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Portable Static Test Facility for Small, Expendable, Turbojet Engines

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Test Devices, Inc. has completed the preliminary design for the Portable Static Test Facility (PSTF) for small, expendable, turbojet engines (50 - 1000 lb thrust) as part of the Phase I effort under SBIR contract DAAH01-94-C-R032. The goal of providing a preliminary design for a development and test facility at a reasonable cost, assembled from standard, transportable modules and requiring minimum setup was achieved.

During the Phase I activities a detailed analysis was performed that covered the description of engines to be tested, engine test procedures, general test specifications, test facility requirements and design considerations, installation, and engine control and test data requirements. From this a preliminary design for the portable test facility was prepared, plus a conceptual installation design and a preliminary design for the engine control and data system.

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LIST OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

A	Monitored cross section
α	Test cell bypass ratio
A_b	Bypass area
A_{bm}	Bellmouth cross-section area
A_e	Nozzle exit area
A_{fc}	Front test cell cross-sectional area
AGTD	Allison Gas Turbine Division
A_{pbt}	Projected boattail area
ASME	American Society of Mechanical Engineers
BM_{dist}	Bellmouth pressure distortion index
CCTV	Closed circuit television system
C_{dbm}	Bellmouth flow coefficient
C_{dfc}	Front cell flow coefficient
CDP	Compressor discharge pressure
CDT	Compressor discharge temperature
CIT	Compressor inlet temperature
D	Engine diameter
δ	Barometric pressure correction factor
EGT	Exhaust gas temperature
F	Net thrust
F_1	Thrust cell
F_2	Calibration cell
F_b	Bypass pressure drag
F_{bt}	Boattail drag
F_c	Corrected thrust
FC_{dist}	Front cell velocity distortion factor
F_f	Skin friction drag
F_{fw}	Wall friction drag
F_{gt}	Engine gross thrust
F_{im}	Intrinsic inlet momentum
F_m	Measured for scale force thrust
F_{tf}	Thrust frame drag
g	Gravitational constant
L	Engine length
L/D	Ratio of length to diameter of the augmentor tube
LDA	Laser Doppler Anemometry (LDA)
LONGFOG	Long Range Fiber Optic Guided Missile
L_w	Overall sound power level
MICOM	US Army Missile Command
M_{max}	Maximum installed flight mach number
N_1	Engine speed 1

N_2	Engine speed 2
N_c	Corrected rotor speed
NFPA	United States National Fire Protection Association
NLOS	Non Line-of-Sight
N_{rated}	Maximum mechanical engine speed
P_{2c}	Corrected compressor discharge pressure
P_a	Ambient (barometric) static pressure
P_{ac}	Aft compressor pressure
P_{adp}	Aft differential backplate pressure
P_{avg}	Average inlet total pressure
P_b	Static pressure at plane b
P_{bt}	Average external nozzle pressure
P_e	Nozzle exit static pressure
P_f	Fuel inlet pressure
P_{fc}	Front cell static pressure
P_{max}	Maximum inlet total pressure
P_{min}	Minimum inlet total pressure
P_{rc}	Rear case pressure
P_S	Inlet static pressure
PSTF	Portable Static Test Facility
P_T	Inlet total pressure or inlet rake total pressure
P_t	Bellmouth average total pressure
P_{te1}	Exhaust total pressure 1
PWM	Pulse width modulation
θ	Ambient temperature correction factor
ρ	Air density
R	Gas constant for air
ρ_0	Air intake density
SAE	The Engineering Society for Advancing Mobility Land Sea Air and Space
SBIR	Small Business Innovative Research
SFC	Specific fuel consumption
SPL	Sound pressure level
T_{4c}	Corrected exhaust temperature
T_a	Ambient temperature
T_{ac}	Aft compressor temperature
T_{fb}	Front bearing temperature
T_{fc}	Front cell static air temperature
T_{ftc}	Forward turbine cavity temperature
T_{fuel}	Fuel temperature
T_{rb}	Rear bearing temperature
T_t	Bellmouth total temperature
V	Average air velocity through the monitored section

V_{0max}	Maximum allowed intake air velocity
V_{avg}	Average front cell velocity
V_e	Nozzle exit velocity
V_{fc}	Test cell front section velocity
V_i	Inlet vibration
V_{max}	Maximum velocity anywhere in the velocity measurement grid
V_{min}	Minimum velocity anywhere in the velocity measurement grid
V_{vol}	Engine volume
W	Airflow
W_a	Sound power
W_{bm}	Bellmouth or engine airflow
W_{bmc}	Corrected engine airflow rate
W_e	Nozzle exit airflow
W_f	Engine fuel flow
W_{fc}	Front cell airflow
W_{fcr}	Engine fuel flow corrected
W_{ft}	Flow function term
W_g	Engine weight
W_s	Engine starting airflow

1.0 INTRODUCTION

In the last ten years, in an effort to expand propulsion technology capabilities, the Propulsion Directorate of the United States Army Missile Command (MICOM) initiated a program to develop a turbojet propulsion system for small tactical missile applications. As a result of this program numerous engine designs have been developed encompassing a wide range of the technology spectrum. Some engine models use commercial rotating components manufactured in volume to contain costs yet achieve satisfactory performance. Other engines employ metal based designs that use advanced aerodynamic rotating components to achieve significant performance improvements, which in turn increases the production cost. The most technologically advanced engines incorporate ceramic components, but this further increases the production cost.

Characteristics common to all small, expendable, turbojet engines are their relatively small size (4.0 to 15.0 inches in diameter) and low target production cost. The thrust levels of these engines range from 50 to 1000 lb. The design of a portable test facility for these engines must accommodate the different sizes, designs, and technologies used in these engines.

The physical characteristics of jet engine test facilities can cause performance problems or induce measurement errors during testing of turbojet engines. The basic requirement in testing engines is to determine the performance of the engine and to insure that all engine systems are functioning properly prior to installation and use. To determine the performance of the engine with a high degree of accuracy a reliable and stable testing environment is needed. Selection of the proper facility type (outdoor or enclosed) is required for a given project.

Outdoor facilities can produce excellent results when engines are tested in non-wind conditions. If all other testing conditions are stable at an outdoor facility the measurement uncertainty can be substantially reduced, making the estimate of the measured thrust force practically equal to the real thrust that the engine can achieve under free field conditions.

An indoor test facility can be defined as an enclosed structure with an engine mounting mechanism that is intended to provide conditions for stable, repeatable, and accurate engine performance testing. In these facilities the engine air inlet and exhaust paths have additional loads placed on them that influence the engine thrust. Thrust drag, for example, is directly related to the aerodynamic interference between the engine and the test cell.

The difference in thrust, air flow and fuel flow between the largest (1000 lb) and smallest (50 lb) engines is a factor of 20; a testing requirement that cannot be satisfied by many existing test facilities. The first phase of this study is to evaluate the most important engine requirements and develop a conceptual solution for a portable static test facility (PSTF) for small, expendable turbojet engines. Subsequently, a preliminary design for a PSTF is created by combining current knowledge and practice with the research results of this project.

2.0 OBJECTIVE

The objective of this report is to present the results and supporting data for the development of the PSTF, which was successfully completed under DOD SBIR Program Phase I contract, DAAHO1-94-C-RO32, topic A93-277.

The primary technical objectives of Phase I were to formulate, design, analyze and demonstrate the feasibility of a PSTF. Extensive work was required to develop a preliminary design which addresses the specific requirements of small size, ease of transportation and installation, reasonable cost, safe work environment, high reliability and ability to successfully test engines with a wide thrust range.

The individual tasks in the study were to:

1. Analyze the general requirements for engine testing.
2. Review the test procedures for small, expendable turbojet engines.
3. Prepare general test specifications for engines that will be tested at the PSTF.
4. Analyze the test facility design requirements, define the factors for evaluating the performance of the test facility and outline the overall design recommendations.
5. Develop the test cell basic requirements, design criteria and design recommendations.
6. Provide an overview of the installation requirements and design recommendations.
7. Analyze the data acquisition and engine instrumentation and control requirements.
8. Formulate a preliminary design for the PSTF.
9. Develop a conceptual installation design for the PSTF.
10. Define recommended solutions for the engine control and data measurement systems.
11. Derive conclusions and recommendations for Phase I and for future activities in Phase II of this project.

To achieve these objectives during the Phase I research program a broad set of activities were conducted. This report highlights the achievements of this investigation.

3.0 ENGINE DESCRIPTIONS

3.1 General Description of Small, Expendable Turbojet Engines

In the last ten years, a development program was conducted by the United States Army Missile Command (MICOM) on a family of small, expendable turbojet engines. This program encompassed more than twenty low-cost, expendable engines from different suppliers.

The objectives of the (MICOM) program were to demonstrate the performance, mechanical integrity and operational characteristics of low cost expendable turbojet engines. This program confirmed that turbojet engines offer several significant performance advantages over existing solid rocket technology. Turbojet engines demonstrated an order of magnitude reduction in specific fuel consumption, a virtual unlimited operating time, minimal visibility and IR signature and full compliance with the Insensitive Munitions criteria [4]. The low specific fuel consumption of turbojet engines enables longer mission duration when compared to a rocket engine of a given weight plus fuel. As an additional advantage the turbojet can be fully throttled to operate in loiter, cruise and dash modes.

The available data used as the baseline for the development of the PSTF are related to 19 engines which are described in reference [4], and which include thrust ranges between 32 and 273 lb. To cover the full thrust range (up to 1000 lb), turbojet engines J402-CA-400 and F408-CA-400 from Teledyne CAE were included in the study and analyzed.

Mutual characteristics of all engines in this class are single entry ram inlet, an annular combustor and a single-stage axial flow turbine. Some design variations exist which depend on the company where the engine was developed.

The five engines developed by Sundstrand Power Systems were based largely on the same fundamental configuration. In all five of the engines the compressor and turbine are mounted back to back with a shaft forming a mono-rotor. All engines include a reverse flow combustor and air blast atomization fuel injection. Engines are designed to include a shaft driven fuel pump which pressurizes fuel for delivery to the atomizers. The metallic engines (TJ-20, -70, -90) use single stage centrifugal compressors and radial turbines. The engine designs integrate the compressor diffusers and turbine nozzles to form a mono-stator. The TJ-50C ceramic engine model was designed with a single stage compressor and a radial turbine.

The engines developed by Teledyne CAE use single stage compressors, slinger fuel injection, and single stage turbines in the same general design configuration. Models 305-4, 305-7 and 318 use centrifugal compressors while the 304, 304C, 305-10 and 305-10C engines are designed with mixed flow compressors. All the Teledyne engines use axial turbines, except the 304 and 304-C models, which employs mixed flow turbines.

The larger engines, J402-CA-400 and F408-CA-400, implement some different designs. The J402 engine has a single entry ram air inlet, an axial centrifugal compressor, an annular combustor and a single-stage axial flow turbine. The F408 engine includes the following design features: a two stage (axial and mixed-flow) compressor, a high work turbine and fully digital electronic control.

The two engines developed by TDI use a single stage centrifugal compressor, slinger fuel injection, and a single stage turbine. The model TD7 uses a radial turbine while the TD4 uses a mixed flow turbine.

The design of model SR30 was developed by TTL and includes a single stage centrifugal compressor, atomizing fuel injectors, and an axial turbine. Model 120 developed by AGTD uses a single stage centrifugal compressor, air blast atomizing fuel injection, and an axial turbine. Neither model SR30 or 120 include the external fuel pump required to pressurize the fuel.

Williams International has delivered two engine models to MICOM for testing and is currently working on two others. The two engines delivered are WJ119-2 and the P8910. These two engines are almost identical externally but the P8910 is substantially uprated. Both engines are axial flow turbojets that were intended to power short range tactical missiles such as NLOS. Both engines use a six stage axial compressor, axial flow annular combustor and a single stage axial turbine. The WJ119-2 is an integrated propulsion module (IPM) which consists of the turbojet engine, fuel delivery system and tank, inlet system, exhaust system, and start system. The WJ119-2 IPM was designed as an integral part of the NLOS missile. The IPM was designed to withstand all of the structural loads, including very heavy shock loads during ground transportation. The missile wings were attached to four lugs that were part of the diffuser housing casting. Since the NLOS missile was fiber optic guided the bifurcated exhaust nozzle was designed to prevent impingement of the exhaust gas on the fiber optic cable. To provide symmetry in the engine installation the inlet system was also bifurcated. The fuel system consisted of a elastomeric fuel bladder which was enclosed in a plastic fairing. The bladder wrapped around the compressor stator and filled in the fairing behind the inlet scoop. An electric motor driven fuel pump was mounted within the hub of the axial compressor. A pulse width modulated (PWM) voltage drove the pump at variable speed to control engine shaft speed and thrust level. The engine was started via a pyrotechnic torch igniter and start cartridge. The start cartridge was nested between the legs of the bifurcated exhaust nozzle.

The P8910 engine was similar to the WJ119-2 but since it was not an IPM it did not include the fuel and start systems as part of the package. Since MICOM intended to test the P8910 in a wind tunnel model of the LONGFOG missile there was a bifurcated inlet and exhaust duct built for the engine.

Williams International is currently conducting tests on a 4-inch diameter turbojet designated the P9005. This engine was originally designed and fabricated a part of the MICOM/ARPA SENGAP program. The P9005 is a conventional turbojet and uses a mixed flow compressor, axial flow annular combustor, and an axial turbine. Due to the small size of the engine the component loading levels for the engine are higher than those of larger engines such as the WJ119-2.

3.2 Envelope Data

In previous sections a general description was presented for small expendable turbojet engines. Each of these engines can be evaluated on physical characteristics or tested performance. Both of these categories are included in Table 1 where un-installed engine performances are presented.

The data shown indicates the most important information about these engines. Information about the reference engine used for the preliminary design of the PSTF was derived from this table. These data are a good representation of the overall characteristics for most existing small, expendable turbojet engines. This information together with engine performance data provides the reference basis for the preliminary design of the PSTF.

3.3 Engine Mounting

All engines are mounted on a thrust stand using an engine adapter kit. Each engine requires a separate interface between the thrust stand and the different systems of the test facility. Some examples of engine mountings are described below.

The WJ119-2 and the P8910 engines are mounted to the thrust stand via a mounting ring that bolts to the wing mounts. The mount has a steel ring with four blades welded into it that mate with the four wing mount lugs on the engine casing. The ring is then attached to the frame of the thrust stand.

The P9005 engine uses a clam shell mounting ring. The lower half of the ring bolts to a stand on the thrust bed. The front of the engine diffuser casing fits into the mount ring and the upper half of the mount ring is bolted in place around the engine.

ENGINE	PHYSICAL CHARACTERISTICS					DIRECT PERFORMANCE				DERIVED PERFORMANCE				INSTALLED
	D (mm)	L (mm)	V_{vol} (m^3)	W_e (kg)	N_{rated} (krpm)	F (N)	SFC (kg/N-hr)	EGT (K)	W_{air} (kg/s)	F/A (N/m^2)	F/W_{air} (N-s/kg)	F/V_{vol} (N/m^3)	F/W_e (N/kg)	M_{max}
TJ-50	101.6	232.4	0.0236	2.7	130	220.71	0.1550	1231.2	0.3506	27224	629.5	9352	81.74	0.69
TJ-50C	101.6	232.4	0.0236	2.7	136.5	294.10	0.1661	1455.7	0.3802	36276	773.5	12462	108.93	>0.80
304	101.6	235.2	0.0239	3.9	126	261.90	0.1239	1053.9	0.4291	32304	610.3	10958	67.15	0.80
304C	101.6	235.2	0.0239	3.6	126	362.65	0.1467	1459.4	0.4290	44731	845.3	15174	100.74	>0.80
P9005	101.6	268.5	0.0273	4.5	115	228.00	0.1457	1205.7	0.3647	28123	625.2	8352	50.67	>0.80
TD4	101.6	266.7	0.0271	3.1	125	227.74	0.1759	1320.5	0.3629	28091	627.6	8404	73.46	0.79
TJ-20	152.4	265.4	0.0404	5.4	103	190.15	0.1406	897.2	0.4625	10424	411.1	4707	35.21	0.40
TJ-70	152.4	265.4	0.0404	5.4	105	318.61	0.1409	1226.3	0.4633	17466	687.7	7886	59.00	0.60
305-4	168.9	283.0	0.0478	6.8	83.2	177.83	0.1452	1023.3	0.3583	7937	496.3	3720	26.15	0.42
SR30	171.5	221.7	0.0380	5.4	87	145.00	0.1625	902.5	0.3592	6277	403.7	3816	26.85	0.34
TJ-90	166.6	287.0	0.0478	4.8	102	430.17	0.1472	1175.4	0.6737	19733	638.5	8999	89.62	0.61
305-7	168.9	327.7	0.0553	7.7	89	405.92	0.1275	1162.2	0.5897	18117	688.4	7340	52.72	0.59
WJ119	177.8	419.6	0.0746	12.5	56	407.88	0.1421	1095.8	0.7448	16428	547.6	5468	32.63	0.54
TD7	177.8	270.0	0.0480	5.2	96	450.14	0.1638	1268.7	0.7067	18130	637.0	9378	72.60	0.61
305-10	168.9	391.2	0.0661	11.8	78	795.75	0.1224	1153.9	1.1249	35516	707.4	12039	67.44	>0.80
305-10C	168.9	391.2	0.0661	11.3	78	971.44	0.1401	1438.3	1.1244	43358	864.0	14697	85.97	>0.80
P5910	177.8	419.6	0.0746	12.7	59.4	641.85	0.1378	1265.1	0.8899	25851	721.3	8604	50.54	>0.80
318	214.4	428.0	0.0918	15.9	72	786.85	0.1206	1108.9	1.1716	21795	671.6	8571	49.49	0.65
120	203.2	440.4	0.0895	7.3	78	1219.64	0.1221	1249.7	1.5472	37609	788.3	13627	167.07	>0.80
J402-CA-400	318	747.8	0.37	46	37.75	2090	0.1224	1116	4.35	70989	480.4	5698	45.4	0.90
F408-CA-400	335	815	0.42	65.8	42.0	4444	0.099	1039	7.36	78781	603.8	10580	67.5	0.90

Table 1. Performance Summary Of Small, Expendable Turbojet Engines

3.4 Bellmouth Requirements

The test facility should include a bellmouth for engines that will be tested. Some examples of bellmouth treatments are described below.

The WJ119-2 and P8910 had unique inlet airflow measurement requirements. On the WJ119-2 it was found that the engine would not run statically with the flight bifurcated inlet system. Flow separation at the inlet lip caused the engine compressor to stall. To cure this problem a plastic fairing was fabricated to prevent inlet airflow separation. To conduct static tests a special inlet adapter was built with two small ASME configuration bellmouths that bolted to the engine inlet housing. The bellmouth dumped into a small plenum in front of the engine inlet with the plastic fairing to prevent separation.

The P8910 was tested in two configurations. During early testing the engine had a single annular inlet duct. A special bellmouth was built with an internal duct to bring the fuel, oil mist, and instrumentation into the inlet housing hub. The special inlet bellmouth was calibrated on a flow bench due to its non standard configuration. Later in the program the engine was tested with a bifurcated inlet system that was built for testing in the LONGFOG wind tunnel model. The inlet was fabricated from two molded carbon fiber and epoxy S-ducts, a mounting flange and machined aluminum lip adapters. The assembled inlet was calibrated on a flow bench to obtain airflow versus delta P curves.

The P9005 uses a bellmouth similar to the early P8910 where engine services, fuel and instrumentation are brought into the engine via a tube in the center of the bellmouth flow path. The P9005 bellmouth was also calibrated on the flow bench.

3.5 Jet Pipe Requirements

During engine testing a jet pipe is usually used to simulate the exhaust conditions of an installed engine. For larger engines jet pipes are used to provide a referee type nozzle for testing. Smaller turbojet engines usually have integral jet nozzles and do not require any additional exhaust treatment.

3.6 Fuel System Requirements

Depending on the type of engine, mode of control, and type of testing, the fuel system requirements can differ greatly. Small turbojet engines require a low flow fuel supply (i.e. 20 pph-1000 pph), with pressure control. Some engines do not use a shaft driven integral fuel pump. In these cases the fuel must flow from the tank to the engine at a fuel pressure high enough so it can be directly transferred to the atomizer. Two options are available to satisfy this requirement: a pressurized tank or an unpressurized tank with a boost pump.

In these applications the fuel pressure level should be up to 150 psig. When engines contain the shaft driven integral fuel pump, pressure requirements are typically lower (below 40 psig). To establish this pressure level the pressure regulator should control the pressure in the line if a boost pump is used, or in the tank if a pressurized solution is implemented. The fuel pressure must remain stable throughout various operational procedures, static or dynamic conditions, with low (20 pph) or high fuel flow (1200 pph).

A 10-micron fuel filter should be used in the fuel supply. A shutoff solenoid valve is used to control the delivery or interrupt the fuel supply, according to the engine control requirements, operator decision, or facility protection alarm. A servo valve is also part of the fuel system requirements and can be included on the engines or in the test facility fuel system.

Accurate fuel flow measurement is critical to proper performance of the test facility. The measurement system should accurately control the measurement of fuel flow through the operating range (20 to 1200 pph), and respond quickly enough so timely fuel flow data can be used for the engine control algorithm. The quantity of fuel stored in the tank must satisfy the requirements for a maximum duration test or risk interrupting the test due to a limited fuel supply.

3.7 Lubrication Systems

Many small expendable turbojet engines are designed for a short operational life and originally had grease packed bearings which did not require an external oil system. In some applications, particularly for development testing, the greased packed bearings were replaced with oil mist lubricated bearings. For these cases the test facility requires an oil mist system.

In the proposed facility, air flows from the facility air system through a 10 micron filter and solenoid valve into the air/oil mist generator. The mist generator decreases air pressure to 40-60 psig and sets the oil droplet rate to 2-3 drops/second. The air/oil mist flows through a 20 micron filter into the engine bearings. This is a typical configuration for an external lubrication system inside the test facility which may be required by some small turbojet engines.

3.8 Starting Systems

These engines are all designed to be started using pyrotechnic torch igniters and start cartridges. A typical torch igniter uses a fuel mixture containing magnesium, teflon and viton which when ignited by a squib burns with a hot flame and many hot sparks. Since this would be costly in a program requiring many engine starts, an alternative system for test cell testing has been developed. Ignition is accomplished using a hydrogen/air igniter torch. The torch consists of a torch housing with inlet orifices for compressed air and hydrogen, a flame tube, an aircraft spark igniter plug, and a control panel to set the gas pressures and turn the gas flow on and off. The gases are regulated to approximately 40 psi above ambient pressure. Hydrogen and air are injected into the torch housing, mixed, and are then ignited by the spark plug. The burning gases flow through the torch tube into the engine combustor where they ignite the fuel/air mixture. The start cartridge is a gas generator device that uses butadiene rubber and ammonium nitrate as the propellant blend.

The air start system for the largest of the expendable engines must sustain high air flow for a short time (10-15 seconds). A high pressure air supply is a reasonable solution, allowing storage of a large quantity of air which is then used during starting. Regulated high pressure air passes through a solenoid up to the impingement nozzles which are integral parts of the mono-rotor housing.

3.9 Electrical System Requirements

Most of the expendable turbojet engines have no alternator installed and do not require power absorption or measurement by the test cell. Some of the engines have shaft speed permanent magnet alternators and require test cell load banks. The maximum electrical power to be absorbed from any of the engines during testing is 6000W (J402-C4-400).

3.10 Installation Interface Requirements

To connect the engines with the test facility, pressure, temperature, and vibration connections as well as fuel and oil mist hook-ups are required. There is also a need for high pressure cranking air and supplies of air and hydrogen for the torch igniter. The engine requires a mounting frame which then mates to the thrust stand. Electric power is required for the spark igniter, the torch and to run the engine fuel pump.

3.11 Engine Control Requirements

There are several speed control methods for small expendable turbojet engines. Most of these are closed loop speed control systems and the purpose and philosophy behind each is similar: the controller stores various control function tables and generates control signals by monitoring the engine speed signals and command speed requirements. The controller then alters the fuel flow drive signal based on these stimuli and adjusts the engine speed to the proper level. Starting the engine requires precise logic to ensure that the compressor does not stall at the end of the start sequence. After the engine reaches a preset speed start cutout occurs and the engine operates on a governor based control system.

To perform static performance evaluations at the test facility each manufacturer must provide a fuel control system for the corresponding engine. Each fuel control can be viewed as a self contained system used to start, operate and throttle the engine. Usually the system consists of a PC based controller, a magnetic speed pick-up, pressure and temperature transducers, and a fuel control device. The fuel control algorithm is mostly based on the calculated engine speed and the inlet pressure and temperature. Each of the control systems is tailored for specific fuel metering devices and other specific engine configurations so it will not work with any other engine.

When engine performance evaluations are conducted by the engine manufacturers at their facilities, specialized fuel control systems are acceptable because these facilities test only a few different engine models and dedicated hardware configurations will not be overloaded. In such facilities engine control logic is evident to the user and control logic algorithms can be adapted or modified on-line.

Specialized systems are not appropriate when engines are tested at other facilities such as the PSTF. This facility will potentially be used to test a large number of small turbojet engines. This concept can have many disadvantages if the manufacturer's fuel control solutions are implemented [26]. Some of these shortcomings are:

-The hardware configuration required is complicated and heavy.

-Each control system is independent and tailored for only one engine model.

-The control algorithms are not reconfigurable.

-Engine start sequencing is non-existent or extremely limited. In many cases an external control sequencer is required.

In a situation where the user has a need to evaluate a number of turbojet engine models from different manufacturers, using a separate fuel control system for each engine model is impractical.

To provide the optimum solution for multi-purpose facilities, the ideal fuel control system is generic in nature and readily adaptable to accommodate a variety of engine models, fuel metering devices, sensor configurations, and control algorithms.

The development of such a system requires the resolution of many problems, especially regarding transient engine control throughout acceleration and deceleration periods. To arrive at a satisfactory solution a few of the following design requirements should be implemented.

-The basic test facility fuel system should be flexible yet stable in both transient and steady-state operation.

-The fuel system should be personal computer (PC) based.

-The response time of sensors, conditioning and converting units must be very short to allow for the dynamic performance of the whole system.

-The control algorithm must be software reconfigurable and easily operated.

-Safety protections must be included which automatically stop the engine if the safety limit is exceeded.

-A manual software stop and a physical electrical engine stop command should be provided.

-Automatic and manual engine control sequencing is required.

-Manual engine throttling should be software based and digitally entered from the PC keyboard.

-An automatic mode for engine throttle commands is required with timed profiles.

-The system should include universal electrical interfaces to accept different metering devices and sensors.

-The software should be reconfigurable to accommodate different hardware configurations.

-A calibration capability must be part of the software and hardware system.

Most of the above design requirements are based on MICOM research on control of low cost, expendable engines presented in reference [26]. The results of this experimental evaluation program demonstrated the generic nature of the PC based fuel system which successfully controlled engines under steady-state and transient conditions, even with different fuel metering devices. The knowledge and experience in developing the PC based fuel control system will allow MICOM to develop and implement this solution in a basic fuel system configuration which will be initially installed in the PSTF.

4.0 ENGINE TEST PROCEDURES

Engine test facilities should enable users to conduct comprehensive test programs intended to fully demonstrate the static operating characteristics of turbojet engines.

Engine procedures required for all test facilities are:

1. Engine starting and shutdown
2. Engine and fuel control system functional check
3. Engine performance testing

Within these activities the following performance investigations can be performed:

-Start impingement trials
-Ignition envelope determination
-Start fuel scheduling and algorithm development
-Acceleration characteristics
-Deceleration characteristics
-Operation at 100% speed
-Optimization of propelling nozzle area
-Engine performance calibration test
-Control system development
-Minimum sustained speed characterization
-Dynamic rotor investigation
-Alternator loading test
-Durability test

Understanding the engine test procedures is a very important factor in the development process of any test facility. The design must enable the operator to conduct test procedures in logical and rational ways. A description of the procedures typical during operation of the PSTF is listed in the following sections.

4.1 Preparation for Testing

In the preparation phase the engine is mounted to the thrust stand. To finish engine installation all interfaces should be defined. Each engine must have installation drawings with relevant information about the interfaces that will be used. A typical list of interfaces follows:

-Bellmouth
-Jet pipe
-Adapter between engine and thrust stand
-Fuel inlet adapter

-Oil system adapter
-Ignition system
-Pressure measurement adapters
-Temperature probes
-Vibration adapters
-Arrangement of speed probes
-Air start adapters
-Adapters for engine drains
-Hydrogen torch adapters
-Alternator connector
-Electrical interfaces
-List and codes of instrumentation to be used

Some of the test procedures can require special adapters and instrumentation that will be installed on the engines.

4.2 Pretest Checks

Before any operation the engine facility service system must be checked as follows:

-Fuel tank level
-Oil level in mist generator
-Readiness of fire protection system
-Electrical service availability
-Air intake door position
-Air system pressure
-Air condition status
-Hydrogen system pressure
-Proper installation of all engine interfaces
-Engine limits adjusted

Before the engine can be started the ignition system must be checked to ensure that it is functional. Audible sparking should be confirmed prior to continuing pretest checks. With the fuel supply connected to the engine and pressurized to the operating pressure level, the engine must be closely examined for any fuel leaks. All leaks must be repaired prior to continuing the test.

The engine inlet area should be visually inspected for damage caused by foreign objects, system leaks and the condition of the inlet duct instrumentation. The exhaust area should also be checked for any damage.

4.3 Engine Testing

The engine should be started using start sequencing and the closed loop speed control system. The engine conditions and parameters must be observed throughout the starting period. If any irregularities are found the starting procedures must be stopped. The starting time in the test protocol and the engine data at idling speed must be recorded. The idle speed should be adjusted and the engine checked for leaks. The speed must be slowly increased up to the maximum speed, adjustments made and parameters recorded. If all parameters are within acceptable limits, the speed should be reduced and the engine cooled and shut down. After these initial checks and adjustments the engine is ready for performance testing.

The performance calibration Test Matrix describes how the flow chart performance curve shall be established. One example of this matrix is shown in Table 2.

Engine Speed [%]	60	60	70	70	80	80	90	90	100	100
Time [Sec]	60	30	60	30	60	30	60	30	60	30
Load [W]	0	750	0	1000	0	1000	0	1000	0	1000

Table 2. Performance Test Matrix

Using these procedures all engine parameters are recorded and performance curves for the most important engine parameters (thrust, EGT, SFC and airflow) are established.

A durability test can be run to prove the engine performance or time life throughout a certain period.

Transient testing demonstrates engine acceleration and deceleration characteristics. Usually the acceleration time from idle to 100% speed and conversely, the deceleration time from 100% speed to idle should be determined. To identify the optimum transient response characteristics the fuel control system gains should be adjusted. If performance testing and transient characterization are successfully completed a special dynamic investigation could be performed. Through all types of testing programs the vibration level and other engine program test parameters must be kept within engine operational limits.

Turbojet engines are affected by the ambient conditions in which they operate. To evaluate performance, engines are tested and parameters are recorded in different ambient conditions. Measured parameters must be corrected to the values corresponding to standard ambient conditions.

Methods for correcting parameters can vary between engine types and models so correction procedures should be contained in the test specification. Most engine parameters are normalized as a function of total temperature and total pressure at the engine inlet. The basic normalizing parameters are:

1. θ - Observed inlet total absolute temperature / absolute temperature of ISO sea level standard day reference atmosphere.

2. δ - Observed inlet total absolute pressure / absolute pressure of ISO seal level standard day reference atmosphere.

Usually, correction of the major engine performance parameters requires the use of the following correction functions:

- Corrected rotor speed N_c

$$N_c = \frac{N}{\sqrt{\theta}}$$

where N is observed speed

- Corrected thrust F_c

$$F_c = \frac{F}{\delta}$$

where F is observed thrust

- Corrected airflow rate W_c

$$W_c = W\frac{\sqrt{\theta}}{\delta}$$

where W is the observed airflow

- Corrected fuel flow rate W_{fcr}

$$W_{fcr} = \frac{W_f}{\delta\sqrt{\theta}}$$

where W_f is the observed fuel flow.

- Corrected exhaust temperature T_{4c}

$$T_{4c} = \frac{T_4}{\sqrt{\theta}}$$

where T_4 is the observed exhaust temperature (EGT)

- Corrected compressor discharge pressure P_{2c}

$$P_{2c} = \frac{P_2}{\delta}$$

where P_2 is the observed compressor discharge pressure

Prior to the calculation of the corrected parameters the observed values must be adjusted for instrumentation errors if applicable. These errors are established during instrumentation calibration.

The importance of proper calibration of the test cell and its instruments cannot be overemphasized. This procedure firmly establishes the accuracy of the individual instruments and system measurements.

Each experimental program can produce voluminous quantities of data, especially if a data acquisition system used. Already there is a great tendency to measure everything that is possible, often without regard for how the data will be presented later. The test report should specify which parameters to measure and present data in a hierarchical form.

5.0 GENERAL TEST SPECIFICATIONS

The Portable Static Test Facility for Small Expendable Turbojet Engines is being developed to permit static test evaluation of a wide range of small turbojet engines with thrust levels ranging from 50 to 1000 lb.

Each of the twenty-one (21) small engines described in Section 3 is characterized by different requirements with which the test facility must comply. To satisfy the overall requirements engine specifications are analyzed and used as preliminary design input data.

From Table 1 the minimum and maximum values are extracted. Using these data a matrix specification is generated as shown in Table 3. The acoustical data, estimated noise spectrum and overall sound power level are calculated using the methodology described in reference [31]. These data are shown in Figure 1.

To generate design input data for different systems an analysis of each individual system was conducted. As a result of this analysis (shown in Table 1) the design range was established for the PSTF and is shown in Table 3. The design range in Table 3 is not equal to the min-max window, because each of the values has some specific requirements. For example, in Table 1 the minimum and maximum flow values correspond to the smallest and largest engines, at maximum speed (100%). These values cannot be used for the design range because the smallest engine will run below the maximum speed and the design requirements for the fuel system must include a stable supply of fuel and measurement for an extended range as shown in Table 3. Similar procedures are conducted for other values. Performance measurement of small turbojet engines is the primary function of the test facility. To access the basic engine performance parameters, the thrust, fuel flow rate, airflow rate, exhaust temperature, vibration etc. must be verified or calculated from other measurements.

Engine Data	D in	L in	W_g lb	N_{rated} krpm	F lb	EGT °F	SFC lb/hr/lb	W_f PPH	P_f psig	W_{bm} lb/sec	W_s lb/sec	L_w dBA
Min Value	4	9.15	5.95	7.35	32	1123	0.971	50	5	0.77	0.05	143
Max Value	13.18	32.08	145	136.5	1008	2130	1.726	989	150	16	1.85	156
Design Range	4-15	8-32	5-150	0-150	20-1000	1000-2500	0.5-2.0	20-1200	5-150	0-16	0.05-2.0	156

Table 3: PSTF Design Range Matrix

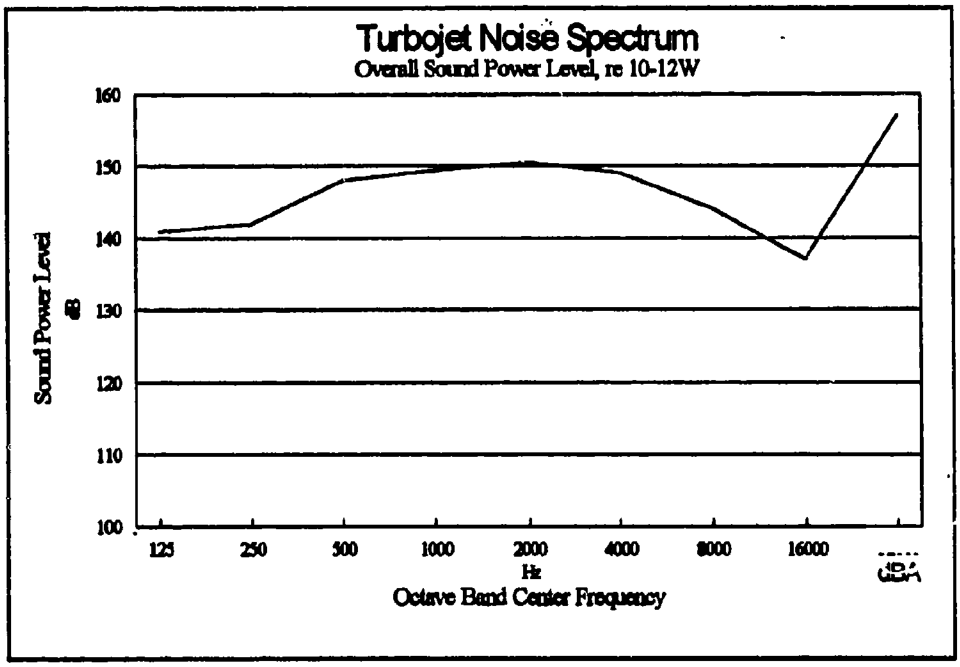


Figure 1: Noise Spectrum for Reference Engine

Each engine that will be tested in the PSTF must have a program of testing that includes a list of instrumentation that will be used. The same engine tested for different programs requires different lists of instrumentation. A list of instrumentation contains:

- -Description of measured parameters
- -Symbol of parameters
- -Type of measurements
- -Range
- -Units
- -Accuracy, if not a standard

An example of a list of instrumentation is shown in Table 4.

By using the requirements of different engines expressed in a list of instrumentation the minimal measuring configuration for the PSTF can be established. In special cases, some additional instrumentation can be installed in the engines or test facility.

ITEM	SYMBOL	DESCRIPTION	TYPE	RANGE	UNITS	ACCURACY
1	N_1	Engine Speed 1	SP	0-60000	rpm	
2	N_2	Engine Speed 2	SP	0-60000	rpm	
3	F_1	Thrust Cell	LC	0-1000	lb	
4	F_2	Cal Cell	LC	0-1000	lb/hr	
5	W_{f1}	Flow Meter 1	FM	0-2400	lb/hr	±0.25%
6	P_b	Barometer Pressure	PT	14-15	psia	
7	T_a	Ambient Temp	TC	0-150	psia	
8	P_{t1}	Inlet Total Pressure 1	PT	0-17	psia	
9	P_{s1}	Inlet Static Pressure 1	PT	0-17	psia	
10	P_{t2}	Inlet Rake Total Pressure 2	PT	0-17	psia	
11	P_{t3}	Inlet Rake Total Pressure 3	PT	0-17	psia	
12	P_{s2}	Inlet Rake Total Pressure 2	PT	0-17	DEGF	
13	EGT_1	Exhaust Gas Temperature 1	TC	0-2500	DEGF	
14	EGT_2	Exhaust Gas Temperature 2	TC	0-2500	DEGF	
15	EGT_3	Exhaust Gas Temperature 3	TC	0-2500	DEGF	
16	EGT_4	Exhaust Gas Temperature 4	TC	0-2500	DEGF	
17	EGT_5	Exhaust Gas Temperature 5	TC	0-2500	DEGF	
18	EGT_6	Exhaust Gas Temperature 6	TC	0-2500	DEGF	
19	EGT_7	Exhaust Gas Temperature 7	TC	0-2500	DEGF	
20	EGT_8	Exhaust Gas Temperature 8	TC	0-2500	DEGF	
21	P_{te1}	Exhaust Total Pressure 1	PT	0-50	psig	
22	P_{te2}	Exhaust Total Pressure 2	PT	0-50	psig	
23	P_{te3}	Exhaust Total Pressure 3	PT	0-50	psig	
24	P_{te4}	Exhaust Total Pressure 4	PT	0-50	psig	
25	CDP	Compressor Discharge Press	PT	0-100	psig	
26	P_{ac}	Aft Compressor Pressure	PT	0-100	psig	
27	P_{adp}	Aft Diff Backplate Press	PT	0-100	psig	
28	P_{rc}	Rear Case Press	PT	0-25	psig	
29	T_{fb1}	Front Bearing Temperature 1	TC	0-300	DEGF	
30	T_{fb2}	Front Bearing Temperature 2	TC	0-300	DEGF	
31	T_{rb1}	Rear Bearing Temperature 1	TC	0-700	DEGF	
32	T_{rb2}	Rear Bearing Temperature 2	TC	0-700	DEGF	
33	CIT_1	Compressor Inlet Temperature 1	TC	0-200	DEGF	
34	CIT_2	Compressor Inlet Temperature 2	TC	0-200	DEGF	
35	T_{ftc1}	Fwd Turbine Cavity Temp 1	TC	0-1000	DEGF	
36	T_{ftc2}	Fwd Turbine Cavity Temp 2	TC	0-1000	DEGF	
37	T_{ac}	Aft Compressor Temperature	TC	0-500	DEGF	
38	T_f	Fuel Temp	TC	0-150	DEGF	
39	CDT_1	Compressor Disch Temp 1	TC	0-700	DEGF	
40	CDT_2	Compressor Disch Temp 2	TC	0-700	DEGF	
41	V_i	Inlet Vibration	AC	0-4	ips	

Table 4. List of Instrumentation

6.0 TEST FACILITY DESIGN CONSIDERATIONS

6.1 General Test Facility Requirements

Accurate, controlled testing of jet engines requires an installation where engines may be operated throughout their full thrust envelopes, under conditions simulating the operational environment and with sufficient instrumentation to assess their performance parameters. These installations, known as jet engine test facilities, have taken many forms ranging from fixed installations to portable facilities, and from altitude test facilities to ground (sea) level test facilities. Different designs and applications of turbojet engines along with large variations in size have resulted in many different designs of test facilities.

The altitude test facility mimics the complete altitude-Mach number envelope that a jet engine could experience in service. Almost all jet engine altitude test facilities have the engine installed in such a manner that the inlet air flows through ducting directly into the engine, while the whole assembly is mounted in a test chamber to maintain the appropriate altitude pressure. These facilities require meticulous attention to air flow-path design along with sophisticated instrumentation for total pressure and temperature measurements to prevent disturbance of the flow or distortion of the air pressure profile. When compared with ground level test facilities, altitude test facilities are substantially more expensive in both installation and operation. Despite the limitations of ground level facilities they still serve as cost effective tools during production, and research and development.

Ground-level test facilities are designed to operate under prevailing environmental conditions of pressure, temperature and humidity. These facilities can be sub-divided into two groups: the outdoor installed thrust stand and the indoor (enclosed) test cell. An important central issue to jet engine testing is the compromise which has to be reached between the need for accuracy of performance measurement and the need for a reliable test environment. An outdoor "free-field" test environment represents the ideal conditions to obtain true thrust measurements. In no-wind conditions the scale force measurement is a direct reading of the gross thrust at the given temperature and pressure, which means that measured thrust is equal to the "true" thrust of the engine. This benefit makes the outdoor test facility an attractive design for engines undergoing sea-level performance evaluations. However, the major limitation of these facilities is that they are subject to the ambient environment. Outdoor testing results are so strongly dependent on the weather, wind strength and direction, humidity, and precipitation, that these facilities are not practical when the goal is a stable, reliable and repeatable assessment of engine parameters. Another problem that is related to the use of outdoor facilities is the impact of the high noise level generated by turbojet engines. In outdoor facilities noise is not locked inside, requiring that such facilities be located far away from populated areas. Also, outdoor facilities are not suitable for operation in environmental conditions which are either very hot or very cold. As a result of the highlighted disadvantages of outdoor facilities, engine testing overall is moving to indoor facilities.

Indoors, a ground level facility test cell is designed as an enclosed area with an engine mounting structure intended to provide stable, repeatable and accurate engine performance testing conditions. To determine the actual performance characteristics of an engine during testing the interaction between the engine and the test cell must be specified. Comparative performance measurements were conducted by the Advisory Group for Aerospace Research and Development (AGARD), to investigate the similarities and the differences in turbine engine performance measurement capabilities at the various test facilities located within NATO countries. The results of these experiments, and similar experiences in other testing found that differences in critical engine parameters were noticeable, even for the same engine used as a transfer standard. It has been confirmed that each test cell has an individual effect on measured parameters which is denoted as the test cell correlation factor.

The most important parameter of a turbojet engine is the thrust value. However, the test cell environment has a significant influence on the measured thrust. Besides the thrust, other engine parameters also significantly depend on test cell characteristics. Usually the correlation factor has various levels for different parameters, but the determination of a correction factor is necessary to identify a reference engine and a reference test facility. When the same test facility is used to test a number of engines of different size, as with the PSTF, the problem is more complicated. The very large difference between the smallest (50 lb) and the largest (1,000 lb) engines requires separate design considerations for both extremes, especially as it relates to test cell aerodynamic performance and measurement systems.

The determination of the aerodynamic performance of a turbojet engine is a complex process. The configuration and accuracy of the instrumentation and many other features will influence the perceived performance of the engine. Factors which could have an influence on the perceived engine data are the test cell environment configuration, the methods of data acquisition and the correction of engine parameters. Depending on the type of test (i.e. production acceptance, developmental or research test), different standards and configurations of instrumentation, test procedures and analysis techniques may be required. Although it is highly desirable to install common instrumentation for the test facility which will satisfy the needs for different types of tests, caution should be used to recognize variations of measured engine parameters and types of engine operation which will be monitored. Three general classifications of engine conditions are often defined: steady state, transient and dynamic.

Steady state conditions correspond to the situation where the turbojet engine is running at a nominally fixed operating point and when engine parameters are stable with time. Even in such tests it must be recognized that the engine cannot be held at a constantly precise level throughout a set period of time and some moderate variations must be expected. These factors should be considered when designing the instrumentation and estimating the degree of measurement uncertainty within the engine test program. Typically engine test specifications allow time for stabilization of aerodynamics and structural temperature gradients at each point before the final measurements are recorded.

Transient conditions are those in which a relatively slow variation is induced during engine operation (i.e. engine acceleration), for which instrumentation capable of accurately quantifying the performance characteristics should be included. The instrumentation must be capable of detecting the boundaries of instability in turbojet engines, such as surge, rotating stall, etc. and changes in performance due to transient operation.

Dynamic measurements that characterize the variation of parameters at high frequency require an instantaneous point measurement or spectral behavior characteristic analysis to determine real processes. In particular, instrumentation which is not usually part of the standard test facilities is required for dynamic measurements.

The basic principle of any measurement is to minimize the disturbance of the measured parameters and eliminate any influence on the system under operation. In an engine test cell this problem can be a serious consideration. In particular, it is critical to minimize disturbance of the parameters and influence on the system in the fields of pressure and temperature measurement. For accuracy purposes it is necessary to verify the performance of all probes to ensure that they are of adequate strength to withstand all aerodynamic loads, including the extreme values which may occur during unsteady testing or high temperature conditions. It is also very important to verify the vibration characteristics of all probes to prevent conditions which could cause error or which are potentially hazardous. These issues are opposite to the air flow disturbance problem. The insertion of probes into the engine will certainly create a disturbance in the air stream, which could result in significant changes to the engine parameters. All measurements which could have an influence on the air flow distortion should be considered and appropriate instrumentation used to obtain reliable evaluations of jet engine performance. Distortion of air velocity and pressure need special consideration in cases involving test facilities for small turbojet engines. Small engines with narrow flow passages, unusual flow path configurations and high rotational speeds require instrumentation techniques which are appropriate to their size. In small engines the influence of the measuring probes on the measured flow is more substantial because of the proportional size of the probes to the air flow. The presence of measuring probes and pressure losses by instrumentation flow blockage directly degrade the performance of jet engines.

A measurement system is composed of many sub-systems (including sensors, scanning devices, power supplies, transducers, cabling, data acquisition and processing control), each interfacing with the next . The design of the measurement system depends on the type of testing to be carried out. For example, the requirement may be limited to steady-state testing or it may be extended to include transient conditions. In routine acceptance testing it is usually sufficient to limit testing to shaft speeds, fuel flow, thrust, tailpipe temperature, air inlet temperature and a few miscellaneous pressures and temperature. Development and research testing on the other hand demands more detailed measurements which can result in the recording of several hundred individual pressures and temperatures.

The design of measurement systems for ground-level test facilities must include detailed definitions of the elemental measurement systems (type, range and quality), with an analysis of measurement uncertainty for each part of the system. The first step in the estimation of uncertainty is to prepare a careful and complete description of the measurement process. This description must account for all of the basic measurement systems which will be used in the process; the test facilities, the test objectives, the sequence of the tests to be performed, and an analysis or math model which will be used to combine and interpret the basic measurements. As part of this analysis, calibration systems should be established as an important feature, to reduce the uncertainty of the engine parameter evaluations.

One of the most important parameters to be measured is thrust. The engine is mounted on a platform which is movable in the axial direction, but rigid in other directions. The load cell should be carefully designed to be accurate and sensitive to axial loads, yet have a very low sensitivity to off-axis loads. The thrust stand must provide very low hysteresis levels, in particular when the measured thrust is very low, as in the case of small turbojet engines. When the difference in thrust measurements is large the test cell design must consider the need to provide a separate thrust stand for small and large engines. A simple, precise, and reliable calibration system should also be provided.

Data from various sensors for all turbojet engine test facilities are collected through a data acquisition system. This computer-based system allows totally interactive, on-line, real time data acquisition and corrections. The major advantage of these systems is that they remove the "slow" operator response and allow the operator to remain directly involved with the system. Data acquisition techniques can affect engine performance measurements significantly. All segments of the data acquisition system should be carefully considered: low level analog signals, line length and quality, digital data transmission, signal conditioning, electrical noise, multiplexers and scanners, A/D converters, filters, interfaces, calibration, etc. Data reduction, processing, display and storage are also important parts of the data acquisition system. General requirements for the data acquisition system for turbojet engine test facilities can be summarized in a few basic features:

-Fast sampling at high accuracy
-Easy storing and processing
-Quick and simple application configuration
-Software and hardware portable across applications
-The number of input channels should be expandable to meet different requirements

All application software run on the data acquisition system must be calibrated and verified. To establish the real performance of jet engines the interaction between the engine and the test cell characteristics must be evaluated. The test cell influence factors are dependent upon the configuration of the test cell, particularly the primary and secondary inlets, augmentor tube and exhaust stack configurations. Airflow demand of the engine, total cell airflow, engine position in the test cell, ambient conditions and surrounding configurations are also important factors that could influence the performance evaluation of an engine. A modern ground-level test facility must have an inlet design which eliminates any possibility of the formation of flow distortion or vortex generation. Inlet type screen density and inlet baffles influence the flow uniformity, pressure and temperature distortions. Together with the exhaust system, the test cell inlets define the test cell bypass ratio. For very small sized test cells like the one currently being designed, the inlet and exhaust systems should be designed in such a manner that test cell performance is independent of outside wind direction and magnitude. Although the PSTF contains a small sized test cell, it must satisfy the primary requirement of correlating with the test cells of the engine producers. It must provide for only minor differences and variations in performance evaluations for small turbojet engines, the same level that currently exists in other facilities.

The fuel supply package, as part of the test facility, must be designed to deliver a stable supply of fuel to the engines under test conditions. The fuel system includes a fuel reservoir, a pump, a filtration package, and a control and measuring section. The system should consist of an assembly that contains all the interfaces between the engine and the facility's fuel supply. To eliminate the possibility of contamination of an engine and the sensitive components of the system, all plumbing must consist of stainless steel lines and fittings.

The test facility design requirements include considerations of fuel supply, different types of fuels and delivery pressure to the engine that could be required at different pressure levels. In particular, this can be required when very small engines are tested and when the fuel pump is not part of the engine but is already part of the auxiliary system. A drain should be included in the test cell that allows for draining of any discharge into a flammable waste-oil container.

A lubrication system is usually installed on turbojet engines as a self-contained system. In special cases some engines require an external system using an oil-mist supply from the test facility installation. This system should be designed to satisfy the engine's requirements.

An engine start system consists of many different possibilities for different engines. For small turbojet engines the starting system can be electrical, pyrotechnic, low air, or high air impingement pressure. Some engines use a hydrogen torch for ignition purposes in place of a pyrotechnic igniter. The test facility design must include all types of start systems to enable starting of any kind of engine that will be tested.

The test facility must consist of the necessary equipment to support the generators that could be installed on the engines. Also, loading systems should be designed to cover these cases. The generator loading system should be able to provide the loading to the engine at different steps according to the engine test specifications.

Electrical system requirements include the proper design of electrical lines and installation according to relevant standards for such facilities, and properly sized noise protected lines must be used. Special caution must be used for low level analog signals that are subject to other degrading influences such as system noise and interference between adjacent lines. Accuracy of the signal conditioning and conversion to digital format is critical for proper design of the test facility. The test facility must include a properly designed grounding network with low resistance connections between the modules of the PSTF. Grounding rods must be driven into the earth and tied to the grounding network to drain off static buildup resulting from high airflow through the facility. The frames of all major test cell electrical equipment should be connected to the grounding network.

An intercommunication system connecting the control console and the test cell should be provided. This system will be used for engine test preparation or during the actual testing when something needs to be done inside the test cell.

The test facility design requirements should also include a closed circuit television system (CCTV) to enable enhanced visual monitoring of engine tests.

Safe operation of the test facility is one of most important parts of the design requirements. Engine inlet protection from foreign objects must be provided by using a screen on the inlet side of the test cell. This solution will also be implemented to improve airflow distribution in the test cell plane upstream from the engine inlet. The test facility design must include a review and interlock system for each part of the system that could interfere with engine operation. Test cell protection is necessary to prevent access by unauthorized persons to the test cell during the operation of the engine.

The jet engine test facility environment is substantially impacted by the high noise levels generated by turbojet engines. Noise reduction in the surrounding environment is one of the primary objectives in the design of the test cell. Taking into account the attenuation of sound over distance the allowable noise level at a reference distance from the test facility should be calculated. These calculations will result in a determination of the noise insulation needed for the test cell walls, air intake and exhaust. The design of noise suppression for the jet engine test cells involves a compromise among design constraints related to the aero- and thermodynamic requirement (already mentioned), engine performance and operation, size of the test cell and the limitations of the materials used in construction.

Fire protection must be one of the fundamental questions that will be taken into account during the design phase of the test facility. From the equipment layout to an analysis of potential fire hazards, a proper fire protection plan and a test facility fire protection system must be carefully developed.

Another important part of the test facility design is related to providing and maintaining a comfortable space for the equipment and the operator, during changing environmental conditions.

6.2 Test Cell System Design Considerations

The turbojet engine test cell is a critical part of the test facility. During the past few years there has been considerable research into the aerodynamic phenomena inside and outside test cells. The research work has led to a greater understanding about the fundamental importance aerodynamics plays in the engine test cell. Together with the development of the large turbofan and turbojet engine many new improvements have been made to satisfy the required engine operational stability, aerodynamic requirements, and acceptable acoustic performance.

Previous research was conducted using numerical techniques for predicting the behavior of fluid flows inside a test cell. Several computer models have been developed that use conservation equations for mass, momentum and energy, reduced to their finite, nonlinear algebraic form. The earliest two-dimensional computer models were based on analyses of vorticity and stream functions. Pressure and velocity were then calculated after a convergent solution had been obtained. It was shown later that this technique has several serious disadvantages [11]:

-It results in large errors in predicted pressure distributions.

-It is restricted to areas with constant density flows.

-The boundary conditions are difficult to determine, particularly when the model needs to be extended to three dimensional flow.

To overcome these difficulties further investigation was directed towards developing new models based on pressure and velocity (p-v) as variables [11]. Adaptation of this model required the use of several approximations:

-The engine, by necessity, was positioned at the axis of symmetry, which is not usually the situation in actual test cells; thus, the results of the velocity distribution in the secondary flow (the flow around the engine) could be different from the predicted value.

-The actual test cell cross section is mostly rectangular, while the engine bellmouth, tailpipe and augmentor tube are cylindrical. The computer p-v model is based on the approximation which uses three concentric cylinders with cross-sectional areas equivalent to the physical cross section of the test cell.

-The engine was modeled as a cylinder with a diameter equal to the actual nozzle exhaust diameter.

Results achieved using the p-v model also demonstrated many difficulties and differences when compared with the actual data. Results depended on the level of air flow. At low flow rates the convergence was quite similar for both models. However, at higher flow rates the p-v model had better convergence than the vorticity and stream function models. In particular, the p-v model is a better predictor of pressure variations inside the test cell. Both the p-v model and the two-dimensional model, similar to a number of other models, require that the user be very knowledgeable and experienced in specifying boundary conditions for the various augmentor combinations.

Many other approaches were tried in determining the test cell aerodynamic performance characteristics using more advanced computational techniques. Kromer-Oehler and Dietrich [24] investigated the problem of test cell flow analysis using a combination technique. It was a developed method which allowed solutions for the front cell and test chamber areas, including the flow into engine bellmouth and around the engine and th st stand. Validation of this method is demonstrated by the experimental examinations obtained from Freuler and Dickman [2].

The most comprehensive investigation of the test cell aerodynamics was done by Karamanlis et al. [1]. They conducted a theoretical and experimental investigation of test cell aerodynamics, using a combination of several flow analyses to provide the flow function distribution and to determine the preliminary performance of the exhaust system. To determine the test cell flow requirements for some engines a one-dimensional ejector analysis was developed. This analysis was based on a compressible, steady, uniform and isentropic flow, which is an ideally mixed condition for the engine and the secondary flow of the test cell, assuming either constant area or constant pressure mixing. Using this model the test cell incoming flows and the exit flow can be specified in both subsonic and supersonic cases.

Using the results from that analysis as the first step of the complex aerodynamic performance assessment, Karamanlis developed a two-dimensional, axisymmetric flow-field analysis. This analysis gives a inviscid flow solution for the test cell chamber area and collector pipe entrance area. By using Navier-Stokes equations it is possible to determine the flow field. Further, by using the STC (stream tube curvature) analysis an evaluation can be made concerning the mixing problem in the exhaust collector pipe. The results presented in reference [1] confirm that this analysis is able to be used in providing a measurement of the test cell flow field properties such as pressure, temperature and velocity of the two interacting flow streams through the augmentor tube. An experimental validation of these theoretical investigations confirmed that there is a strong correlation, and it also proved that this model could be used as a first step in aerodynamic performance assessment.

As mentioned above, using mathematical models to determine test cell aerodynamic performance characteristics resulted in limited success, requiring the use of some additional tools for more reliable and more accurate predictions. One of the most useful supplemental tools for determining pressure and flow distributions and for investigating the interaction between the test cell and the engine characteristic is scale model testing. When the scale model is developed and approved with full-scale test cell results it can be used successfully to determine the aerodynamic performance characteristics.

Model testing is a powerful tool for predicting the air flow in full-sized test cells and for studying the air flow characteristics in a test cell. Using scale model test methodology it is possible to determine test cell performance, either for new test cell design purposes or for modifications of existing cells. This technique is useful for determining the test cell envelope for different sized engines and for assessing the capability of the test cell in future engine testing. In combination with flow visualization techniques, it is possible to illuminate flow patterns.

A number of scale model engine test cell investigations were conducted to improve the performance of the existing test cell and to recommend clearly defined modifications. The results of the research were announced by Freuler [8,9] and Karamanlis [1,12], and were confirmed by full-scale tests after modification. These investigations demonstrated the impact of the various components on the test cell aerodynamics. Acceptable test cell aerodynamic performance boundaries have been determined by flow visualization techniques, and by the measurement data recorded by transducers located at different points in the test cell. A very important achievement of scale model testing is that the results of the investigation produce an extensive database and library for different test cells and engines. These results can be transferred to the other test cells to provide a baseline for problems connected with aerodynamic performance.

A number of comparisons have been made between scale model testing and full-scale investigation [1,8,9]. Data gathered during these comparisons, has shown that there are some differences between the two techniques. The most important differences found are in the front cell airflow indication and in the test cell bypass ratio. The front cell airflow in the full-scale test was 14.5 to 16.5 percent higher than the measured airflow in the model test [9].

To explain the differences between the model and the full-scale test cell, a number of possible influences need to be considered. The effects which have been investigated and often suggested are stipulated below:

-Velocity measurement and instrumentation.

-Difference between the model and full-scale exhaust temperatures.

-The exhaust plane thrust measurement, of the engine simulator.

-Total pressure loss in the test cell exhaust system.

-The design and implementation of the engine simulator

Through dedicated research work each of the mentioned phenomena has been examined. It has been confirmed that even hot wire instrumentation can be subject to a variety of errors, and that disagreements in data are not a result of velocity measurement problems. A similar conclusion was reached explaining the differences in exhaust temperature between the model and the full-scale test cell, but the research has not found a significant effect on pumping performance. It is indicated that there are minor differences in the measured thrust, caused by the calibration problems and "free-field" phenomena. The total pressure losses in the test cell exhaust system, as was described previously, have a significant impact on test cell pumping performance. It has been determined that the simulator exhaust airflow rate is more critical than the exhaust loss predictions. To improve scale model techniques it is necessary to make corrections in the prediction methodology of the exhaust airflow and to reduce discrepancies between the two comparative results.

Research has confirmed that there is no established methodology for assessing the aerodynamic performance of the turbojet engine test cell. Rather than deriving conclusions about any singular method of approaching the problem, investigations have clearly demonstrated that predicting test cell aerodynamics is a several step process. Each of the test cell designs must consider many factors which influence the aerodynamic performance of the test cell. Using a combination of analytical tools, scale model techniques and results, and experience and recommendations gained from developing the test cell, it is possible to produce a test cell design with good aerodynamic performance.

The major structural elements of the engine test cell are the inlet plenum, the test chamber, the augmentor tube and the exhaust stack which are shown in Figure 2. Depending on the design of the test cell, many different arrangements can be devised. Precise guidelines must be provided for the design of each part of the test cell structure.

The preceding discussion of design considerations and methods has been presented to provide a background and understanding of the issues which must be considered in the design of test facilities. Although the issues discussed are derived from research and practices appropriate to larger engines, the principles outlined apply directly to the design of the PSTF. Further detailed discussion of these design principles is available in SAE publication AIR 4869. The SAE document is an excellent guideline for test cell design. It has been confirmed that engine test cells conforming with the requirements of AIR 4869 achieve stable engine operation within +/- 5 rpm. A preliminary calculation demonstrates that the procedures outlined in the document will yield a design suitable for engines to be tested in the PSTF. This is particulary important in cases when scale model testing cannot be implemented in the development phase.

6.2.1 Inlet Plenum

The primary function of the inlet plenum is to supply the proper quantity and quality of airflow to the engine test chamber. Airflow must be uniform and stable at all engine operating conditions. At the same time, the inlet plenum provides noise control (attenuation) and thereby ensures compliance of the test facility with environmental noise regulations.

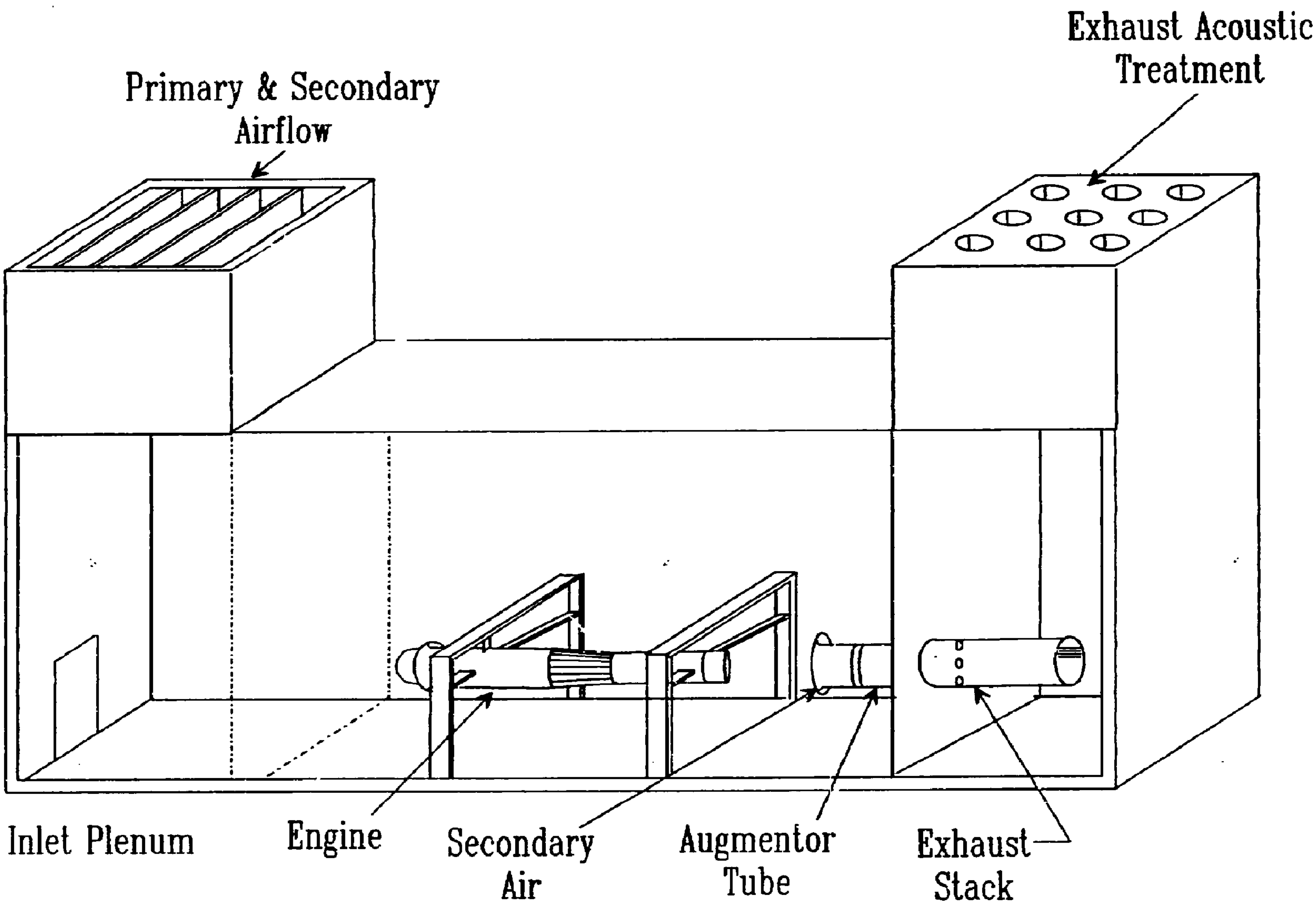


Figure 2: Schematic of Typical Turbojet Test Cell

The inlet plenum can be arranged in different ways. The air inlet may be horizontal, vertical or combined (horizontal & vertical) air path. The inlet plenum may provide the total amount of airflow to the test cell, primarily for the engine air flow and secondarily for the airflow around the engine. In some cases the secondary airflow could be jointly supplied by the inlet plenum and an additional air inlet on the rear side of the test cell. Turning vanes may be installed in the inlet plenum to reduce aerodynamic loss and air stream distortion.

The inlet plenum can be considered as an interface between the engine, or the test chamber, and the outside environment. The inlet plenum must attenuate the noise produced by the engine and keep the test chamber and the engine at a reasonable noise level. The main design criteria for controlling the noise level are the test cell location, the duration of the test and factors dealing with the acoustical design (see section 6.3.5). The inlet plenum must also ensure that the test cell and engine are isolated from the surrounding environment and protected from the influence of wind strength and direction, humidity, and precipitation. As part of the inlet plenum the inlet screen is used to protect the test chamber from foreign objects and to provide some improvement of the pressure distribution.

The design of the inlet plenum for an engine test cell requires a compromise among constraints (related to engine performance), stable operation and the limitations on the inlet plenum size and the materials used for its construction. As a result of different constraints the solution for some applications is not acceptable for other situations. It is recognized that even when engines of similar types are tested, a wide variety of solutions can be expected for the test cell and accordingly the inlet plenum. Regardless of the complexity of testing a common feature of all solutions must be that data recorded at a facility be comparable to the reference test facility. This fundamental requirement allows only a narrow "window" for the inlet plenum design criteria. A description of the most significant influences of the inlet plenum on the test cell performance are presented in section 6.3.

6.2.2 Test Chamber

The test chamber is the part of the test cell that includes the engine thrust stand, which is attached directly to the test cell superstructure. Some support packages such as the air start system, the fuel installation, measurement system, and the fire protection system are integrated into the test chamber. While the test cell inlet and outlet configurations may vary from one facility to another the test chambers tend to be similar in design. This tendency towards similarity does not belittle the need for meticulous attention during the design of the test chamber. The design must eliminate or at least minimize any projections into the flow field, particularly those that affect the portion of the air flow which enters the engine bellmouth. These projections can cause wakes and distortions in the bellmouth and the first stages of the engine compressor, which could result in unstable engine operation. To assess engine performance accurately, engine speed variations must be eliminated.

Air flow along the test chamber is characterized by a rapid acceleration as it approaches the engine bellmouth, because the flow captured by the engine has a cross-sectional area larger than the engine itself. To ensure that air is not recirculating by the engine the test chamber design must provide a significant amount of secondary air to eliminate the formation of a vortex [10]. The point where secondary air separates from the engine intake flow is a function of the test cell bypass ratio as well as the ratio of bellmouth area to cell cross-section. For high bypass ratios, it is possible for the flow separation point to occur downstream of the bellmouth, forcing the intake air to reverse direction. This phenomenon should be avoided to assure uniform inlet flow.

To minimize the reingestion and recirculation of air the test cell design must provide for a sufficient bypass flow rate. A compromise must be found between the bypass flow rate and the test cell size, particularly when all sections of the test cell must be small in physical size. This is one of the basic requirement in developing the PSTF. In these situations, any projections into the airflow of the test chamber, such as frames, piping, lighting fixtures and other equipment, may induce the formation of the vortices which could be transferred into the engine. Even the thrust stand structure should be designed with the measurement characteristics and aerodynamic performance in mind.

6.2.3 Test Cell Exhaust System

The hot gases ejected by the engine must be extracted from the test cell without reingestion and recirculation. The exhaust gases exiting the engine are characterized by high temperature and velocity and produce a large radiating noise level. Engine exhaust gases must be captured and transferred outside the test cell.

A major concern in the design of a test cell exhaust system is the selection of components in such a way which satisfies the necessary acoustic and aerodynamic requirements. The design of the exhaust system has a great influence on the engine performance. The exhaust system controls many functions such as the amount of secondary airflow through the test chamber, back pressure on the engine tailpipe, and the sound absorption and pollution of the exhaust gases.

Depending on the purpose of the test facility the test cell exhaust system can be designed in many different ways. Basically, the test cell exhaust system contains two sections, the augmentor/diffuser and the exhaust stack, which are shown in Figure 2 . In some instances both of the exhaust sections are integrated in a combined configuration, which is particularly true of portable test facilities.

The primary purpose of the augmentor tube is to capture the engine exhaust gases and induce secondary airflow through the test cell. The augmentor tube operates in combination with the engine exhaust momentum as the ejector ingests cool secondary air from the surrounding test cell environment. The effectiveness of this pumping is influenced by a number of factors including the engine nozzle/augmentor diameter ratio, the distance between the engine nozzle and augmentor entrance plane, the pressure losses in the exhaust system, the length of the augmentor and the engine exhaust temperature. Secondary air is crucial for cooling external sections of the jet engine and for reducing the mixed gas temperature inside the augmentor. Small amounts of secondary air will allow reingestion and recirculation of the exhaust gases, which can produce pressure distortion and unstable engine operation. Too much secondary air causes excessive static pressure gradient between the engine bellmouth and tail pipe, which results in a deviation of the measured thrust of the engine. For test cells that will be used for testing different sized jet engines, adjustment of the secondary airflow rate is not simple. The analytical procedure includes many variables and the resulting data are not applicable without corrections.

One of the most important factors influencing the augmentor performance is the length of the augmentor tube. It has been confirmed that the ratio of length to diameter (L/D) of the augmentor is critical to attaining good acoustical and aerodynamic performance. It is recommended that the L/D ratio for proper design should be 4.0 or greater. If the ratio for some other reason must be reduced, the actual entrained secondary air and mixing of gases will be significantly weaker.

Depending on the test cell configuration there are many designs for the augmentor tube. Experimental investigations done by Sapp [28] demonstrated that the inlet portion of the augmentor tube performed better if bellmouth or conical type augmentor inlets are used. These inlets were found to be the most efficient pumping designs. It is interesting that for both of these augmentor inlets the performance was virtually identical, and the more expensive bellmouth configuration was not justified.

A straight augmentor tube, without an inlet section, showed a reduction in performance, which can be explained as a consequence of the airflow spilling over the edge of the tube. This spilling over forms a region of flow separation that increases the loss at the inlet side of the augmentor. Similarly, weaker results are achieved when reverse conical and flat plate inlets are used, because the inlet area is reduced.

The distance between the engine nozzle and augmentor tube has little influence on the secondary airflow. Investigations conducted by this principal investigator for the VIPER 632 engine [15] confirmed that changes in distance between the augmentor tube and the engine nozzle by more than three nozzle diameters did not visibly influence the performance of the engine.

Changes in distance influenced the secondary air flow very slightly and these changes were characterized as being oscillatory in nature, which was also confirmed by Sapp [28]. The influence of the distance between the augmentor tube and nozzle is more substantial in the static pressure field at the engine nozzle exit. A larger distance between the augmentor tube and the nozzle also cause an increase in noise level within the test cell because the noise radiation path from the jet stream is larger in volume.

An important part of the exhaust system design is clarifying the mode of operation in the test cell. In previous investigations [15, 28] it was discovered that the secondary airflow rate and the bypass ratio for the same augmentor tube both depend on engine airflow. Even for the same engine at different speeds the bypass ratio changes as a function of the engine speed and airflow. For a larger engine airflow the test cell bypass ratio decreases. Besides influencing the bypass ratio the secondary airflow is also a function of the engine exhaust temperature. The bypass ratio varies approximately by the square root of the ratio of the total exhaust temperature to the total ambient temperature. This is clear confirmation that the exhaust system must be designed to handle the largest engines operating at their maximum power. For smaller engines the bypass ratio will be several times greater than that of the largest engine. That indication is not critical because it will not result in pressure and velocity distortions at the front plane of the engine bellmouth. Some experiments have been carried out [15] to try and reduce the bypass ratio for smaller engines by trimming the augmentor tube with varying orifices. The results achieved did not suggest that the different sized orifices should be used.

To improve the performance of the exhaust system, the augmentor tube should have a constant diameter, or some careful diffusion of the augmentor tube can be included. The choice between a constant diameter augmentor and an augmentor/diffuser combination becomes more important when the test facility is used for a wide variety of engines. The main goal in designing the diffuser section is to ensure high pumping efficiency while avoiding flow separations. Recent research has confirmed that diffusers with diffusion angles up to 3° or 4° perform better than those used in the past with angle values of 6° or 7° [12].

The exhaust stack is provided as part of the exhaust system for larger test cells. The purpose of the exhaust stack is to direct the hot exhaust gases away from ground level. The exhaust stack also reduces the noise level outside of the test cell. The combination of the flow-redistribution device and the acoustic silencer package control the noise level within the stack, and keeps the noise level outside the test cell at an acceptable level. For smaller test cells, the augmentor/diffuser and the exhaust stack can be integrated. In any case, one of the design criteria that must be satisfied is that the maximum velocity of the exit gases must be limited to reduce self-generated noise produced by the exit gas stream.

6.3 Factors for Evaluating Test Cell Performance

In testing jet engines a variety of performance parameters must be measured. These most often include:

- Engine thrust
- Engine fuel flow
- Engine temperatures
- Engine vibrations
- Engine speeds
- Engine pressures

-Engine airflow
-Engine inlet conditions
-Engine power extraction
-Test cell temperatures
-Test cell pressures
-Test cell airflow

In a previous section, design requirements were considered for different parts of the test cell and the influence of the design on the stability of the engines during operation in the test cell was explained. Some of the most important factors for evaluating test cell performance will be presented in the following sections.

6.3.1 Test Cell Aerodynamic Thrust Performance

The most important part of engine parameter evaluation is the engine thrust. For jet engines the thrust is defined as the increase in momentum of the air passing through the engine during operation. Under stable conditions, as in the static test facility, the engine spends some amount of energy accelerating the air from outside, pulling it towards the inlet, and bypassing some of it around the thrust stand. For different test cell configurations the amount of energy required depends on the aerodynamic interference between the engine and the test cell. The need for aerodynamic thrust corrections cannot be ignored even in a well-designed test cell. To establish the thrust of the engine an evaluation must be made of the aerodynamic interference.

The aerodynamic thrust corrections must be applied to the measured thrust to determine the gross thrust of the jet engine. An explanation of the nature of the corrections and a quantification of each of the aerodynamic factors was given, in a more precise way, by MacLeod [10].

The standard gross thrust can be considered the stream force at the engine nozzle plane, which can be expressed as

$$F_g = W_e V_e + A_e(P_e - P_a) \qquad (1)$$

where

F_g – engine gross thrust
W_e – nozzle exit airflow
V_e – nozzle exit velocity
A_e – nozzle exit area
P_e – nozzle exit static pressure
P_a – ambient static pressure

It is typical to incorporate a strain gauge load cell into the thrust stand design as part of the thrust measurement system. At an outdoor test facility under "ideal" no-wind conditions a jet engine operates in a uniform static pressure field. Under these conditions the pressure in the plane of the nozzle exit is the same as the pressure surrounding the engine. In this situation, the measured thrust at the load cell is equal to the engine gross thrust.

In an indoor facility the exhaust collector is generally placed in close proximity to the nozzle exit, creating an ejector effect and thereby inducing secondary air flow through the test cell. This can result in significant differences between the scale force reading and the amount of gross engine thrust. To aid in the understanding of the physical phenomena inside the indoor test cell the model of this cell (shown in Figure 3) was used [10].

The differences between the scale force reading and engine gross thrust level is equivalent to the force required to sustain the air flow from the outside and throughout the test cell. A summary of the analytical derivations [10] describes the gross engine thrust behavior inside indoor test cells as:

$$F_g = F_m + F_{im} + F_b + F_{bt} + F_{tf} + F_f - F_{fw} \qquad (2)$$

where F_g represents the gross engine thrust in this equation. The seven terms referred to are

- F_m - measured thrust
- F_{im} - intrinsic inlet momentum
- F_b - bypass pressure drag
- F_{bt} - boattail drag
- F_{tf} - thrust frame drag
- F_f- - skin friction drag
- F_{fw} - wall friction drag

Measured thrust (F_m) is defined as the reading of the engine thrust vector from the thrust measurement system. The measuring system should be designed to minimize the possibility of errors from hysteresis, thermal radiation from the engine exhaust, nonlinearity and nonrepeatibility.

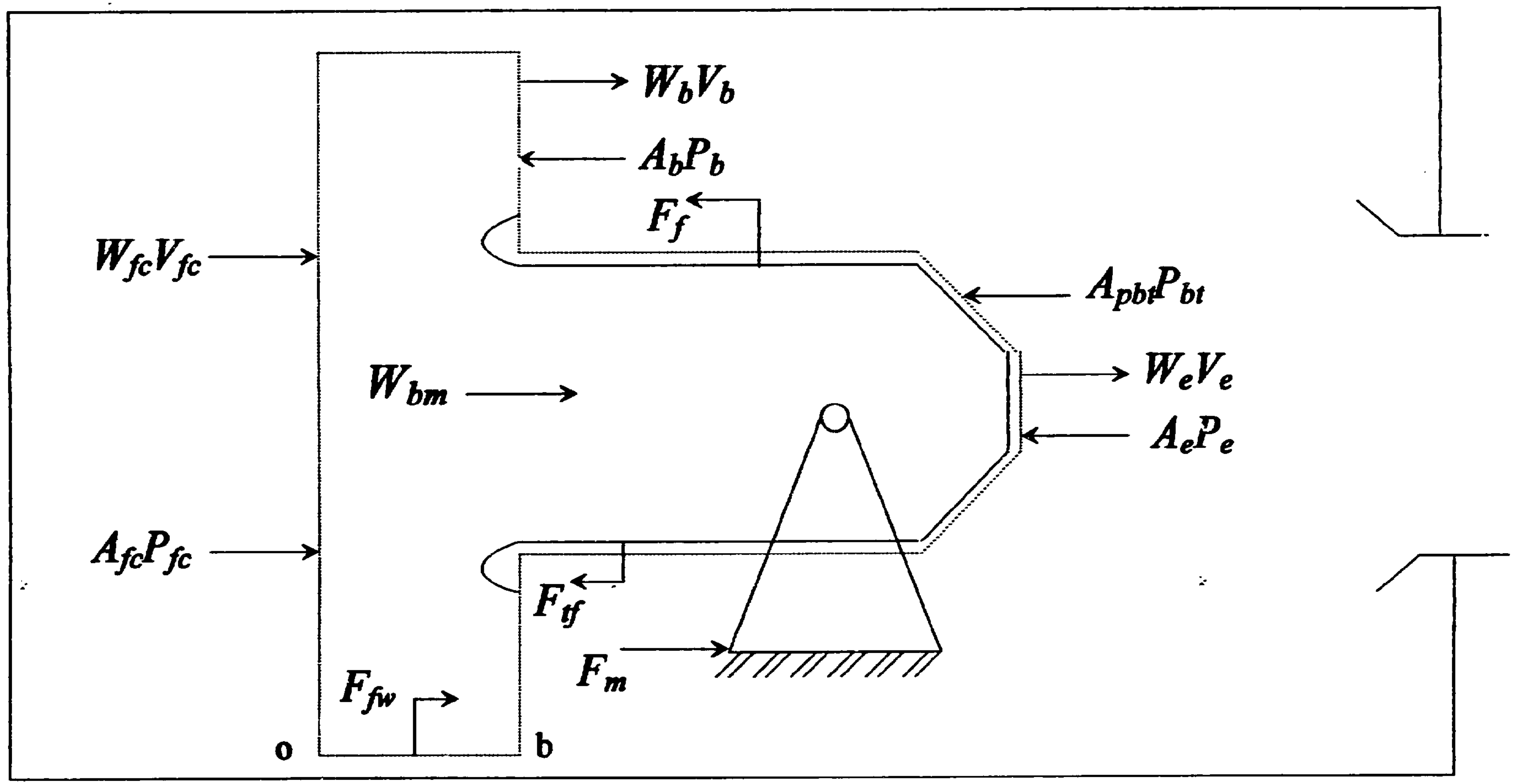


Figure 3: Engine and Test Cell Arrangement

The most significant aerodynamic thrust correction is the inlet momentum drag (F_{im}), which applies a force on the engine as a result of drawing air into test cell. This force is characterized as a drag because engine work is involved in drawing air inside the test cell. The inlet momentum function can be calculated as:

$$F_{im} = \left[1 - \left(\frac{\alpha}{\alpha + 1}\right)^2 \frac{A_{fc}}{A_b}\right] W_{fc} V_{fc} \tag{3}$$

where

α	-test cell bypass ratio
A_{fc}	-test cell area
A_b	-bypass area
W_{fc}	-test cell front mass flow
V_{fc}	-test cell front section velocity
W_b	-bypass or secondary air mass flow

From equation 3 it can be concluded that the inlet momentum is a function of the engine air flow, air velocity (in front of the engine) and secondary air flow. For static engine testing the magnitude of this force may be substantial. Inlet momentum drag values can be expected from 1% to 10% of the measured thrust, and therefore it must be calculated and applied as a correction to measured thrust.

The boattail drag (F_{bt}) is a result of the static pressure drop around the engine exit nozzle. As a result, the secondary airflow accelerates along the external surface of the nozzle and into the augmentor tube. The magnitude of this thrust may be calculated using the equation:

$$F_{bt} = (P_{fc} - P_{bt}) A_{pbt} \tag{4}$$

where

P_{fc}	-static pressure in front of plane of engine
P_{bt}	-average external nozzle pressure
A_{pbt}	-projected boattail area

The boattail drag is the second largest correction term and can be expected to be less than 1% of the scale force measurement. The amount of drag depends a great deal on the test cell exhaust system arrangement.

The bypass pressure drag F_b can be calculated as

$$F_b = (P_{fc} - P_b) A_b \tag{5}$$

where

P_b -static pressure at plane b

A_b -bypass area

As a result of the rapidly changing airflow profile the pressure drop (P_b) immediately behind the bellmouth will produce the force drag (F_b). This is a function of the bypass ratio and the relative size of the jet engine to the test cell cross section size.

The thrust frame drag is produced by the secondary air stream impinging on the thrust stand and pushing it in the direction of the stream. If the thrust stand is streamlined the thrust stand drag will be minimized.

The skin friction drag and the wall friction drag terms describe the action of the bypass airflow as it scrubs the exposed surface of the engine casing and the test cell walls. These two forces are very small and do not need to be considered in the design of the test cell.

Analysis of the most significant aerodynamic components of the thrust measurement confirm that the test cell performance evaluation must include calculations of the expected aerodynamic thrust drag. This drag, along with other features, define the test cell's characteristics and its ability to properly evaluate the performance of jet engines.

6.3.2 Front Cell Velocity Distortion

The front cell velocity distortion factor is used as a general indication of the test cell airflow uniformity and quantity. To define this factor it is necessary to provide a grid velocity measurement in the test cell plane for the front of the engine bellmouth. It is recommended [7] that a minimum grid spacing matrix of 5 x 5 measurement locations, or a total of 25 points located at the centers of equal areas be used. The velocity measurement plane should be located between three or four bellmouth throat diameters in front of the bellmouth entrance plane. A selected plane must be far enough away from any silencer baffles or flow-straightening screen.

The velocity distortion parameter is defined by the equation:

$$FC_{dist} = \frac{V_{max} - V_{min}}{V_{avg}} \tag{6}$$

where

FC_{dist} -front cell velocity distortion factor

V_{max} -maximum velocity anywhere in the velocity measurement grid

V_{min} -minimum velocity anywhere in the velocity measurement grid

V_{avg} -average front cell velocity

For this purpose, the velocity measurements are usually taken using an array of hot anemometry probes in combination with a traversing system. In some cases a Laser Doppler anemometry (LDA) system can be used.

6.3.3 Front Cell Airflow

The front cell airflow defines the quantity of air flowing through the front section of the test cell. If the test cell does not include an additional air inlet the front cell airflow will represent the total airflow entering the test cell. The front cell airflow can be determined using data from the velocity measurements.

The front cell airflow can be calculated using the equation:

$$W_{fc} = \frac{P_{fc}}{T_{fc} R} V_{fc} A_{fc} C_{dfc} g \qquad (7)$$

where

W_{fc}	-front cell airflow rate
P_{fc}	-front cell static pressure
T_{fc}	-front cell static air temperature
V_{fc}	-average front cell velocity
A_{fc}	-front cell cross-sectional area
C_{dfc}	-front cell flow coefficient
R	-gas constant for air
g	-gravitational constant

The flow coefficient is used to correct the test cell physical cross section and to define the equivalent flow area. The value of this coefficient is slightly less than unity because at the same cross section border the airflow can be very small.

6.3.4 Bellmouth Total Pressure Distortion

The engine bellmouth steady state total pressure distortion index is a distortion parameter used to identify the relative size of the engine inlet airflow field at the engine bellmouth plane. To investigate pressure distortion a combination of the distortion-descriptor elements is used. The elements should be located close to the engine-face plane, but at the same time installation of the instruments must not effect engine performance and stability. Detailed considerations of inlet pressure distortion and recommendations for investigation of these phenomena are presented in documents ARP 1419 and 1420 [29,14].

The bellmouth total pressure distortion is defined as follows:

$$BM_{dist} = \frac{P_{max} - P_{min}}{P_{avg}} \quad (8)$$

where

BM_{dist} -bellmouth pressure distortion index
P_{max} -maximum inlet total pressure
P_{min} -minimum inlet total pressure
P_{avg} -average inlet total pressure

A typical array for measuring inlet pressure distortion consists of eight equiangularly spaced rakes with five probes per rake, as shown in Figure 4. The rake size and the diameter of the probes should be carefully selected when investigating pressure distortion in small jet engines.

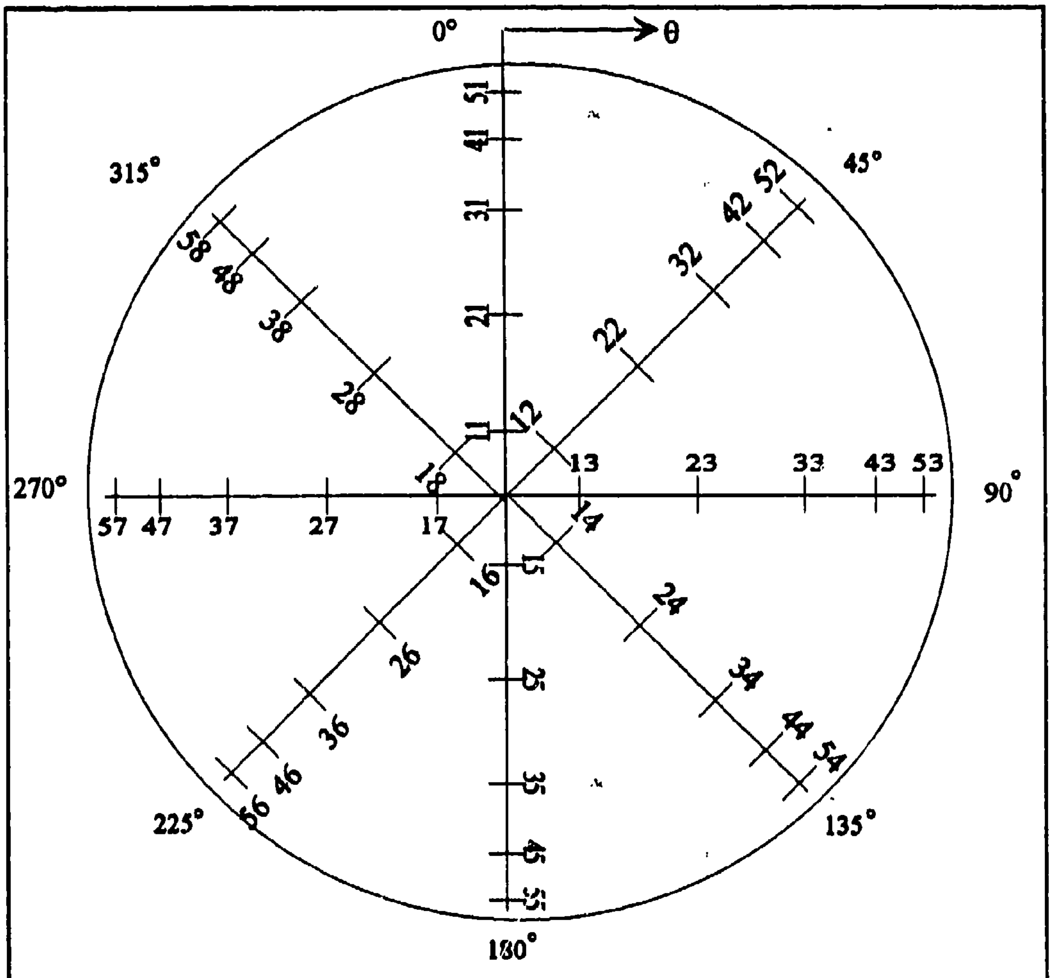


Figure 4: Probe Orientation - View Looking Forward

6.3.5 Bellmouth Airflow

The engine bellmouth airflow represents the amount of air flowing through the engine inlet. It can be defined using the equation [9]:

$$W_{bm} = W_{ff} \frac{P_t A_{bm}}{\sqrt{T}} C_{dbm} \qquad (9)$$

where

W_{bm}	-bellmouth airflow rate
W_{ff}	-flow function term
P_t	-bellmouth average total pressure
T_t	-bellmouth total temperature
A_{bm}	-bellmouth cross-section area
C_{dbm}	-bellmouth flow coefficient

6.3.6 Test Cell Bypass Ratio

As was mentioned in previous statements, the secondary airflow passing around the engine bellmouth defines the aerodynamic characteristics of a test cell. The secondary air, together with inlet pressure and velocity distortions determines the stability of the test cell and the quality of the engine performance evaluations at the test facility.

The test cell bypass ratio is defined as the ratio of the secondary air flow to the air flowing through the engine inlet and can be calculated using the equation:

$$\alpha = \frac{W_{fc} - W_{bm}}{W_{bm}} \qquad (10)$$

where

α	-test cell bypass ratio
W_{fc}	-front cell airflow
W_{bm}	-bellmouth or engine airflow

For calculation purposes the engine airflow (W_{bm}), derived from the engine specifications, can be used as the maximum value for engine airflow. When a test cell is used for testing varying types of engines it will supply different values for coefficient α.

To investigate the stability of the test cell during engine testing the test cell bypass ratio and the velocity distortion are analyzed in reference [2]; the results are presented in Figures 5 and 6.

Figure 6 shows lines of constant velocity in a test cell in m/sec (see reference [2]). Investigations have shown that vortices do not form in square cross-section test cells when the test cell bypass ratio is greater than 0.80. These results are achieved in the front cell with a velocity distortion of around 30%. At higher distortion values vortex formation should be expected and the test cell bypass ratio must be increased.

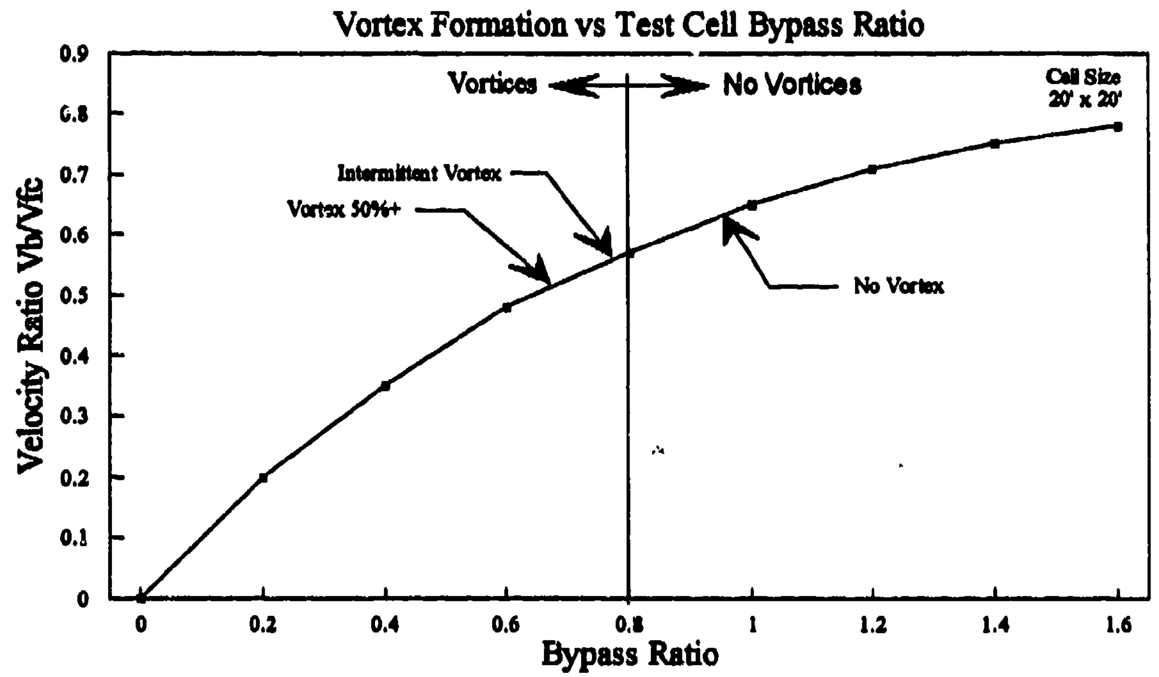


Figure 5: Vortex Formation as a Function of Test Cell Bypass Ratio

6.3.7 Test Cell Depression

As a result of air acceleration and inlet losses during the operation of jet engines the static pressure inside the test cell will be sub-ambient. As described in 6.3.1, the static pressure is different at different test cell locations. Barometric pressure is an important inlet parameter for correctly calculating the performance data of jet engines. This pressure can be measured outside the test cell or inside when the engine is stopped.

The static pressure inside the test cell, particularly in the front cell, is also very important. It determines the inlet barometric conditions for an engine being tested, which must be known in order to calculate correct engine parameters.

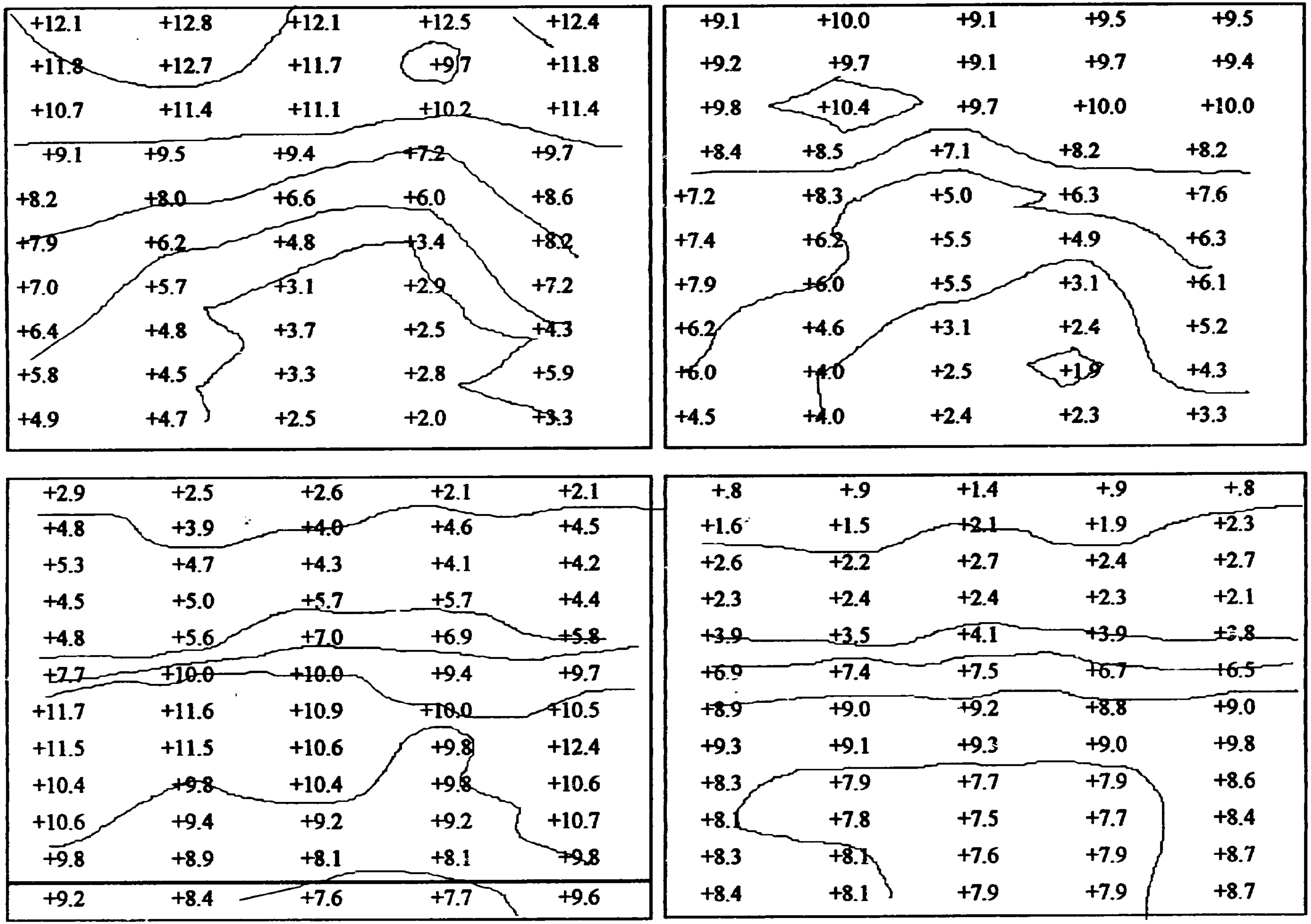


Figure 6: Test Cell Velocity Distortion

The difference between the barometric pressure and the static pressure in the front cell is denoted as the test cell depression:

$$\text{Cell Depression} = P_a - P_{fc} \qquad (11)$$

where

P_a -ambient (barometric) static pressure

P_{fc} -front cell static pressure

Test cell depression is directly related to the aerodynamic performance of the test cell. The test cell must be designed to withstand the forces produced by the lower pressure inside. This is particularly critical for the PSTF because of its relatively light construction.

5.3.8 Acoustic Performance Requirements

During operation in the test cell a turbojet engine produces a high acoustic noise level. The acoustic power level of a jet engine depends on the type of engine and the conditions it operates under. Even when operating a small engine inside the test cell the acoustic power level can be very high. In any case, the design of the test cell must include acoustic performance.

The acoustic energy generated inside the test cell is transmitted through the walls, doors, and the intake and exhaust channels. The sound intensity at a given point is the sum of the sound intensities that penetrate through different segments of the test cell. The amount of acoustical treatment that needs to be provided for each segment has to be determined through analysis. Ideally, an acoustically balanced solution is one where each sound propagation path, outside of the test cell, delivers the same amount of noise to the receiver. This is the most economical solution but difficult to implement. Even if a jet engine inside the test cell could approximate as a monopole noise source the transfer function of the individual cell sections (walls, door, intake and exhaust), would demonstrate different frequency characteristics. It is clear that if even one of the test cell sections does not satisfy the noise criteria all of the money spent on the other treatments is wasted. This is because at a single point in the multi-directional noise path, the maximum perceived noise depends on the maximum power level of any of the individual noise paths.

For solid structure test cells customarily used in stationary test facilities the most critical noise paths are the test cell intake and exhaust openings. In designing a portable test facility each part of the test cell must be acoustically balanced.

The acoustic power level (PWL) radiating from the jet engine strongly increases as the exhaust gas velocity intensifies. The acoustic power (W_a) is approximately proportional to the nozzle exhaust area (A_e) and the jet velocity (V_e) raised to the eighth power [30].

$$W_a = k_1 A_e (V_e)^8 \qquad (12)$$

Using the gross thrust function (F_g) the acoustic power can be expressed as

$$W_a = k_2 F_g (V_e)^6 \qquad (13)$$

It is not practical to express noise power in watts so a level scale is normally used. The fundamental purpose of a level scale is to relate power, intensity or energy density to a logarithm ratio of that quantity to a reference amount. The logarithm argument is dimensionless and the scale is said to give the level in decibels (dB) above or below the reference level that is determined by the reference quantity.

Sound power level is defined as

$$L_w = 10\log_{10}\frac{W_a}{W_{a0}} \qquad (14)$$

where

$$W_{a0} = 10^{-12} \text{ Watts} \quad \text{-reference sound power} \qquad (15)$$

W_a -sound power

Acoustic energy radiates from the volume surrounding the engine and leads to a sound intensity I in $\frac{\text{W}}{\text{m}^2}$ at a distance r from the source.

The sound pressure level is defined as

$$L_p = 20\log\frac{P}{P_0} \qquad (16)$$

where

$$P_0 = 2x10^{-5}\frac{N}{m^2} \quad or \quad 29x10^{-9}\frac{lb}{in^2} \qquad (17)$$

The sound pressure drops by the inverse-square-law $(-10\log 4\pi r^2)$, from the noise source which must be taken into account. For calculation purposes the noise level readings must be taken at the same distance from the facility. Inside the closed area, similar to the indoor test cell, the sound waves are partially reflected by the walls and propagate through the intake and exhaust openings.

The sound energy and pressure are also characterized by a frequency spectrum. To provide an acoustically treated test cell it is necessary to determine the maximum noise spectrum which the engine can generate. This noise spectrum is the primary basis of the acoustical design. Sometimes this data is not available because the noise measurements have to be taken under special environmental conditions, which are often absent. An analytical prediction of the noise level can be made [31]; however, the differences between the theoretical and real data can be significant. This error is the result of the influence of the different compressor designs, engine speed ranges and other engine characteristics which are not included in the prediction method.

If the maximum engine generated noise spectrum and directivity of propagations are known the maximum allowable noise level around the test cell must be defined. The human ear is not equally sensitive to all sound frequencies in the hearing range 20 Hz and 16 KHz, so the objective sound pressure level (L_p) is not a good measure of noise level. Scale A is included in the sound measuring instrumentation to aid in calculating the sound level for human ear reception. The frequency response of the meter is corrected throughout the frequency range using an electrical weighting network. An octave-band filter with a standardized center frequency is most often used. The reading from those instruments is the subjective noise level in dBA.

One of the most important decisions that has to be made during the development of a test facility is the maximum noise level allowed in the zone around it. For stationary facilities the zone normally would not be defined as a circle. In some directions better attenuation can be required, where the noise could disturb working and living conditions. Due to the flexibility of installation (anywhere in any direction), acoustical protection should be provided for the total circumference of the circle zone around a portable test facility.

The next question is [illegible]e distance required to meet the noise criteria. In the existing literature, different [illegible]ecommended for the circle zone, from 150 to 750 feet. The greatest distances [illegible] [illegible]rge test cells for military engines with afterburners, and these test cells are usually ins[illegible] [illegible]tantial distances from other workshops or buildings. Shorter distances, such as 150 feet, [illegible] appropriate for small test cells so they could be used in populated areas with factories or offices.

The recommended noise levels are typically given in dBA's and are a function of the selected distance. The sound pressure level decreases with distance, as shown in Figure 7. The allowable level in the free field zone, according to many national standards, is 90 dBA for steady-state noise. For noise sources with variation levels some intensity-time calibration is needed. It is accepted [32] that noise with an A-weighted sound level less than 80 dBA can be disregarded once all corrections have been taken into account. This was confirmed in many test cell solutions, and will be used as the design criterion for the PSTF.

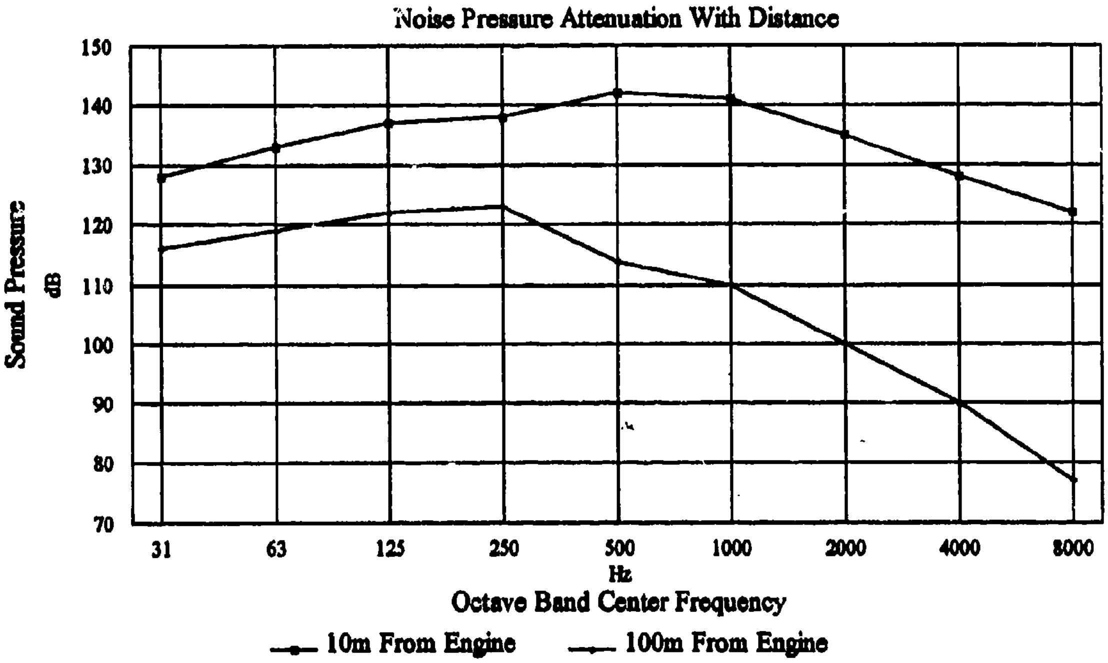


Figure 7: Noise Pressure Attenuation With Distance

By using the allowable noise level, the maximum engine noise spectrum, and the characteristics of sound propagations, it is possible to determine the difference between the expected and allowable noise levels. This difference indicates the attenuation which needs to be provided by the acoustical treatment. The next step must investigate the impact of the different sound paths to the total sound pressure level at a given distance. As it was stipulated earlier, a balanced acoustical design must be included in the design of the test cell. Each sound path should include noise attenuation for ideal conditions, so the objective sound intensity, at a given distance, will be the same. To satisfy this theoretical approach, an acoustical analysis must be done.

The interaction between the aerodynamic and acoustic characteristics of the test cell are very strong. This is especially true in the case of air intake and exhaust systems. As explained earlier, the cross sections of the intake and exhaust systems must be large enough to prevent loading of the engine and to sufficiently cool the exhaust gases.

The interaction between the acoustic and the aerodynamic designs can be defined by the effort expended in providing noise attenuation in the exhaust part of the test cell. To reduce the acoustic power from the exhaust system, and to allow the use of certain acoustical materials in the exhaust path, the temperature of the exhaust gases must be reduced. This is most easily accomplished by mixing the hot exhaust gas with the cooler secondary air. The temperature of the mixed gas is a direct function of the quantity of secondary air flow, and thus the exhaust system temperature capability establishes the minimum secondary air flow required. Total front cell airflow (W_{fc}) is simply the sum of the engine intake flow W_{bm} and the secondary flow W_b:

$$W_{fc} = W_{bm} + W_b \tag{18}$$

The engine secondary airflow and velocity limitations in the test cell enable calculation of the cross sectional area of the test cell [30] by using the flow equation:

$$W = AV\rho \tag{19}$$

where

W	-flow through the monitored section
A	-monitored cross section
V	-average air velocity through the monitored section
ρ	-air density

Equation (19) can be used for the different cross sections (Figure 3), but it is especially important to consider the possibility of defining the air intake and test cell cross sections.

The air intake cross section (A_0) can be calculated by using the equation:

$$A_0 = \frac{W_{bm} + W_b}{V_{0\max}\rho_0} \tag{20}$$

where

$V_{0\max}$	-maximum allowed intake air velocity
ρ_0	-air intake density

As discussed in previous sections, the maximum allowed velocity influences many cell parameters. The suggested guideline for this parameter is that the maximum velocity between the acoustic intake panels should be less than 30 m/s [30].

The bypass cross section (A_b), can be calculated by using the equation:

$$A_b = \frac{W_b}{V_{b\max}\rho_b} \tag{21}$$

where

$V_{b\max}$	-maximum allowed bypass air velocity
ρ_b	-air density at plane b

The maximum bypass velocity has to be below 10 m/s, or preferably 6m/s to be acceptable. The maximum velocity in the forward section of the test cell must less than 15 m/sec and should be less than 10 m/sec.

To get the values of the secondary air at the defined test cell cross sections, adjustments should be made to the size of the augmentor tube and its distance from the engine. As was mentioned in section 6.2.3, it is recommended that the length to diameter ratio of the augmentor tube should be 4.0 or greater. The diameter of the augmentor tube is usually three times greater than the engine nozzle diameter. The distance between the engine nozzle and augmentor tube has little influence on the secondary airflow. Unpublished work of the principal investigator indicates that satisfactory performance is achieved with nozzle to augmentor distance greater than three and less than eight nozzle diameters.

6.4 Conclusions and Overall Design Recommendations

Theoretical considerations used for explanation and analysis are fundamental to establishing design recommendations for jet engine testing facilities. The test facility is a combination of many different components: the test cell with air intake and exhaust systems, the control room, a preparation area where the engine is prepared for testing, equipment rooms for electrical power, and an area for compressed air and storage of engine fuel.

The access doors should never be located in the wall separating the test cell from the control room. In all cases, communication between the test cell and the control room (through control cables, measuring lines, ducting) must be designed with a sealing mechanism to prevent any acoustical or pressure leaks in the test cell from entering the control room.

Acoustic performance requirements are established by the sound pressure levels in the audible frequency range necessary to satisfy allowable environment restrictions and operational limitations. High energy, low frequency pressure waves can cause mechanical vibration modes in the test cell structure and in the surrounding buildings. The test cell design must provide protection from low frequency noise (below 20 Hz) to avoid excitation at building resonance frequencies which can result in structural damage.

The recommended design criteria for noise attenuation can be targeted from a distance of 150 feet and from a height of 7 feet above the ground, in such a way that the A-weighted sound level is less than 80 dBA. In the center of the control room, the allowable noise level should be less than 75 dBA. Appropriate sound treatment material must be used to achieve the stipulated acoustical noise level; however, the noise suppression system must be reasonably priced. All acoustical equipment must be designed to withstand aerodynamic and thermal loading, as well as changing environmental conditions. All of the test cell parts must be designed to withstand a sustained negative pressure (depression) of 0.29 psi (8 inches of water) and positive peak pressure of 1.0 psi (27.7 inches of water).

The airflow in the test cell and the gasflow in the augmentor must remain unidirectional and without recirculation. External cell recirculation could cause reingestion of the hot gases ejected by the augmentor tube. The influence of the wind on the exhaust must be minimized. The horizontal inflow in small test cells reduces the likelihood that hot gases will be ingested.

The ambient pressure of the engine under test is the static pressure in the test cell. The test cell design must prevent the cell depression from reaching 4 inches (100 mm) of water. Within this limit the engine flow field will remain uniform and prevent engine speed fluctuations and thrust measurement variations.

Another test cell performance requirement is the need for sufficient secondary air. A uniform low distortion front cell airflow field with adequate secondary airflow provides undistorted engine inlet and reduces the risk of vortices forming in the bellmouth. The design criterion for the front cell velocity distortion index, measured at a distance of three to four bellmouth throat diameters in front of the engine is 0.35 or less.

To meet engine specifications for performance testing, the engine bellmouth total pressure distortion index should be less than 0.0015.

To satisfy the above requirements, the secondary airflow must be sufficient to achieve a cell bypass ratio equal to or greater than 0.80. A compromise between the size and the performance of the test cell must be reached during the design phase. Using the suggested guidelines for maximum allowable air intake velocity, bypass air velocity and cell bypass ratio goal, the test cell cross section can be defined using equations (20) and (21).

The walls and ceiling of the test cell should be finished with a high quality epoxy paint. The floor should be designed to support the loads produced during handling of engines, and must be finished with an oil-resistant material. A drain must be included in the test cell area to prevent any fuel spillage from exiting the test cell.

The test cell entrance must be secured by a specially designed acoustical door. As part of the sound treatment, the test cell intake will be protected by a one inch non-corrosive mesh screen, to prevent foreign objects from entering. The test cell intake must have a door that can be closed during inclement weather, when the test facility is not in use. The augmentor tube design must include a way to close it off when not in use. Safety protection must be provided for both the intake and exhaust doors, to prevent operation of the engine before the doors are completely open.

The test cell will be lit by high intensity lamps mounted in fixtures designed for use in severe acoustical environments. The lighting will be designed to provide general light intensity of at least 400 lux and 1100 lux in the engine area.

General purpose compressed air (shop air) outlets and utility electrical outlets must be provide in convenient locations throughout the test cell.

An inter-communication system (between the control room and the test cell) must be provided, allowing operators inside the test cell to communicate with those inside the control room.

A fire protection system must be included, which is manually operated from the control console, for protection during testing.

The test cell and equipment located in the facility should be designed to operate in a full range of outdoor air temperatures.

A closed circuit television system should be installed to allow observation of the engine while it is running.

7.0 PORTABLE TEST FACILITY TEST CELL BASIC REQUIREMENTS AND ANALYSIS

The basic design requirements for the PSTF follow from the design recommendations established for indoor, fixed test facilities as described in a previous section. The test cell design criteria for portable test facilities are similar to the major features of fixed test facilities.

The objectives for both facilities are the same: to provide an installation where engine performance may be evaluated throughout the full thrust envelope. The configuration and accuracy of the instrumentation, along with many other features will be very similar in both types of facilities. The aerodynamic performance of both test cells should be at the same level since all influences on the stability of operation and the performance assessment are identical.

Although fixed and portable test facilities are developed to satisfy the same fundamental requirements there are significant differences in philosophy upon which their designs are founded.

The fixed test facility is installed in a known location with defined weather patterns. These can then be incorporated into the design phase to optimize test facility performance. Some of these optimizations are related to the prevailing wind direction and orientation of the test cell, extreme ambient temperature conditions and design factors that can assure good mechanical stability, satisfactory acoustical performance and a stable supply of electricity.

A portable test facility for turbojet engine testing is required to move to different locations that have different weather conditions. This requirement does not allow use of location data during the design and construction of the test facility.

In the development and design of the portable test facility many issues are encountered regarding the basic requirement that the facility be small in physical size and completely portable. These requirements are in opposition with the objective that the portable test facility be mechanically stable and acoustically well insulated.

The small size of the facility means that the size of the test cell must be reduced to the very minimum that will satisfy aerodynamic performance requirements. The distance between the test cell intake and exhaust needs to be carefully considered to prevent the reingesting of hot gases from the exhaust into the inlet. This could be particularly dangerous when operating in windy conditions. Mechanical stability inside a portable test cell is more difficult to obtain because the test cell structure is not fixed and the acoustical system must include light components and materials. If these components are designed to be removable during transportation, additional acoustical leakage can be expected.

The electrical supply for the portable test facility can be from an independent electrical source which may influence the stability of operation in the facility. The interconnections of the major subsystems should be removable for transportation purposes, which can cause reliability issues if not designed correctly.

7.1 Influence of Maximum Engine Airflow on the Test Cell Size

The first step in attempting to design the test cell is to determine the test cell size. As described earlier the test cell size influences many factors in the facility. To calculate the test cell size it is necessary to define a reference engine to be used. The reference engine can be a real engine or a virtual engine that is derived from data envelopes of real engines. The latter option is more reasonable because it is possible that some parameters from different engines overlap. As a result one engine, even with the largest amount of thrust, is not enough to represent the needs of all types of engines to be tested. This is especially important in the design phase of the test facility when it is necessary to determine the configuration of the separate systems and measuring instrumentation.

Defining the test cell size from the matrix specifications that represent engines needs requires the use of design inlet data. The reference engine provides the required data.

The engine bellmouth and tail pipe lengths determine the test cell length. The distance between the augmentor tube and the engine tail pipe is not a significant factor, which was explained in section 6.2.3. The inlet plenum length is dependent on the amount of velocity distortion that is measured in a plane which is three to four bellmouth throat diameters in front of the engine, and must be 0.35 or less. If the physical size of the engine configuration plus the bellmouth and tail pipe determine the length of the test cell, then the airflow of the reference engine defines the test cell cross section.

The maximum engine airflow (W_{bm}) is derived from existing or future engines assuming the largest amount of airflow that would be used. For example, if the test facility is to be used for testing turbojet engines with a maximum thrust of 1000 lb, then all types of engines inside this range can be tested. When this value is determined it can be used as the maximum airflow (W_{bm}) for the reference engine. To demonstrate the procedure for calculating the cross section, some values can be presumed.

If the maximum airflow for the reference engine (W_{bm}) equals 10 kg/s, then according to section 6.3.8, it is necessary to determine the bypass or secondary airflow (W_b) of the reference engine. As explained in section 6.4, to reduce the pressure and velocity distortion the test cell bypass ratio must be 0.80 or greater.

In this example the test cell bypass ratio can be any value above 0.80, for example $\alpha = 1.0$. This means that the bypass or secondary airflow (W_b) equals 10 kg/s.

The test cell cross section (A_0) can be defined using equation (20)

$$A_0 = \frac{W_{bm} + W_b}{V_{0max}\rho_0} \tag{22}$$

The maximum allowable velocity (V_{0max}) through the front section of test cell, as discussed in section 6.3.8, should be less than 15 m/s or more than likely 10 m/s. If the value 10 m/s is selected using an air density for estimated conditions of $\rho_0 = 1.25\frac{kg}{m^3}$, then the front cross section of the test cell can be calculated as:

$$A_0 = \frac{10+10}{10*1.25} = 1.60 \text{ m}^2$$

The defined cross section of the test cell should satisfy all requirements related to test cell performance.

The test cell cross section was calculated using the methodology described in 6.3.8 and 6.4. In addition, the PSTF model created during this research under the software package GasCAD [33] has been shown to provide results which are very close if not identical. GasCAD software is based on the cylindrical pipe model and the test cell has been designed as a cylindrical area. Using this model estimations can be made of the drops in pressure throughout the test cell.

For engine ranges which are of interest to this project the cross sectional area is calculated as a function of engine airflow. The results achieved for various test cell bypass ratios are presented in Figure 8. From this diagram, the cross sectional area can be defined, and the maximum engine airflow in the test cell can be determined.

7.2 Other Criteria and Considerations in the PSTF Test Cell Design

In comparison with larger jet engine test cells, the test cell design requirements for the portable test facility presents several problems:

The small size of the test cell does not allow for operational flexibility inside the test cell. The acoustical design criteria are not easily satisfied because the air intake and augmentor systems must be limited in size. There are special problems in the test cell related to the interconnecting lines from other sections of the test facility. When a fixed facility is in the design phase it is possible to provide a high degree of test cell acoustical treatment including pipes, ducting lines and ventilating channels. For the portable test facility these treatments cannot be used because the connections to the test cell must be designed in different ways.

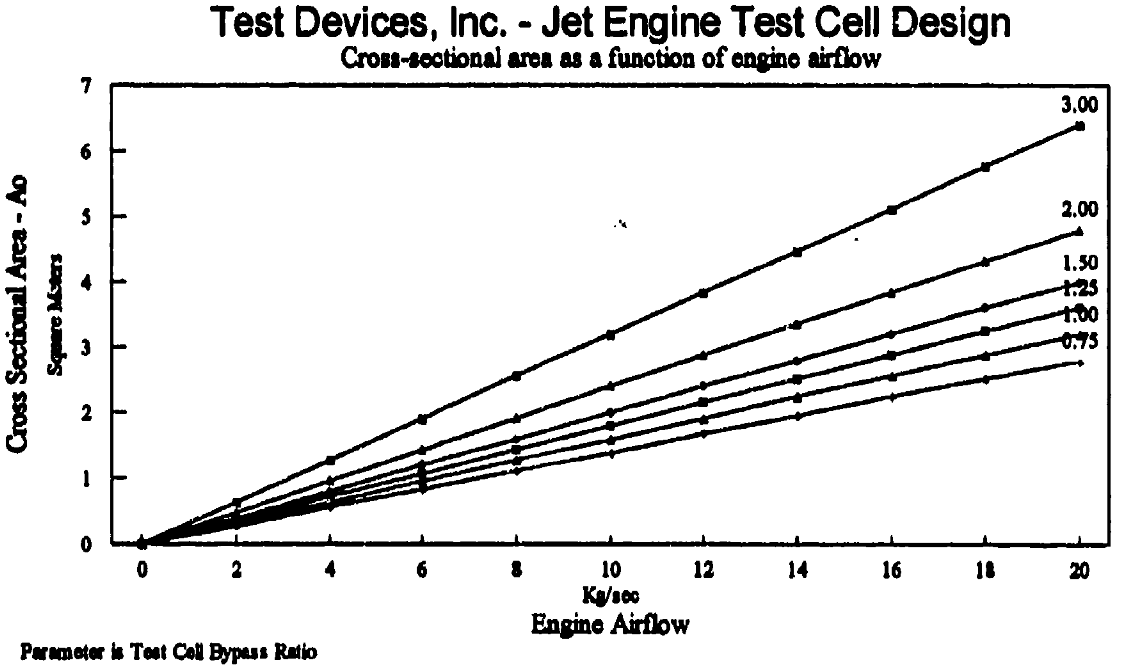


Figure 8: Test Cell Cross Sectional Area as a Function of Engine Airflow

Small expendable turbojet engines are characterized by a wide variation in thrust, from below 50 lb up to 1000 lb. For this reason the thrust stand design of the portable test facility should be given special consideration. Strain gauge type load cells are recommended for use and may be mounted near the front or rear of the thrust stand, in the compression or tension mode. For smaller engines the tension solution may be preferable.

The thrust measuring system should be designed to minimize errors caused by temperature fluctuations due to the changing ambient temperature or thermal radiation from the engine exhaust. Stand stiffness, spring rate, and hysteresis have to be accounted for in such a way that the thrust measurement allows very little linear error and can be compensated by calibration. To improve the performance and stability of the thrust stand a simple, precise and reliable calibration system should be incorporated into the design of the thrust stand.

The PSTF must provide access for many different supply lines (fuel, air, lubrication, electrical, signal) which must be highly reliable. The test cell structure must be strong enough to support the loads resulting from handling the engines.

7.3 Test Cell Safety Analysis

One very important aspect in the development of jet engine test facilities is the reliability and safety of operation. Test facilities for small expendable turbojet engines are potentially dangerous systems. In particular, the conversion of a considerable amount of energy in a limited amount of space inside the test cell needs to be carefully considered.

As a result of engine operation hot gases are produced, with temperatures which can exceed 1500° F. The hot section of the jet engine can be characterized by a very high surface temperature. The engine circulates flammable fluids (fuel, lubrication oil), and any leakage of these liquids from their installations can result in potentially dangerous fires.

To minimize the possibility of fire as a result of fluid drops hitting hot sections of the jet engines, the fluid lines must be far removed from the hot sections of the engines. Flexible supply and measuring lines must be designed to withstand pressure and other loading in many environmental conditions. Sometimes physical barriers can be placed between the fluid section and the hot engine section. The engine drain sink, which is for extracting fluids from the test cell, must be separated from the hot zones.

If a fire occurs, even with precautions, the operators must be able to put out the fire. For this purpose a fire extinguishing system must be provided. The system should be designed to meet the requirements of the United States National Fire Protection Association (NFPA), bulletin 423 "Standards for Construction and Protection of Aircraft Engine Test Facilities". Because the PSTF contains a small sized test cell the fire extinguishing system need not be as extensive as those for large, permanent test cells. Besides portable wall-mounted extinguishers inside the test cell, a manually operated CO_2 bottle system that the operator can control from the console must be included.

The engine test cell design must include provisions to protect the engine during operation from any foreign disturbances. Special protection should be included to prevent foreign objects from entering the test cell. For this purpose the test cell intake should be equipped with non-corrosive one-inch mesh screen. This is especially important for excluding the access of birds. The acoustical door and intake roll-up door will each be equipped with limit switches or position sensing devices. These signals will be incorporated into engine logic, and will assure that the engine cannot be started if any of the signals are incorrect. At the same time additional protection features, including test facility systems and engine parameter limits, should be included to prevent the possibility of improper operation.

The last issue which must be considered is the safety of the engine during testing. Some test cell failure modes are caused by test cell equipment (high pressure, high temperature, high vibration) and can be remedied by the operator. Engine failure, though rare, is a dangerous problem and must be given special attention. Jet engines, particularly small expendable turbojet engines, operate at very high speeds, approaching 150,000 RPM. At this speed, the stress inside the rotating components can be very high and very close to burst levels. If for any reason the maximum engine speed control fails the resulting engine overspeed can cause the engine to burst. The kinematic energy of the rotating jet engine components is very high, and if a burst occurs, the fragments of the disk can do serious damage to the test cell structure and even injure people outside the test cell.

As explained in the test cell design requirements, protection of personnel, particularly those in the control room, requires that the test cell lay out be adjusted in such a way that the test cell is installed in the middle of the test facility. The control room is located at the front and to the side of test cell, outside the plane of the centrifugal forces of the rotating parts of engines. To prevent fragments of bursting components from entering the control console, the test cell wall must be strengthened on the control room side.

7.4 Conclusions and Portable Test Facility Test Cell Design Recommendations

The results of the investigations conducted regarding this work have produced a definition of the most critical factors in the development of the Portable Test Facility for Small Expendable Turbojet Engines. Recommendations given in section 6.4 were derived from an analysis conducted regarding this project, along with our experience in developing and operating portable test facilities. Following is a summary of PSTF design recommendations:

The PSTF should be modular in design, small in physical size, but large enough to satisfy aerodynamic performance requirements. The modular nature of both the test cell and the test facility as a whole should allow for deployment at different locations. The test cell must be fully enclosed and protected from the environment. The test facility design should allow for integration of the test cell with the other sections of the test facility.

The distance between the test cell intake and exhaust should be large enough to reduce the amount of hot gases reingested by the inlet. The inside of the test cell should be mechanically stable in order to prevent movement of the thrust stand during engine testing.

The test cell design must provide acoustical treatment according to the design criteria outlined in section 6.4. The acoustical door and the test cell walls must withstand aerodynamic and thermal loading.

The airflow in the test cell and the gasflow in the augmentor tube must remain unidirectional without recirculation. To ensure these conditions, the design recommendations for the test cell size should be based on the maximum intake cross section velocity which should be less than 10 m/s. The test cell design must prevent the test cell depression from surpassing 2 inches (50 mm) of water, preferably 1 inch (25 mm) of water.

The test cell bypass ratio should be targeted to be greater than 1.0, which enables the velocity distortion index to be less than 0.35, and the total pressure distortion index to be less than 0.0015.

The other general test cell design recommendations (lighting, intercommunication, fire protection, painting, etc.) are described in section 6.4.

8.0 TEST FACILITY INSTALLATIONS

8.1 Review of Installation Requirements

The Portable Static Test Facility for Small Expendable Turbojet Engines is designed to test a wide variety of small engine models up to 1000 lb thrust. A review of the engine matrix specification defines the most important inlet data required for the test facility, and dictates the installation requirements. From the matrix specifications the needs of all of the systems which are required for normal engine operation can be derived.

A sea level performance test is included to verify the predicted engine performance. The typical performance test for small expendable turbojet engines includes the following phases:

-Start Impingement Trials
-Ignition Checks
-Acceleration to and Operation at 100% Speed
-Operation at Different Speed
-Durability Test
-Performance Calibration Test

During testing phases, additional performance investigations can include:

-Rotor Dynamic Investigation
-Optimization of Propelling Nozzle Area
-Rotor Clearance investigation
-Control System Development

The test program is usually designed to verify the mechanical integrity of the engines, validate the control system, establish the performance characteristics, and document the compliance with specifications. Because each engine must complete the Acceptance Test Procedure (ATP) it is one of the most important parts of the test program.

The Acceptance Test Procedure (ATP) is used to verify the performance repeatability of engines of the same type and to establish the performance baseline under sea level conditions. At the same time the engine performance will be fine tuned and the engine will be approved for further testing.

The performance baseline includes a sea level steady-state performance calibration of the engine, recorded while the engine operates at speeds ranging from the minimum speed up to 100%. The recorded data should be corrected for both ambient and barometric pressures to properly evaluate the performance of engines. This process is called making standard day corrections, according to the ISO sea level standard day reference atmosphere.

During the performance evaluation, the following engine parameters should be either calculated or recorded:

-Thrust
-Rotor Speed
-Fuel Flow
-Air flow
-Air Inlet Temperature
-Compressor Discharge pressure
-Jet Pipe Temperature
-Jet Pipe Total Pressure
-Vibration
-Bearing Temperature
-Fuel Pump Pressure
-Alternator Voltage, Current and Power
-DC Generator Voltage, Current and Power

Depending on the type of testing, the additional parameters listed below can be monitored and recorded:

-Engine Acceleration and Deceleration Time
-Inlet Pressure Distortion
-Velocity Distortion
-Electrical Starter Voltage and Current
-Air Impingement Parameters
-Lubrication Data
-Test Cell Depression

During acceleration and deceleration performance testing, the test characteristics should be recorded. The time from initial acceleration to idle, and to 100% speed, should be determined, as well as deceleration time from 100% speed to idle. Through engine testing the fuel control system gains should be adjusted to meet the optimum transient response characteristics.

Some small expendable turbojet engines include AC or DC generators. During performance evaluation or durability testing the engine should be loaded using a resistor bank.

To satisfy all of these requirements the PSTF must be equipped with different systems and installations. The most important service systems in the test facility are listed below:

-Fuel System
-Lubrication System
-Ignition System

-Air Start System
-Electrical Start System
-Electrical Loading System

These systems support the engines during testing by supplying services for starting and running. The support systems in the PSTF should be common and available to all engines tested. Each engine model to be tested should be interfaced with the test cell system through an engine adapter kit.

9.0 TEST FACILITY MEASUREMENT REQUIREMENTS

Requirements for engine testing stem from the need to investigate different engine characteristics. Throughout the measurement process it is important to transfer the information from the engine to the user. The volume and configuration of the test facility measurement system must be defined based on engine requirements and future projections.

From the general test specifications (section 5.0) and lists of instrumentation required for different engines, it is possible to determine the basic configuration of the measurement system. It is necessary to take into consideration each engine that will be tested at the test facility and specific tests that could be expected in the future. Test objectives have influence on the instrumentation range and accuracy. Depending on the type of test, different configurations of instrumentation may be required. Installing common instrumentation in the test facility is desirable, because it will satisfy the needs of different engines and different types of tests.

General elaborations of the measurement system for turbojet engines test facilities were presented in section 6.1. The first step in defining a measurement system is recognizing the engine conditions to be investigated. Each of the three general test classifications: steady state, transient and dynamic, require special instrumentation that must be determined before an instrumentation proposal can be made.

The basic component of all measurement systems is the transducer, the device that changes the physical value of the measured parameter to an electrical signal, which is further processed and converted to engineering unit data. Some of the most important transducers that should be selected throughout this project are analyzed below.

Fuel flow measurement at turbojet engine test facilities is usually done with a turbine flowmeter or a positive displacement meter. The turbine flowmeter is perhaps the most commonly used transducer. It has considerable advantages: simplicity, small size, accuracy, fast response, and adaptability for remote indication and telemetry. Pressure losses across the turbine flowmeter are proportional to the flow rate squared, but usually only a few psi at the rated flow. The signal frequency is the parameter which the readout system senses as the flow indication. The turbine flowmeter is characterized by a calibration factor rated as the number of pulses per unit volume (f/ν). This factor is a function of the turbine frequency divided by the kinematic viscosity. The calibration factor is constant in some f/ν range, described as the turbine linear range, usually within 5 to 1 for smaller turbines and 50 to 1 for larger ones. The nonlinear performance occurs at lower f/ν values. This feature can limit turbine application in cases where the system requires a wider flow range. However, recalibration of a turbine flowmeter demonstrated that repeatability of the calibration factor always repeated the original data to within ± 0.1%, regardless of whether the operation was in the linear or nonlinear region. This allows a turbine flowmeter to be implemented with a 500 to 1 rangeability. Because the turbine flowmeter is a viscosity sensitive device, each different fluid supplies a new calibration factor, also the same fluid at a different temperature will produce calibration factor deviation. If this change is readable it could be implemented in the measurement system, which would significantly increase the performance of the flowmeter.

The transient response of flowmeters used at turbojet engine test facilities is very important, especially when the fuel flow signal is used in a closed-loop control of turbojet engines. Transient response of turbine flowmeters is discussed by Grey [34] in which time constants are predicted in the range of 1 to 10 milliseconds as the response to a step function, depending upon blade range, meter size, and flow rate. This prediction was experimentally confirmed by NIST, which determined the turbine flowmeters transient performance to be acceptable, even for dynamic applications.

Positive displacement technology is a direct non-inferential method of measurement that has been known for many years. The primary operation is separating a flowing stream into a series of discrete portions of liquid, and then counting the portions flowing through the meter per unit time (flow rate). This is analogous to filling and emptying chambers of known volume continuously. The system is based on measure, volume and time, giving accuracy typically ± 0.5% of the actual flow. Accuracy is unaffected by wide variations in fluid viscosity, which is very important for applications with different fluids or wide temperature variation. The dynamic performance of displacement meters is significantly worse in comparison with turbine flowmeters, excluding displacement meters in applications where reasonable dynamic performance is required.

The Pressure measuring system usually consists of transducers, tubing connecting the measurement points and transducers, and a recording unit. Today, a wide variety of transducers of different design and performance are available. For applications like test facilities for turbojet engines, transducer characteristics must abide by engine requirements. The most important transducer characteristics are related to:

- -Pressure range
- -Operating temperature
- -Accuracy including nonlinearity and hysteresis
- -Pressure media
- -Overpressure limits
- -Long term stability
- -Response time
- -Supply requirements
- -Vibration influence on the performance
- -Electrical output level
- -Reliability prediction
- -Size
- -Weight
- -Price

Each static test facility operates under different temperature conditions. To attain the required pressure measurement accuracy, it is necessary to verify the total error achieved with selected transducers, and compare this error with the permitted limits. If the error is not within limits two options are available: the error can be reduced if the transducer is mounted in a temperature controlled box or a new transducer can be selected with better temperature compensation.

From experience in using transducers in engine performance evaluations, it has proven preferable to use transducers with higher voltage output. This will reduce the influence of the electrical noise and at the same time the output signal will be easily accepted by the data acquisition system for further processing.

Dynamic pressure measurement has requirements different from steady state pressure measurements. Typically the frequency of a pressure signal is important information. The dynamic pressure system has a sensing port, complying tube, transducer, and a recording system, all of which contribute to the frequency response of the system. The first step in dynamic pressure measurement is to minimize the distance between the transducer and the measuring point. The natural frequency of the transducer must be high enough to provide linear transducer response throughout a wide frequency range.

Pressure measurement systems are usually required to measure a large number of pressures rapidly. This goal can be achieved by using pressure scanners which can perform high speed measurement at different pressure ranges. The total system combines high speed electronic multiplexing of transducer output with an on-line calibration feature. Prior to the selection of the system, it is very important to evaluate all parts of the proposed system, especially as it relates to measurement uncertainty.

Thrust measurement is a critical feature of the PSTF. The engine is mounted on a flexible thrust stand which can move axially, but is rigid in all other directions. The actual forward motion of the thrust stand is restrained by a measurement load cell, which is very stiff. The load cell must be very sensitive to axial loads and less sensitive to off-axis loads. The calibration system must use a calibration load or a dead weight method. The thrust measurement system design should be low in both non-linearity and hysteresis. Some requirements must be taken into consideration in designing installation interfaces (pipes, lines, cables, probes, wires), between the movable part of the thrust stand and the fixed structure to reduce the hysteresis and non-linearity.

Thrust measurements between test facilities is usually restricted in its variation to no more than ±0.3% of full scale. To assure this, the aerodynamic design of the test cell must be proven and the thrust calibration system well established. The uncertainty of the calibration process should be within ± 0.2%, of the full scale. In some cases when the thrust ratio of tested engines is high, it may be necessary to add another load cell or change the thrust stand.

Temperature measurements at engine test facilities are mostly made with thermocouples. Although thermocouples are simple devices, in order to achieve precise results, the measuring system must be correctly established The first issue that should be resolved is installation of the known reference junction temperature, because any uncertainty in that temperature must be added to other uncertainties in the system.

When the temperature measurement system has a large capacity, the reference junction solution must include a uniform temperature in the area where the thermocouple leads will be connected. This can be accomplished using a uniform temperature reference (UTR). Electrically insulated isothermal blocks are installed inside a heavily thermally insulated box to minimize thermal gradients in the assembly. The electromotive force generated by the temperature difference between the measuring point and the reference junction (UTR) is transferred from UTR to the measuring instrument by cooper wires. The temperature of the UTR block is measured by an RTD, and this data is included in the temperature measurement system.

The UTR should have an uncertainty no greater then ± 0.2° F. To attain this accuracy the following precautions must be taken:

-Use calibrated RTD for reference block temperature measurement

-Protect the UTR from severe blasts of hot or cold air in order to limit thermal gradients

-Install the UTR in a zone where there is no rapid temperature change

The thermocouples used at engine test facilities should be properly selected and calibrated. Some periodic checking must be established. Calibration uncertainty can be controlled at a level ± 2° F, if a proper calibration system is established.

Vibration measurement of jet engines at test facilities is done primarily to prove the mechanical stability of rotating parts and to alert the operator if vibration exceeds safe operating limits. Velocity transducers are often selected for engine test facilities because of their simplicity. The linear frequency range of velocity transducers is limited to about 2000 Hz, they are unsuited to the high frequencies common to the engines tested in the PSTF. Accelerometers must be used because they are small, light weight, and provide adequate frequency response (20 KHz and higher).

Each part of the vibration measurement system must be carefully treated. Installation of the accelerometer on the engine must be in such a way that the interface does not change the character of the vibration. The connection between the accelerometer and preamplifier should be by special low noise coaxial cable. The filtration of the vibration signal allows the operator to analyze any signal from the vibration spectrum.

Speed measurements provide information about engine rotor speed. Different types of transducers can be used; however, for smaller engines, magnetic transducers are usually implemented. If the engine blades are non-magnetic, an eddy current sensor may be used. The speed transducer is connected to the *f*/v converter, and converts the frequency to D. C. voltage, which is used in data acquisition and engine control systems. Performance of the speed measurement system depends on the type of testing. For steady-state conditions the average speed readings throughout some period of time are eligible. For dynamic measurements and engine control purposes, a fast response system is the first requirement.

Measurement systems for engine test facilities can be expanded to measure additional parameters such as airflow, power extraction, acceleration and deceleration times etc. If such systems are included, the design must incorporate all precautions stipulated above for similar systems.

Measurement uncertainty is an important part of the measuring system. A measurement system at jet engine test facilities is composed of many subsystems, each interfacing with the others. The performance characteristics of each subsystem, the transducers, pre-amplifier, signal conditioning, instrumentation cables, and data acquisition system has an influence on measurement uncertainty. To calculate measurement uncertainty a calibration process must be established and the performance of the calibration system determined.

Elemental error sources can be classified as either precision (random), or bias (fixed) errors. Precision error can be determined by repeatable measurements of a single value. This error can be expressed through precision index or standard deviation. The bias error is the systematic error which is constant for repeated measurements and can only be determined by comparison with the true value of measured quantity.

Basically, a single measuring chain stretches from the measuring point via a probe and connecting line to the transducer, and from there via an electric line-preamplifier-to the multiplexer, amplifier and the signal conditioner to be recorded. Each step in the data sequence contributes to the overall data error in its own way. To identify the measurement uncertainty for an engine parameter, the error propagation through the whole chain must be followed, including the influence of the calculation coefficients from the individual measurements.

From experience with fixed facilities the range of estimated measurement uncertainty for some of the basic measurements of engine performance parameters are noted below [17].

Basic Measurements	Estimated Uncertainty
-Scale Force	± 0.4 to 0.5%
-Fuel Flow	± 0.4 to 0.6%
-Inlet Pressure	± 0.2 to 0.3%
-Inlet Temperature	± 0.3 to 0.8%

Performance Parameters	Estimated Uncertainty
-Net Thrust	±0.5 to 0.6%
-Specific Fuel Consumption	±0.9 to 1.2%
-Airflow	± 0.3 to 0.7%

These data are achieved with larger engines. For smaller test facilities, like the PSTF, the measurement uncertainty is estimated to be slightly above these values.

10.0 PRELIMINARY DESIGN OF A PORTABLE STATIC TEST FACILITY FOR SMALL, EXPENDABLE, TURBOJET ENGINES

As a result of this Phase I study, a preliminary design of the Portable Static Test Facility for Small Expendable Turbojet Engines has been developed. The test facility has been designed to be a modular and completely portable, self contained system requiring minimal external support facilities.

The test facility will consist of three sections of equal size (8 x 8.6 x 20 feet). The first segment contains the engine test cell, the second the controls and instrumentation and the third houses the fuel, oil and air systems. All of the sections are designed to be moved and positioned with a forklift. All of the test facility components are transportable on a standard flat bed trailer. The facility is designed to be installed and operated on flat terrain (A-mode of operation is shown in Figure 9). In special cases the facility can be operated on the flat bed trailers used for transportation (B mode of operation, shown in Figure 10).

10.1 Engine Test Cell

The first phase in the design stage was the establishment of a reference engine. Teledyne CAE's turbojet engine F408-CA-400 was used as the reference engine for the aerodynamic and acoustic design of the test cell. The performance specifications for this engine indicate that the maximum thrust is 1008 lb, air flow is 16 lb/s and the exhaust gas temperature is 1412° F. The noise spectrum overall sound power level (shown in Figure 1) from the reference engine was used as a general guideline for the acoustic design of the test facility.

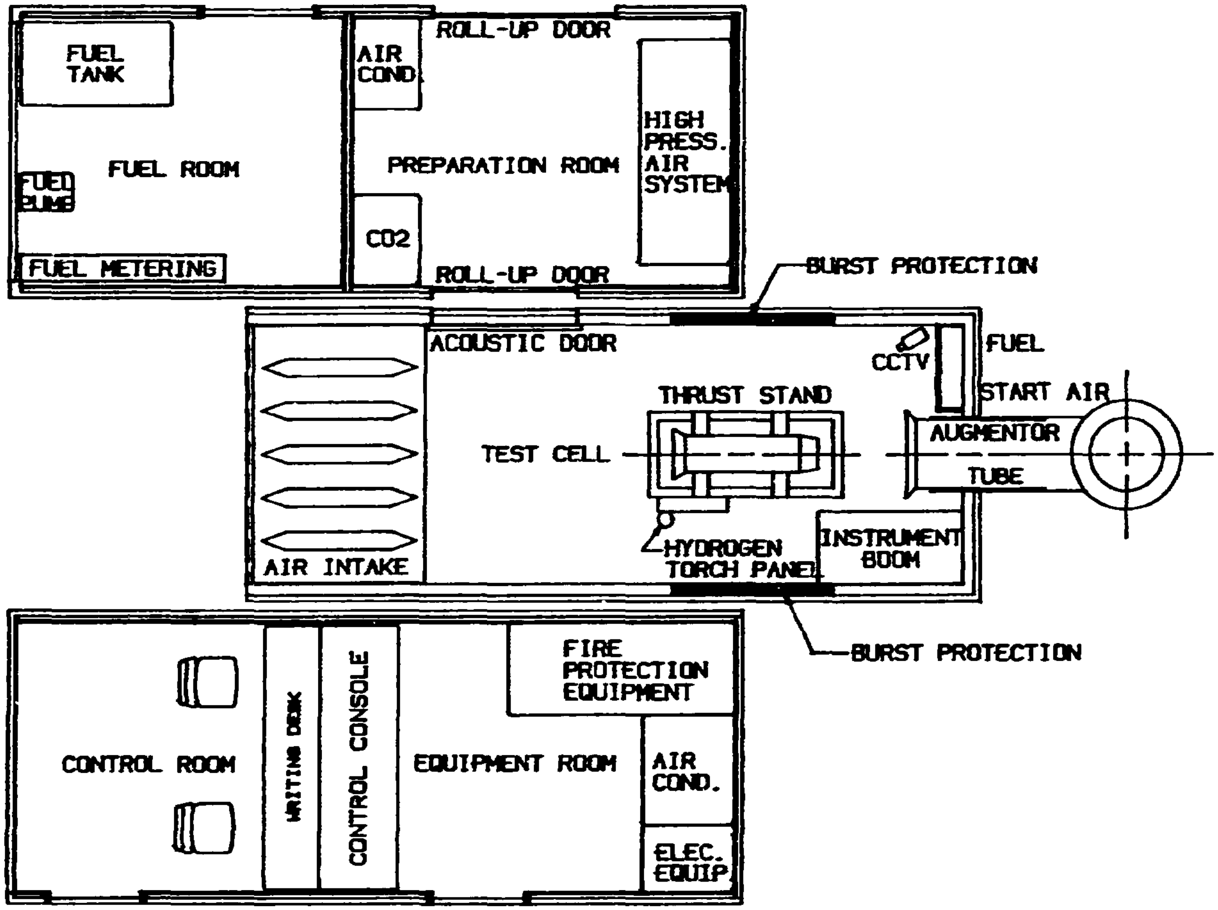
Two critical parameters of the test cell design are aerodynamic and acoustical performance. The aerodynamic calculations are presented in Table 5.

Using the data shown in Table 5, the aerodynamic performance of the test cell design can be summarized. The test cell performance is based on the largest engine that will be tested in this facility.

-Total test cell airflow	42 lb/s
-Maximum air velocity in the test cell air intake silencer	42 ft/s
-Engine test chamber air velocity	10 ft/s
-Test cell depression	3 mm H_2O
-Approximate gas velocity in the exhaust silencer	220 ft/s
-Augmentor exhaust gas temperature	680 °F

F408 CA 400 ENGINE			INLET 1			DETUNER			TEST CELL			EXH SIL	DA	0.4
Engine gas flow	W_{tm}	Kg/s7.25	WIDTH	LA1	M 2.3	Ø	DM	M .4	WIDTH	L4	M 2.2	Ø	DS	M .8
Fuel flow	W_f	Kg/s.43	LENGTH	LO1	M 1.0	LENGTH	L3	M .5	LENGTH	H4	M 2.3	Augm Sect	SA	M2 .1
Thrust	F	N 4,566	SECTION	S1	M2 2.3	SECTION	S3	M2 .1	SECTION	S4	M2 5.1	SECTION	SS	M2 .5
EGT	Tm	degC 766	AIR TEMP	T1	deg C 15	GAS TEMP	T3	degC 337	AIR TEMP	T4	degC 15	MIX TEMP	TM	degC 360
EGT	TM	degK 1,039	AIR TEMP	T1	degK 288	GAS TEMP	T3	degK 610	AIR TEMP	T4	degK 288	MIX TEMP	TM	degK 633
Ø NOZZLE	TM	M .20 M2 .03	AIR FLOW	W_a	Kg/s 18.5	AIR FLOW	W_d	Kg/s 18.9	AIR FLOW	W_4	Kg/s18	GAS FLOW	W_s	Kg/s 19
SECT NOZZLE	DN.		FRT VEL	VFT1	M/s 6.5	FRT VEL	VF3	M/s 260.4	FRT VEL	VFT4	M/s 3.0	VELOCITY	VS	M/s 675
JET PRES	SN		SECT/PAN	SP1	M 21.2	THRUST	Jd		W_v	W_4	M3/s15	W_e	W_5	M3/s34
			PD COEF	KA1	5.02	PD COEF	KR	0	DEPRESS	DR1	mmCE 3	PD COEF	KR	1.15
			VEL/PAN	VP1	M/s 12.9			0				DR		mmCW 2,36
			MASS VOL	R1	Kg/m3 1.2	MASS VOL	R3	Kg/m3 3.6	MASS VOL	R3	K/gm3 1.2	MASS VOL	R_4	Kg/m3 .56
			BYPS RATIO	α	1.55									
TEMP °C	15	100	150	200	250	300	350	400	450	500	550	600		
TEMP °K	288	373	423	473	523	573	623	673	723	773	823	873		
Cp J/Kg °K	952.17	998	1020	1040	1058	1074	1089	1103	1116	1128	1139	1149		
W_{tm} Kg/s	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25		
V_f Kg/s	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43		
W_t Kg/s	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68	7.68		
EGT °C	767	767	767	767	767	767	767	767	767	767	767	767		
EGT °K	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040		
Cp egt J/Kg °K	1180	1180	1180	1180	1180	1180	1180	1180	1180	1180	1180	1180		
α	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00		
W Ind	1.81	3.63	5.44	7.25	9.06	10.88	12.69	14.50	16.31	18.13	19.94	21.75		
wt	9.49	11.31	13.12	14.93	16.74	18.56	20.37	22.18	23.99	25.81	27.62	29.43		
a=W_t x EGT	5891	5891	5891	5891	5891	5891	5891	5891	5891	5891	5891	5891		
a x Cp egt	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06	6.95E+06		
a1=W ind x 15 x 952	2.59E+04	5.18E+04	7.77E+04	1.04E+05	1.29E+05	1.55E+05	1.81E+05	2.07E+05	2.33E+05	2.95E+05	2.85E+05	3.11E+05		
Σ a.a1	6.98E+06	7.00E+06	7.03E+06	7.06E+06	7.08E+06	7.11E+06	7.13E+06	7.16E+06	7.19E+06	7.21E+06	7.24E+06	7.26E+06		
T mix °C	647	560	494	442	400	366	337	313	292	274	258	244		
T mix °K	920	833	767	715	673	639	610	586	565	547	531	517		
Kr	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00	1.15E+00		
b=Kr/19.81x273x1.2	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04	1.65E-04		
Ø detuner m	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40		
S Detuner m2	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13		
b/s^2	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02	1.04E-02		
Δ Pr mm CE	864	1110	1376	1662	1968	2295	2641	3007	3393	3799	4225	4670		
α	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00		

Table 5. Aerodynamic Calculation of Portable Static Test Facility Test Cell



FLAT TERRAIN MODE OF OPERATION (A)

Figure 9: Flat Terrain Mode of Operation

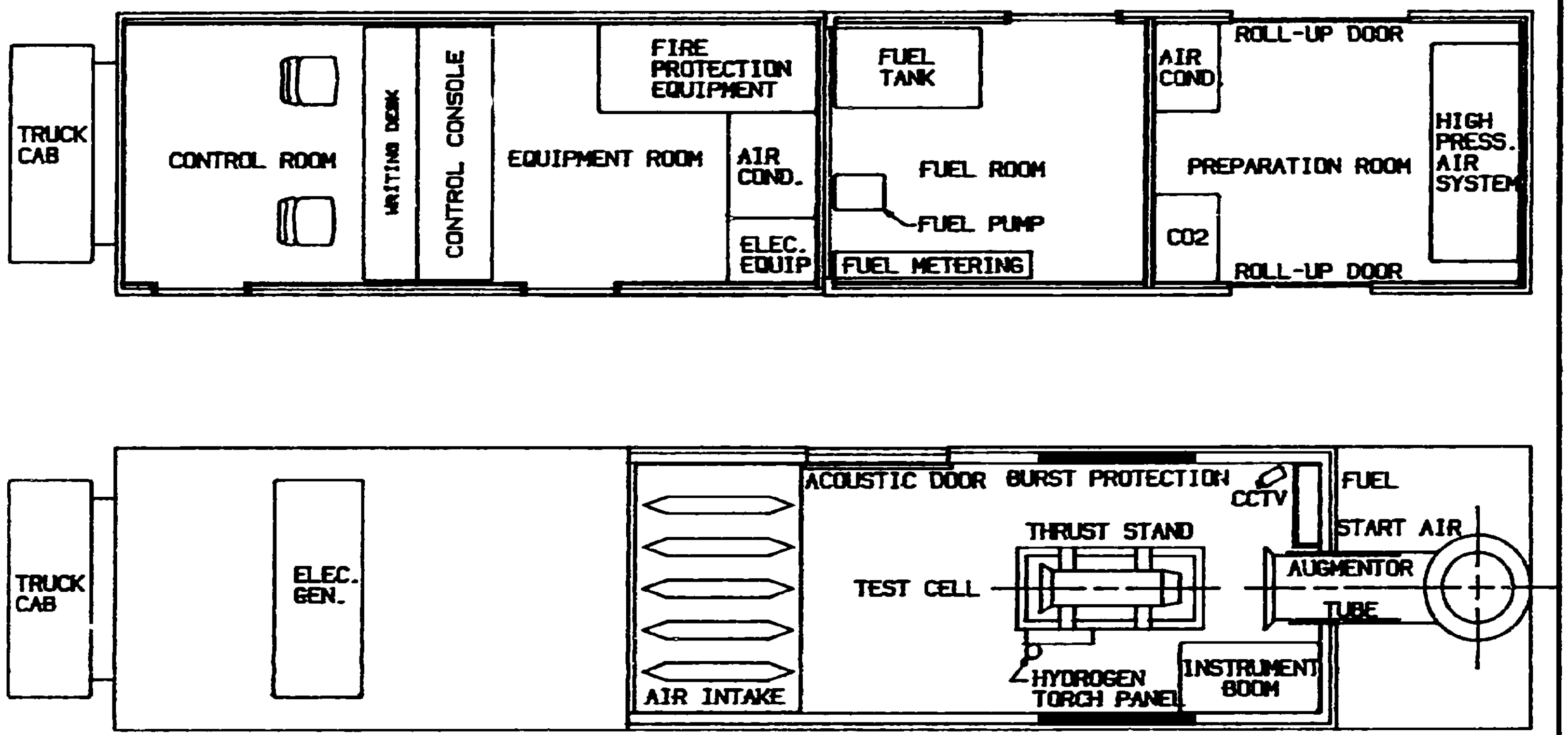


Figure 10: Flat Bed Trailer Mode (B) of Operation

In an analysis presented in section 6.4 it was confirmed that two critical aerodynamic parameters in the design of the portable test cell are **test cell bypass ratio** and **test cell depression**.

If the test cell bypass ratio is above the required 0.80 then vortices will not form and the risk of velocity and pressure distortion will be minimized.

Test cell depression is directly related to the aerodynamic performance of the test cell. The test cell structure must be designed to withstand the forces produced by the lower pressure inside the cell. As section 7.4 concluded, the preferred test cell design must not exceed 2 in. (50 mm) H_2O and is preferred to be less than 1 in. (25 mm) H_2O.

The preliminary design of the PSTF has a test cell bypass ratio of 1.55 and test cell depression of 3 mm H_2O, both of which are much better than required. According to the theoretical investigations in sections 6 and 7, aerodynamic performance of the proposed test cell will be excellent.

Low air velocities throughout the test cell, combined with a relatively high bypass ratio (more than 1.55) and a very low test cell depression (3 mm H_2O), guarantees that the test cell performance will approach that of an outdoor "free field" test facility. This will be particularly true when small sized turbojet engines are tested.

The recommended acoustical design criteria for noise attenuation (section 6.4) are targeted at a distance of 150 feet from the test cell and a height of 7 feet from the ground, so that the A-weighted sound level is less than 80 dBA. The noise level in the center of the control room should be less than 75 dBA.

It is possible to determine the amount of acoustical treatment needed for the test cell by abiding by the permitted noise level, at a given distance using the peak of the engine noise spectrum. The overall sound power level (re 10^{-12} W, Figure 1), which is established from the reference engine, can be determined at the center of the octave band frequency:

Hz	63	125	250	500	1000	2000	4000	8000
L_w (dB)	135	137	142	148	150	151	149	144

Table 6: Sound Power Data from Figure 1

Acoustical treatment for the test cell is included in the preliminary design along with the acoustical calculations which were computed to determine the acoustical performance of the test facility. The results of the acoustical calculations are shown in Table 7. From the data it can be concluded that the maximum sound power level at a distance of 150 ft (50 m) is 71.7 dBA, well within the required design parameters.

Acoustic Performance											
Dimensions [ft]	Long	High	Area	Wide	Sect.						
0	20	8.6	160	8.0	68.8						
Distance [ft]	150	W_e=	16lb/s	V=	64fts	DH=	4.8ft	L_W=	99	F	7
Frequency [Hz]	31.5	63	125	250	500	1000	2000	4000	8000		A
Engine L_W [dB]	130	135	137	142	148	150	151	149	144		156
$L_{P\,int}$ [dB]	122	127	129	134	140	142	143	141	136		148
Container STL	17	21	25	32	38	47	55	62	55		
SPL	75	76	74	72	72	65	58	49	51		
Air	0					0	0	0	0		
SPL	75	76	74	72	72	65	58	49	51		71.7

Table 7: Acoustic Calculation For PSTF

A detailed technical description of the preliminary test cell design, including all materials and components is presented in the following sections. The basic test cell structure is housed in one ISO standard storage & shipping container. Some sections of the container are shown in Figure 11. The container shall conform to the requirements specified in ISO 1496/1 without damage or permanent deformation.

A summary specification for the container is given below:

-External size	20' 0" L x 8' 0" W x 8' 6" H
-Internal measurements	19' 4" L x 7' 8" W x 7' 10" H
-Cubic capacity	1.169 ft^3
-Floor area	149.22 ft^2
-Tare weight	5,250 lb
-Maximum loading weight	39,600 lb
-Constructed of	1.6 - 2.0 mm gage steel
-Floor	Hardwood
-Roof	Self draining
-Forklift pockets	Provided

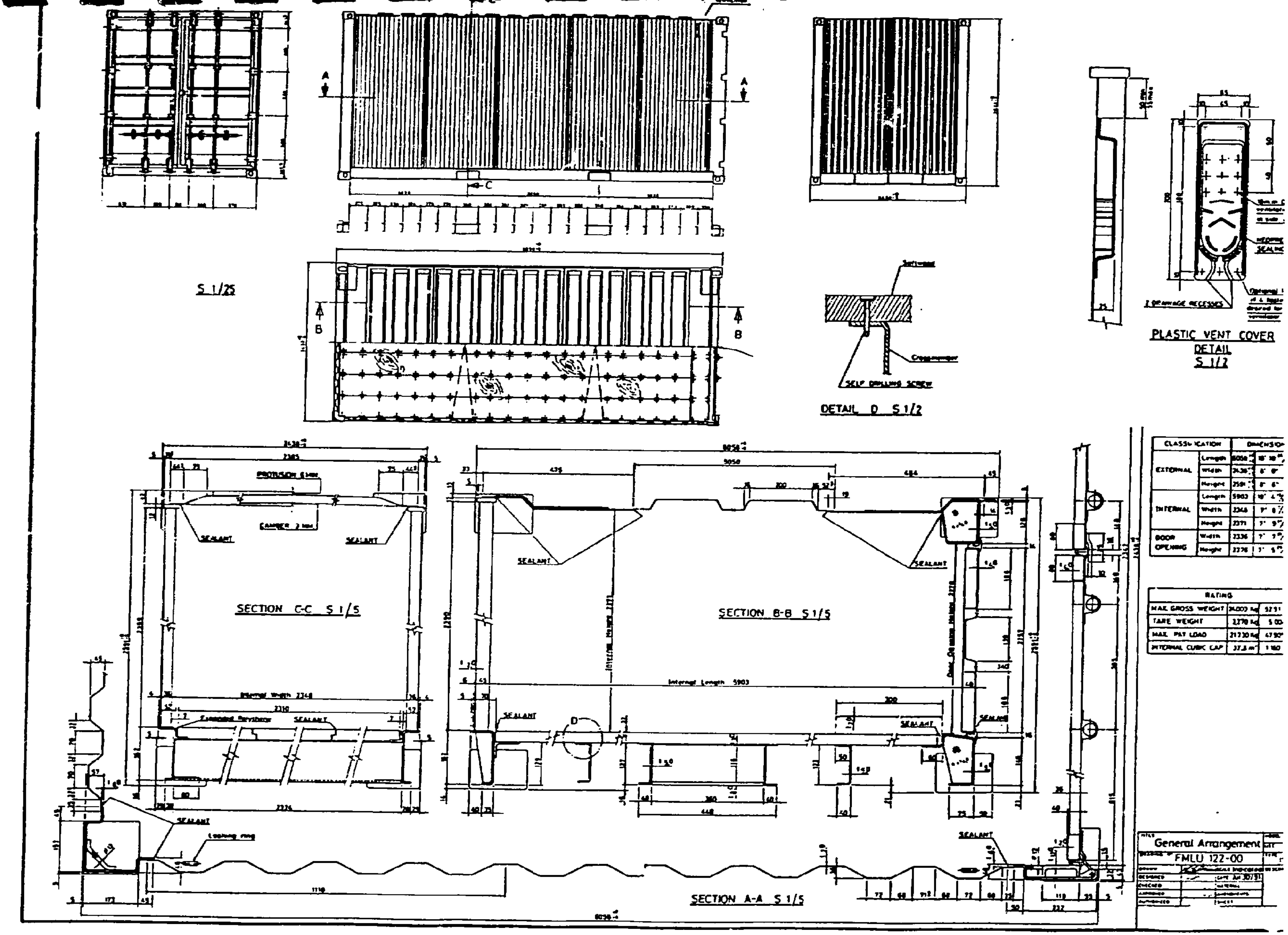


Figure 11: Container Section

The test cell container will be modified and equipped as illustrated in Figure 12. The major modifications to the test cell container will be described in later sections.

10.1.1 Air Inlet Acoustical Treatment

The test cell air intake is a horizontal design, based on the test cell size and the characteristics of the engines that will be tested. The airflow path is changed and adapted to accommodate the engine center line.

The test cell air intake cross section is designed to supply the proper quality and quantity of airflow to the engine test chamber, while providing noise attenuation and ensuring the compliance of the test facility with environmental noise regulations.

The test cell air inlet (3' x 8') is equipped with an acoustical silencer that includes one row of baffles. Each acoustical splitter is made of two folded perforated sheets welded and assembled. They are closed at each end with a U channel, which is also used for bolting on the inlet deck. Various reinforcements complete the inlet structure.

The perforated sheets will have a special perforation ensuring the greatest efficiency as well as good mechanical resistance. The internal space of these modules are filled with a blanket of absorbing material. The density is dictated by the required acoustical results. A fiberglass foil protects the absorbing material against any stripping. The filling is a complex fiberglass wool in semi-rigid panels that is imputrescible and flame retardant. As part of the test cell intake, a 16 x 16 (cross section 3' x 8') wire mesh screen is installed to protect the test chamber from foreign objects and to provide some correction of pressure distributions. The stainless steel wiremesh will be framed to avoid any damage caused by vibration.

The supports and hardware for the inlet will be made of galvanized steel. The wiremesh screen will be installed by bolting it to the container support structure.

10.1.2 Test Chamber Acoustical Treatment

The standard container which will be used as the basic test cell enclosure is a relatively poor acoustical attenuator. To reduce the amount of noise radiating from the engine to the outside of the test cell the test chamber will have additional acoustic treatment.

The acoustical treatment for the walls and ceiling of the test cell will be corrugated, perforated, galvanized sheets and rockwool mattresses. Stiffeners will be installed in order to increase the vibration resistance of the walls and the perforated sheets.

The acoustical treatment is designed to reduce noise reverberation and to reduce the sound pressure level in the test cell. The lining is modular and made of perforated sheets with an

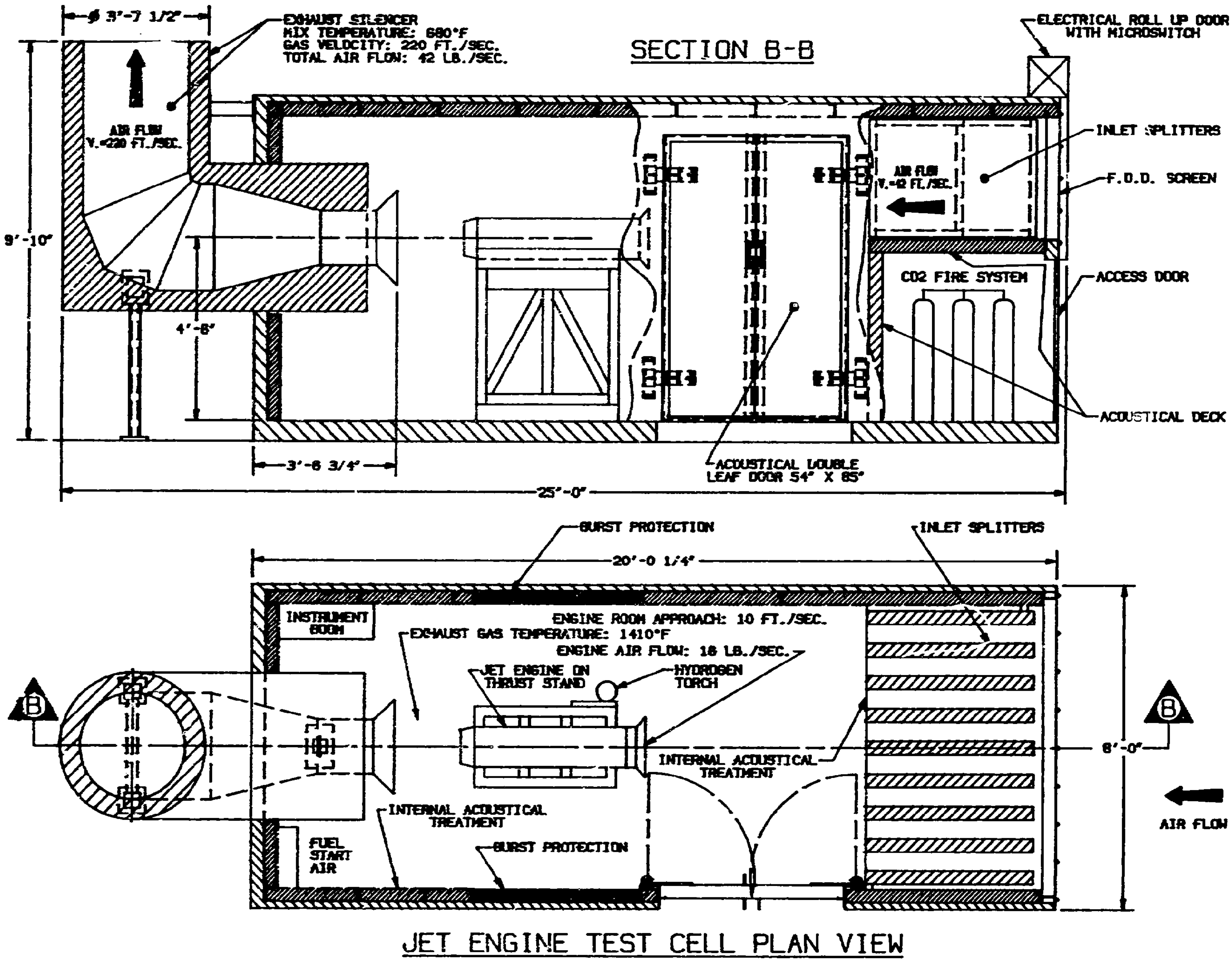


Figure 12: Jet Engine Test Cell Plan View

absorptive material protected by fiberglass cloth. The openings in the test cell for cables, pipes, and doors are also acoustically treated.

The engine access door will be an acoustical double leaf swinging door, 6.4 ft high and 4.2 ft wide. The frame and the door will consist of folded and welded steel sheets. The door will be made of two solid steel panels, one on each side, with a high efficiency acoustical filling. It will be equipped with two seals for acoustical tightness, and have reinforcing pins for the hinges and lock. The door will be mounted on hinges and equipped with a 3 point locking device. The frame will be bolted to the support structure of the container.

10.1.3 Exhaust System Acoustical Treatment

The primary function of the exhaust system is to capture the engine exhaust gases and to induce secondary airflow circulation through the test cell. By the combination of gasflow redistribution and noise attenuation the exhaust system controls the noise level outside the test cell.

The exhaust system consists of a **detuner, a diffuser, an elbow** and an **exhaust stack silencer**.

The detuner has been designed to direct the engine exhaust air flow and to cause pumping of secondary air. An acoustical joint prevents noise leakage from escaping through the wall passage and allows for thermal expansion.

The diffuser ensures a good connection between the detuner and the sound proofed elements. It is used to regulate the mixture of hot engine exhaust gases with cool secondary air provided by the pumping action, and reduces the velocity of the mixture before it enters the detuner. Besides these functions, the diffuser plays a significant part in the whole acoustical treatment of the test cell.

The elbow directs the gas mixture upwards at a 90° angle away from ground level.

The exhaust stack silencer is included to complete the acoustical treatment. It is placed above the elbow, is cylindrical in shape and tall enough to prevent recycling of exhaust gases. Construction of the exhaust silencer is similar to the diffuser. It has a solid outer ferrule and a perforated inner sheet.

All sections of the exhaust system are provided with lifting eyes for handling. The elbow has a drain included at the lowest location. The sheets used in the exhaust system design are made up of ASTM A 36 or equivalent. The hardware is cadmium plated or equivalent.

All parts of the exhaust system are integrated into the aerodynamic and acoustical designs, and allow the PSTF to operate reliably with any engine within the thrust range of 50-1000 pounds.

10.2 Fuel Delivery System

The fuel system is designed to be compatible with JP4, JP5, JP8, JP10, and Jet A fuels. All lines and fittings will be stainless steal. Pump housings will be brass or stainless steel. Pump elements will be carbon. Elastomers used are fluorocarbon, fluorosilicon or nitrile. The fuel pump will be a self priming Procon rotary vane pump with a capacity from 5 to 11GPM and 150 psi. Down stream from the pump is a filter to collect any debris from pump wear or failure. The system pressure is controlled by a Cashco pressure relief valve. The relief valve line returns directly to the tank. The system contains a manual stainless steel ball valve to allow the system to be shut down for repair or replacement of components. A remotely operated (from the test cell console) solenoid is located outside the test cell. This solenoid is connected to a safety shut down, fire system and panel control. A check valve is located around the solenoid valve sealing in the direction of system flow. This check valve allows for pressure to bleed off when fuel is trapped and expands due to heat. Directly inside the test cell wall is a manual ball valve for servicing the system.

An accumulator compensates for pump pulses and fuel expansion due to heat. A 10 micron absolute filter is located before the cell fuel measuring station. A filter is installed prior to the fuel control to protect it from contamination.

The fuel measuring section consists of a Quantum Dynamics advanced flow instrumentation system that has become the de facto standard flow instrumentation system for jet engine test facilities. The type selected for use with the PSTF is a 3/8"-sized QAF-6-VWR-1SC (TC) flow sensor equipped with Pt100 RTD. This flow sensor has a rangeability of 0.04 GPM to 4.0 GPM. In the fully developed flow range the sensor will have a K-factor of approximately 10,000 pulses/gallon. At 3.0 GPM the flow sensor will have a frequency output of approximately 500 Hz. The flow sensor is equipped with an integral Pt100 RTD that will be used to perform temperature to density compensation and temperature to viscosity compensation. The flow sensor will be factory calibrated at 1.0, 2.5 and 5.0 centistokes. The flow computer translates the temperature sensor output to the corresponding density and viscosity. The viscosity and flow sensor frequency are mapped to the appropriate volumetric flow rate, which yields the mass flowrate when multiplied by the density.

The flow computer's dynamic flow option updates the instantaneous flowrate on a once per pulse basis, i.e. when the flow sensor has a 500 Hz output, the computer's analog output will be updated at a rate of 500 Hz. This feature is very important in any transient mode of operation, especially when the flow signal will be used in an engine control algorithm. Digital data are available and can be transferred through a serial port.

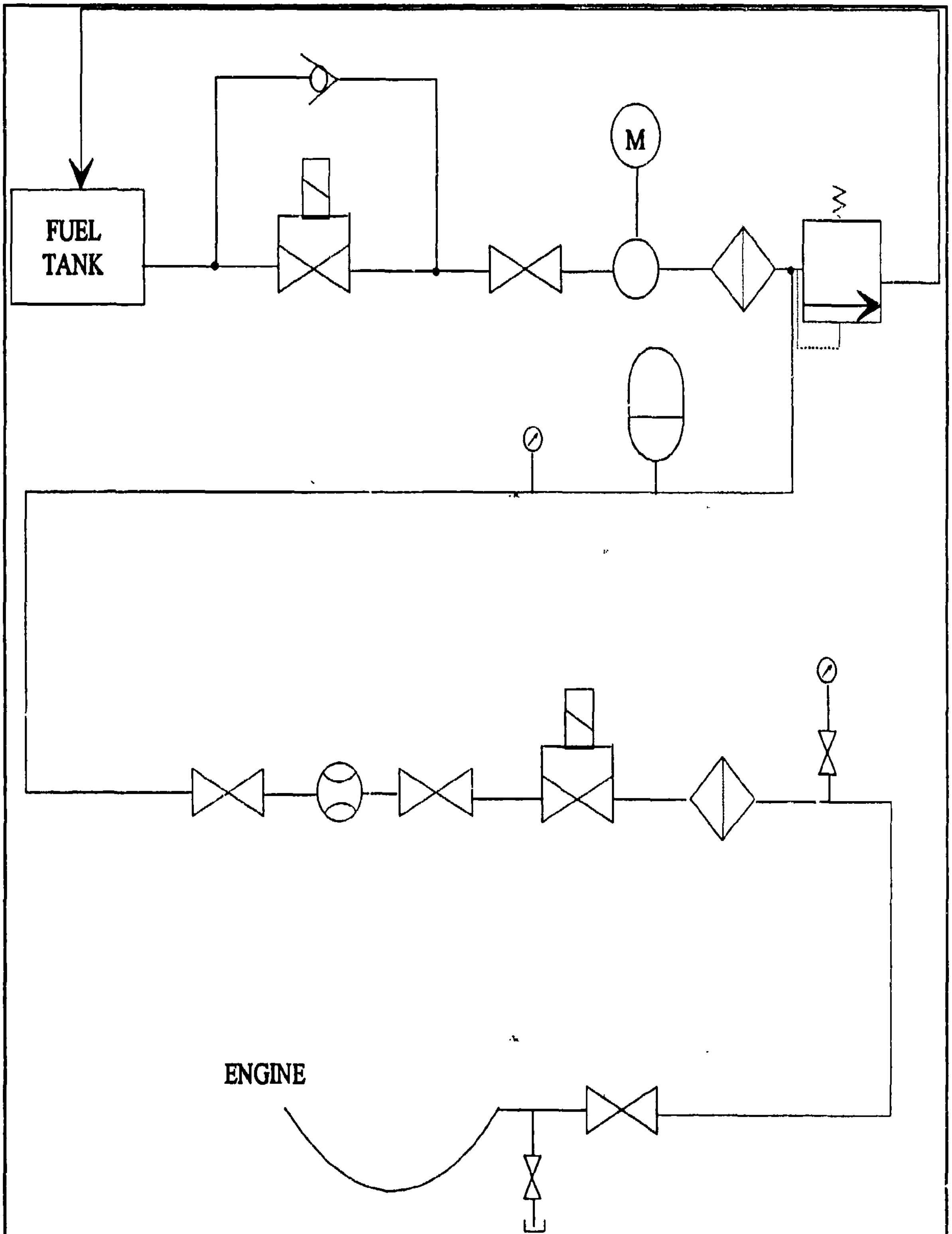


Figure 13: Fuel Delivery System

The system is sized to accommodate engines rated to 1000 lb thrust. Assuming a worst case SFC of 1.2 should provide adequate margin for system sizing. A 1000 pound thrust engine with a SFC of 1.2 would require a fuel delivery and measurement capability of 1200 PPH. Average engine fuel consumption during a test procedure can be calculated as 0.7 multiplied by maximum flow of the largest engine. Using this methodology the maximum average engine flow that can be achieved is less than 2.5 GPM. The system should be sized to give a run time of at least 30 minutes when the largest engines are tested. For JP4 fuel this equates to a minimum of 75 gallons of fuel storage. The fuel system diagram is shown in Figure 13. The system is located in container #3, which is air conditioned or ventilated, and fire protected. From the storage unit fuel is transferred to the test cell via flexible hose.

10.3 Air Start System

The air start system is designed to allow engine starting in any mode of operation of the PSTF.

The system consists of the following:

- -A fully packaged Bauer High Pressure Air Compressor
- -Refrigerated air dryer to remove the water from the system
- -Proper high pressure pre- and coalescing filters to remove the oil from the system
- -Receiver tank to store the air
- -Pressure transducer to send a pressure signal back to the control room
- -Safety valve
- -Pressure regulator to regulate the high pressure within the range of 150 to 1000 psig.
- -Solenoid valve to remotely open and close the system outlet

The supplied air will be clean (20 micron maximum particle size) and dry (dew point 65° F or lower) with storage capacity of 60 pounds of compressed air. Maximum flow of the system is rated at 2 lb/sec, which will allow starting of the largest engines (1000 lb thrust). The system can recharge in 40 minutes from a low pressure of 150 psi to a ready state of 1000 psi, suitable for one full start.

The air system is located in containers #1 & #3. The high pressure air compressor, prefilter, dryer, filter and receiver are located in third container, which is adapted to provide an inlet to the compressor and extraction of heat (12.500 BTU/HR) generated at maximum compressor loading from the receiver (container #3). High pressure air is transferred to the test cell with high pressure flexible hose.

The test cell interfaces with the facility air at the outside of the cell wall with a manual ball shutoff valve on the main supply line. Inside the test cell is a manual ball valve which is used to shut the system down for maintenance or system lockout. A filter is next in the system to protect regulators, valves, instrumentation and the engine from contamination. A pressure regulator adjusts system pressure to the required level and pressure is adjustable from 150 PSI to 1000 PSI. An air driven ball valve controlled from the test room console is used to start the engine. A pressure gage and transducer are teed between the ball valve and the engine to read pressure delivered to the engine. This instrumentation is isolated by ball valves to enable calibration. Connection to the engine is completed with a flexible metal hose to avoid thrust tares on the thrust system. The line can be fitted with adapters to mate to specific engine configurations. The air start system diagram is shown in Figure 14.

10.4 Lubrication System

The lubrication system is designed to provide the lubrication for oil mist lubricated engine bearings. This is obtained using air from the air start system, which passes through a 10 micron filter and solenoid valve, into an oil/mist generator. The mist generator drops the air pressure down to 40 to 60 psig and sets the oil droplet rate per engine specifications. The lubrication system diagram is shown in Figure 15. The oil mist generator is located inside the test cell, close to the engine bearings.

10.5 Ignition system

The ignition system is designed to be interfaced to three different engine start configurations. It consists of a 28 volt DC, 10 amp capacity power supply, a momentary switch at the control panel, and an electrical connector interface in the test cell. The system delivers a 28 volt DC signal to operate the ignition source. A block diagram of the system is shown in Figure 16.

The primary ignition source is a hydrogen/air torch system used to simulate a pyrotechnic torch igniter. The torch control system is mounted on a panel and contains all the interfaces, solenoids and gas sources to drive the torch head assembly mounted on the engine housing. The torch head consists of a housing with orificed inlets for compressed air and hydrogen, a flame tube, and an aircraft spark igniter plug. The gases are regulated to approximately 40 psi above ambient pressure at the engine. Hydrogen and air are injected into the housing where they mix and are then ignited by the spark plug. The burning products flow through the torch tube into the engine combustor where they ignite the fuel/air mixture. The hydrogen igniter configuration is shown in Figure 17. The gases feeding the ignition system flow at a rate of approximately 1 to 2 SCFM for a period of 5 to 15 seconds for each engine start. A small 24 inch tall by 6 inch diameter 2200 psig hydrogen bottle is attached to the control panel and supplies enough gas for 40 to 100 starts.

The second ignition system consists of a electrical ignition exciter (a high voltage capacitive discharge system) that fires an igniter plug. The system is controlled by the 28 volt signal from the test cell control console. The exciter and igniter plug assemblies are engine specific. Exciter systems typically produce from 1/2 to 3 joules output power.

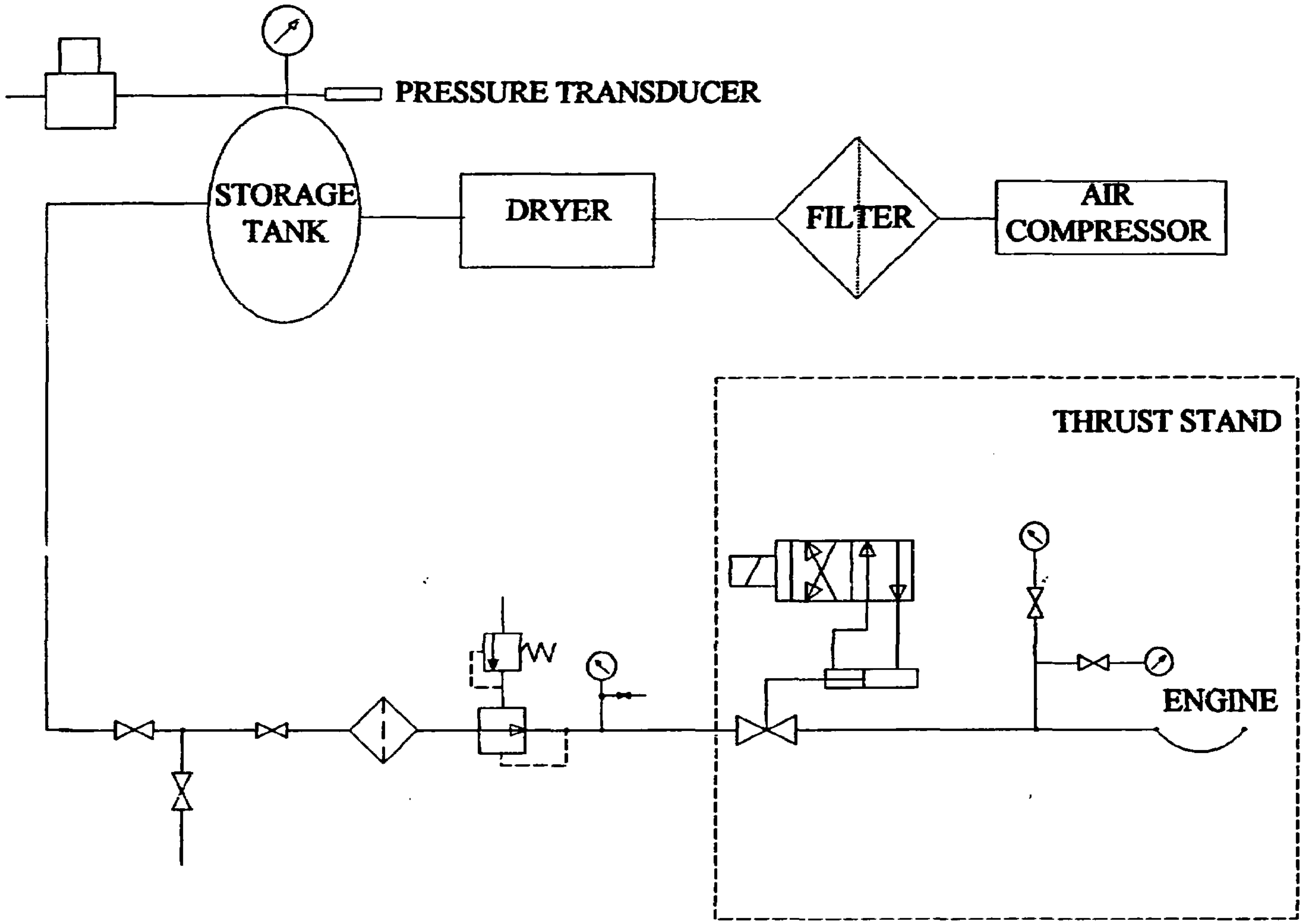


Figure 14: Air Start System

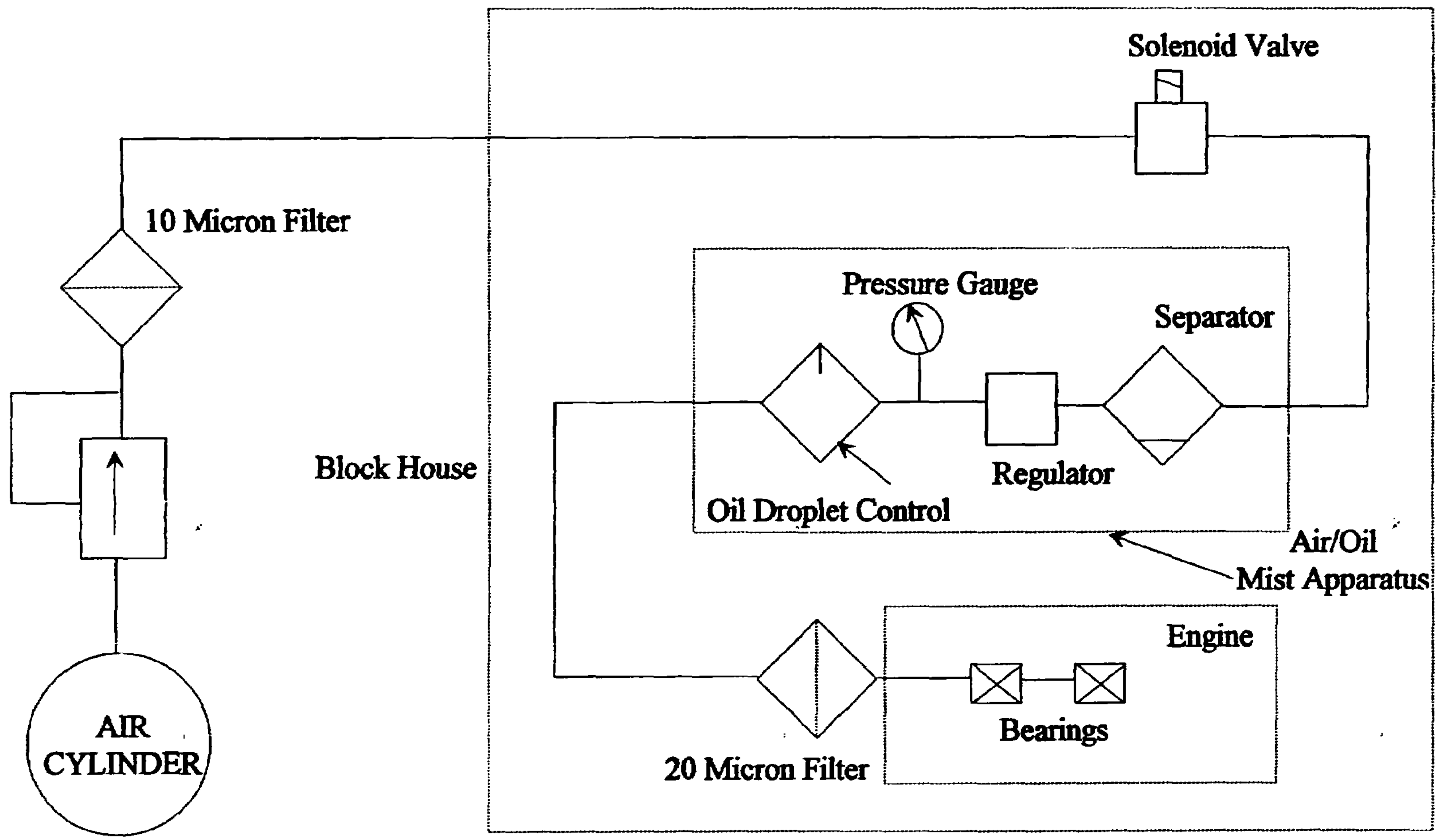


Figure 15: Lubrication System

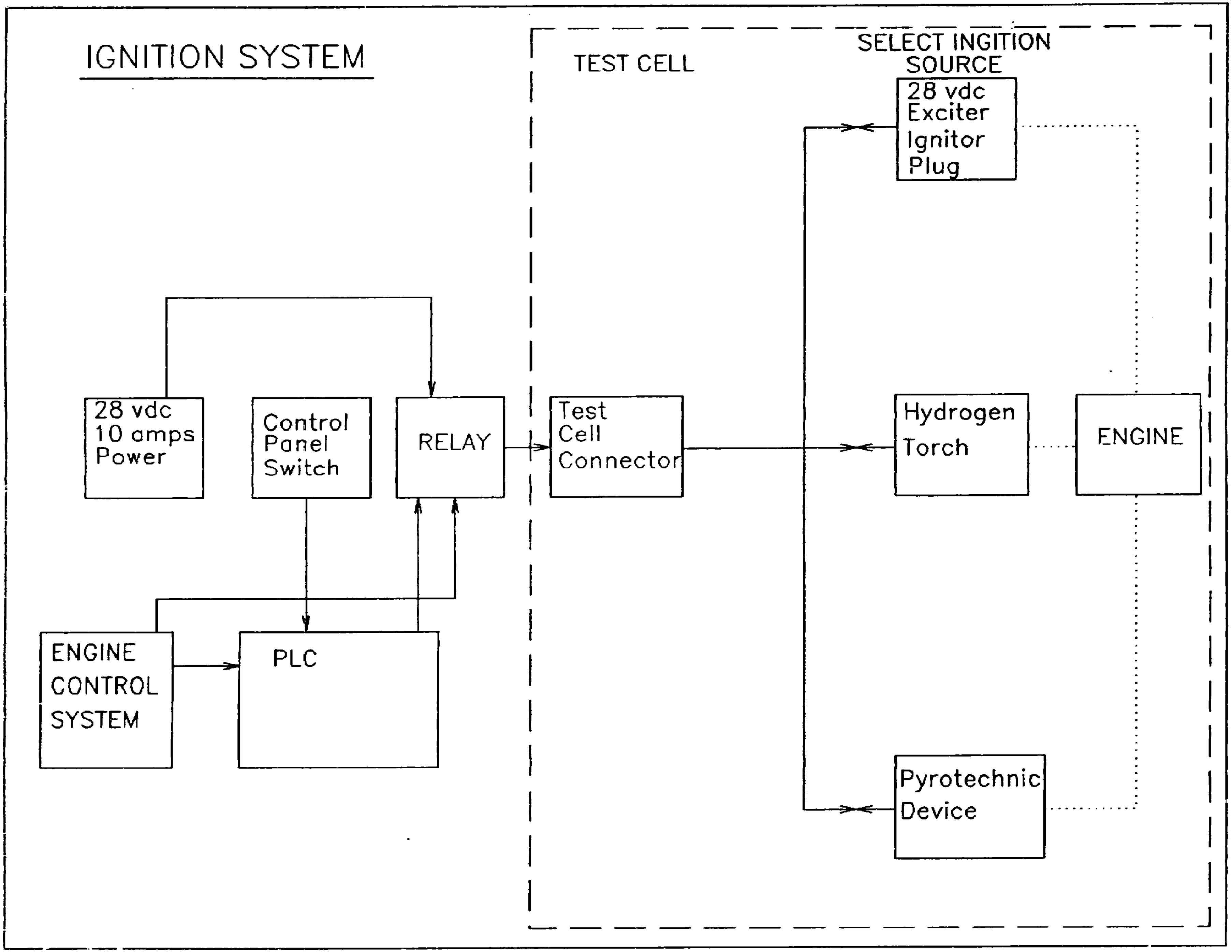
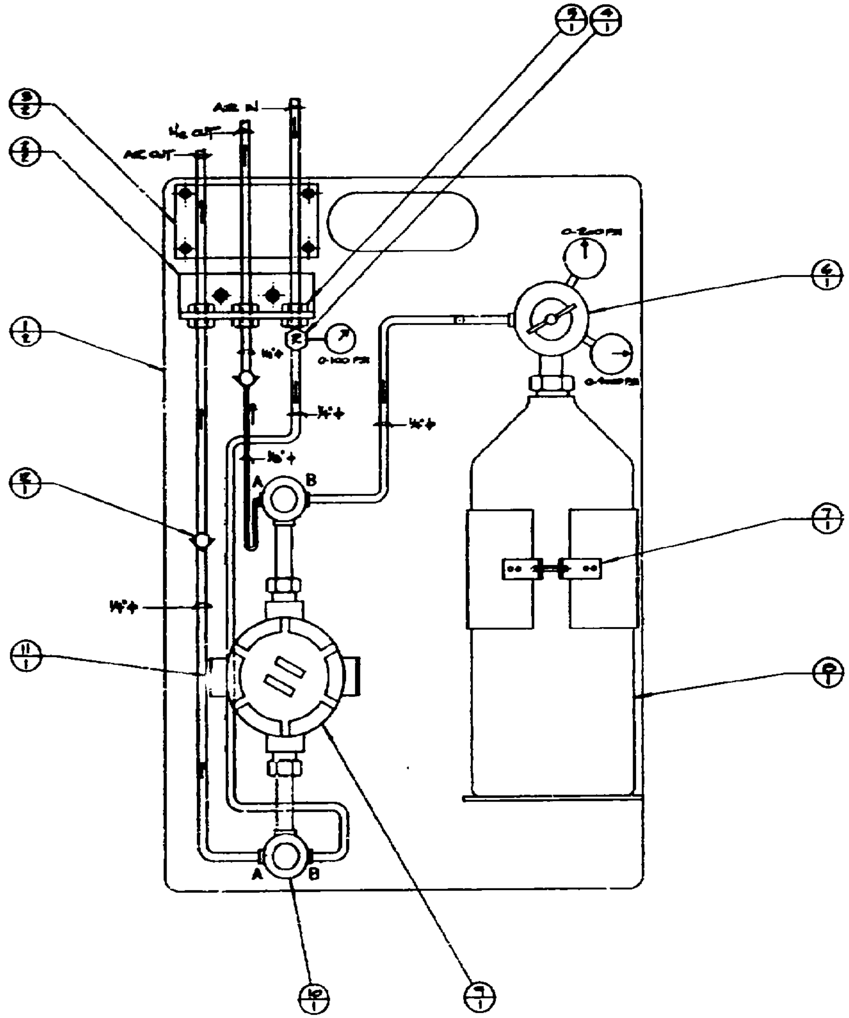


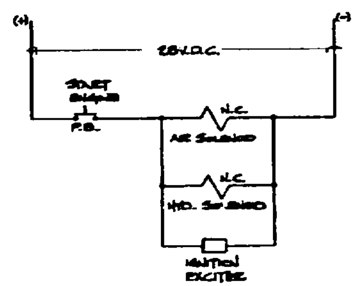
Figure 16: Ignition System



ITEM #	QTY	DESCRIPTION	SHT #
1	1	PANEL	2
2	1	BRACKET	2
3	1	NAME PLATE	2
4	1	AIR REGULATOR W/GAUGE ARO # [illegible]	1
5	6	BULKHEAD UNION SWAGELOK # [illegible]	1
6	1	HYDROGEN CYLINDER REGULATOR VICTOR # VTS [illegible] W/GAUGE (DUAL STAGE) SET DELIVERY FOR 60 PSI	1
7	1	CYLINDER CLAMP	1
8	1	HYDROGEN CYLINDER [illegible] 20 CU/FT CAP.	1
9	1	HAZARDOUS LOCATION [illegible] CONDUIT BOX (3/4" HUB) CROUSE-HINDS # [illegible]	1
10	2	SOLENOID VALVE ALLEN AIR # [illegible] 125 PSI, .125 ORIFICE, 7W, 24VDC, NORM. CLOSED	1
11	2	PIN LUG # MS-[illegible]	1
12	2	CHECK VALVE SWAGELOK # [illegible] [illegible] PSI CRACKING PRESS.	1

NOTES:

ALL TUBING TO BE 304 STAINLESS STEEL (.035 WALL - SEAMLESS)



ELECTRICAL SCHEMATIC
NO SCALE

Figure 17: Hydrogen Engine Igniter

The third system consists of a BOM engine mounted pyrotechnic igniter. The system is fired by a 28 volt control room ignition signal. The control room signal will have provisions for actuating the start command from the engine control computer.

10.6 Data Acquisition, Test & Measurement Systems

The purpose of a data acquisition system is to acquire real-time data from numerous sensors, convert the raw signals to engineering units, calculate engine parameters, display raw and calculated values to the operator, and store data for later analysis. The data system does not control the engine, control the test facility, or make decisions on engine health. Systems that do provide control must, by design, be inflexible, with fixed responses to specific conditions. This is usually not the case when doing development testing so a data system for this purpose must be flexible in terms of both hardware and software configuration changes.

The data system is composed of off-the-shelf, proven, commercially available components whenever possible. The components are chosen from manufacturers whose main product is the component being purchased. The components are organized in a modular configuration allowing for easy fabrication and replacement. The separate PC, Uniform Temperature Reference (UTR), and multiplexer arrangements give the best system flexibility, allow for individual component upgrades in the future and provide sufficient room for proper ventilation of electronic board assemblies.

As concluded in previous sections the data acquisition system is the heart of modern jet engine test facilities. Research activities conducted during this Phase I contract investigated many different data acquisition systems.

An objective evaluation and subsequent selection of a computer-based data acquisition system is complicated by both a lack of industry standards regarding performance specifications and the number of options available from different manufacturers. Because the systems' primary function is to make measurements, the emphasis ultimately must be placed on those system attributes that directly influence the system's ability to perform this function. These include measurement accuracy, bandwidth, and sensor compatibility. Depending on the application, some characteristics may be more critical than others. An objective selection of the most cost-effective solution for the given application can then be made weighing all comparison values for each system.

Three potential solutions were extensively analyzed:

-AutoNet data acquisition & control software from Imagination Systems

-Labview from National Instruments

-Dasy Lab from Microstar Laboratories

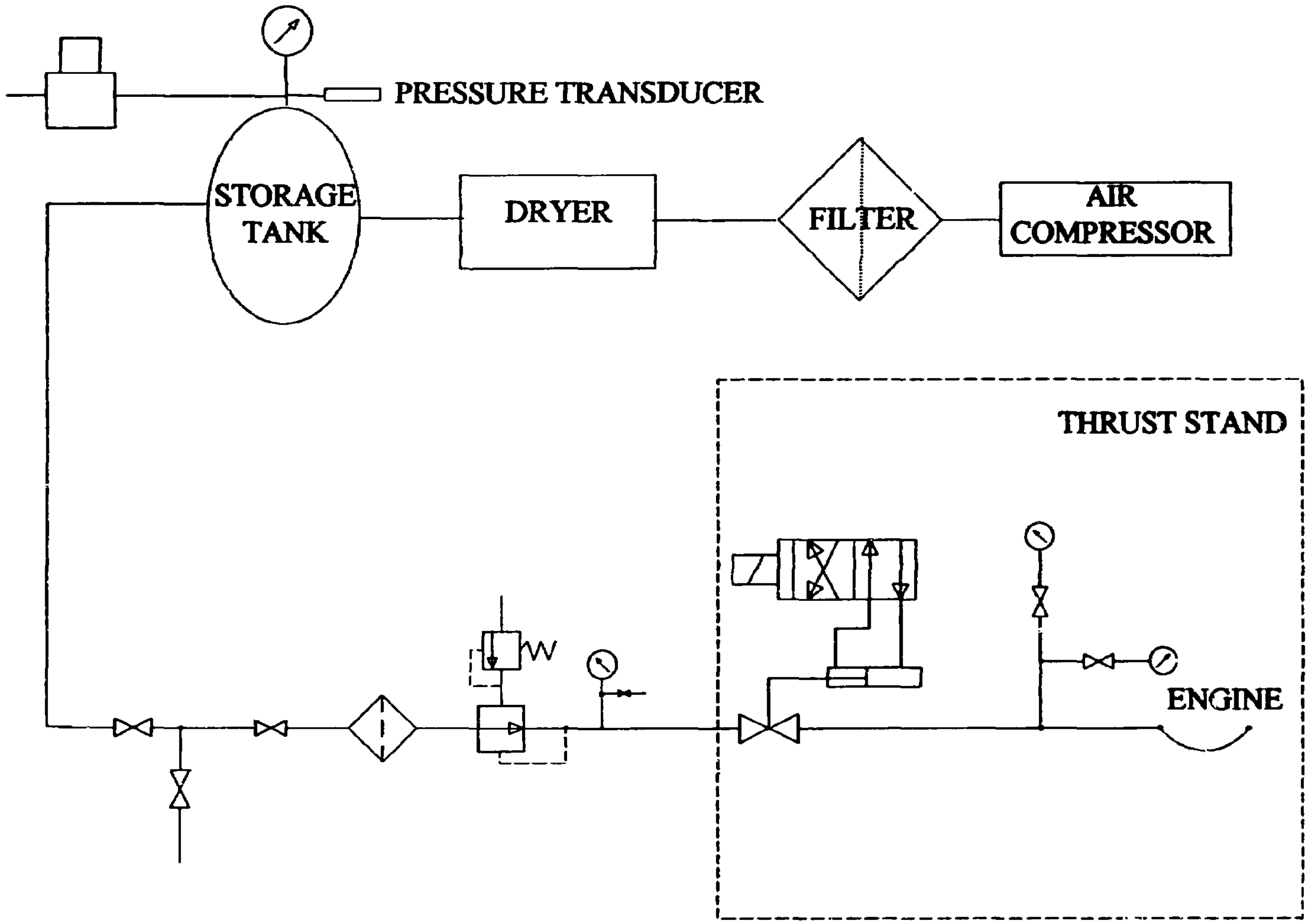


Figure 14: Air Start System

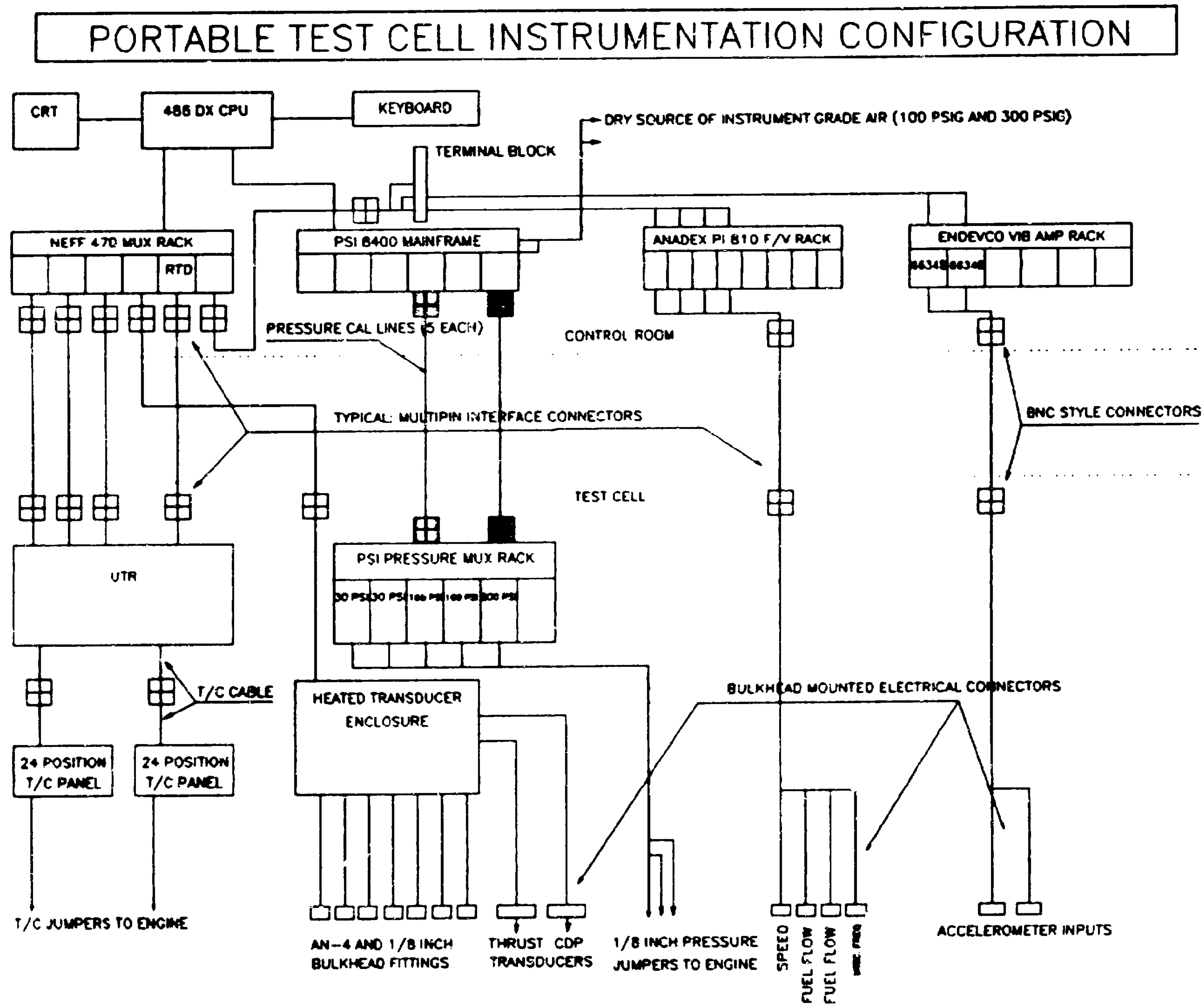


Figure 18: Test Cell Instrumentation

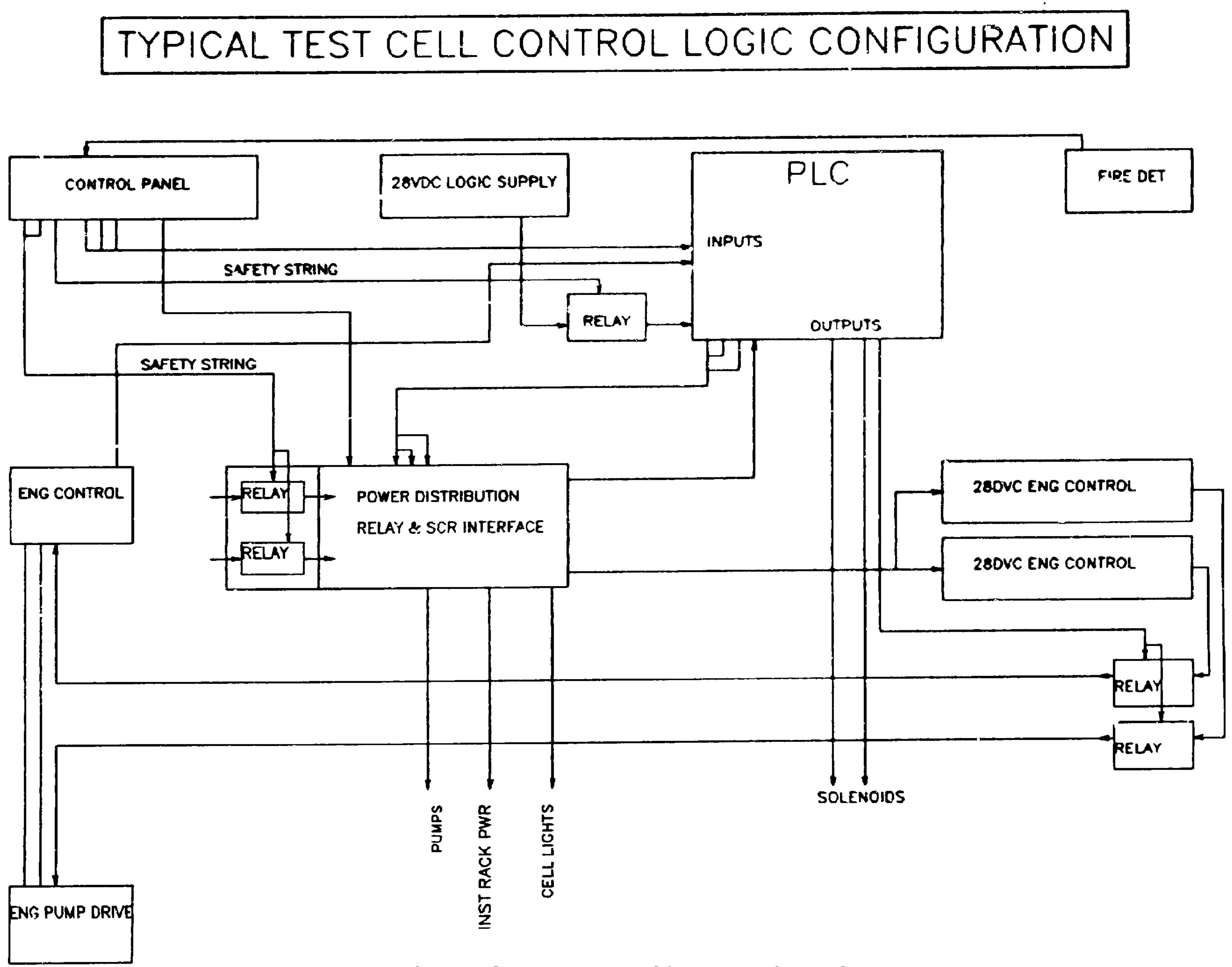


Figure 19: Test Cell Control Logic

10.6.1 Data Acquisition Computer

The data acquisition hardware platform is an IBM compatible, industrially hardened personal computer with an Intel 80486DX 50 MHz processor. The chassis is rack mountable with a multi-slot ISA passive backplane. The unit is powered by a 250 watt supply and is cooled by a filtered fan assembly. The PC is configured with 8MB of RAM (expandable to 32 MB), a 128KB disk cache and in IDE hard drive/dual floppy controller. Peripherals include a 500MB hard disk drive, 1.44mb floppy drive, 14" VGA rack mount color monitor, cartridge tape drive and a laser printer. All drives are shock mount isolated to prevent damage from vibration. Two serial ports, one parallel port and a keyboard are also provided. The system also includes the IEEE 488 and SCSI cards to interface to the NEFF and PSI systems.

10.6.2 Software System

The proposed data acquisition software is AutoNet from Imagination Systems. This software provides a complete framework for programming and running engine tests. Basic AutoNet comes with a real-time UNIX operating system and can support up to 250 simultaneous tasks, 64 data logs, and 8 full screen windows/users. A separate disk partition can be set up to run DOS applications. AutoNet can convert logged data to many popular DOS formats including PRN, WK1, DBF, DIF, and ASCII.

AutoNet is a mature software package that incorporates device handlers, graphic displays, file management, program editing, and data acquisition into a menu driven integrated package.

AutoNet menu features include:

- Configuration of the NEFF system 470 and PSI 8400
- Setup of data logging schedules, (channels and rate).
- Creation of multiple graphic screen displays, (gauges, strip charts, bars etc.).
- Control of system security, (passwords, priorities, user names).
- Software calibration module
- Real-time and historic data displays
    - Strip charts
    - Trends
    - X-Y Plots
- Disk file management
- Data transfer / conversion
- Four levels of alarms, (HI-HI, HI, LO, LO-LO).
- Printout of logged data

All aspects of AutoNet may be set up through interactive menus, then stored and used repeatedly. The menu setup greatly reduces the learning curve. AutoNet also can be programmed in ACL, a specialized language similar to "C". ACL programming provides increased flexibility in data handling and operator interface. By mixing menu programming and ACL programming the system can be configured to do any application.

AutoNet provides pre-programmed menu configurable interfaces for each multiplexer device. Setups can then be stored to be used later. Graphic displays, tabular displays, strip chart setups, trend charts, x-y plots, and operator interfaces can also be menu programmed and stored. Data logging to disk can be set up, and rates and channels are independent of scanning lists. Multiple setups for different engines or tests may be stored and recalled at a later date. Data report printouts can be generated and sent to printer, screen or file. Screen prints can be made at any time.

For applications that require more than straight data acquisition, the ACL programming language is included. ACL programs may be written to do real-time calculation, special data handling or printouts. Any function available from the menu selections is available from an ACL program. ACL programs may be attached to "sets" or may be used to configure the system.

Using the ACL programming language a system of menus has been set up for load cell constants and engine specific data. Each device has an ACL program associated with it that runs each time the device is scanned. This allows the programming of real-time calculations and program response to operator inputs. A post test program moves data to a holding directory on the disk and prepares the system for the next engine test.

The system is equipped with a laser printer. Custom printouts can be programmed using ACL and the printers PCL language. Font, size, margins, form feeds, and position are all programmable through PCL.

The complete data system is designed to be flexible. No programming experience is necessary. The user can easily modify the data acquisition set up and store it on disk through the program menus. Each engine can have its own configuration setup stored.

A complete system of priorities, user ids, passwords, and scripts are available to setup multiple users with different system access. A user id can be set up that automatically runs a stored setup without using the menu system at all.

AutoNet is fully supported by Imagination Systems. Software maintenance agreements are available as well as basic and advanced training courses.

10.6.3 Multiplexer

The data are acquired by a NEFF 470 low level multiplexer. The data system performance and accuracies are as follows:

Scan Rates

The NEFF 470 multiplexer is capable of scan rates up to 10,000 channels per second. It can handle 16 input or output boards, with a maximum channel count of 16 channels per board. A typical data system contains 48 low level thermocouple channels, 32 analog voltage channels and 4 RTD channels, totaling 6 I/O boards and 84 channels.

The NEFF 470 contains two 4096 byte memory banks to buffer data. By using two buffers data may be acquired and transmitted at the same time.

Data are transmitted to the computer across a SCSI (Small Computer System Interface) link. The SCSI link supports DMA data transfer rates of 5 Mb/sec. Data are stored in the computer memory's Point Data Base, PDB.

Maximum data rates to disk vary with disk access time. Average disk access rates range from 8 to 15 ms, limiting disk access to about 50 times per second. Data from the NEFF 470 may be saved directly to circular disk buffers using the AutoNet NEFF event mode, at rates of 40 times per second.

Data from the Point Data Base are available for display, logging, and calculations. Data may be displayed at user selectable rates from once per second to 40 times per second. Data may be logged from the Point Data Base to disk at rates up to 40 times per second. Typical system data logging rates are:

NEFF event logging	40 times per second
Transient logging	40 times per second
Periodic logging	1 per second
Single Scan	Average data over 10 seconds

The NEFF 470 has a full scale accuracy of ± 0.05%, and ± 0.002%/ °F.

Data are acquired by a NEFF system 470 low level multiplexer. The system 470 contains a 16-bit A/D converter, scaleable input amplifiers, and SCSI or IEEE-488 computer interface logic. Individual channels may be programmed with full scale ranges from 5mv to 10.24 volts, and thermocouple signals may be read with no additional amplification. The standard system 470 may be configured with up to 16 function cards. Function cards are available for strain gages, RTDs, potentiometers, thermocouples, frequencies, and digital I/O. Each card can acquire up to 16 channels of data allowing a maximum channel count of 256. Higher channel counts can be achieved by adding a slave system 470 chassis. The maximum aggregate data throughput rate is 10,000 samples per second. The recommended base system is configured with 48 thermocouple channels, 32 analog voltage channels, and 4 RTD channels. The thermocouples are type K, Chromel-Alumel, although other types can be supported with the proper reference junction compensation. The analog voltage channels are used to acquire thrust, speed, fuel flow, and pressure signals. Appropriate signal conditioning will be provided to convert frequency signals to analog voltages. The RTD channels will be used to read the thermocouple reference junction temperature.

The main components of the system are:

Item	Description	Model	Qty
1.	NEFF rack	NEFF 470100	1
2.	T/C Mux	NEFF 470051	3
3.	Volts Mux	NEFF 470050	2
4.	RTD Mux	NEFF 470055	1
5.	Connectors	Matrix	8

10.6.4 F/V Converter

The frequency interface will be handled by high speed Anadex Model PI-810 F/V's. These F/V's provide the slew rates (3 msec for a 2:1 step change in input frequency) necessary to give reasonable speed information at high data system scan rates (40 scans/sec). They are highly linear (+/- 0.02% of full scale) and will not add any significant error to the frequency conversion process. The F/V conversion process is performed by a period time measurement and time to frequency conversion program. These units provide no ripple in the output voltage at low frequencies and can be scaled for any full scale range of 50 Hz to 51,200 Hz. The main components of this system are:

Item	Description	Model	Qty
1.	F/V	Anadex PI 810	4
2.	F/V rack	Anadex HR-810	1

10.6.5 Vibration Measurements

Vibration signals will be handled by Endevco 6634B charge amplifiers which will interface with the user's piezoelectric accelerometers via a panel mounted coaxial cable interface in the test cell equipment rack. The 6634B amplifiers feature a programmable digital display that provides vibration information in many common formats such as g's or ips in RMS or peak units. The amplifier has programmable input sensitivities and a programmable bandwidth filter that can be setup with user defined high pass and low pass frequency limits. The 6634B amplifiers will be mounted in the control room for easy operator programming and monitoring. These amplifiers have a DC output that is proportional to the displayed vibration signal. This output will be routed to the NEFF 470 analog voltage inputs for data system logging. The vibration amplifiers also have conditioned AC outputs that can be routed to user equipment for spectral analysis. The proposed system will be supplied with two 6634B amplifiers mounted in a six position rack. The user can add up to four additional amplifiers to support additional testing needs. The selected amplifiers are used in many test cells and have provided excellent stability for monitoring a variety of piezoelectric accelerometers under many different operating conditions. The main components of the system are:

Item	Description	Model	Qty
1.	Vibration amps	Endevco 6634B	2
2.	Amplifier rack	Endevco 4948	1
3.	Accelerometer	Endevco 2221F	2

10.6.6 Uniform Temperature Reference (UTR)

Thermocouple cold junction connections will be made through a UTR (uniform temperature reference) unit that uses a platinum RTD for reference junction temperature measurement. The UTR is mounted within the test cell boom.

Placing the cold compensation termination in a rack adjacent to the engine greatly reduces the thermocouple (T/C) wiring costs. The interface cables carrying the T/C signals are conventional shielded multi-pair copper twisted pair assemblies. The UTR assembly is fabricated as a modular unit with all interface cables attached prior to installation in the equipment rack.

Conventional brass pin and socket terminations are used on the thermocouple cable assemblies at the multipin connector interfaces. Williams International has been using these techniques for over 15 years with no sacrifice in accuracy. The two T/C mating wires are axially within 1/2 inch of each other, surrounded by thermally conductive brass. The use of brass pins and sockets in circular style connectors has proven to be an acceptable method for T/C cable connection for test cell interfaces. Thermocouple material pins and sockets are quite cost prohibitive for multi-channel use (cost per T/C pair for one set of connections is approximately $30 to $50). Thermocouple calibrations from the boom end back to the data system at prevailing ambient temperature conditions (-10 deg F to + 110 deg F) have been successfully demonstrated and no problems have occurred with temperature induced offsets in the multipin T/C wiring connectors.

A Computer Products UTR will be used. It is an industry standard and is used in a number of data systems including the Modcomp and Aero Systems acquisition systems. They consist of a solid massive UTR block encasing tapped brass feed through tie points. The thermocouple wire and copper wire are attached to opposite ends of the tie points with a rugged screw, lock washer and wire bushing assembly. These tie points are easy to wire, offer a secure attachment point and are spaced sufficiently to eliminate any wire-to-wire shorts. The massive UTR block combined with insulation approximately 3 inches thick offers very good temperature uniformity. A platinum RTD senses the UTR temperature and is connected to a RTD card within the data system MUX rack.

RTDs provide a good long term stable method of UTR block temperature measurement and are easily read by the data system input card. This technique has been used at Williams International for the past 18 years. During the past 5 years the UTRs have been mounted in the test cells for both permanent and portable test stand applications.

Marlin Manufacturing T/C connection equipment will be used. Marlin plugs and jacks offer positive wire retention, easy assembly and can be supplied with optional strain relief hardware.

The system consists of:

Item	Description	Model	Qty
1.	UTR 48 ch wired	Computer Prod	1
2.	Connectors	Matrix 39 & 55 pin	8
3.	Jack Panels	Marlin Mfg	2
4.	T/C cable	Marlin Mfg	1000'
5.	T/C connectors	Marlin Mfg	120

10.6.7 Pressure Scanning System

The dry pressure scanning system is a PSI 8400 series multiplexing scanner that uses a "transducer per channel" technology. The 8400 system scans pressures in 16 channel banks with the banks being electrically multiplexed into the 8400 system processor. The system processor is housed in the control room data acquisition rack and connected to the transducer banks in the test cell boom via a multi-conductor cable. A PSI rack adapter frame houses and holds up to 6 banks each of 16 channel pressure scanning modules. Each pressure scanning module contains 16 each, 1/8 inch swagelok female fittings that provide a convenient engine interface. The pressures are then plumbed from the boom to the engine using 1/8 inch diameter nylon or Teflon tubing. The close proximity of the equipment rack to the engine facilitates easy line plumbing and verification of proper connections.

The system processor rack in the control room contains the multiplexer that reads the individual pressure modules, a 16-bit digitizer, the system processor and the pressure calibration modules. The calibration modules provide a 5 point pressure calibration for the system transducers each time the system is brought on line. This automatic calibration feature provides for extremely high accuracy measurements (+/- 0.1% FS). The calibration modules connect to the boom rack through a combination of five 1/8 inch and 1/4 inch nylon pressure lines. These lines operate the pneumatic calibration valves in each scanning module and provide the reference pressure sources to the transducers during the calibration cycle. The electrical interface and pneumatic interfaces from the control room all enter the modules through a backplane combination electrical/pneumatic interface. Modules can easily be changed from the front panel. The system capability can be easily upgraded by purchase of additional pressure scanning modules. The output from the system processor is linked to the data acquisition computer via an IEEE 488 cable.

The initial system configuration will consist of two 16 channel modules of 30 psi range scanners, two 16 channel modules of 100 psi range scanners and one 16 channel module of 200 psi range scanners for a total capability of 80 dry pressures. The system has the ability to accept one more 16 channel module. Expansion of the channel count beyond 16 channels will require a second rack adapter and cabling.

The rack mounted pressure scanners with front panel 1/8 inch swagelok fittings provide the pressure scanning and test cell interface in one package. No additional pressure boom panels and plumbing are needed. System upgrades are made by just plugging in the additional scanners, configuring the data system to read them and plumbing the engine parameters to the swagelok ports. Plumbing confusion is eliminated by having the channel number and pressure ranges clearly marked on the module face.

The system consists of:

Item	Description	Model	Qty
1.	Mainframe	8400 system processor	1
2.	Pressure scanner	S1600	5
3.	Calibration unit	8432	3
4.	Cables, misc panels		1 lot
5.	Scanner digitizer	8488	1
6.	Scanner interface	S16R-01	1

10.6.8 Transducers

The development of fast real time data displays, more stable high level output transducers and decreasing test cell budgets has lead to the elimination of transducer signal conditioners and dedicated readouts. Reliability of data systems has become such that the test engineering community feels comfortable monitoring critical engine parameters with the computer data system displays. A combination of strain gage and variable reluctance style transducers will monitor the engine parameters. These transducers will be configured as high level output type units (5 to 10 VDC output for FS input) with 28 volt DC unregulated power input. The transducers will be packaged in heated transducer boxes whenever possible to help reduce the number of direct engine mounted units. The reduction of the number of transducers hanging on cabling has eliminated a lot of cable repairs, damage to transducer fittings and provides for better long term stability (3 to 6 months).

Two styles of transducers are being proposed to meet the needs of the test facility. Strain gage units will be selected for those measurements that need high accuracy and the operational ranges are well known (CDP, air flow delta-pressures, barometer, fuel pressures, etc.). The strain gauge transducers meet a best straight line fit (BSL) of 0.15%FS to 0.35%

FS static accuracy. Variable reluctance units will be selected for less critical parameters such as oil pressures, hydraulic pressures, bleed pressures and pressures with uncertain maximum ranges. The variable reluctance units typically have a BSL of 0.5% FS to 1% FS static accuracy. Variable reluctance units can be easily re-ranged with a low cost diaphragm replacement. This construction will also allow for easy, low cost repair of the transducer in the event an overpressure condition is experienced during testing. The user will be able to easily adapt the variable reluctance units to changing test pressure measurement requirements.

Individual transducers will be mounted in a heated box located inside the equipment enclosure adjacent to the test stand. This configuration limits the thermal drift of the transducers and mechanically protects them. The box is kept at an elevated temperature using a solid state controller. The transducers are interfaced to the boom rack by bulkhead fittings.

Close coupled transducer requirements will be met by providing boom panel mounted electrical connectors and short cables to power the engine mounted close-coupled transducers. The individual transducers are wired via a terminal strip to the 28 VDC power and the multipin interface connectors for data system input. The terminal strip connections for the box mounted transducers and the close coupled bulkhead connectors are made inside the equipment enclosure for ease of installation and troubleshooting.

During the past seven years Williams International has been using high output level Druck and Validyne transducers for most of the new test cell configurations and test cell upgrades. The Druck units have proven to be quite stable and offer good accuracy and stability. The Validyne units are being chosen for their ability to be easily re-ranged and repaired. The transducer electrical connections are industry standard MS 3116 style bayonet connectors with the excitation being on pins A and D and signal output being on pins B and C. The pressure ranges are based on engines having a maximum expected compression ratio of 9:1.

The set of transducers which are included in the preliminary design are listed below:

Item	Description	Manufacturer	Qty
1.	Barometer	Druck PDCR 130/W/C Range 15 psia	1
2.	Close Coupled CDP	Druck PDCR 350 Range 150 psig	2
3.	Inlet Delta	Druck PDCR 130/WL Range 2.5 psid	1
4.	Start air press	Druck PDCR 330 or Validyne P365 Range 300 psi	2
5.	Fuel pressure	Druck PDCR 330 Range 150 psig	2
6.	Cell Delta press	Validyne P305 Range .2 psid	1

7.	Oil mist, Main Oil	Druck or Validyne Range 100 psig	2
8.	Misc pressures ranges	Validyne P305 with ten interchangeable diaphragms	3
9.	Spare channel for future needs		1
10.	Channel for thrust load cell		1

These transducers have compensated operating ranges of -65 deg F to +250 deg F. The total error band over the whole temperature range can reach approximately 3% to 5% of FS range. The use of a heated transducer box and/or careful placement of the transducers helps reduce error due to temperature excursions.

10.6.9 Thrust Measurements

The thrust measurement needs will be met by a combination of two thrust beds that will cover engine thrust levels from 20 to 1000 pounds. Figure 20 details the stand that will be used to measure thrust levels up to 500 pounds and Figure 21 details the stand that will be used to measure thrust levels up to 1000 pounds. Both of these stands were developed at Williams International and have been in use for over 18 years. The stands employ a flexure hung thrust bed design with a tension loaded force cell mounted under the stand. The stands are a tube and plate fabricated assembly that attach to the floor or the test cell. Only one thrust stand is installed at any one time.

The load cell for thrust measurements is an Interface model 1010 low profile unit. A Precise Sensors 9000 series DC powered signal conditioner is used to convert the load cell reading to a high output level (nominally 10 VDC for 1000 lb). The signal conditioning unit is mounted in the heated transducer box and interfaced to the load cell via a panel mounted multipin connector. These thrust measuring systems have a long term stability of +/- 0.5% of reading +/- 0.1% FS range. They typically do not require any signal conditioning adjustment for periods greater that a year.

The main parts of the thrust measurement system are:

Item	Description	Manufacturer	Qty
1.	Thrust stand	WI	2
2.	Load cell	Interface 101	2
3.	Signal conditioning.	Precise Sensor	2

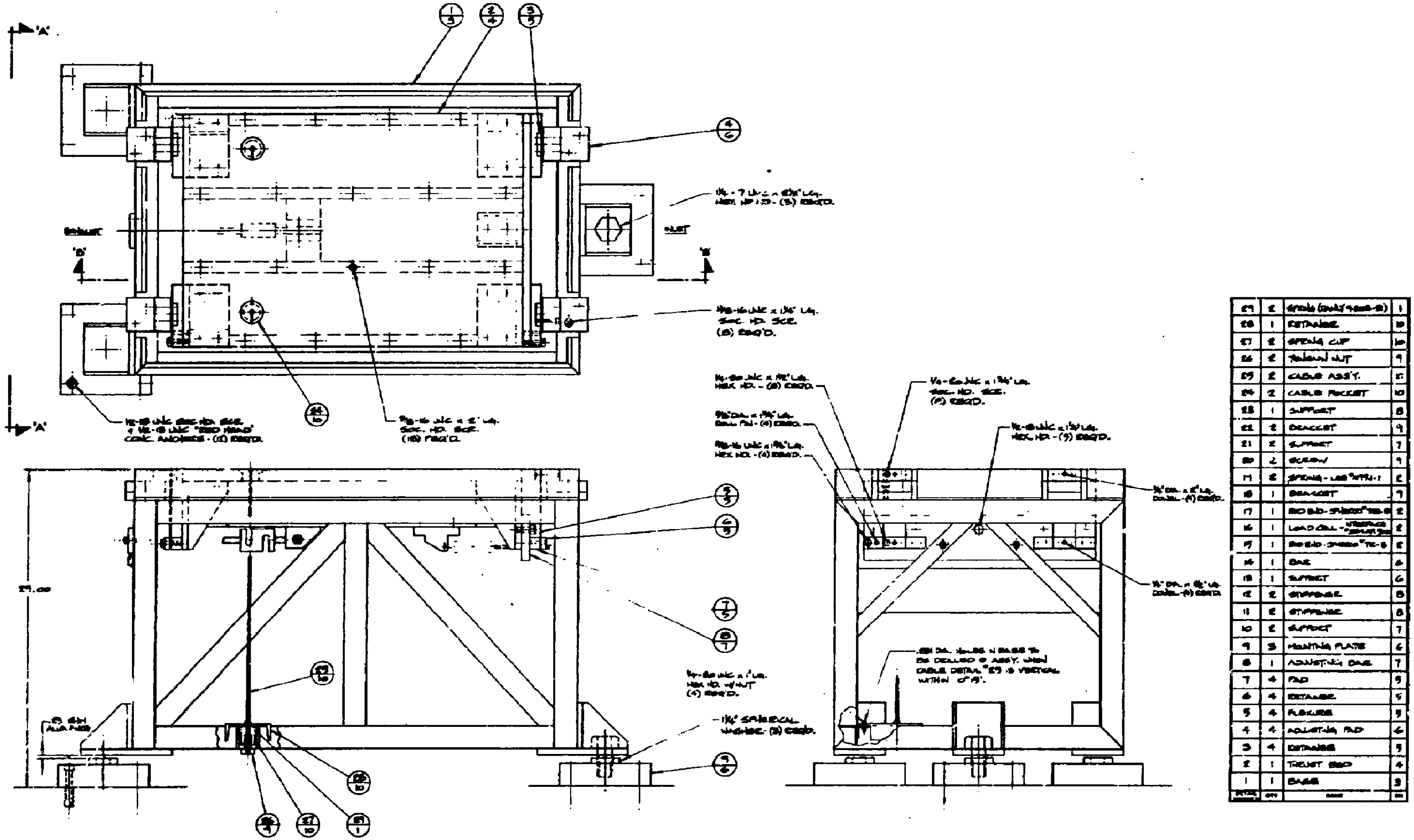


Figure 20: Thrust Stand 20 - 500 lb

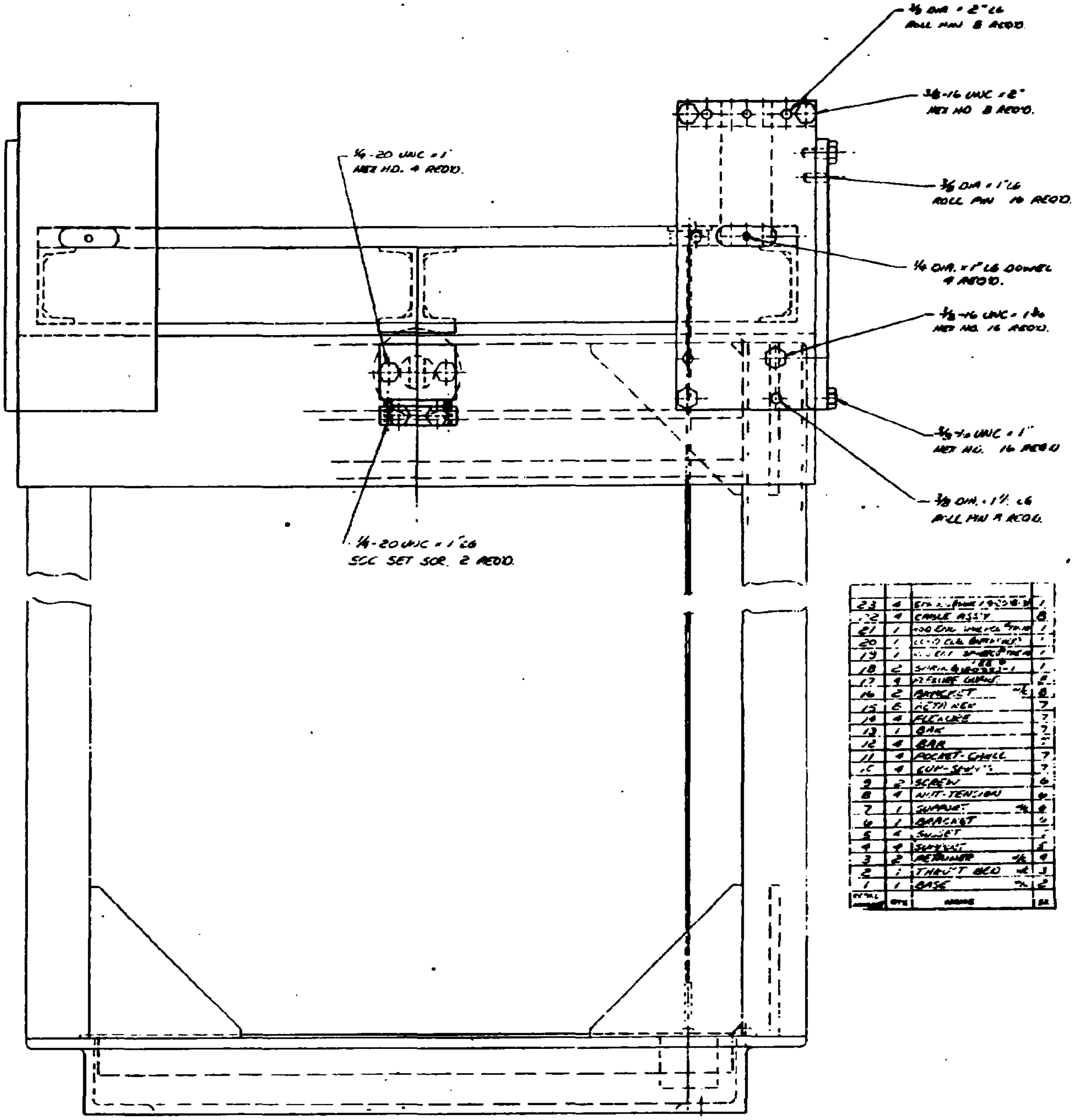


Figure 21: Thrust Stand 20 - 1000 lb

10.6.10 Test Cell System Interfaces

A variety of interfaces are used to connect the different parts of data, test and measurement system. The main interface between the test cell and engine is through an instrument boom consisting of a 19 inch panel rack cabinet (24" wide x 32" deep x 68" tall) that houses the pressure transducers, UTR (T/C interface), dry pressure scanning modules, frequency connections and the vibration monitor connections. The boom is placed adjacent to the test stand and connections are made to the engine via short cable and pressure line jumpers. This configuration allows for easy hook-up of the engine parameters, quick verification of instrumentation channel to engine port inner-connections and ease of maintenance.

The connections to the instrument boom are made through commercially available connectors and fittings. The boom is connected to the acquisition cabinet (24" wide x 32" deep x 78" tall) in the control room via multipin connectors and cables. The acquisition cabinet houses the data system , NEFF 470 MUX, frequency interface instruments, vibration readout equipment and the data system display terminal. The use of multipin interface connections eliminates errors during installation and allows for quick dismantling and reassembly of the test system. No cables remain attached to the cabinets during moves. Initial check out is easily done and field damaged cables can be quickly replaced with minimal down time.

Using identical multipin cables provides for a calibration interface into the data system that only requires one or two calibration cables to be fabricated. Multiple channels can be calibrated at one time with one jumpered calibration cable set. By interfacing the calibration equipment at the multipin connection furthest from the data system a near "end to end" calibration can be accomplished. This methodology allows the calibration status of the data system to be verified quickly on site after equipment installation.

The number of different connectors are kept to a minimum, with only two types of connectors used to make the majority of the instrument connections (a 55 pin size 22 Matrix connector for T/C interfaces and a 39 pin size 20 connector for copper connections). The wiring codes are standardized and both ends of the jumper cables are identical. The use of identical cables for hook up allows easy swapping to aid troubleshooting and spares can also be kept to a minimum. The test cell interface rack is shown in Figure 22. The equipment layout in the test cell is shown in Figure 23.

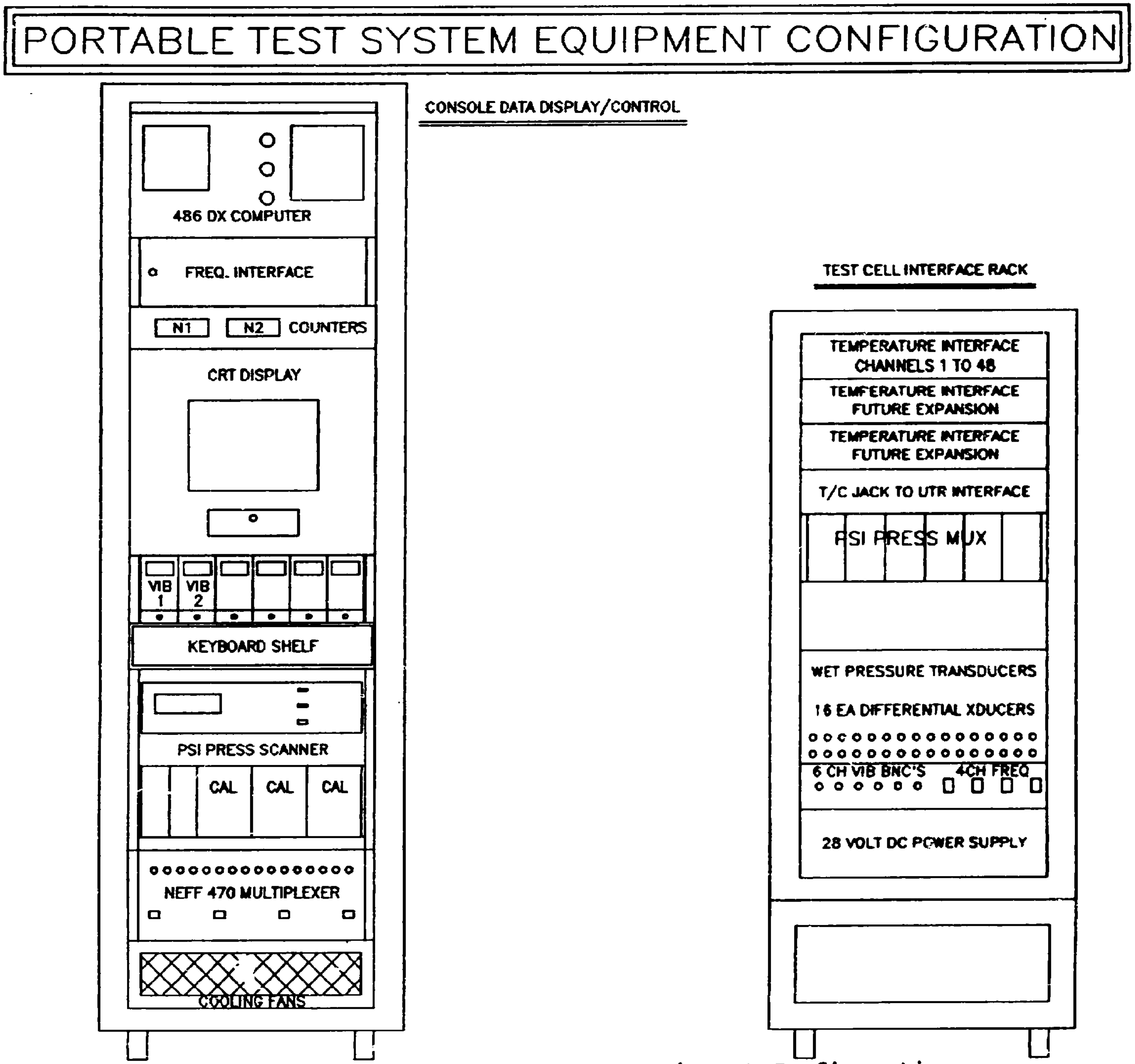


Figure 22: Test Equipment Configuration

PORTABLE TEST CELL EQUIPMENT LAYOUT

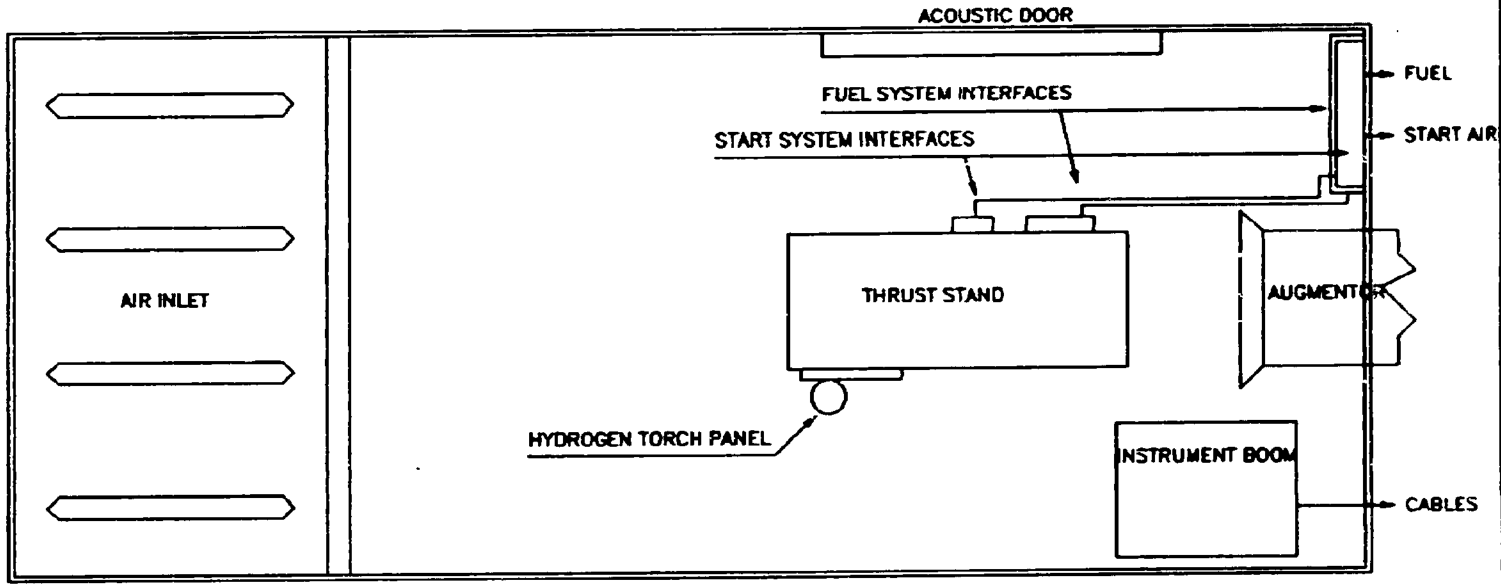


Figure 23: Test Cell Equipment Layout

10.6.11 Calibration System

To keep measurement uncertainty within acceptable limits a calibration system must be established and the performance of the calibration system determined. The recommended system calibration interval is 3 to 6 months. The accuracies listed below are the accuracies that the system can hold for the length of the calibration period in a relatively stable test cell environment. The frequency and conditions of equipment transportation may require adjustment of these recommended calibration intervals. The system is being designed so that a minimum of equipment will be need to calibrate the system. The modular construction allows for easy calibration access and verification of system performance. The minimum recommended calibration equipment is:

Item	Description	Manufacturer
1.	Thermocouple simulator	Ectron Model 1000 or equivalent
2.	Pressure calibrator press up to 300 psig	Druck DPI 510 multi-range calibrator or equivalent with barometric option and vacuum capability
	Press above 300 psig	Master test gauge (.25% or .1% accuracy) and adjustable pressure source (hyd hand pump or high pressure air bottle)
3.	Frequency calibration	Wavetek 171 signal generator or equivalent
4.	Voltage calibration	EDC Model 330 or equivalent
5a.	PSI Scan modules	PSI Cal modules provide system cal each time system is brought up on line
5b.	PSI Cal modules	Return to Factory or suitable metrology lab for yearly recertification
6.	Thrust	Dead weight calibration pull (via a low friction pulley assembly) with force applied to stand at the nominal engine center line. Alternate method would be to use a calibration master load cell (thrust force still applied at the nominal center line for the engines). Calibration interval is initially 3 months increasing to 6 months as system stability is verified.
7.	Fuel flow	Calibrate meters in suitable metrology lab. Typical calibration interval is 6 months to one year.
8.	Vibration Amp	Calibrate in suitable metrology lab. Required equipment is a calibration capacitor (1000 pf) and an adjustable AC voltage source (with 100mv, 2 volt and 20 volt ranges). Calibration interval 3 to 6 months.

The calibrations are performed on the system after installation and are generally done from the test cell interface boom. The calibration consists of two procedures. During the first procedure, the "as found" status of the instrument or system is determined. This "as found" calibration check verifies the status of the system at the end of the calibration cycle. During the second procedure, any necessary adjustments or repairs are made to the system and an "as left" calibration check verifies the final status of the system. If the system meets the calibration accuracy requirements during the "as found" check no further adjustments or calibration checks are required.

The thermocouples can be gang calibrated (24 at a time) with a jumpered multipin connector that inputs the calibration signal into the boom mounted UTR thermocouple interface connections. This methodology checks the complete T/C measurement system (connectors, UTR, MUX , A/D, data transfer to the PC and software display functions). Typical calibration intervals are 3 to 6 months single point (zero and FS checks) validations with full multi-point calibrations run on a yearly basis.

In practice with this calibration system the thermocouple accuracy can be maintained at the following accuracies.

± 1.0 °C up to 200 °C
± 3.0 °C above 200 °C
± 4.0 °C above 800 °C

The high level voltage channel inputs to the data system are calibrated by DC calibrator signal input at the ends of the MUX interface cabling. The data system scaling factors are set to unity gain with a calibration setup file and the performance of the A/D and MUX cards is verified. Typical calibration intervals are 3 to 6 months single point (zero and FS checks) validations with full multi-point calibrations run on a yearly basis.

Typical voltage accuracies that can be maintained at the test facility are:

± 0.1 % of FS range	(A/D)
± 1 % of parameter FS range	(individual channel)

Pressure transducers are calibrated at the boom interface by applying pressure signals into the interface ports with the Druck calibrator. The calibrator values are compared to the computer display screen readings. Optional voltage readings can also be taken at the terminal block interface inside the test cell cabinet for reference and troubleshooting purposes. The data system is usually scaled in nominal engineering units (1 volt = 100 psig) and the transducers adjusted to provide the proper outputs. For pressure ranges above 300 psig a master gauge and adjustable pressure source technique is used. The transducers are checked at a minimum of zero 1/2 and full scale inputs.

Frequencies are calibrated by using the Wavetek oscillator (item 3 in this section) to inject signals into the test cell boom interface connectors. The oscillator frequencies are determined by applying the scaling factors for the parameter being checked. The computer system stores offsets and gain values to convert the F/V DC signals into proper frequency engineering units. Speeds generally have a data system stored scaling factor that is used to display engineering units on the system CRT. The other frequency signals are generally calibrated to read in units of Hz and further scaling is done with the calculated channel displays. This end-to-end calibration technique of applying a signal at the boom interface and reading the response on the system data terminal verifies the whole frequency measurement process.

The thrust calibration is done on the installed thrust stand using a centerline pull technique. A minimum of three load cycles of 0, 25%, 50%, 75%,100%, 75%, 50%, 25%, 0% applied force are required for each calibration. The load cell system has a typical accuracy of 0.5% of reading +/-0.1% FS range.

10.6.12 Facility System for Engine Control

The facility should be provided with a combination of PLC control functions and a hard wired safety string composed of discrete relays and switches. The block diagram of this system is shown in Figure 19. The safety string controls the fuel solenoid, start air, oil pump, fuel pump and test cell power enabling circuits. The safety string is wired in a series string and is terminated with a normally closed emergency stop button. Pushing this button will drop out the safety string and shut down all test cell functions. The test cell fire system is also wired into this safety string. The console PLC and control buttons are interlocked so that they have to be in an off state before the test cell panel can be energized.

Typical engine running sequences will require some method of connecting the engine control computer to the functions that turn on/off the start air, ignition and 2 or 3 spare circuits.

In the control room approximately 30 inches of 19 inch rack space is provided to support installation of the support electronics for the engine control system (see Figure 22). Additional table space may be needed to hold external monitoring PC's and analysis equipment. Small, expendable engine controls are configured with the PC or terminal in the control room. A fuel control computer module is mounted in the control room rack or adjacent to the engine and a power driver module is next to the fuel delivery unit (pump or metering system). This arrangement helps to reduce the noise feed back from the PWM signals driving the fuel metering system and keeps the voltage drops/phase lag low in the lines feeding the fuel pump. An isolated 28 volt power supply with at least 10 or 20 amp rating is usually required as a power source for the fuel metering systems. This supply will often connect directly to the power driver module and be configured in a single point ground arrangement to the engine frame.

It is important to keep the power lines feeding the pump driver module and the signal lines separated. The routing of cables from the control room to the test cell should have provisions for separate raceways for instrumentation and control/power lines. As the distance from the control room to the test cell increases, the separation of these lines becomes more important.

The routing for the fuel control system cabling should allow the use of one uncut cable length without intermediate connections. The engine fuel control systems are sensitive to cable configurations and most users prefer to bring their own cable assemblies. Adequate access ports in the control room and test cell will aid in the timely installation of these cables. The bulkhead connector fitting is not recommended. To provide the control function for special components a 28 volt 20 amp DC power supply is provided.

10.7 Fire Protection System

The PSTF for Small Expendable Turbojet Engines includes three separate containers with different functions. To protect the facility if fire occurs a Fire Protection System is provided. The Fire Protection System is designed in accordance with National Fire Protection Association (NFPA), Standard 423.

According to the above standard, there are a series of fire protection systems and fluids that are available for turbojet engine test facilities. As the optimum solution, two fluids are selected: Carbon dioxide (CO_2) and FM-200 (recently approved replacement for Halon 1301).

The carbon dioxide system meets the requirements of the NFPA's 12 Standard on Carbon Dioxide Extinguishing Systems. The FM-200 system meets the requirements of the NFPA's 2000 Standard on Clean Agent Fire Extinguishing Systems and all of the above requirements. The fire protection system is described below:

The control equipment for the fire protection system will be located outside the hazard area. All fire protection control equipment is identified, the function performed described, and the method of operation specified. The manual fire protection system will be conveniently located and accessible at all times.

The system will have a connected reserve supply of not less than 100 percent of the primary supply, for immediate manual discharge in case of fire. After activation of the system the following events occur:

-Fuel valves supplying fuel to the protected areas are closed.

-Alarm devices are activated to warn personnel to evacuate the protected area.

Actuation of the total flooding system will do the following:

- Provide sufficient time to allow personnel to exit before the extinguishing agent is discharged, and

- Shut off ventilating fans and close doors and other openings to minimize the leakage of the extinguishing agent from the protected area.

The three separate containers will be protected by three different subsystems. The test cell and the preparation area will use CO_2 as the agent, and the control console area will use FM-200. During engine operation inside the test cell it is not possible to close the air intake and the augmentor tube, so a local fire protection system is provided to protect the engine being tested. For this application a carbon dioxide system is designed to apply carbon dioxide directly to a fire which may occur in an area with essentially no enclosure surrounding it.

The important factors that were considered in the preliminary design of the engine fire protection system are the rate of flow, the height and area limitations of the nozzles, the amount of carbon dioxide needed, and the piping system. The design uses two spot nozzles propelling CO_2 fluid at 23 lb/min. in the test cell area. To attain this performance goal the total capacity of the storage cylinder is 75 pounds.

The flooding concept will be used to protect the area for preparation and fuel storage. In this case a 36% concentration is used for the preliminary design calculation. NFPA 12, Chapter 2, establishes a material conversion factor which permits calculation of the required quantity of CO_2 agent. The required quantity of this agent for this container is 50 pounds.

The fire protection system for the control console area will use FM-200 as the agent. The design requirements of NFPA 2001 along with manufacturer's recommendations call for a 7.4% concentration of this agent by volume. As a result of these criteria the preliminary design sets the container size at 40 pounds of agent.

The heart of the Portable Test Facility Fire Protection System is the control panel. All the circuits are monitored for trouble conditions. Through this panel the release of agent is selected according to zone and to selector valve. The entire system is backed up by batteries in case of a power failure.

Each zone has both manual and automatic activation capabilities. There are horn and light units to signal the status of the system. The Fire Protection System will be integrated into the engine and facility monitoring system.

10.8 Air Conditioning System

The PSTF is intentionally designed to operate in a wide range of environmental conditions. Different parts of the test facility require separate consideration of the temperature level that can be maintained during extreme outside weather conditions.

The test cell unit is ventilated by outside air because at all times secondary airflow is maintained when an engine is operating. While the engine is running temperature controls are not required inside the test cell. For the PSTF and similar facilities, outside air will enter the engine bellmouth at practically the same temperature as outside the test facility. The secondary airflow temperature also stays at the same level throughout all cross sections of the test cell. As a result of the air stream energy movement direction, the influence of the hot exhaust gases on the test cell ambient temperature is negligible.

When the engine is not running the test cell temperature must be regulated, especially during winter when the operator prepares an engine for testing. In this case the test cell intake roll-up door will be closed and the augmentor slave cover also will be inserted into the detuner aperture. The test cell will be heated using a space heater with a capacity of 3 KW, to cover the zone where the operator will be working.

The control and instrumentation container houses a variety of electronic equipment which require a stable temperature. The temperature requirements which are used in the preliminary design maintain the temperature inside the zone at 73 ±5 °F. This is required for instrumentation systems which will be housed in these areas. Also, temperature control will contribute to the comfort of those who will spend the most time in the control console room. To improve the temperature conditions inside this area the container will be thermally insulated. Using the thermal performance of the insulated container, the required heater performance can be computed.

The inlet data used for temperature calculations are based on the following assumptions:

- -Maximum outside temperature of 110 °F
- -Minimum outside temperature of -20 °F
- -Two people within the container
- -Return air temperature of 73±5 °F

The results of the load calculations are shown in Table 8. A total cooling load of 21,274 BTU/HR is derived from these calculations. The required heating capacity is 21384 BTU/HR (6.35 KW). The design of the air-conditioning system is based on the above data. The solution selected includes use of a ceiling mounted supply air duct, which runs from the air conditioner installed inside the container. The tentative return air path would be through grills in the interior partitions.

Container #3 houses fuel, oil and air systems. The air conditioning system must satisfy the fluid temperature requirement, particularly for fuel which must be maintained within safe operational limits. The air conditioning system must also extract fuel vapors. Air supply to the compressor should be provided using local ducting for the compressor inlet.

ITEM	DESCRIPTION	UNITS	DESTINATION	COOLING		HEATING	
				Container 2	Container 3	Container 2	Container 3
1	Temperature	°F	Outside	110	110	-20	-20
2	Temperature	°F	Inside	78	78	68	58
3	Transmission Losses	BTU/HR	Roof	4320	4320		
			Walls	6146	6146		
			Floor	1080	1080		
			Total	11546	11546	17512	15522
4	Internal Losses	BTU/HR	Lights	320	160		
			Personnel	1200	600		
			Other Load	6800	1700		
			Total	7320	2460		
5	Ventilation	BTU/HR	Outside	1408	484	3872	1716
6	Total Load	BTU/HR	Container	21274	15090	21384	17238
		KW	Container	6.35	4.44	6.29	5.07

Table 8. Air Conditioning Calculations for PSTF

Calculations for this container are based on the following assumptions:

- -Maximum outside temperature of 110 °F
- -Minimum outside temperature of -20 °F
- -One person within the container
- -Return air temperature of 73±15 °F

The results of the load calculations are shown in Table 8. From these results the total cooling load is determined to be 15,090 BTU/HR. The required heating capacity is calculated to be 17,238 BTU/HR (5.07 KW), based on a return air temperature of 60 °F.

The location of the air-conditioning system is shown on Figure 9 (Mode A).

From the calculated data it is obvious that the heating mode is the greatest power demand on the temperature boundary conditions. The electrical power supply must be able to accommodate the added demand for heating during the winter months.

10.9 Closed Circuit Television System

The closed circuit television (CCTV) system is designed to allow the operator to monitor the engine and test cell condition throughout the test.

The main components of CCTV system are:

- -Camera assembly, BE-3-15-18-E-6-25
- -Pan 8 tilt, PT570P
- -Control, Pan 8 tilt, Zoom BEPT-115LZOT
- -Color monitor, BECM-2411k
- -Wiring harness WHPT-115F

The camera system is a 10:1 auto-iris zoom lens using a high resolution color chip camera in a sealed, corrosion proof enclosure. The pan 8 tilt unit provides 350 degrees of rotation and 90 degrees of axis tilt up and down. This will allow the operator to control the camera from the control console, and adjust the focus and focal length (zoom) to detect specific problems on or around the engine. The color monitor is mounted on the console cabinet rack.

10.10 Intercommunication System

A Stentofon communication system is provided for use between the control console and the test cell. The intercommunication system will include two portable remote intercom stations and two headsets. This system will allow a person in the test cell to communicate with the operator at the control console even with an engine in the test cell running at idle.

10.11 Electrical Supply

The electrical supply for the test facility is provided as part of the overall facilities package. Electrical requirements of the individual systems are presented in Table 9.

ITEM	NAME OF SYSTEMS	INSTALLED POWER (KW)	PEAK POWER (KW)
1	Air Conditioning	11.36	11.36
2	Air Starting	6.00	12.00
3	Fuel	3.00	5.00
4	Fire Protection	0.50	0.50
5	Light	0.90	0.90
6	Control Console	2.00	2.00
7	Test Cell Heater	3.00	3.00
TOTAL		26.76	34.76

Table 9: Electrical Supply Requirements of Individual Components

From the above, the power demand for the PSTF for Small Expendable Turbojet Engines requires a continuous supply of 26.76 KW. At the same time peak demand, resulting from compressor and fuel pump motor surge, is equal 34.76 KW. From the projected operation mode of test facility and the probability flow diagram of system loading, the power factor for simultaneous operation of all devices in some cases could be very close to unity. To obtain stable and reliable electrical supply in any mode of operation, and to provide some spare energy, the GENERAC model GT45 36 KW diesel generator is provided.

Basic technical data of the generator are following:

-Voltage	Three phase 208/240/480
-Excitation	Direct
-Continuous Output	32 KW
-Surge Output	60 KW
-Frequency	60 Hz
-Fuel Capacity	30 gal
-Voltage Stability	±1%
-Output Protection	Included
-Sound Level	63dBA at 23 feet
-Coolant Heater	Provided

The diesel generator will be designed to operate in outside environment. This unit is compact, rugged and is mounted on the trailer.

11.0 CONCLUSIONS

During the Phase I SBIR Program Test Devices has completed the preliminary design of a Portable Static Test Facility for Small Expendable Turbojet Engines. The results of the research and investigations are presented in this report. The report contains the detailed calculations, analysis, and discussions conducted throughout this program.

The primary technical objectives of Phase I were to formulate , design, develop, analyze and prove the feasibility of the Portable Static Test Facility for Small Expendable Turbojet Engines. Extensive work was required to develop a preliminary design which addressed the specific requirements of small size, ease of transportation and installation, reasonable cost, safe work environment, high reliability and ability to successfully test engines with a wide thrust range.

The individual task objectives were:

-Analyze the general requirements for engine testing.

-Review the test procedures for small expendable turbojet engines.

-Prepare general test specification for engines that will be tested at the PSTF.

-Analyze the test facility design requirements, define the factors for evaluating the performance of the test facility and outline the overall design recommendations.

-Develop the test cell basic requirements, design criteria and design recommendations.

-Provide an overview of the installation requirements and design recommendations.

-Analyze the data acquisition and engine instrumentation and control requirements.

-Formulate the preliminary design for the Portable Static Test Facility.

-Develop the conceptual installation design for the Portable Static Test Facility.

-Define the recommended solutions for the engine control and data measurement systems.

-Draw conclusions stemming from the results of the Phase I study and make recommendations for future activities in Phase II.

To achieve the above tasks different methods of investigation and analyses were implemented. All results of research and investigations conducted throughout this work clearly confirm the feasibility of the concept of Portable Static Test Facility for Small Expendable Turbojet Engines. The preliminary design of this facility has generated a technical solution based on a new and unique concept of an engine test facility. All critical requirements for such facilities were examined and appropriate solutions were provided.

The development of the PSTF can be an enabling force in the development of a new class of small expendable turbojet engines. A wide range of engine technology can be tested under different engine environmental conditions using the new PSTF.

The development and use of the PSTF will significantly aid in the development of a new generation of high performance, long range, extremely flexible, small tactical missile. This facility can also be a milestone in increasing and maintaining a high level of reliability for small tactical missiles, because it will enable engine testing at simulated operational locations and environments.

The future marketing of this facility will be concentrated around the commercial gas turbine manufacturers and educational institutions. The PSTF has already been used as model in the development of mobile test equipment in a number of different fields where requirements exist for on-site testing of flexible and transportable systems. Test Devices is actively pursuing these markets targeted at test stands for airline companies.

The results of the research work in this Phase I SBIR Program has conclusively demonstrated that the Portable Static Test Facility for Small Expendable Turbojet Engines is feasible, appropriate and a viable solution for performance evaluation of small expendable turbojet engines. To take full advantages of the benefits of this design work should be continued into Phase II to refine, document, build, test and deliver the Portable Static Test Facility for Small Expendable Turbojet Engines.

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