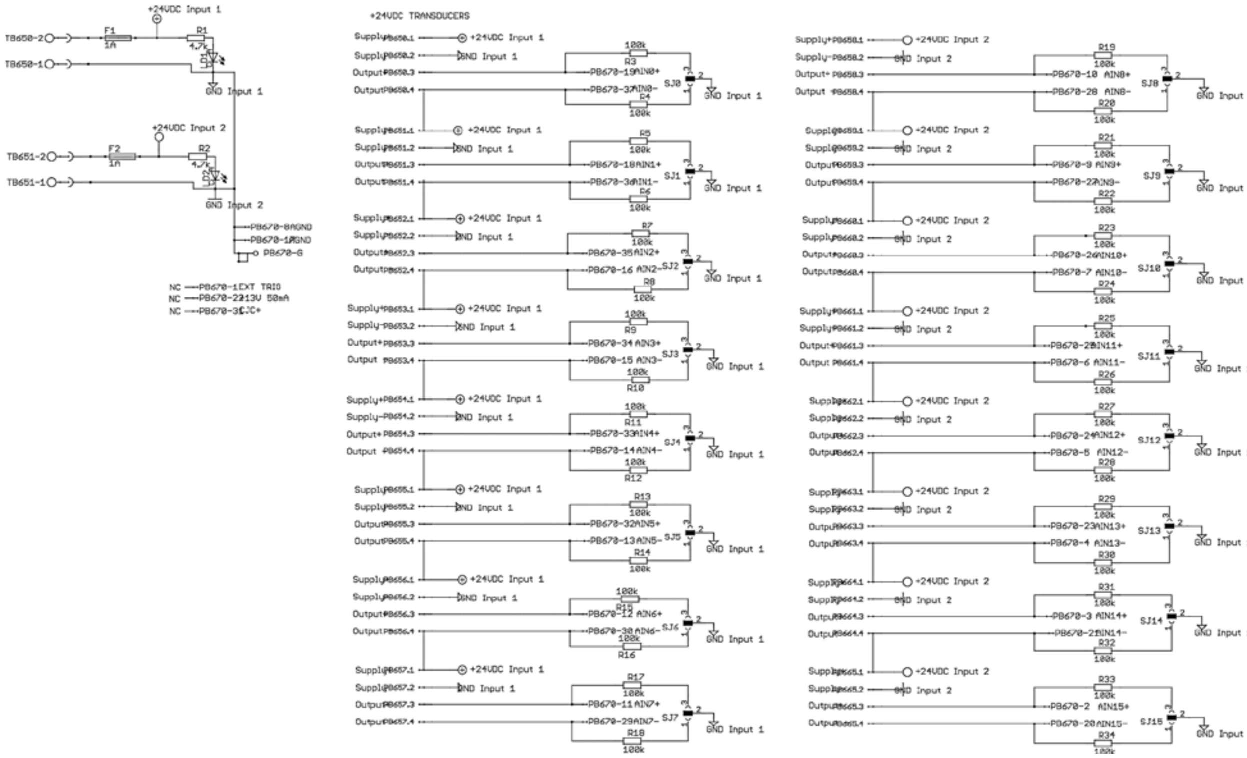

Figure 22 – PC4 Transducer PCB, schematic

P100 Specific Analog Input PCB

The P100 Specific Analog Input PCB was designed to help reduce the footprint of the JBOX. This analog input board includes the resistors used in the oil systems. By incorporating these resistors on the PCB, surface mount resistors could be used instead of using large resistor terminal blocks. While using the resistor terminal blocks would have provided for easier maintenance, it was decided that space was a more important attribute as the realistic failure rate of surface mount resistors is low.

In addition to the oil system signals, the Specific Analog Input board also transfers the voltages from the GCU’s amplitude and frequency measurements to the PowerDNA; the board also powers the DSCA modules that read the amplitude and frequency of the phases. While these six measurements could have been included with the generic transducer PCB, it was decided that the best place for these signals would be the specific PCB. Had the phase measurements passed through the generic analog input board, they would have filled up all the channels on that PCB and subsequent PowerDNA card, preventing future expansion of the pressure transducers.

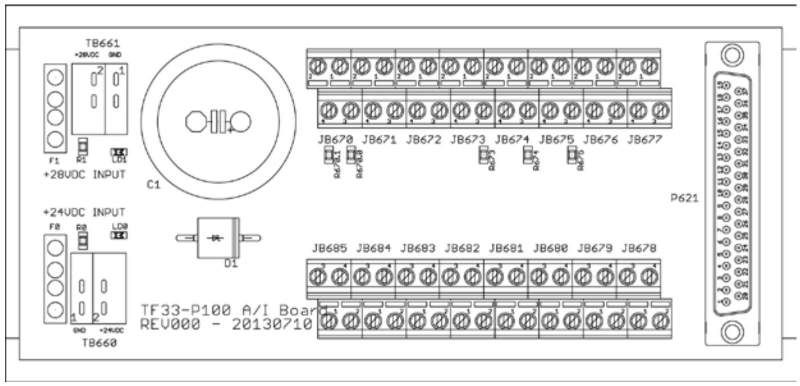

Figure 23 - TF33-P100 Analog Input PCB, flatshot

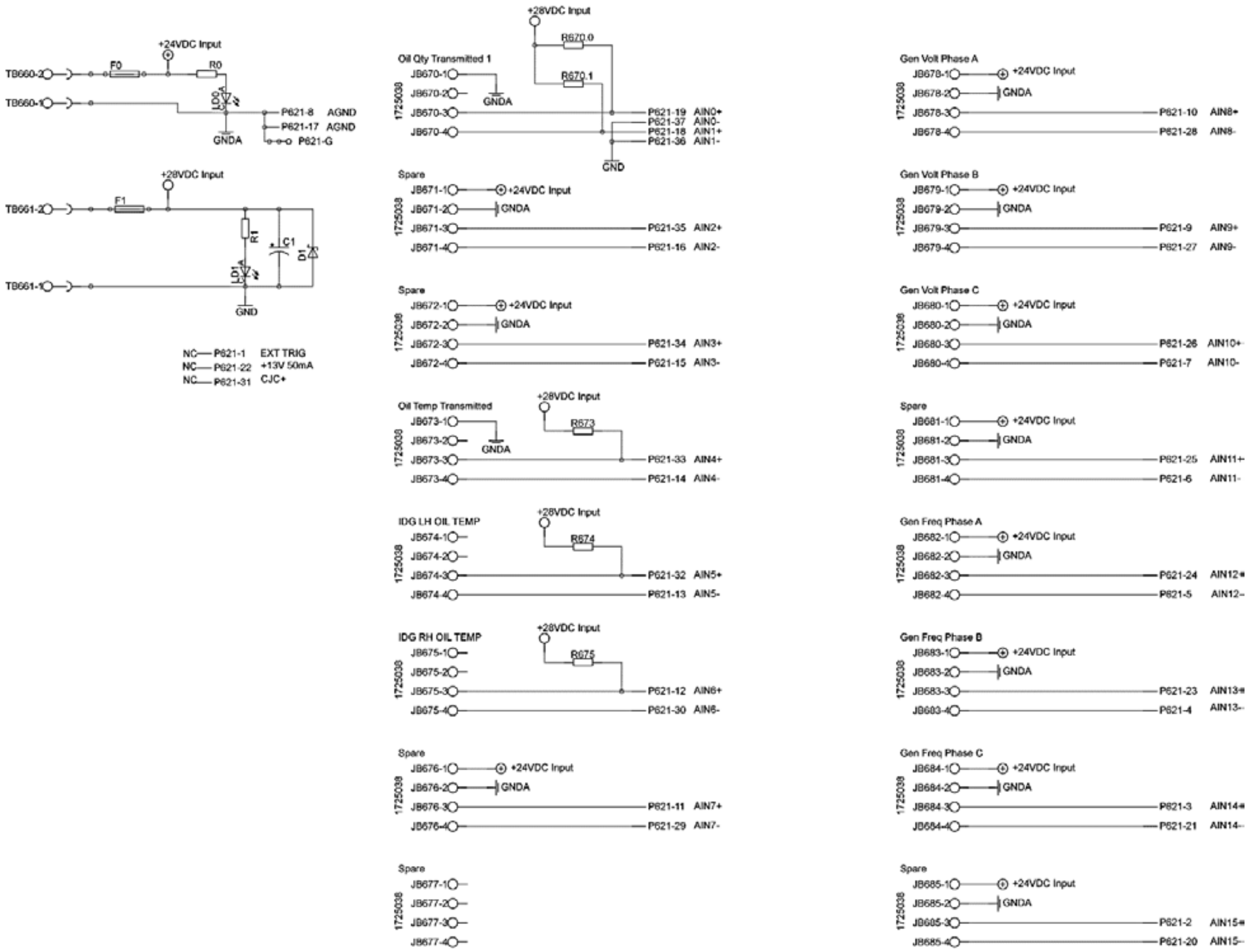

Figure 24 - TF33-P100 Analog Input PCB, schematic

P100 Relay PCB

The P100 relay PCB has the distinction of being the largest frame PCB to date. This is due to the large amount of operator/pilot controls on the P100. The relay PCB is 58.5 square inches in area, 19.5 inches in length, and fits into a three inch SNAPTRAK channel (standard size for industry use). The relay PCB uses 18 DPDT power relays to control engine accessories and 12 small signal SPST relays to monitor engine feedback signals. As is standard practice with PC4 relay PCBs, the P100 relay PCB incorporates LEDs to visually indicate relay switching inside the box. This is just another way that PC4 provides troubleshooting capabilities that were non-existent in

PC3. The P100 relay PCB is designed for ease of maintenance by utilizing sockets for relays and fuses allowing for quick replacement of faulty components.

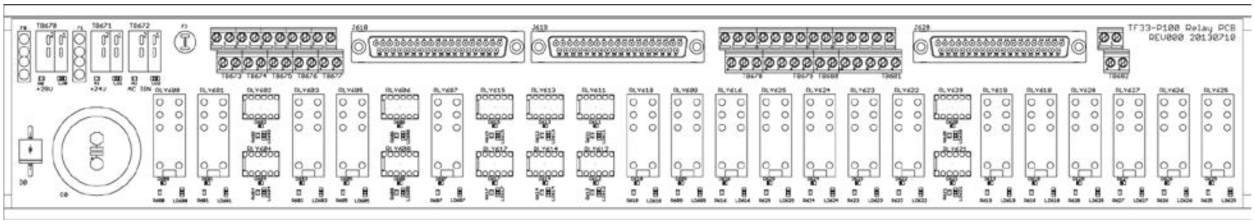

Figure 25 - TF33-P100 Relay PCB, flatshot

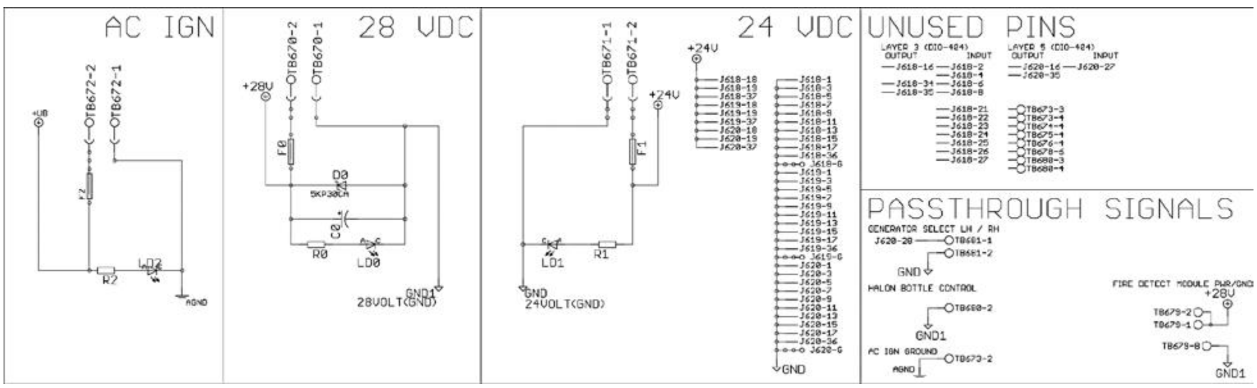

Figure 26 - TF33-P100 Relay PCB, schematic (1 of 3)

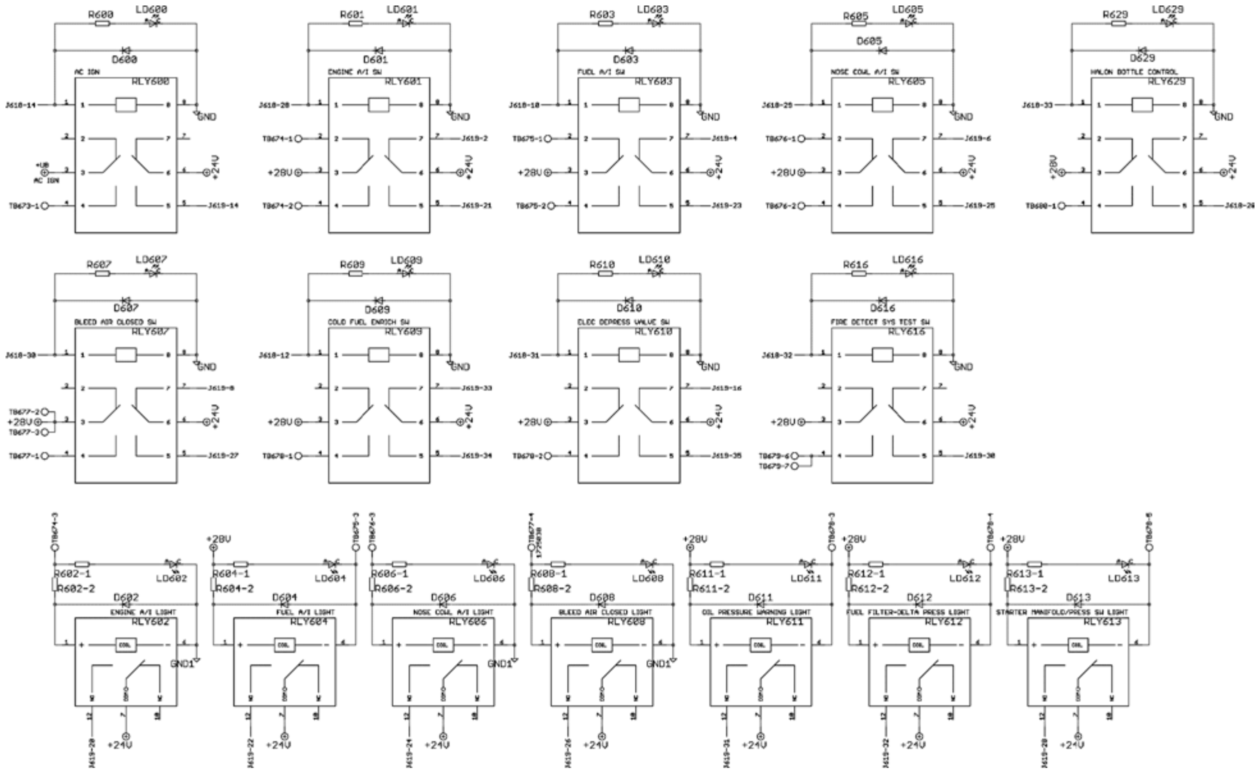

Figure 27 - TF33-P100 Relay PCB, schematic (2 of 3)

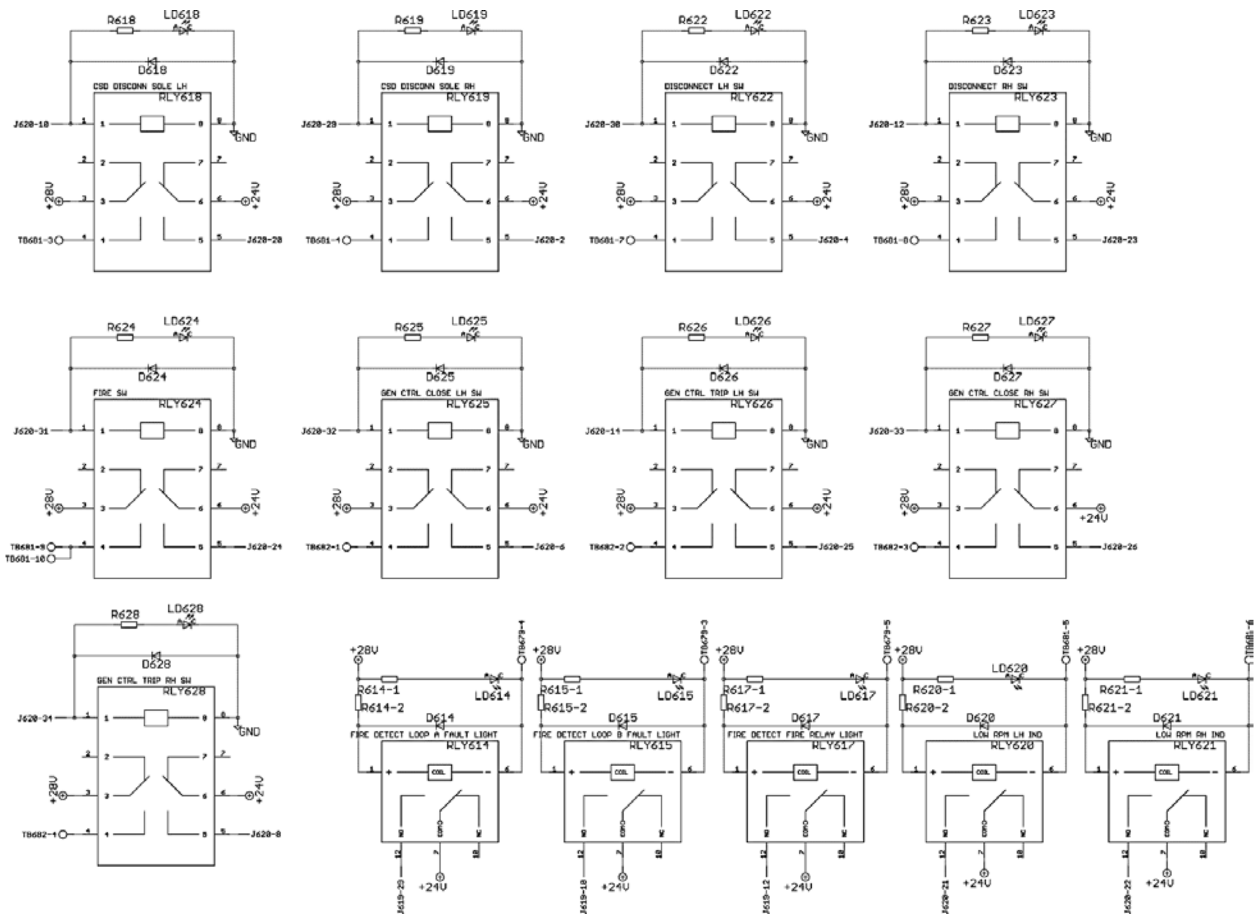

Figure 28 - TF33-P100 Relay PCB, schematic (3 of 3)

PowerDNA Component Theory

The PowerDNA from UEI is a core piece of the PC4 system. It is capable of recording the measurements of almost all engine signals inside the JBOX on frame. This has allowed PC4 to eliminate about 70% of cable runs that PC3 required. In fact, the PowerDNA could read every signal, however due to the scope of the project, certain signals are read in the facility (safety parameters). This is required for safety concerns over losing communication to the PDNA. As mentioned before, the PDNA communicates to the facility via Ethernet protocol; using Ethernet allows a very large bandwidth for transferring data (10Mbit/s).

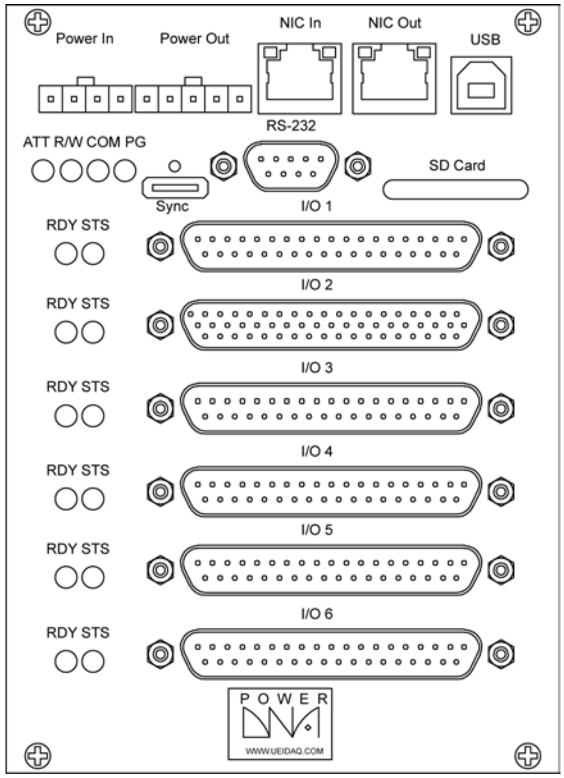

Figure 29 - UEI PowerDNA Cube, flatshot

This particular frame calls for the use of several cards:

- DNA-PPC8
- DNA-AI-207
- DNA-AI-225
- DNA-DIO-401
- DNA-DIO-404
- DNA-STP-AI-U

DNA-PPC8

The DNA-PPC8 is the main controller for the PDNA cube. The chassis can handle up to six different I/O cards, exactly enough for the P100 application. The processor inside the PPC8 is a 32-bit, 400MHz MPC5200 with 128MB of memory. It can operate in almost any environment, certainly any conditions that the test cell might throw its way, up to 185°F at 95% humidity. The PDNA can also handle impressive vibrations of 5G! At a low price (starting less than $1000), the PDNA integrates nicely into the PC4 system, operating at a voltage up to 36VDC, easily capable of handling the 24VDC the facility provides. The PDNA can also be mounted in a variety of ways; for this application, a DIN-rail compatible back plate was ordered to replace the stock plate. This allows the PDNA to be placed virtually anywhere inside the JBOX.

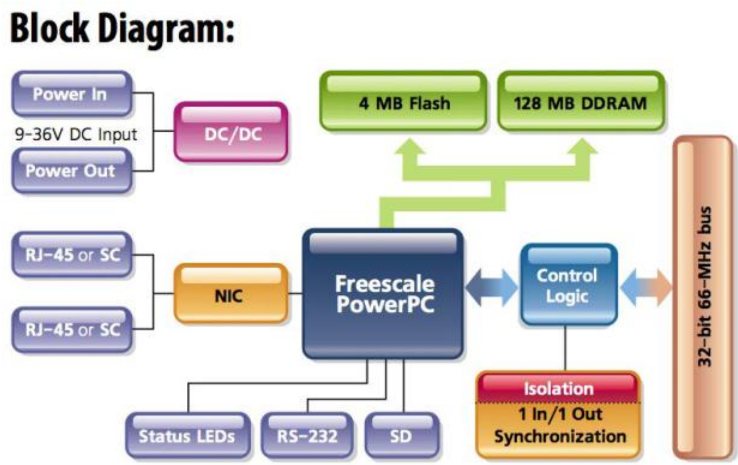

Figure 30 - DNA-PPC8 Block Diagram [19]

DNA-AI-207

The -207 card is responsible for general analog input. The -207 has 16 fully differential analog inputs that can sample ±10VDC signals at up to 16kS/s max. However since most of the inputs will be used, the card will only sample at 1kS/s. This is still more than sufficient to catch any engine problems. The card converts the samples into a digital format with 18-bits of resolution, ensuring an accurate representation across the Ethernet signal. In addition to high precision in the ADC process, the initial measurements are read to an accuracy of ±287.59µV. Due to the large number of signals, two of these cards are used: one for the transducer PCB and another for the P100 analog input PCB.

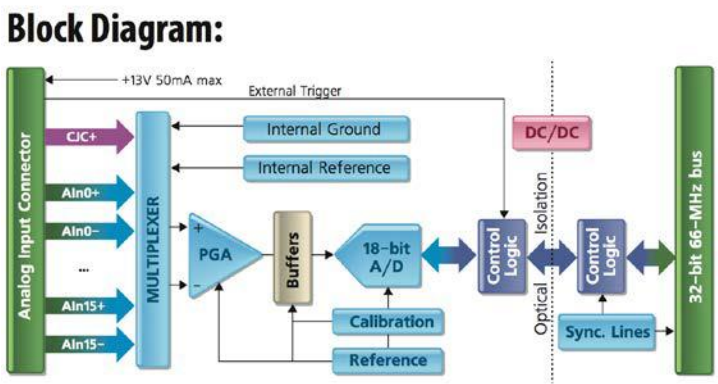

Figure 31 - DNA-AI-207 Block Diagram [11]

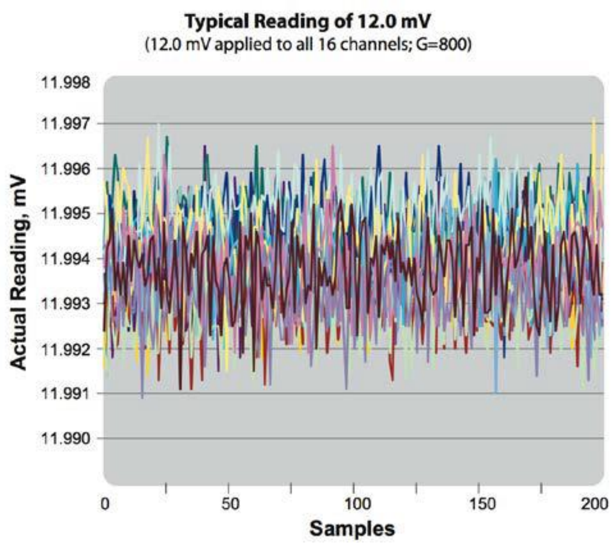

Figure 32 - DNA-AI-207 Typical Reading of 12.0mV [11]

DNA-AI-225

The -225 card is responsible for handling the thermocouple readings in the JBOX. Working with the DNA-AI-STP-U, the -225 is cold junction compensated (CJC) to measure and convert thermocouple millivolt signals into degrees Fahrenheit. The -225 has 25 channels that it can sample at a rate of 1kS/s. The -225, along with the CJC board, can sample at an accuracy of 0.18°F on any thermocouple type with 24-bit resolution for the ADC process. At 1kHz sampling, the -225 can convert from the voltage signal to a temperature degree representation in 0.57msec. For use in the P100 JBOX, the -225 and CJC board read and process all thermocouple signals: anti-ice air temps and EGT spread temps. As noted previously, the EGT average signal is categorized as a safety parameter and must be read in the facility.

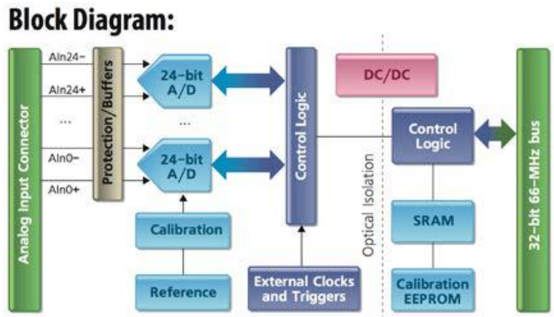

Figure 33 - DNA-AI-225 Block Diagram [20]

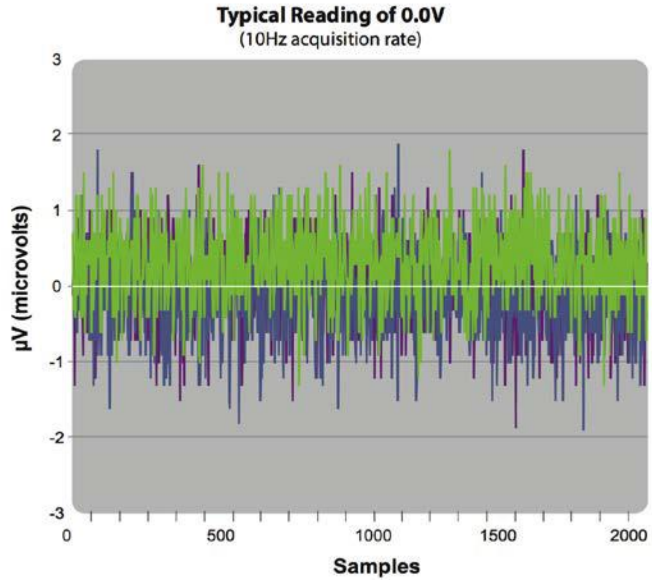

Figure 34 - DNA-AI-225 Typical Reading of 0.0V [20]

DNA-DIO-401

The -401 card is a digital input card that can read up to 24 channels. Each channel operates at up to 36VDC, however in all PC4 applications, only 24VDC is used. At the 24VDC level, a high is signified by a signal of 10.5VDC or higher. On the relay board, 24VDC is used as a feedback mechanism. On the other end, a signal less than 6.75VDC is considered to be an input low. Each channel on the -401 samples at a rate of 2 kHz, but only processes the I/O throughput at 1 kHz max. The system sets the operating voltage (24VDC) of the card by externally supplying the power to the card. This is different than the AI cards, which are powered through the cube's power input. This card is used to provide additional digital inputs on the relay PCB for feedback from relay switching and engine indicators.

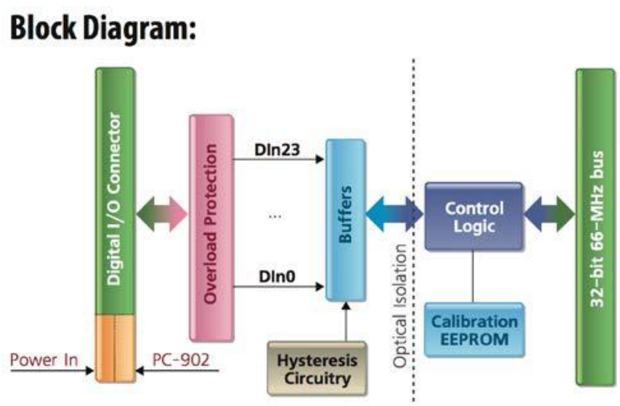

Figure 35 - DNA-DIO-401 Block Diagram [21]

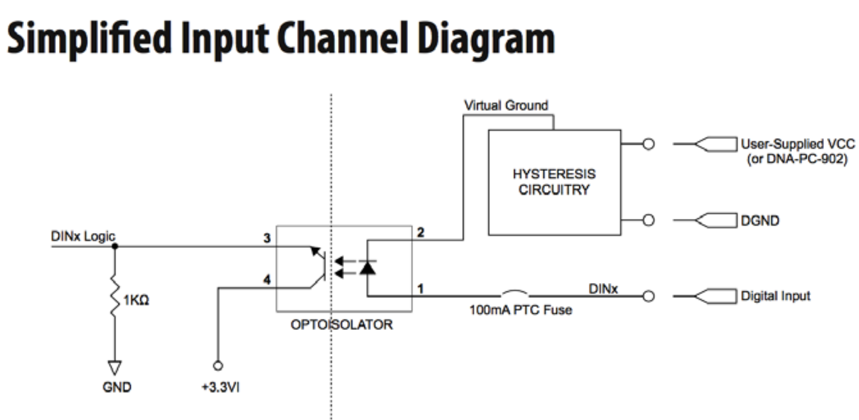

Figure 36 - DNA-DIO-401 Input Channel Diagram [21]

DNA-DIO-404

The -404 card is a digital input/output card used to switch relays on the relay PCB. The -404 card has 12 inputs and 12 outputs that source up to 36VDC (dependent, like the -401 card, on the user supplied voltage). Again, in the PC4 application, 24VDC is used. The output channels can source up to 350mA per channel, enough to drive multiple relays found on the relay PCB. The I/O throughput of the -404 card is significantly higher than the -401 at 100kHz. This allows the card to switch outputs virtually on-demand. The -404 card is used to switch the relays on the relay PCB and provide a number of feedbacks from the relays for troubleshooting purposes. By reading the feedbacks of the relays on the UEI PowerDNA Explorer, engineers can remotely monitor the status of the relays. Due to the number of relays required, the P100 system uses two of these cards.

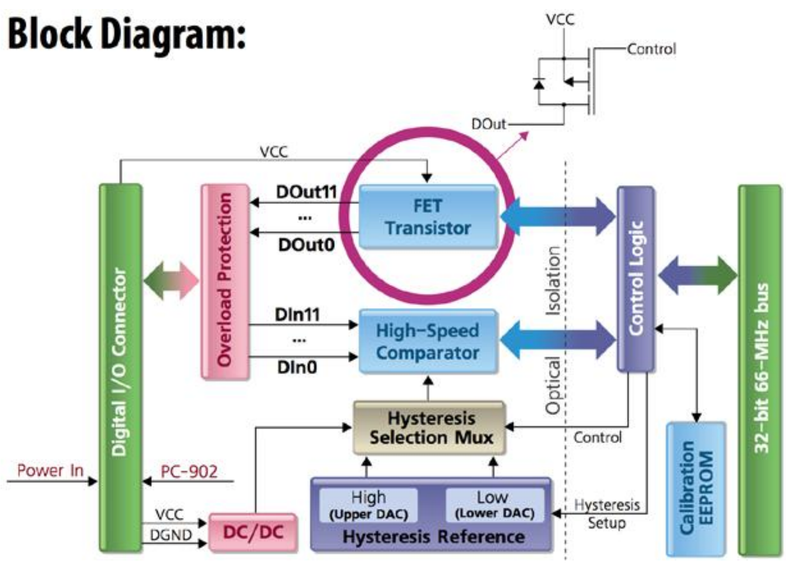

Figure 37 - DNA-DIO-404 Block Diagram [22]

DNA-STP-AI-U

The DNA-STP-AI-U PCB is a cold junction compensator board to accurately measure thermocouple signals. Used with the DNA-AI-225 card, the CJC board can measure and convert up to 25 different thermocouple signals at an accuracy of 0.18°F. The CJC board can also provide a +5VDC-regulated signal, however the P100 doesn’t require it. The CJC board can read any thermocouple type, as configured in the PDNA’s INI file. Typically in PC4 only K-type and J-type thermocouples are used, although E-types are used. The P100 only uses J-type for anti-ice air temps, and K-type for EGT signals. The CJC can also double as an analog input board, limited to the 10 VDC input voltage of the -225 card. Conveniently shipped with DIN-rail mounts, the DNA-STP-AI-U integrates seamlessly into the JBOX.

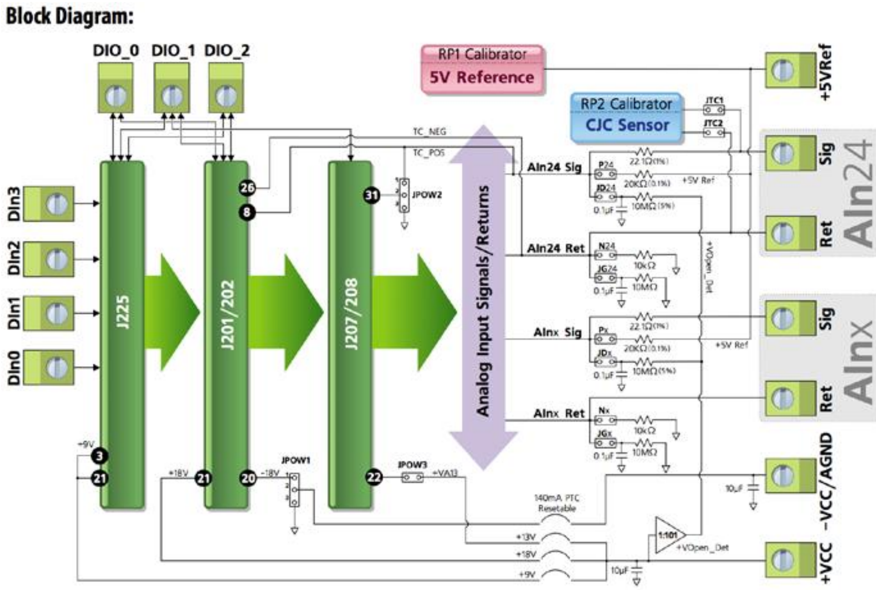

Figure 38 - DNA-STP-AI-U Block Diagram [23]

Dataforth DSCA Modules

In order to measure and record the generator output line signals, the P100 PC4 design calls for the use of two different DSCA modules (three of each): the DSCA33 and DSCA45 modules. The DSCA33-04 is a RMS voltage to DC convertor that can record VRMS signals up to 150VAC and then convert it to a 0-10VDC signal at a working frequency of 400Hz. At the 400Hz frequency, the DSCA33 can measure accurately to 0.25% of the reading.

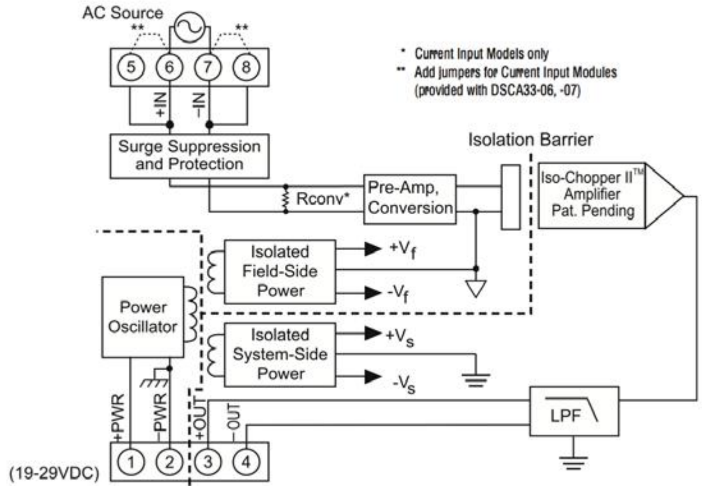

Figure 39 - DSCA33 Schematic [24]

The DSCA45-01 is a frequency to DC convertor that can record frequency of AC signals up to 500Hz. The frequency produced by the P100 generators is 400Hz. The DSCA45 then converts the signal into a 0-10VDC output.

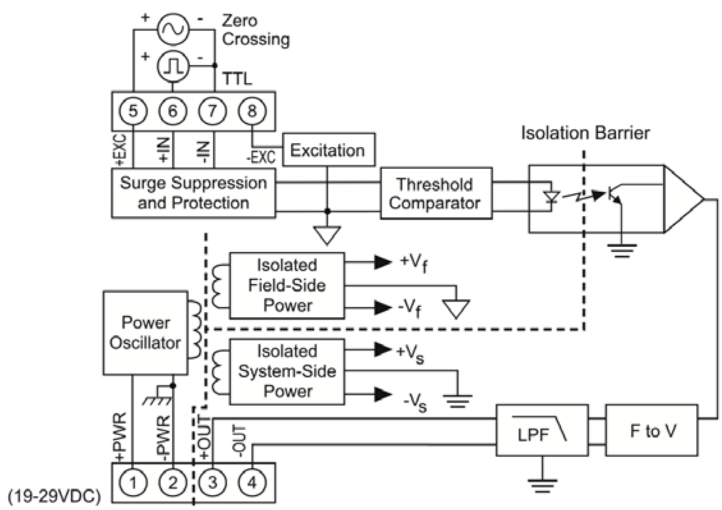

Figure 40 - DSCA45 Schematic [25] [26]

Both modules are powered by the 24VDC supply from PC4. Three of each module is used so that PC4 can monitor both the amplitude and frequency of each phase of the generator signal simultaneously. The outputs from all six modules are run to the P100 analog input PCB, where the DNA-AI-207 card reads them. Using these modules provides an easy conversion to the convenient +10VDC signal for input into the PDNA as well as easier maintenance; should one of the modules break, a replacement can be ordered and received quickly.

TF33-P100 Safety Parameter LabVIEW Design

The P100 frame engineer is responsible for writing the Safety Parameter library. In order to facilitate code design and maintenance, certain LabVIEW VI's (Visual Instruments; basically a file of code) are reused if possible from engine type to engine type: for instance, the P100 shares an oil pressure transducer transmitter with the F101 engine and can therefore use the F101 oil pressure VI. The Safety Parameter project has many VI's in it, but the main VI in the program is the SP Run.vi.

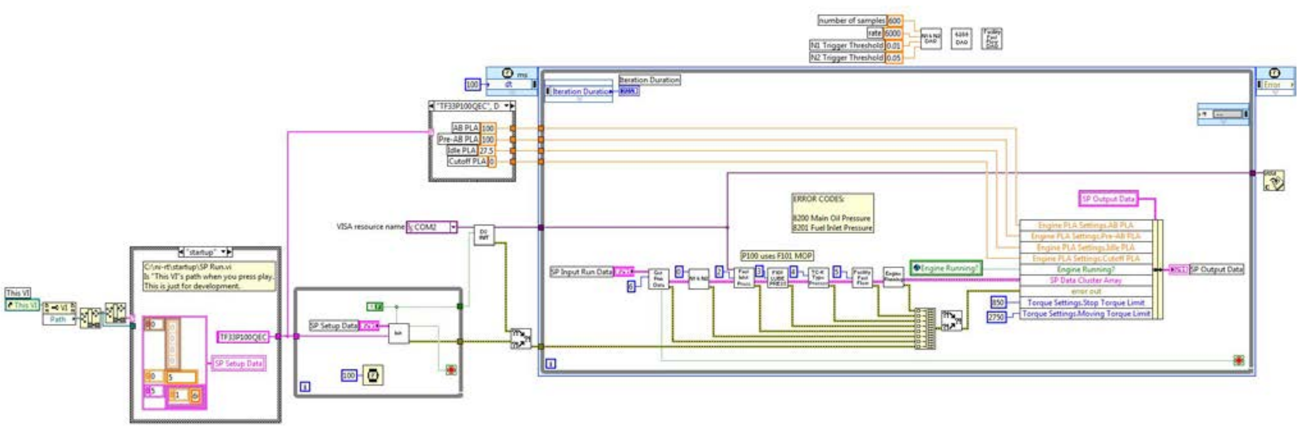

Figure 41 - SP Run.vi LabVIEW

It is important when creating this VI that there is communication with the software engineer in charge of writing the main P100 LabVIEW code to ensure that order of the parameters is correct with the TPS software. As seen above, LabVIEW is a graphical programming environment that makes visualizing the flow of data easy. Each block is an individual VI that runs sequentially down a wiring path, or in parallel if left alone. The VI “6289 DAQ” at the top of the SP Run VI runs in parallel to the other VI’s to the left and right of it, as well as the main “for” loop below it. The “6289 DAQ” VI (Figure 42) handles the recording of the signals coming into the PXI-6289 card on the Throttle PXI chassis. As seen below, this VI will pull in recorded data for processing in parallel. After manipulation, each signal is written out to a variable for use in other VI’s. As noted previously, the P100 shares an oil pressure transmitter with the F101 and other TF33 variants, and can thus use the same VI for processing.

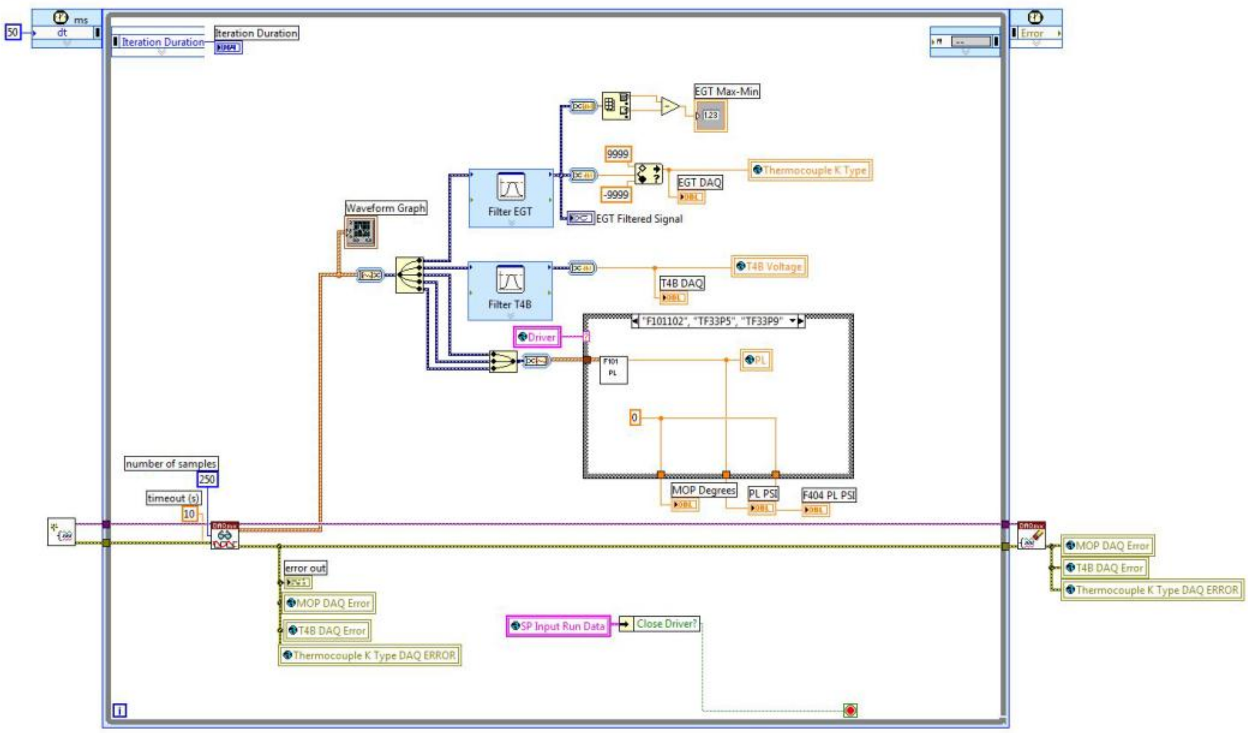

Figure 42 - 6289 DAQ.vi LabVIEW

For the oil pressure transmitted, the P100 uses the F101 PL VI (Figure 43). The oil pressure transmitter on the P100 is a ratiometric transducer. By comparing the signal voltage to the excitation voltage of 26VAC, the oil pressure can be obtained by interpolation over a table obtained from the engine’s TO.

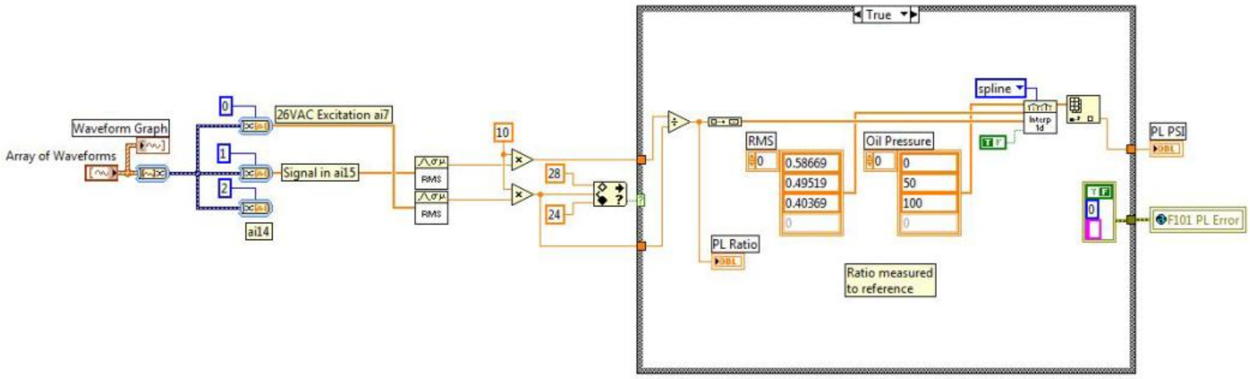

Figure 43 - F101 PL.vi LabVIEW

Working from the bottom up, LabVIEW incorporates many smaller files into one large process. By using this methodology, the LabVIEW project code can be written and maintained in an easy fashion: depending on the circumstances, only one VI will have to be changed, compared to the whole project. This also allows for multiple engine types to share the same VI's that are in common, while having different VI's for other signals. This modularity allows for greater efficiency in creating new engine projects. However, it does add some complexity to changing a VI: consideration for how it will affect other engines must be taken into account and tested prior to production use.

PC4 Documentation Package

When PC4 presents a frame or test cell for sell-off to PMXG, it also provides a documentation package containing a data package, a drawing set, and a parts list. With this documentation package, PMXG can completely replicate a frame down to every last nut and bolt with little direction from PC4. If maintenance is required in the future, the PMXG team has no problems figuring out what parts to purchase and how to install it into the system. Should the situation arise for a new signal to be incorporated into the system, all information about available channels and locations are contained in the data package.

PC4 Data Package

The data package is essentially the "end-all, be-all" for information on the parts contained in the PC4 system. Broken up by drawing packages, information and data sheets are contained for each and every part in the system. Further broken down by drawing numbers (the dash numbers, -10, -30, etc), engineers can examine each and every specific part that makes up the system. This is important in case a particular part is no longer produced; the engineer can take that data sheet to a manufacturer to search for a competitive part or an exact replacement.

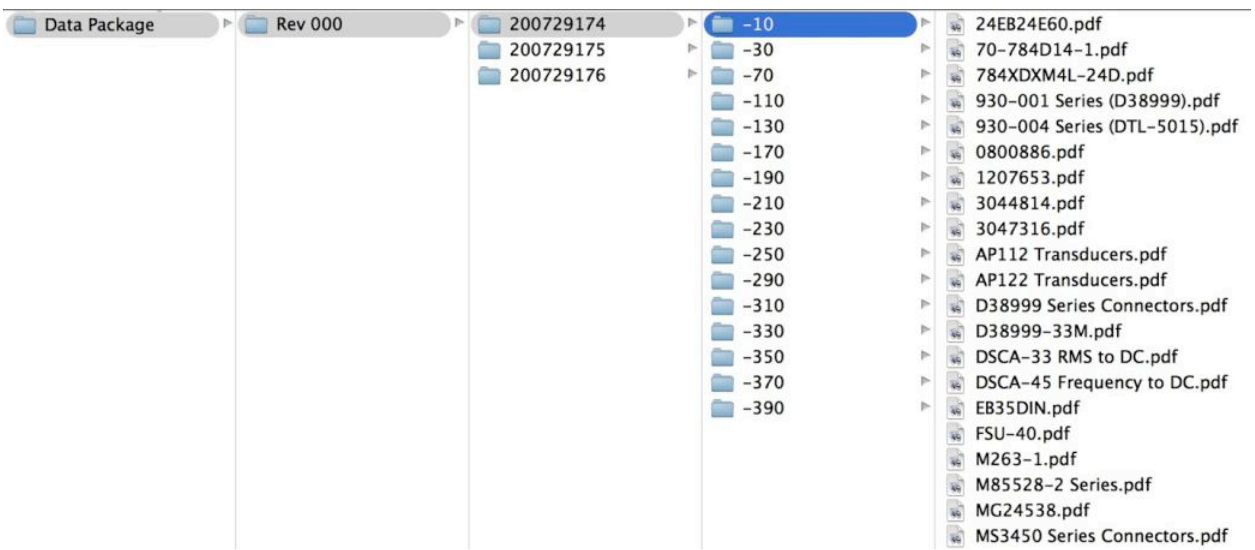

Figure 44 - Data Package Example

PC4 Drawing Package

PC4 engineers provide a drawing set that contains four different individual drawings: an assembly set (Figure 45), an internal (to JBOX, or PC4 rack) cabling set (Figure 46), a workhorse cabling set (Figure 47), and an end-to-end wiring schematic package (Figure 48). With these four drawings, an engineer or technician can replicate the entire PC4 system, or more realistically, efficiently repair and maintain the system. Each drawing is assigned a unique drawing number; for the TF33-P100, the drawing numbers are as follows:

- 200729174 - TF33-P100 Assembly
- 200729175 - TF33-P100 Internal Cabling
- 200729176 - TF33-P100 Workhorse Cabling
- 200729177 - TF33-P100 End-to-End

The end-to-end drawing is with respect to the frame only. The facility has its own end-to-end for each drawing set. Each drawing, with the exception of the end-to-end, provides the engineer the wiring schematic and a visual representation of each and every cable in the system, as well as the physical construction of the JBOX or rack assembly. They also include find numbers that correspond to the parts list (Figure 49) for a specific drawing.

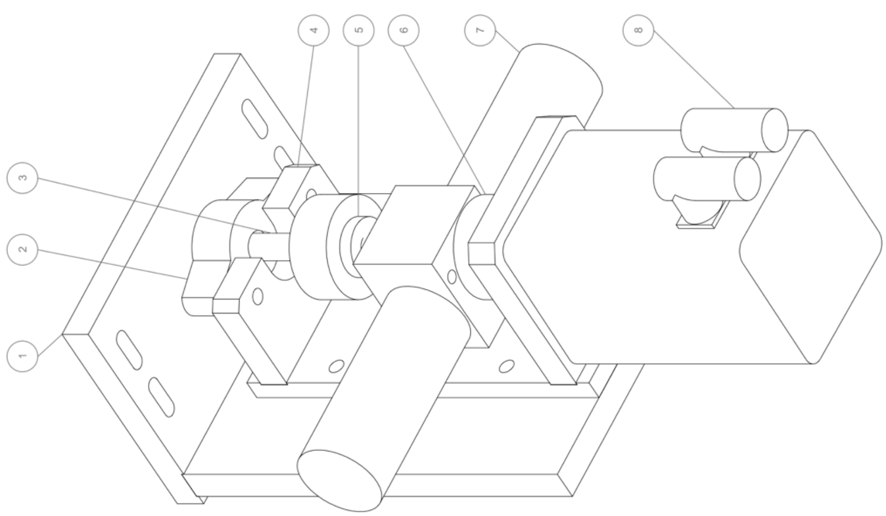

Figure 45 - Assembly Drawing Example

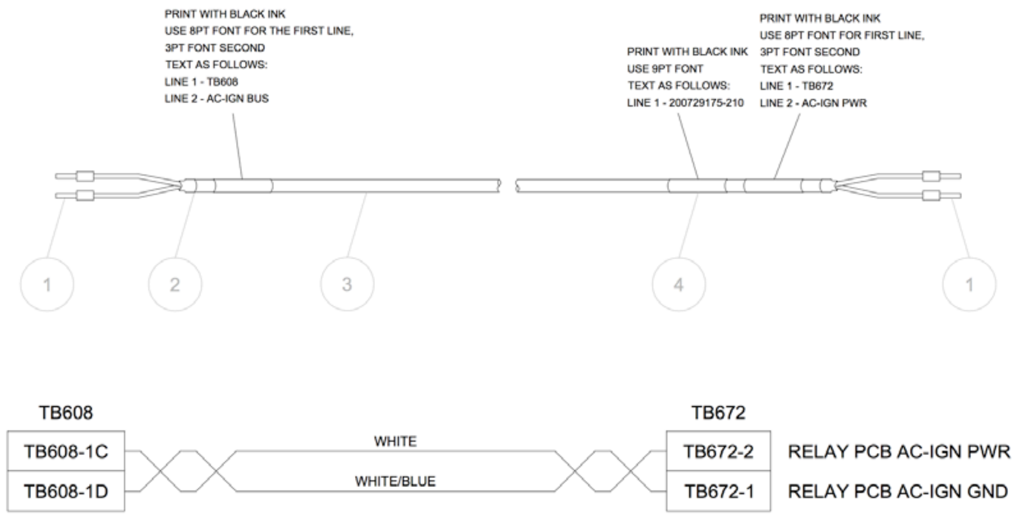

Figure 46 - Internal Cable Drawing Example

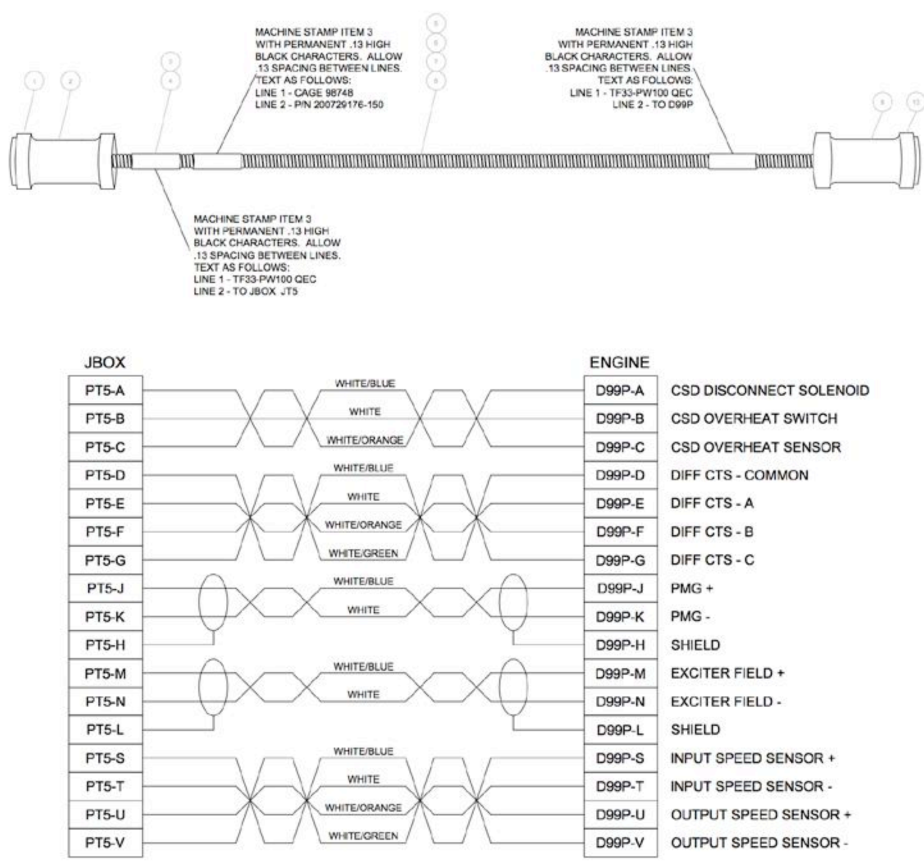

Figure 47 - Workhorse Cable Drawing Example

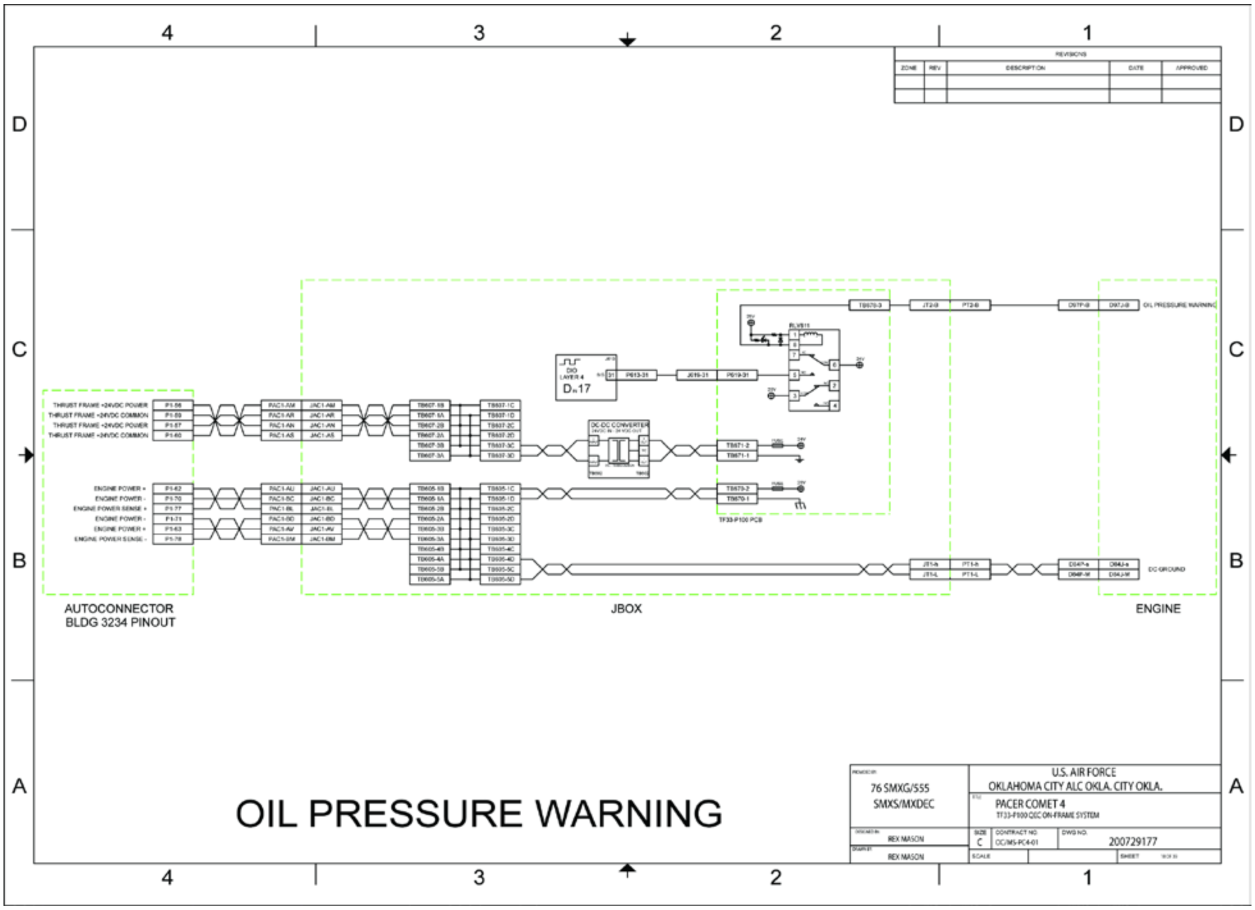

Figure 48 - End-to-End Drawing Example

PC4 Parts List

The final piece of the documentation package is the parts list (Figure 49). For every assembly, cable, and wire, a parts list is included so that an engineer knows exactly what is used to make up the PC4 part. Included in this parts list is information on the part number, who manufactured the part (CAGE code), description of the part, and what quantities are required. The "FIND NO" column corresponds to the find numbers in the drawing, calling out which part is which.

FIND NO.	PART NUMBER	CAGE	DESCRIPTION	UNITS PER ASSY	USABLE ON CODE	SMR CODE
	200729176-70	98748	TF33-P100 QEC PT1 TO D84J WORKHORSE CABLE	REF		
1	D38999/26FJ37PN	49367	CONNECTOR, PT1	1		
2	370HS001M2528H6-445	6D470	BACKSHELL, PT1	1		
3	PSPT-500-175-WT	85480	LABEL, HEAT SHRINKABLE, WHITE	3		
4	M83519/2-3	81343	TUBING, HEAT SHRINKABLE, CLEAR	AR		
5	M27500-16ML4T08	1P787	CABLE, 16 AWG, 4 CONDUCTOR, TWISTED, SHIELDED	AR		
6	M27500-16ML3T08	1P787	CABLE, 16 AWG, 3 CONDUCTOR, TWISTED, SHIELDED	AR		
7	M27500-16ML2T08	1P787	CABLE, 16 AWG, 2 CONDUCTOR, TWISTED, SHIELDED	AR		
8	ZCT-TE-080	32039	CONVOLUTED TUBING, PTFE, BLACK	AR		
9	370AS001M2806H4-445	6D470	BACKSHELL, D84J	1		
10	MS3450L28-21S	49367	CONNECTOR, D84J	1		
-	M39029/58-364	06324	CONTACT, PIN, D38999, #16	30		
-	M39029/30-218	06324	CONTACT, SOCKET, MS3450, #16	28		
-	M83519/2-5	3T899	SHIELD TERMINATOR, SOLDER SLEEVE	1		
-	PSPT-125-175-WT	85480	LABEL, HEAT SHRINKABLE, WHITE	58		

- NOT ILLUSTRATED

Figure 49 - Parts List Example

TF33-P100 Frame Construction

The PC4 configuration for the TF33-P100 engine modifies a pre-existing PC3 frame owned by PMXG at Tinker AFB. The PC4 Statement of Work calls for two frame modifications by the end of the project. The first frame is designed and constructed under funding FY07 for use with Test Cell 9 at TAFB. The second P100 frame falls under FY09 funding for use with Test Cell 11; as mentioned previously, either frame will be able to run in any building 3234 or T9 test cell at TAFB. The PC4 portion of frame construction falls into three categories: the JBOX (with the additional GCU box), workhorse cables, and throttle motor assembly.

TF33-P100 JBOX Construction

It is standard practice in PC4 to use Hoffman/Pentair stainless steel enclosures to house equipment. These boxes can be found throughout the facility and on-frame across all Air Force installations where PC4 is implemented. Hoffman manufactures each JBOX to meet the PC4 Statement of Work required NEMA-4 rating. The NEMA-4 rating provides indoor and outdoor protection from solid foreign objects, such as falling dirt and dust, and provides splash proof fluid protection. Before sell-off, each PC4 frame is subjected to a spray down test to ensure enclosure seals are appropriate.

In addition to NEMA-4 rating, Hoffman allows custom box creation to fit customer needs, allowing each JBOX design to be fully optimized for frame integration. Ideally, the frame design would call for an off-the-shelf box to minimize lead-time should a replacement be required. However due to the specialized nature of the frames and physical constraints of the box mounting locations, more often than not a custom box is required. Save for a longer lead-time, Hoffman is able to produce these boxes with no issues. For the TF33-P100 box, a custom enclosure was required. Hoffman takes the closest off-the-shelf box and then will chop it up and weld as necessary to meet the desired dimensions. PC4 engineers also provide component mounting hole locations so Hoffman can precisely punch out holes for mounting connectors, transducers, and support plates. This option provides both a more professional product as well as reducing labor costs assembling the box (PC4 engineers design and assemble the JBOX and all the components that go on-frame).

PC4 JBOX Design and Construction

In order to get a box manufactured by Hoffman, the JBOX, and, in the case of the P100, the GCU box, are designed in AutoCAD. Using this software allows the designer to produce a 3D image of the JBOX to ensure that all required hardware will physically fit into the box, while maintaining maintenance viability. During the PC4 design phase, the engineer determines what hardware will be required in the box. The P100 design requires the following pieces of commercially-available-off-the-shelf parts and PCBs:

Part Name	Quantity Used
PowerDNA Cube Assembly	1
Acopian DC-DC 24V Converters	3
UEI CJC PCB	1
PC4 PCBs	
Transducer PCB	1
P100 Specific Analog Input PCB	1
P100 Relay PCB	1
Dataforth DSCA 33 AC to DC Converter	3
Dataforth DSCA 45 Frequency to DC Converter	3
Boeing Fire Detection Module	1
Pressure Transducers	6
Schneider Electric 10A Circuit Breaker	2
Terminal Blocks	As Required
Circular Cannon Connectors	As Required

Table 8 - PC4 JBOX Components

Once all the parts have been decided upon, the designer models each part in 3D in AutoCAD. Luckily, the majority of the parts have CAD drawings provided by the manufacturer, greatly aiding the process. The PC4 designer can begin to arrange the parts in various manners, all the while keeping in mind the ease of wire routing and maintenance work.

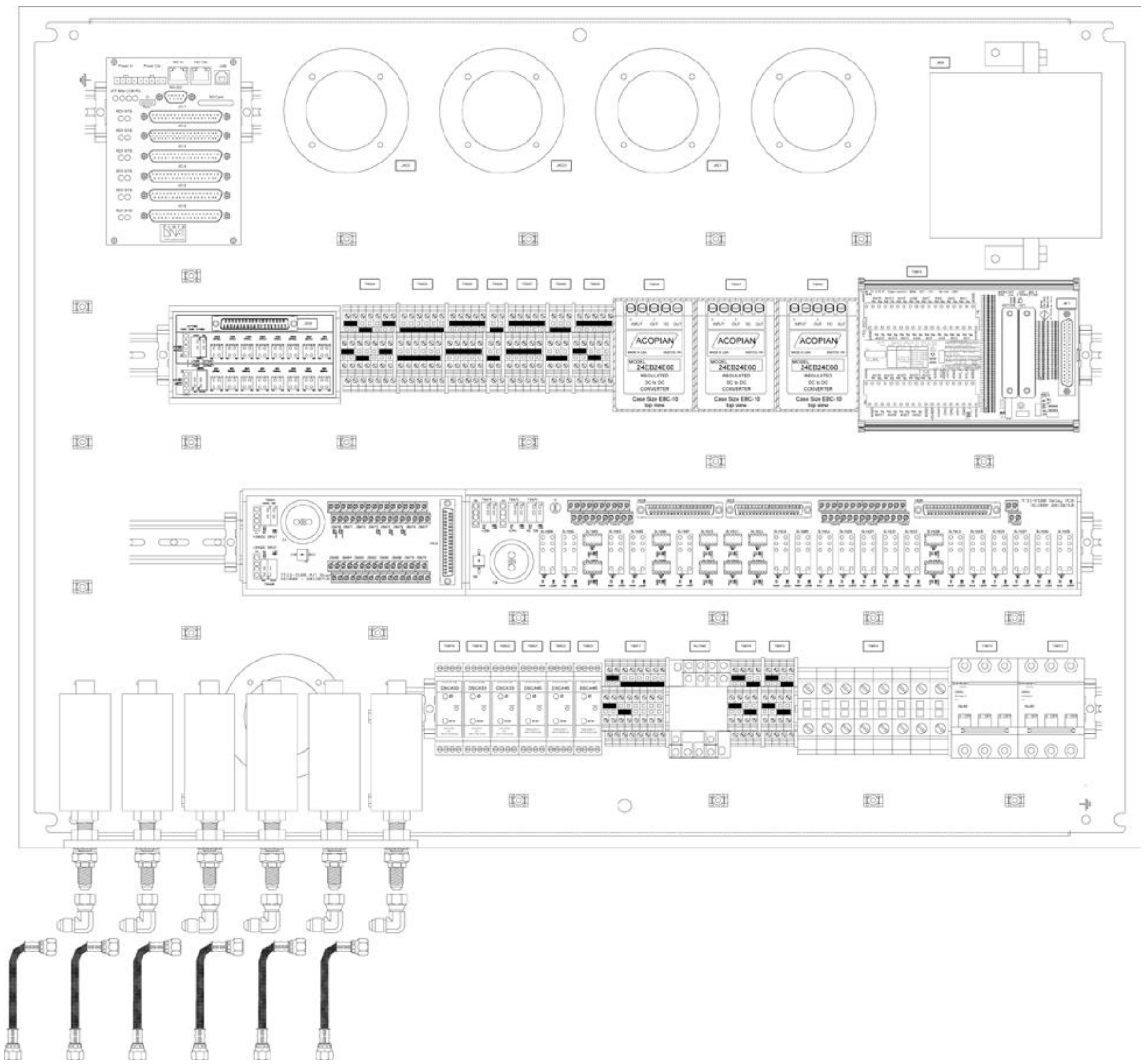

Figure 50 - JBOX Component Arrangement

Hoffman Box Design and Manufacturing

After laying out all the parts in AutoCAD, it was determined that the P100 JBOX should be 36” wide, 27” tall, and 10” deep. This size box would be large enough to accommodate all the equipment and provide ample maintenance room. Coincidentally, to date, this is the largest JBOX that PC4 has designed. The biggest reason for this large box is the very large Relay PCB. The PCB itself measures 19.5” long; a half-inch longer, and it would have exceeded the PCB manufacturer's specs for a mass produced board and would have driven up the cost of production significantly. The closest off the shelf enclosure is a 36x30x10"; Hoffman takes this box and modifies it to the design specifications.

In addition to the box, Hoffman also includes a mounting panel with each box. Just as dimensions and punch-outs are included in the box order, the same markings are included with the panel directions. Using the AutoCAD layout of the box, holes can be marked and drilled into the panel for mounting hardware. All hardware in the box is mounted on DIN rail, an industry standard mounting system created by the German Institute for Standardization. By modeling the DIN rail, locations for mounting screws can be marked and fit can be verified. In addition to the holes for DIN rail mounting, holes for cable tie downs are also included. Adding these tie downs makes it significantly cleaner to route wires, adding to the quality of the final product. The included mounting panel is powder coated for a clean, professional look, while the JBOX is made of high quality stainless steel.

The final piece of information to send to Hoffman for production of the box is the description of the door. Typically there is nothing special required for the door, although some PC4 frames do mount connectors to the doors when space is limited. However, the P100 was a special case as it is the only JBOX that has an unhinged door. There have been issues in the past with opening JBOX doors when the frame is in the test cell header. Support beams block the swing of the door, preventing access to the box. While the doors can be removed easily, they still have to be opened fully, a step that requires unlocking the frame from the header and pulling it out away from the stand. This process can take a significant amount of time and can only be completed by a certified operator, someone who is not always available.

It was determined that the door would be impeded in the test cell due to the location of the P100 JBOX, so an unhinged door was approved. PMXG initially denied all doors of this type, but was convinced to go with this on the P100 due to the inclusion of a safety strap and handles. The P100's door includes two flush mounted handles for easy support and control, and a quick dis-connect safety strap to prevent the door from falling on the engine or the floor of the test cell. The JBOX is mounted approximately 15 feet off the floor; a fall from that height would certainly damage the door and anything underneath. The door is also equipped with 10 quarter-turn latch-es. This latch style is powerful enough to ensure a tight seal on the gasket, preventing water leaks while also providing a quick and easy way to open and close the door.

JBOX Assembly

After receiving the JBOX, assembly begins. The first step in the process is the assembly of the mounting panel's items. Using dimensions obtained from the AutoCAD drawing, lengths of DIN rail are cut and mounted to the panel. Since vibrations are significant on the frame during engine runs, locknuts are used to ensure the bolts won't come out and become FOD (foreign object damage), a significant danger in the test cells (FOD is a very large concern for the Air Force; a single dime can cause hundreds of thousands of dollars of damage to an engine). The design calls for DIN rails due to their industry use as an easy way to mount parts. Ordered in sticks of 48-inch length, the DIN rail is cut by band saw to match the drawings.

During the design phase, the final layout of parts in the box is completed. Working from the de-sign, the components in the JBOX are installed on the DIN rail, or mounted on specific brackets as required (e.g. the Boeing fire detection module). Tie-downs are installed in the pre-drilled mounting locations. These tie downs allow all internal wiring to be secured neatly and cleanly. The PC4 standard typically calls for tie downs every six inches, however in JBOXs, separation distances range from three to six inches, depending on wire routing. Adding multiple tie downs in close proximity to each other help form the wires around bends; it also makes installation easier by essentially providing a third hand to the engineer doing the installation.

The wall connectors are typically installed after the components on the panel are installed. In order to maintain NEMA-4 rating, the wall connectors are installed with the addition of a gasket and nut plate. The nut plate provides a couple of benefits over simple screws and nuts. The nut plates allow installation with only a screwdriver and screws; there is no need for a nut and wrench on the backside. The nut plate also spreads out the pressure across the whole connector, ensuring a complete seal around the gasket.

JBOX Internal Wiring

After the installation of all the parts in the JBOX, wiring can begin. There are a couple of working methodologies for wiring in the PC4 group: wiring from the components to the wall connectors, and the reverse, wiring from the wall connectors to the components. For this particular build, wiring from the wall connectors to the components was used. Since it is a requirement for the wiring to be neat and organized, while still encouraging easy and efficient maintenance, the bulk of the time building the JBOX is spent routing and rerouting the cables and wires to ensure the best path is chosen. When laying out the box in AutoCAD, cable pathways are at the top of the list of considerations for choosing part placement. This preplanning helps to speed up the routing time when building the box.

JBOX Wiring Verification

In order to check the wiring of the JBOX, several tests are conducted. First, a peer review of the box is completed. Another PC4 engineer will sit down with the internal and end-to-end drawings printed out and go wire-by-wire, drawing-by-drawing, verifying that all the cables are there and in the right places. After that, an engineer will take a digital multimeter and check for shorts and opens on the power and ground connections to ensure nothing will be damaged on the first power up.

After verifying the JBOX as much as possible, workbench power is applied to the box to power up the PowerDNA and DC-DC converters (which then power the PCBs). After making sure power is where it's supposed to be, the engineer handling the software will install the P100 configuration into the PowerDNA. This configuration file contains the IP address that is specific to this frame and some basic configurations for card input/output channels. Installing this configuration into the PDNA will allow the use of the PowerDNA Explorer software that UEI has to communicate to the PDNA. This software provides an interface to check each and every channel on the PDNA. The software will read every input, analog or digital, and can produce both analog and digital outputs, which are used to test the relays on the PCBs.

Using the PowerDNA Explorer, the engineer will simulate temperatures on the thermocouple inputs with a heat gun. The engineer doesn't necessarily care, at this point, what the specific temperature is, but rather is looking for a rise in voltage by applying heat to a thermocouple pigtail. After seeing that all the thermocouple inputs are reacting, the engineer then checks the transducer signals by verifying the input voltage is around what ambient pressure should be (for a 100PSIA transducer, the voltage seen on the PowerDNA should be around 1.4VDC). Next the engineer will toggle the outputs to the relay PCB to ensure that the appropriate relay is switching properly. This completes the workbench verification of the JBOX wiring. Further verification of the signals will occur during frame integration and then furthermore in the frame calibration.

Workhorse Cable Construction

The cables that connect to the outside of the JBOX and run to the engine or autoconnector are called the workhorse cables. In PC3, workhorse cables were constructed in a variety of ways over a period of many years, depending on the application. This required the maintenance crew (MAD) to stock a large number of different parts and material to be able to fix any given cable at any time. In order to reduce this inventory requirement, and to improve the overall aesthetics of the finished product, PC4 standardizes the procedure for constructing these cables. The work-horse cable must be able to meet several criteria: be environmentally sealed, provide proper heat and electrical shielding, and have uniform construction. The PC4 workhorse cables meet all criteria by use of environmental backshells with electroless-nickel finish and PTFE convoluted tubing.

The backshells that PC4 uses are typically manufactured by Glenair and have several attributes to support the cable requirements. The backshell is typically made of multiple sections depending on the shell size and length of it (Figure 51). At each junction, there is a connector that has self-locking teeth designed to prevent accidental back off and to improve the seal around the joint. There is also a rubber grommet that, when the strain relief is tightened, collapses around the inserted cable, ensuring a complete seal of the backshell. The follower is a little metal sleeve that the strain relief presses on when tightened; it has a concave curve to the end that mates with the grommet to facilitate the shaping of the grommet around the cable. The backshell is also equipped with a heavy-duty strain relief that will transfer any tension from the cable to the back-shell and then to the engine or JBOX, preventing damage to the rather fragile pins in the connector.

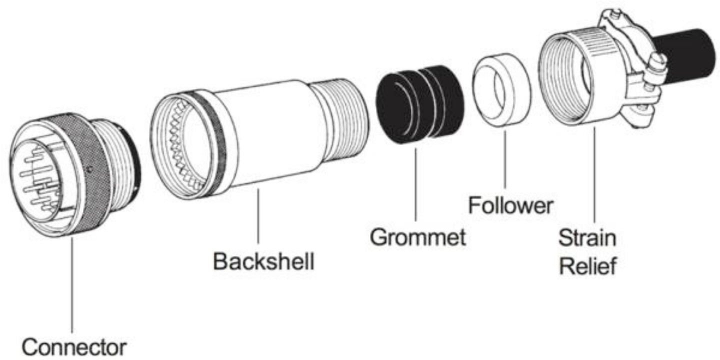

Figure 51 - Environmental Backshell Diagram [26]

The backshell, and the mating connector, is coated in electroless-nickel, a standard in avionic equipment, due to its highly conductive nature and superior corrosion resistance. This provides excellent grounding to the frame, preventing noise from entering the system. It also allows for easy connection to ground by connecting a wire to the screws on the strain relief via a circular lug. This is used in particular on the P100 for the HALON bottle connection. The connector on the HALON bottle has a single pin to carry 28 VDC and requires a connection to the frame via the backshell for ground to complete the circuit.

All cables and wires that make up the workhorse cable are housed in PTFE convoluted tubing, with the exception of the autoconnector cables. PTFE, polytetrafluoroethylene (better known by the brand name, Teflon), is hydrophobic, making it a perfect material to use to shroud the cables. PTFE has a very low coefficient of both static and dynamic friction (0.02-0.2; ice on ice has a coefficient of 0.02-0.09), making it very easy to clean. Another important reasoning for the use of PTFE is that it has favorable dielectric properties and a high melting point (620°F, but rated for sustained use up to 500°F). The cable is convoluted to allow for superior flex around a tighter bending radius while having a smaller wall size. This allows for a properly chosen tube to be inserted completely inside the backshell, further improving the environmental sealing. This type of tubing is popular enough in aerospace applications that it even has its own mil-specs: AMS-T-81914/1 through AMS-T-81914/6.

The autoconnector cables are typically too large to be put in a convoluted tubing package. Instead, the cables are run through liquid-tight, non-metallic conduit. Glenair produces backshells that will accommodate the conduit to ensure environmental protection. In order to ensure uniformity, all autoconnector cables, regardless of the number individual conductors, are installed in a 1.25-inch liquid-tight conduit. Special to the P100, a pass through cable that connects the JBOX to the GCU Box is constructed of a slightly larger, 2-inch, conduit than the autoconnector cables.

As the final step in the construction of the workhorse cables, each cable has its own set of custom labels. Each label set is comprised of three individual labels, covered by a clear heat shrink with adhesive. The three labels are as follows: one on each end of the cable denoting what the connection point is and the engine's model and variant, and a label on one end that contains the part number for the drawing, as well as Tinker AFB's CAGE code. For example, the D84 engine control cable has labels as shown in Figure 52:

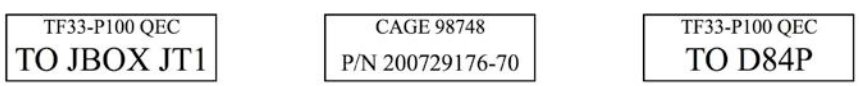

Figure 52 - Workhorse Label Example

The process for building the workhorse cables for the P100 has three steps. The first step is building up the JBOX side of the cable in the shop. The second step is to obtain lengths for cables after the JBOX is installed on frame by routing the cables to their locations and cutting the cables to length. The third and final step is to return the cables to the lab to be completed. The reason for the multiple steps is that since this is a new frame design, lengths for the cables are unknown. By waiting until the JBOX is mounted on frame, the exact lengths can be obtained for a more efficient installation. The measurements are then recorded in the workhorse cable drawing package.

PC4 Standards for Individual Cable Construction

PC4 has a particular way of building each individual cable in addition to its workhorse cable standards. For starters, each cable that has its jacket removed to expose individual conductors has a 1-inch piece of heat shrink placed over the cut insulation. Any heat shrink that goes over a conductor (like on a drain wire for a thermocouple cable) must be partially covered by the 1-inch jacket heat shrink. The amount of jacket stripped off is left up to the engineer on a per case basis, but the length should be the same for all similar cables. If a shield is to be connected, a solder sleeve must be used on the cable. While arguably not the cleanest option, the solder sleeve, if properly installed, can function as the heat shrink covering a jacket cut.

Each conductor in a cable, whether it is in a workhorse cable or part of the internal wiring of the JBOX, has its own identifying label stating its connection point. This ensures that the individual conductor is connected to the proper terminal point. It also makes it easier for wiring verification and troubleshooting in the future. All labels face the same direction in the box; e.g., if you rotate your head to the left, you can read all the vertical labels as you would normally read (left to right). Naturally, all horizontal labels are in the upright position, easily read left to right. The cables in the internal wiring also have a labeling scheme similar to that of the workhorse cables; instead of the engine name however, it has the signal name. Single wires do not require the three additional labels; instead only the terminal point labels are labeled.

When a conductor is mated to a ferrule, lug, or connector contact, there should be no exposed bare wire protruding from the connector. The insulation of the conductor should extend far enough into the connector to provide some strain relief. Appropriate sized connectors are used as specified by the manufacturer. If the proper wire gauge cannot be used, a crimp adapter is used in order to ensure correct mating to the connector, and is called out in the cable's parts list.

TF33-P100 Installation

The frame that PC4 will be installed on is a new PC3 frame never used in test. Typically, PC4 is installed on frames that are currently being used for active PC3 testing. However, this frame was commissioned for PC3 use, but was never used in a test. This doesn't make any difference other than for the engineers installing; an unused frame is magnitudes cleaner than the used frames.

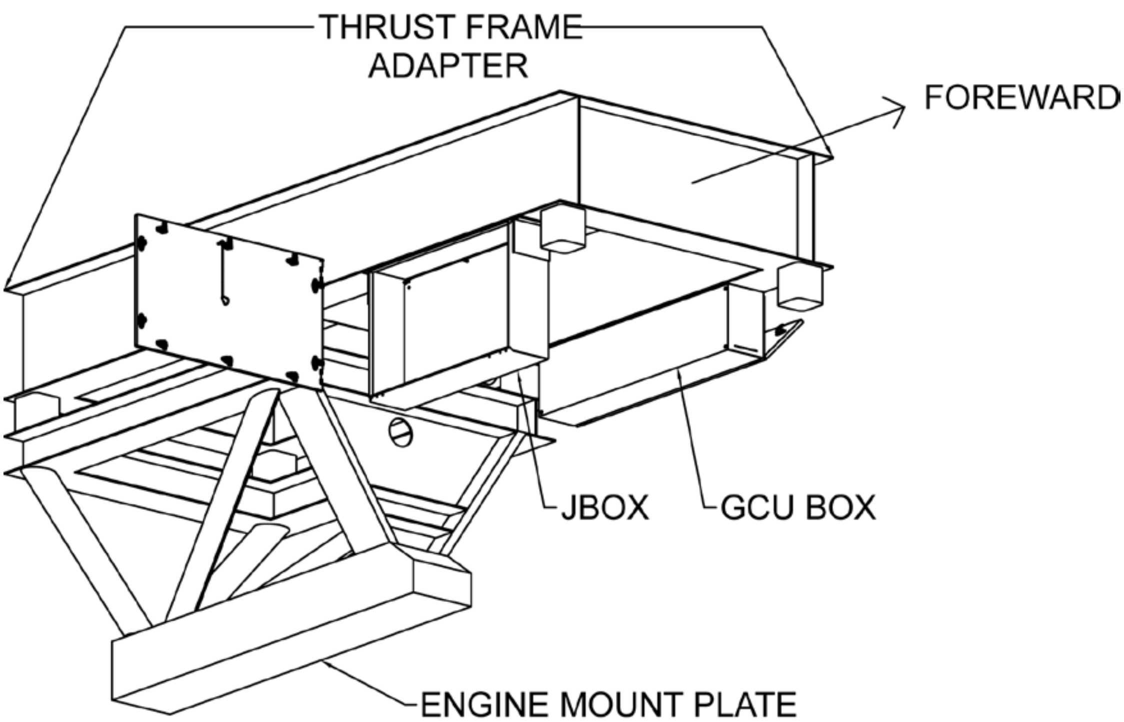

Figure 53 - TF33-P100 Frame with JBOX, flatshot

The process for installing the PC4 on-frame system is as follows:

1. Use mount brackets to mark position of holes in frame.
2. Drill holes (ten for the JBOX, four for the GCU box).

3. Secure JBOX and GCU Box to frame with mount brackets and bolts.
4. Obtain lengths for all cables (autoconnectors, workhorse, and pass-through cables).
5. Finish building cabling and install on frame.

PC4 On-Frame Integration

Once the JBOX, GCU Box, and cabling are completely installed on the frame, initial integration occurs. The first step is to use a digital multimeter to verify there are no shorts on the cabling or in the box. Although this was done on the JBOX wiring in the office, it is important to double and triple check to ensure nothing has changed; the last thing anyone wants to happen is to damage a multimillion-dollar engine by shorting power across it. After ensuring there are no shorts, power is applied through autoconnector cabling to the box. At this point, instead of rudimentarily simulating signals as was done in the office prior to frame installation; actual legitimate signals are generated using calibrated test standards, provided by PMEL.

Using the PC4 Calibration software, each and every signal is generated and read through the PowerDNA for accuracy and precision. Thermocouples signals are generated using a Fluke 525B temperature and pressure calibrator; the 525B standard can produce all thermocouple type signals to an accuracy of 0.216°F. Pressures are regulated by a Druck pressure standard. A function generator generates analog inputs that the PowerDNA will then read back. Using these standards, each signal is checked for accuracy; any deficiencies that surface from this are corrected and rechecked. When everything is checked and verified, word is passed to PMEL for the official calibration.

PC4 Calibration

Before any piece of equipment can be used to test an engine on base, it must have an official calibration sticker signifying that the PMEL group certifies that the equipment can be used. With regards to the PC4 system, both the test cells and frames have to have a calibration sticker. In addition to the initial calibration, each stickered item has to be recalibrated every six months. Prior to any engine buildup or installation into the test cell, the frame must be calibrated by PMEL. The process that PMEL goes through is identical to the process the PC4 engineer goes through in the frame integration step. This is why PC4 engineers go through those steps in the previous process, to ensure that the calibration goes as smooth as possible. Any issues that PMEL might find are addressed and if warranted, calibration is completed again.

PC4 Test Cell Integration

After PMEL certifies the frame by calibration, the frame can finally be put into the test cell for integration. Usually the frame is installed in the test cell prior to having an engine put on it, but depending on schedule, this is sometimes skipped. Either way, workhorse cables are disconnected, initially, when the power is applied through the cell. Again, the box is checked for any potential shorts; then power can be applied through the test cell. At this point, the host computer and TPS are used to read the signals. Generally at this point, as long as the host can communicate with the PDNA over Ethernet, signals will come through fine.

However, there are signals that do not come through the PDNA that need to be verified. These signals come through the PXI's and are calibrated with the test cell. Calibration of the test cell is not needed for each frame, provided that the six-month schedule is maintained. Occasionally, if a signal is acting up, PMEL will be called out to verify the calibration of the signal. At this point, workhorse cables connect the engine to the PC4 system. Now, without the engine running, switches can be actuated from inside the test cell control room; valves and actuators should open and close on the engine and frame. Using a two-man team, one engineer will hit switches inside the control room while the other verifies that the appropriate valve is actuated in the test cell. This part of integration is referred to as the static integration of the engine.

Once all switches and signals are verified, under the supervision of an operator, starter air is applied to the engine. This causes the engine to rotate, allowing additional engine specific signals to be checked, such as fan and core speeds. On certain engines, some signals will only be produced when the engine is turning. The process of applying starter air, but no fuel, to the engine, causing an increase on the fan and core speeds, is called dry motoring. While adhering to the TO's specifications for motoring times, this process is repeated until the software engineer determines the software is ready to proceed. The next step in engine integration is wet motoring. This process is similar to dry motoring except now fuel is actually flowing through the engine. This allows the operator and software engineer to verify that fuel pressures and flows are reading appropriately. The final step is to ignite the fuel, which actually starts the engine.

After wet motoring, the fuel is ignited and the engine is now live. When the engine is lit off for the first time, the engine is never taken above idle for quite some time. Typically, the operator and software engineer will verify signals and test steps at idle for several days, depending on if any issues arise. It's a rather special, albeit unofficial, event when the engine is brought above idle for the first time. After successfully taking the engine above idle, the operator and software engineer will go through each test step repeatedly in both manual and automatic mode to ensure multiple things: one, that the test step is correct, and two, that the software works correctly. After ensuring that all test steps are complete, acceptance can begin. The length of time from the moment the engine is installed in the cell to being ready for acceptance is about two weeks.

PC4 Acceptance

After fully integrating the new PC4 frame, the operator and engineer can begin the acceptance runs. During integration, the majority of the time was spent one on one with the operator and the engineer. Now, two operators are required and typically the PMXG engineer over the engine is present as well as the PC4 engineer. The operators run the engine alone; the PC4 engineer is there only should questions or problems come up. The operators run full test runs multiple times until the PMXG engineer is satisfied. During this process, the PMXG and PC4 engineers sign off on the System Test Description (STD) document.

The STD is a document created by PC4 engineers and management for PMXG that contains all the descriptions of the tests that need to be completed before the frame can be sold. These tests contain everything from workmanship issues to documentation requirements, as well as tests of functionality of the system. The STD also has places to write in deficiencies and comments from PMXG for official record keeping. After the STD is completed, it is inserted into a System Test Report (STR). The STR is a written report of the STD including any deficiencies and comments from PMXG as well as SMXG's responses to each. Typically, once SMXG presents the STR for signatures, PMXG has 30 days to review the document and sign. Once SMXG and PMXG sign off on the STR, the P100 project is complete, funding is closed, and the next project begins!

Conclusion

By designing and implementing the Pacer Comet 4 on-frame engine test system on the TF33-P100 engine frame, PMXG can now run the P100 in any cell at Tinker AFB. PC4 was able to eliminate 70% of the cabling running through the facility by incorporating the on-frame data acquisition system. With provided documentation, future engineers will be significantly more efficient at troubleshooting problems, which will in turn greatly reduce the impact to the production schedule. PC4 provides a safer and more efficient production environment for both the engines and operators at Tinker AFB. The work done on this thesis was an excellent opportunity to test and validate skills obtained through graduate education. From circuit design to integration, all the way to system troubleshooting and program management, this total-system design serves as an appropriate culmination of the education and training obtained through the University of Arkansas Electrical Engineering Graduate Program.

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