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A DERIVATION OF GROSS THRUST FOR A SEA-LEVEL
• JET ENGINE TEST CELL

By

James D. MacLeod

A thesis submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements for the degree
of Master of Engineering.

Faculty of Engineering
Carleton University
Ottawa, Ontario
February, 1988

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ABSTRACT

For accurate, indoor ground-level testing of jet engines, the influence of the test cell on the thrust produced by the engine must be established. The "true" gross thrust may be derived from the measured scale force, if the aerodynamic conditions inside the test cell are known. The "test cell effect", may also be quantified using correlation factors determined from comparison of test data taken from indoor facilities, and reference outdoor or "free-air" test stands.

In this thesis, the influence of the test cell on engine performance is described. The forces measured in a particular indoor test cell are derived, and a comparison of actual test data from an indoor test cell to an outdoor test stand is made. The results show that if all the aerodynamic forces have been accounted for, which in this case require corrections of up to two percent, the corrected thrust in an indoor cell is the "true" gross thrust.

ACKNOWLEDGEMENTS

Completion of a project of this magnitude cannot be done by one person alone. Assistance in many different forms has come from a great many people, over a period of several years. Unfortunately, to name all of them would fill an entire book, however, there are some people who deserve special mention.

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LIST OF SYMBOLS

Names

AGARD - Advisory Group on Aerospace Research and Development
NAPC - Naval Air Propulsion Centre
NASA - National Aeronautics and Space Administration
NRC - National Research Council
RAE - Royal Aeronautical Establishment
UETP - Uniform Engine Testing Program

General

A - Area
 α - Bypass ratio
C - Coefficient
dhF - Deviation from standard day enthalpy
F - Thrust
FAR - Fuel-air ratio
 γ - Specific heat ratio
H - Total enthalpy
h - Specific enthalpy
LHV - Lower heating value
 η - Efficiency
P - Static pressure
 ρ - Density
q - Dynamic pressure
Q - Heat rate
V - velocity

v - Volume
W - Airflow
WARO - water-air ratio
WF - Fuel flow
WORK - Work rate

Subscripts

b - Bypass
bt - Boattail
c - Combustion
d - Drag
e - Nozzle exit
f - Friction
fw - Wall friction
g - Gross
i - Incremental
im - Inlet momentum
in - Intake
m - Measured
out - Outlet
pbt - Boattail, projected
ref - Reference
stack - Exhaust stack
t - Time
tf - Thrust frame

tot	- Total
w	- Wall, surface
wet	- Wetted
x	- Axial direction
0	- Reference plane in test section
∞	- Ambient free stream

Engine Specific

EC	- Compressor efficiency
FGR	- Corrected gross thrust
NLR	- Corrected low Pressure compressor rotor speed
NHR	- Corrected high pressure compressor ratio speed
NLQNH	- Spool speed ratio
P3Q2	- Compressor pressure ratio
P5Q2	- Engine pressure ratio
PS7QAMB	- Nozzle static pressure ratio
SFCR	- Corrected specific fuel consumption
T3Q2	- Compressor temperature ratio
T5Q2	- Engine temperature ratio
WA2R	- Corrected engine airflow
WFR	- Corrected engine fuel flow

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CHAPTER 1

1.0 INTRODUCTION

The requirement to quote engine performance in absolute terms has become increasingly more important in the last decade. With new higher performance engines coming off the drawing boards, and the reliance on accurate absolute engine performance data needed to estimate the capabilities of new aircraft designs, the future requirements on the quality of engine test cell data will be increasingly stringent.

Accurate, controlled testing of high technology gas turbine engines requires installations where engines may be operated throughout their entire thrust range under approximately sea-level-static conditions. When a jet engine is run in an indoor test cell, its performance is altered because of aerodynamic interference between the engine and the cell. To establish the "true" performance of the engine, the interaction between the engine and the test cell environment must be evaluated. This is analogous to the installation effects experienced in wind tunnel testing. There are several factors which contribute to the "test cell effect". The major factors are test cell geometry and the

size of the engine relative to the cell. The minor factors include test cell wall friction losses and exhaust back pressure.

The reasons for analyzing the effects of test cell environment on engine performance are important. Engines of similar types are tested in a wide variety of test facilities, ranging from old reciprocating engine test cells converted to jet cells, to modern cells specifically designed for turbofans. The types of testing performed in each of these cells may vary from a basic function and leak check, to sophisticated research tests. No matter how simple or complex the type of testing may be, the common factor is the need to compare data recorded from one facility to another or to declare the performance relative to a known reference standard. Depending upon the design and operating conditions of the test facility, the magnitude of the "test cell effect", and hence the correlation factor used to relate one cell to another, could vary greatly.

The correlation of one test cell to another is often more of an art than a science. The same applies for the actual design of a test cell. While specific design characteristics vary from one facility to another, the basic test cell consists of an air intake, a test section and an exhaust outlet. In most cases, both the intake and exhaust sections are acoustically treated to reduce the noise pollution in the surrounding vicinity. All three sections of the test cell have a strong influence on the magnitude of the "test cell effect". Without fully understanding the effect that the test cell has on the performance of the engine, it is impossible to accurately measure the difference

between the performance of an engine tested inside two different test cells, or to an engine installed in an aircraft.

The test cell generated performance results will only be relative to some unknown datum unless a correlation between that test cell and an outdoor, "free-air" test stand has been carried out. In gas turbine engine testing, the outdoor "free-air" test represents the ideal condition in terms of thrust measurement. When an engine is tested on an outdoor stand during no-wind conditions, the engine only draws the air that it requires to satisfy the thermodynamic cycle. For this reason, all the scale force measured is considered to be the "true" thrust.

The ideal solution would be to do all ground level engine testing in outdoor stands. However, this is obviously not practical, especially in harsh climates. With the proper correlation factors known, any test facility should be able to quote absolute performance results.

The interest in correlation testing and test cell influences has been stimulated by NRC's involvement in the AGARD sponsored Uniform Engine Testing Program (UETP) initiated in 1982. The UETP was instigated to correlate various national engine testing facilities around the world. Eight test facilities in five different countries were involved in the program. Four of these facilities were altitude chambers, three were ground level test cells and one was an outdoor test stand. This program provided the opportunity to compare data from indoor and free air test cells.

One of the primary objectives of the UETP was to provide a basis for improving the standards of gas turbine engine testing within NATO countries. This was to be accomplished by comparing test procedures, instrumentation techniques, and data reduction methods, to increase confidence in performance data obtained from various test facilities. A secondary objective of the UETP was to compare the performance of an engine, measured in ground level and in altitude test facilities at the same non-dimensional conditions, and to investigate the reasons for any observed differences.

To accomplish these objectives, two J57 twin-spool, non- after-burning turbojets were to be tested in each facility, and performance results compared. Each of the participating facilities was to use the test procedures, instrumentation arrangements and analysis methods which they were accustomed to using, to define three basic engine performance parameters: airflow, gross thrust, and fuel flow. Certain reference instrumentation was also provided to travel with the engine.

Following the various studies of test cell effects, it appears that many of the engine test cells being used today are operating unaware of what effects the test cell environment is having on engine performance. Therefore, it is intended that this thesis will begin to consolidate and rationalize the existing knowledge of test cell/engine interactions, and consequently improve the quality of engine testing in general.

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The main purpose of this thesis is to identify the contributing components of the "test cell effect", and attempt to quantify them using variables readily measured during an engine test. Having identified these components, correlation of test cells could then be more accurate. This approach would particularly apply to correlations used by engine manufacturer's development and production test cells, engine and airframe test facilities, or military depot and overhaul contractor sites. Test cell designers would also benefit from this information by establishing design criteria for future test cells, thus controlling the "test cell effect".

The results of this study will be used to develop design modifications for the existing test cells at the National Research Council of Canada's Engine Laboratory, and establish design criteria for a new combined indoor/outdoor engine test facility which is slated for construction over the next four years.

CHAPTER 2

2.0 CELL DESIGN CONSIDERATIONS

There are three types of gas turbine engine test facilities: altitude chambers, ground level indoor cells, and "free-air" test stands. For the purposes of this study, only the ground level, enclosed facility will be considered. A typical layout of a general test cell is given in Figure 1. The basic test cell is made up of three components: the air intake, the test section, and the exhaust outlet. A description of some of the test cell design criteria is presented here, so that one might more fully understand the complex interaction between the engine and the test cell. Each of the three major components of the cell will be discussed separately.

2.1 Air Intake

The intake of the test cell may be either horizontal or vertical with turning vanes. The main design criteria for the intake are to attenuate the noise produced by the engine, while providing a fully uniform, low-turbulence flow field to the engine face, with minimal

pressure loss of the incoming airflow. The airflow path should be relatively unrestricted and of sufficient size to keep the air velocity in the cell to a minimum, thus reducing the static pressure depression. It is desirable to keep the cell ambient static pressure depression to about one inch of water in order to minimize the air pressure and ram ratio correction factors, and to reduce undue stresses on the building caused by the pressure differential (SAE, 1976).

Engines operating within a test cell can encounter temperature and pressure distortions in the engine inlet which introduce increased uncertainty about performance measurements, since most engine parameters are referenced to the inlet conditions at the compressor face (Karamanlis, 1985). These distortions are generally attributed to the aerodynamic design of the cell and are more likely to occur when one cell is used to test several engines with different airflow requirements and installation configurations. Problems arising from these distortions can be as minor as unsteady engine speed or thrust, or in the worst case, a complete stall which could result in serious engine damage (Lee, 1985). Poor cell inlet design is a major contributor to the formation of flow distortion and vortex generation. The inlet type, turning vane geometry, screen density and silencer baffles all influence the flow uniformity. The inlet should also be designed such that test cell performance is independent of outside wind direction and magnitude.

General Electric, for example, in their design criteria for cell inlets, states that an acceptable cell shall have a front cell velocity

distortion of only 20 percent, with no vortices entering the engine bellmouth, and a minimal effect on the velocity distortion, when influenced by a 32 KPH crosswind (Karamanlis, 1986).

2.2 Test Section

After the incoming air passes through the inlet, it enters the test section where the engine is mounted on a thrust cradle. While inlet and outlet configurations may vary from one facility to another, test sections tend to be similar in layout. An important factor in test section design is the geometric ratio of engine diameter to the cross-sectional area of the cell. Another significant design consideration is the bypass ratio, which is defined as the ratio of the secondary air flowing past the engine to the airflow entering the engine inlet. Both the bypass ratio and the area ratio have a direct influence on the velocity of the air bypassing the engine, which should preferably be less than 9.8 metres per second (SAE, 1976). To meet this requirement, the maximum engine size for a given test section may be approximated by:

$$W_e = 12 * A_{cell} / (\alpha + 1)$$

where W_e = maximum engine airflow (in Kg/s)
 A_{cell} = test section flow area (in m²)
 α = bypass ratio.

High bypass air velocities cause a reduction in static pressure along the engine length, resulting in forces which would not occur in

open air testing. These pressures acting on the engine will alter the measured thrust by producing axial buoyancy forces. The major effect of these buoyancy forces is generally near the exhaust end of the engine where the secondary flow velocities are high. If the flow velocity in the test section is significant, tailpipe ambient pressure will be reduced relative to the engine inlet pressure. The result is equivalent to an apparent forward velocity for the engine, and at a slightly higher altitude. The use of a high loss protective screen in front of the engine may lower the inlet pressure to the engine even further.

Flow along the test section wall experiences a rapid acceleration as it approaches the engine bellmouth since the flow captured by the engine has a cross-sectional area larger than the engine itself. Boundary layer analysis (Kromer, 1985) indicates that flow along the wall separates for all cell bypass ratios. The separation location moves downstream as the bypass ratio increases. For high bypass ratios, the separation point moves downstream of the bellmouth entry plane, which will prevent vortex ingestion. For low bypass ratios, the flow separation point moves upstream of the bellmouth inlet, which may lead to vortex formation. Keeping the separation point at or behind the bellmouth inlet should reduce vortex formation (Kromer, 1985). An approach to eliminate vortex formation is to reduce the diffusion along the test section walls by reducing the cross-sectional area of the cell in the vicinity of the bellmouth inlet. Varying the cross-sectional area of the cell will however create additional pressure forces, which then must be properly accounted for in calculating gross thrust.

A secondary design consideration for test sections is streamlining. Any projections into the airflow of the cell, such as heating ducts, piping or lighting fixtures may induce the formation of vortices, which could be ingested into the engine. Even the thrust stand to which the engine is attached should be carefully designed. To reduce the pressure forces generated by the air flowing past the engine, the stand should be aerodynamically streamlined.

2.3 Exhaust Outlet

Probably the greatest impact on engine performance is the design of the exhaust outlet. The exhaust outlet not only controls the amount of secondary airflow in the cell, but it also controls the back pressure on the engine, the sound absorption and the production of exhaust pollution. Most modern engine testing facilities use an augmentor tube to capture the engine exhaust gas and induce secondary airflow through the cell. The exhaust is directed into the augmentor tube, then expelled into the atmosphere. The augmentor tube acts in combination with the engine exhaust momentum to form an ejector, which entrains cool, secondary air from the test cell. In the past, augmentor design was basically an art and test facility people had only quantified some of the parameters concerning ejector performance (Sapp, 1978).

The secondary or bypass flow is important for cooling the exterior of the turbine casing and the exhaust duct of the engine, as well as the exhaust silencer and the augmentor tube itself. It is preferable

to use an augmentor tube which has a collector that can be moved relative to the engine exhaust plane, and a variety of insert sizes to modify the flow area. This type of design allows easier control over the airflow pumping requirements, noise and the local static pressure at the jet nozzle exit plane. More importantly, the quantity of secondary air entrained is crucial for proper engine testing (Hayes, 1975). Too little secondary air allows recirculation of exhaust gases within the cell, resulting in overheating of the engine components and the augmentor tube. Too much secondary air causes excessive static pressure gradients between the engine inlet and exhaust planes, which require large corrections to the measured thrust. However, sufficient secondary air must be entrained to lower the kinetic energy of the exhaust to allow the silencing equipment to perform properly. Turbofan engines, for example, tend to overpump the system and the augmentor tube must be modified to restrict the amount of entrained air (Sapp, 1978).

The major design elements of an augmentor tube include the nozzle/augmentor diameter ratio, the inlet configuration, the engine airflow, the nozzle/augmentor spacing and the engine exhaust temperature. Each of the parameters will have an effect on the cell bypass ratio, the total cell airflow, and the pressure, temperature, and velocity profiles in the augmentor tube.

The collector to engine nozzle diameter ratio is a very important parameter in the augmentor design. The bypass ratio decreases with decreasing diameter ratio because of the reduced secondary flow area

(Hastings, 1983). As the diameter ratio increases, the entrance losses become less important because the secondary air enters the augmentor tube in a more axial direction. A converging-diverging engine nozzle will reduce the bypass ratio because of the increased secondary flow blockage from the diverging nozzle flow, and because of the decreased diameter ratio from a modulating nozzle.

There are several types of augmentor tube inlets in use today. The bellmouth and conical inlets are the most commonly used designs, because they are the most efficient at pumping air. Straight-edged inlets result in increased entrance losses, which reduces the flow capacity. Reverse conical or flat plate designs, have very high loss factors which reduce the cell bypass ratio and may result in damage to the augmentor tube because of recirculation of hot exhaust gases inside the tube itself (Sapp, 1978).

The airflow of the engine being tested in the cell has a direct impact on the operation of the augmentor tube. For a fixed exhaust nozzle, as the engine airflow increases from idle to maximum power, the secondary airflow increases, but the cell bypass ratio decreases. This relationship between engine airflow and bypass ratio has been found to apply to the full spectrum of engine sizes. Large engines installations usually operate with a cell bypass ratio between 1.0 and 2.0, although some do operate below 1.0. For small engines, normal bypass ratios can be greater than 5.0. The operation of a large engine in a test cell at low bypass ratios can amplify or introduce adverse flow effects that can occur during engine testing. The bypass ratio

influences the location of the engine airflow stagnation point in the bellmouth. Decreasing the bypass flow moves the stagnation point upstream, while increasing the bypass will move it downstream towards the engine compressor face. The location of this stagnation point has a strong influence on the compressor blade tip circumferential and radial distortion, which may affect compressor performance (Freuler, 1982). High-bypass turbofan engines are more susceptible to inlet distortion and vortex ingestion than low-bypass engines, because of their increased inlet flow area.

The engine nozzle/augmentor tube spacing has a lesser influence on the secondary airflow. The bypass ratio increases slightly with spacing because of reduced blockage of the nozzle, then decreases because of increased flow blockage of the spreading exhaust plume (Sapp, 1978). More importantly, the spacing affects the static pressure field at the nozzle exit, which ideally should be the same as the static pressure field around the engine. Increasing the spacing causes an increase in the noise produced within the cell because of the larger shear layer between the jet exhaust stream and the low velocity secondary air.

The secondary cell bypass flow is also a function of the engine exhaust temperature. The cell bypass ratio varies approximately as the square root of the ratio of the exhaust total temperature to the engine inlet total temperature (Hastings, 1983). Military engines, because of their inherently higher exhaust plume temperatures, induce higher bypass ratios.

The interaction between the high temperature exhaust plume and the secondary cooling air, also influences both the noise and exhaust pollutants emitted from the test cell. For non-afterburning engines, the temperature of the exhaust gases is sufficiently low that the chemical reactions are kinetically inactive, and the secondary air merely dilutes the existing pollutants. For afterburning engines, the exhaust temperatures are high enough to allow chemical reactions to occur outside the engine and the secondary flow will react with the exhaust thus modifying the type and concentration of the pollutants emitted from the test cell.

2.4 Future Trends

Model testing is a useful tool to study cell and engine flow interactions, to develop new test cell designs, or to modify existing cells. For more than a decade there has been a significant increase in the size, thrust and airflow of gas turbine engines. In contrast, there has not been any significant change in most engine test cells, which were generally designed and constructed for much smaller airflow engines.

With the future demand for higher thrust-to-weight ratios, the next generation of engines will consume more air and produce higher thrust. The current development of ultra high bypass and propfan engines shows the trend towards more airflow. Existing ground level test facilities may experience difficulty in accurately measuring the

performance of these new engines because of the increased aerodynamic interference of the test cell.

CHAPTER 3

3.0 ANALYTICAL THRUST CALCULATIONS

To accurately calculate correlation factors to account for the "test cell effect", it is essential to completely describe the measurement of thrust. For gas turbines, thrust is defined as the momentum increase of the air passing through the engine. The term gross thrust designates the force that can be attributed to the engine under static conditions, ie., no forward motion or ram effects. The engine is responsible for accelerating the air from rest to the prevailing inlet velocity and any drag forces are properly credited as thrust corrections to static conditions. Most of the existing literature on thrust measurement focuses on in-flight thrust derivation; however, there is enough information available to describe the components of thrust in an enclosed ground level test cell. A summary of the information from these articles follows.

3.1 Literature Survey

From the existing literature, four representative samples of information regarding the definitions of thrust components, and correction factors for external drag forces have been reviewed. Reference 1, contains the definitions of gross thrust and its components. The standard gross thrust is the sum of the intrinsic thrust and the intrinsic momentum drag. The standard gross thrust is the stream force at the exit plane of the nozzle and is mathematically defined as,

$$F_g = W_e V_e + A_e * (P_e - P_\infty) \quad (1)$$

where

- W_e = nozzle exit mass flow
- V_e = nozzle exit velocity
- A_e = nozzle exit area
- P_e = nozzle exit static pressure
- P_∞ = ambient static pressure

The intrinsic momentum drag is calculated by,

$$F_{imd} = W_0 V_0 + A_0 * (P_0 - P_\infty) \quad (2)$$

where

- W_0 = inlet mass flow
- V_0 = inlet velocity
- A_0 = inlet area
- P_0 = inlet static pressure
- P_∞ = ambient static pressure

Duncombe and Smith, take the definition of gross thrust and expand it to compare the effects of various intake ducts on the measured thrust

of a jet engine. From their analysis it is apparent that the configuration of the intake, ie. whether it attached to the engine thrust measuring device or not, makes a significant difference in the magnitude of the measured thrust.

In General Electric, 1979, a description of the components of what General Electric refers to as the "cell factor", is given. These flow-induced forces are broken down into three components:

- 1) an external friction force acting on the bellmouth, engine and thrust frame,
- 2) an exhaust nozzle boattail drag, and
- 3) a momentum drag force.

The friction force is described as a function of cell bypass ratio, while the two drag forces are related to a pressure differential between the engine inlet and exhaust planes. To estimate the airflow through the test cell a total energy balance formula is used. This formula relies on an accurate measurement of the average exhaust stack temperature, which is often difficult to obtain. To overcome this, the test cell flow must be measured by a flow survey and calibrated against the test cell static pressure depression.

A slightly different approach to thrust accounting is outlined in Ashwood, 1984. This paper describes the experimental investigation of

thrust measurement errors at the Royal Aeronautical Establishment (Pyestock). These errors were attributed to the secondary flow generating forces that act on the thrust frame. The main effects were divided into:

- 1) a force on the inlet bellmouth caused by the air entering it,
- 2) a force on the nozzle caused by the reduced external static pressure resulting from the increased velocity of the secondary air entering the exhaust collector, and
- 3) a drag force on the frame supporting the engine resulting from the secondary flow over it.

The general conclusion from the literature survey is that there appears to be some commonalty on the subject of making corrections to the measured thrust to offset external aerodynamic drag. There is, however, no complete derivation of the forces generated by an engine in an indoor cell with clearly defined planes of accounting. Since the work of Duncombe and Smith has been confirmed by more recent results by General Electric, 1979, Covert, 1985 and Oates, 1984, it is considered that their combined efforts should form the basis of the rationalization of the gross thrust measured in a test cell.

3.2 Rationalization of Gross Thrust

Consider the engine/test cell control volume as shown in Figure 2. In this installation, the bellmouth is mechanically coupled to the engine stand. The locations of the planes of accounting are somewhat arbitrary, except for the exhaust exit plane. The requirements for planes 0 and b are uniform static pressure and velocity. Definition of planes 0 and b might prove difficult in test cells which have distorted flow fields, which may occur with a vertical inlet.

The sum of the forces acting on the control volume, under steady-state conditions, is equal to the change in axial momentum across the control volume. A comprehensive algebraic derivation of the momentum equation is given in Appendix A. A summary of the pertinent equations is as follows:

$$\begin{aligned} F_m + A_0 P_0 - A_b P_b - A_{pbt} P_{bt} - A_e P_e + F_{tf} + F_f - F_{fw} \\ = W_e V_e + W_b V_b - W_0 V_0 \end{aligned} \quad (3)$$

where F_{tf} = drag force on the thrust frame

F_f = friction drag on the engine

F_{fw} = friction drag on the walls.

Given that the bypass ratio is defined as,

$$\alpha = \frac{W_b}{(W_0 - W_b)},$$

then

$$W_b = \frac{\alpha}{(\alpha + 1)} W_0 \quad \text{and,} \quad (4)$$

$$V_b = \frac{\alpha}{(\alpha + 1)} \frac{A_0}{A_b} V_0 \quad (5)$$

where

$$A_b = A_0 - A_{bt} - A_e \quad (6)$$

Substituting equations (4), (5), and (6) into equation (3), and solving for F_m gives:

$$F_m = W_e V_e + \left[\left[\frac{\alpha}{\alpha + 1} \right]^2 \frac{A_0}{A_b} - 1 \right] W_0 V_0 + A_0 (P_b - P_0) + A_{pbt} (P_{bt} - P_b) + A_e (P_e - P_b) - F_{tf} - F_f + F_{fw} \quad (7)$$

From equation (3), the force measured in the test cell is equivalent to the intrinsic thrust, from equations (1) and (2), plus some additional terms which result from the flow of secondary air over the external carcass of the engine.

Since the gross thrust, from equation (1) is defined as,

$$F_g = W_e V_e + A_e (P_e - P_0)$$

$$\text{or } F_g = W_e V_e + A_e (P_e - P_b) + A_e (P_b - P_0)$$

then,

$$F_g = F_m + \left[1 - \left[\frac{\alpha}{\alpha + 1} \right]^2 \frac{A_0}{A_b} \right] W_0 V_0 + A_b (P_0 - P_b) + A_{pbt} (P_0 - P_{bt}) + F_{tf} + F_f - F_{fw} \quad (9)$$

These seven terms are referred to as scale force, intrinsic inlet momentum, bypass pressure drag, boattail drag, thrust frame drag, skin friction drag, and wall friction drag. Each of these terms is described separately in the following sections.

3.2.1 Scale force

Having defined the thrust of an engine, the next step in measuring it is to determine what thrust is being measured in the test cell. In most indoor ground level test cells, the engine is mounted on a thrust frame which is secured to the ground by flexures in a pendulum arrangement. The thrust frame pushes against a load measuring device such as a strain gauge load cell. The force that is measured by this device is known as the scale force.

3.2.2 Intrinsic inlet momentum

The most significant aerodynamic component of the thrust measurement is the intrinsic inlet momentum, which produces a force on the engine as a result of drawing air into the test cell (Oates, 1984). For static engine testing the magnitude of this force may be substantial. Since this force is, in effect, a drag term, it must be added to the measured thrust of the engine. The intrinsic inlet momentum is calculated as,

$$F_{im} = \left[1 - \left[\frac{\alpha}{\alpha + 1} \right]^2 \frac{A_0}{A_b} \right] W_0 V_0$$

where α = bypass ratio

A_0 = test cell area

A_b = bypass area

W_0 = test cell mass flow

V_0 = test section or engine approach velocity

From this equation, it is obvious that the intrinsic inlet momentum is a function of the engine airflow and the bypass secondary flow, and is therefore strongly affected by both the size of the engine, and the aerodynamic qualities of the test cell. Therefore, this thrust component must be accounted for in all indoor testing.

3.2.3 Bypass pressure drag

The bypass pressure drag is that force generated by a pressure deficit immediately behind the bellmouth caused by the sudden expansion of the secondary flow as it spills past the engine intake. Sometimes referred to as bellmouth form drag, this force is a strong function of the cell bypass ratio. For test cells with low secondary flow, the magnitude of the bypass pressure drag may be small enough to be neglected. For higher bypass ratios, this force can become significant, and may be approximated by,

$$F_b = (P_0 - P_b) * A_b$$

where P_0 = static pressure at plane 0

P_b = static pressure at plane b

A_b = bypass area

Since bypass pressure drag is a function of the bypass ratio in the test cell, this parameter is sensitive to the aerodynamic characteristics of the cell, and to the size of the engine relative to the cell.

3.2.4 Thrust frame drag

The thrust frame drag is defined as the pressure force generated by the bypass flow pushing against the exposed structure which supports the engine on the thrust measurement device. The magnitude of this force is rather small, since most modern thrust frames are reasonably well streamlined. This force must be calculated using the bypass flow, the projected area of the thrust frame, and a drag coefficient as,

$$F_{tf} = C_d * A_{tf} * q_b$$

where C_d = equivalent flat plate drag coefficient

A_{tf} = thrust frame projected area

q_b = cell dynamic pressure = $\frac{1}{2} \rho_b V_b^2$

The bypass velocity V_b may be computed by,

$$V_b = \frac{\alpha}{(\alpha + 1)} \frac{A_0}{A_b} V_0$$

The bypass density is assumed to be equal to the upstream density in plane 0.

The value of C_d may vary slightly, depending on the shape of the particular thrust frame components. Hoerner (Hoerner, 1965) provides values of C_d ranging from 1.0 to 1.5. General Electric recommends using a value of C_d equal to 1.17 (General Electric, 1979).

The thrust frame drag force is a direct function of the secondary flow in the test cell. This component of thrust will then vary from one cell to another, but would only be present on an outdoor test stand during high wind conditions.

3.2.5 Skin friction drag

The engine skin friction drag is that force produced by the bypass flow scrubbing the exposed surface area of the engine casing. The magnitude of this force is usually considered negligible; however, it is included for completeness. Flat plate theory is also used to calculate this force as,

$$F_f = C_f * A_{wet} * q_b$$

where C_f = effective skin friction coefficient

A_{wet} = wetted surface area of the engine casing

q_b = cell dynamic pressure

The effective skin friction coefficient for turbulent flow over a rough flat plate is approximately 0.005.

The magnitude of the skin friction force will be directly affected by the bypass flow in the cell, and would therefore vary from facility to facility depending on the aerodynamic conditions in the cell.

3.2.6 Boattail drag

With the close proximity of the exhaust collector inlet to the engine nozzle exit, the secondary flow accelerates along the external surface of the nozzle and into the augmentor tube. This acceleration results in a static pressure gradient along the nozzle, which when integrated over the surface area, generates a net force with a horizontal component in the direction opposite to the measured thrust of the engine. This component is very sensitive to the size of the collector insert, and the spacing between the exhaust nozzle and the collector. The magnitude of this thrust component may be calculated by,

$$F_{bt} = (P_0 - P_{bt}) * A_{pbt}$$

where P_0 = static pressure at plane 0

P_{bt} = average external nozzle pressure

A_{pbt} = projected boattail area

3.2.7 Wall friction drag

The wall friction drag is the force generated by the airflow scrubbing the wall surface defined between the planes of accounting. As was the case for the skin friction drag on the engine, the wall

friction drag is small, however, it is included to describe all of the forces acting on the control volume. The wall friction drag may be calculated by,

$$F_{fw} = C_f * A_w * q_0$$

where C_f = effective wall friction coefficient

A_w = wall surface area between planes 0 and b

q_0 = dynamic pressure at plane 0 = $\frac{1}{2}\rho_0 V_0^2$

The effective wall friction coefficient for turbulent flow over a rough flat plate is approximately 0.005. If any wall projections normal to the flow exist between planes 0 and b, then an additional drag force should be accounted for, as was described under thrust frame drag.

3.3 Secondary Flow and Wall Interference Effects

Basically, scale force thrust is true engine gross thrust minus the equivalent force required to sustain the secondary flow around the engine. In other words, the engine must be credited with the work required to accelerate the large volume of secondary flow. When these forces have been properly accounted for, the resultant calculated gross thrust represents the true engine gross thrust that would exist in the absence of the cell secondary flow. These forces are completely dependent upon the size and layout of the individual test cell, and therefore must always be included in any discussion of the "test cell effect".

The presence of walls around the engine, which alter the flow conditions around the engine produce external forces which are measured by the thrust measurement system, and should be credited to the engine.

As noted in the previous section, these thrust corrections for an indoor test facility are attributed to the secondary airflow around the engine. It is therefore very important to accurately estimate the magnitude of the bypass ratio. There are two methods to calculate the total cell flow. The first method utilizes an energy balance across the test cell. The second involves traversing velocity measurements across the cross-sectional area of the cell.

The energy balance method comprises a calculation of the change in enthalpy from the cell intake, to the exhaust outlet, accounting for the energy input of the fuel consumed by the engine. A derivation of the energy balance method is given in Appendix II. The cell flow is then found by

$$W_0 = WF * (LHV * \eta_c + h_{ref} + dhf - h_{stack}) / (h_{stack} - h_{in})$$

where WF = engine fuel flow

LHV = fuel lower heating value

η_c = combustion efficiency

h_{ref} = fuel reference enthalpy at standard day temperature

dhf = increment of fuel enthalpy from standard day temperature to the temperature entering the combustor

h_{stack} = enthalpy in the exhaust stack

h_i = enthalpy at the cell intake

In order to calculate the enthalpy in the exhaust, one must first determine the stack fuel-air ratio from,

$$\text{FAR}_{\text{stack}} = \text{WF} / (W_0 * (1 + \text{WARO}))$$

where WF = engine combustor fuel flow

W_0 = total cell mass flow

WARO = inlet water-air ratio

The enthalpy of the exhaust stack is then computed using the exhaust stack temperature, the stack fuel-air ratio, and the inlet water-air ratio. From the above equations, it is apparent that this calculation is an iterative process which requires an initial guess of the bypass ratio. To begin the iteration, it is common to use a bypass ratio of 1.0 as a first approximation. The main drawback of this method is that not all exhaust stacks have a uniform temperature profile, which makes the measurement of the average temperature very difficult, if not impossible. An additional problem occurs during afterburner operation. The exhaust stack may not withstand the high gas temperatures so water injection is often used, which makes the energy balance calculation virtually impossible.

The second approach to quantifying the total flow in the test cell is to traverse the cross-section of the cell using either a

pitot-static probe to infer velocity, or a vane or hot-wire anemometer to directly measure the velocity. The local air mass flow may be calculated by,

$$\dot{W}_i = \rho_i * A_i * V_i$$

where ρ_i = incremental air density

A_i = incremental flow area

V_i = incremental velocity

By integrating the incremental airflows across the cell cross-section, a total cell flow may be calculated. The accuracy of this method is dependent upon how many incremental measurements are made. Traversing the entire flow area of the cell is a slow and painstaking procedure, which is costly in terms of operating expenditures. However, it is possible, for a fixed test cell configuration, that the calculated cell flow could be calibrated against the cell static pressure depression P_0 , thereby removing the need to perform iterative calculations or traverses on every engine test. Since test cell depression is a relatively easy parameter to measure, this procedure would appear to be very attractive, and is also likely applicable when water injection is used in the exhaust. However, in some test cells, the aerodynamics may be too poor to permit an accurate calibration. In addition, test cells which are altered upstream of the test section to accommodate a variety of engine configurations would require a separate calibration for each configuration.

3.4 Outdoor Thrust Calculations

In an outdoor stand the measurement of "true" gross thrust is greatly simplified because of the lack of secondary bypass flow around the engine. As a result, several of the parasitic thrust components become equal to zero, in no-wind conditions. For outdoor testing, the bypass ratio becomes negative one-half. This means that the engine draws in air equally from all directions, ie. half of the intake air comes from behind the bellmouth entry plane. Similarly, since the bypass flow area becomes infinite, the bypass pressure drag, the thrust frame drag, and the skin and wall friction drag go to zero. Without an augmentor tube behind the engine, there is no accelerating airflow over the boattail, therefore no boattail drag exists either. Wind conditions may contribute very small drag forces on the engine stand or carcass. If the engine is not aligned with the wind direction, the measured thrust may be affected by some component of inlet momentum, or axial pressure forces, because the engine no longer draws air equally from both sides of the bellmouth. Determination of these forces could only be done empirically. Since accurate engine tests are not normally performed under high wind conditions, these parasitic forces are very small. Thus, for no-wind test conditions, the scale force reading on an outdoor test stand indicates "true" engine gross thrust.

CHAPTER 4

4.0 TEST DESCRIPTIONS AND INSTRUMENTATION

The test vehicle used for the UETP was a Pratt & Whitney J57-P19W twin-spool non-afterburning turbojet engine. This particular engine was chosen for several reasons. First, the J57 has no variable geometry which might alter the behavior of the engine as a result of inlet temperature. Second, the engine covers a fairly wide thrust range (up to 45 kN). This is important when trying to resolve measured differences, and in relating results to more modern engines in this thrust class. Finally, the J57 used in the UETP had a fixed area exhaust nozzle, which simplified any calculations of thrust or flow coefficients in the tailpipe.

The basic J57 engine is a two spool axial flow engine with a nine stage low pressure compressor, a seven stage high pressure compressor, a cannular combustor, a single stage high pressure turbine, and a two stage low pressure turbine, followed by a fixed convergent nozzle with a tail cone. The engine has an intercompressor bleed which discharges

air overboard during starting and low power operation. For the data comparison, only higher power data were used, to avoid the effects of the bleed valve operation.

The tailcone of the standard J57 engine extends through the nozzle exit plane, which makes it difficult to accurately describe the nozzle flow conditions. For the UETP, the standard nozzle was replaced with a cylindrical tailpipe and a convergent nozzle, which provided a more uniform nozzle inlet profile, and allowed more accurate measurement of the temperature and pressure conditions at the nozzle inlet.

Instrumentation used on the J57 was grouped into two categories, primary or facility instrumentation, and secondary or reference instrumentation. The primary instrumentation was used to determine those parameters needed to calculate airflow, thrust and specific fuel consumption. The reference instrumentation was used to determine environmental conditions, to monitor engine health, and record any engine deterioration between tests. Engine station designations are numbered as shown in Figure 3. The numbering system used agrees with the SAE-755A recommendations (SAE, 1974).

Reference instrumentation consisted of pressure and temperature probes at the engine inlet, high pressure compressor discharge, turbine discharge, exhaust nozzle inlet, exhaust nozzle trailing edge, as well as speed sensors, turbine-type fuel flowmeters and vibration pickups.

Test conditions were established by locating the values of high pressure rotor speed when the bleed valve just closed and at military power. By dividing this region up into eight equal increments, nine power settings were obtained. Since the bleed valve closed point was a function of inlet temperature, the individual test points varied from one run to another.

For this study, the test results were obtained from two of the UETP participants, the Naval Air Propulsion Center and the Engine Laboratory of the National Research Council of Canada. A description of these two facilities and the test conditions observed during their testing is presented.

4.1 Outdoor Test Stand

The Naval Air Propulsion Centre outdoor test stand is a free-air ground_level test facility located at Lakehurst, New Jersey, U.S.A. The layout of the site is shown in Figure 4. The turntable test stand illustrated in Figure 5, is set in the center of an asphalt and concrete pad completely exposed to the open air so as to eliminate any aerodynamic influence associated with enclosed test cells. The stand consists of a rotating platform with a thrust bed supported by four flexures which permit only axial movement. Engine instrumentation, fuel and test stand services are provided via a boom suspended over the center of rotation of the turntable. A mobile shelter is used to protect the engine from the elements when it is not in use.

The thrust measurement system incorporated a strain gauge load cell mounted below the thrust bed along the centreline of the engine. The load cell was calibrated in situ at three different rotational positions to ensure that there was no difference in thrust measurement as a result of the turntable position.

The testing procedures outlined in the General Test Plan (UETP, 1982) were observed. However, because of limitations in the data acquisition system, not all of the UETP reference instrumentation parameters were measured.

The environmental conditions for the outdoor testing were reasonably constant. The ambient temperature ranged from 285 K to 290 K, the ambient pressure from 100.4 to 101.8 kPa, the relative humidity from 43 to 73 percent and the wind velocity from 1.6 to 11.3 m/s. A complete list of the average test conditions are given in Table 1.

4.2 Indoor Test Cell

The test cell used for UETP testing at the Engine Laboratory NRCC, at Ottawa, Canada, was Cell No. 5. A layout of this ground level static test cell is shown in Figure 6. Ambient air enters through three banks of 9.5 m wide, 4.6 m high zigzag silencing splitters. The planar dimension of the cell reduces obliquely from 9.5 m to 4.6 m in the inlet plenum, leading into the constant 4.6 x 4.6 m area at the test section. The test cell inlet can be closed with

bifolding doors at Station A. The entire cell is constructed of heavy reinforced concrete.

Engine exhaust and the entrained secondary airflow are ducted from the cell through a collector/augmentor tube to a vertical silencer that discharges to the atmosphere.

The control, observation and data acquisition room is located on the starboard side of the cell, on a mezzanine floor, about 1.5 m above the test cell floor. An operator's window and a closed circuit television camera permit visual monitoring of the engine.

The engine installation is shown in Figure 7. The engine bed is suspended by four 300 mm long flat plate flexures from the thrust frame which is anchored to the floor of the test cell. A single dual bridge strain gauge load cell, mounted in compression, measures thrust at the base of the bed. The thrust measurement system is calibrated using a centreline pull device which incorporates a reference load cell.

For controlling the secondary airflow in the test cell, the collector inserts of various diameters can be placed in the exhaust collector. Test cell velocity was kept within 5 to 7 m/s by sizing the exhaust collector to 0.84 m in diameter, and locating it 0.46 m behind the exhaust nozzle exit plane.

The engine mounted bellmouth directed incoming air into a cylindrical flow measuring section just ahead of the compressor. All

parts were hard mounted to the thrust bed so that forces generated by the bellmouth were transmitted to the load cell. An antipersonnel screen was anchored directly to the test cell floor, in front of the engine bellmouth.

Since humidity affects the thermodynamic properties of the engine cycle, and to avoid condensation in the inlet air stream, the following atmospheric limitations were observed:

maximum relative humidity: 75%

maximum absolute humidity: 14 g water per kg of air.

The ambient temperatures during the testing ranged from 288 K to 294 K, with a ram ratio of 1.005, and ambient pressures from 99.1 to 99.5 kPa. A complete list of the average ambient test conditions during the NRC testing is given in Table 2.

CHAPTER 5

5.0 THRUST CORRECTIONS

The objective was to determine the magnitude of the corrections that must be applied to the thrust measured in an indoor ground level test facility. To obtain the gross thrust, several important cell aerodynamic parameters must be calculated or measured. These parameters include test cell airflow, average velocity through the cell, cell ambient pressure, and various surface and flow areas in the cell and on the engine. For the NRC test data used in this study, these parameters are presented in Table 3. The bypass ratio of the NRC No. 5 test cell (Figure 8), shows a decrease with increased engine mass flow, as was discussed in Chapter 2. However, an overall increase in the cell airflow causes a rise in the average cell velocity (Figure 9), which will increase the magnitude of the thrust corrections.

The forces generated by the operation of a jet engine inside a test cell are grouped into their individual terms as described in Chapter 3. Each group will be analyzed individually.

5.1 Correction Factor Calculations

The magnitudes of the thrust correction factors have been calculated using the equations given in Chapter 3. Each of these individual forces have been normalized using the measured scale force, and are presented in Table 4. When calculating these forces, it became apparent that some approximations would have to be made regarding the measured data. For example, the pressure along the boattail varies over the converging surface. To calculate the boattail drag, a linear average of the boattail pressure was used. Another assumption was made regarding the pressure in plane b. The only available pressure in that plane was on the rear face of the bellmouth, which was shielded from the bypass flow. Some error in the calculation of the bypass pressure drag may result from assuming that this pressure was uniform throughout plane b.

The intrinsic inlet momentum (Figure 10) is by far the largest of the thrust corrections, ranging from 1.7 to 2.0 percent of the scale force. The boattail drag (Figure 11) is the second largest correction term, varying from 0.4 to 0.6 percent of the scale force measurement. The bypass pressure drag (Figure 12), is the same order of magnitude as the boattail drag except that it is negative. This results from the diffusion of the bypass air passing the plane of the bellmouth. This diffusion causes an increase in the static pressure in plane b, which acts on the bypass area. Since this pressure increase is very small, but the bypass is very large, the uncertainty in the bypass pressure

drag may be higher than expected. The scatter in the bypass pressure drag shown in Figure 12, confirms the higher uncertainty.

The remaining drag terms are viscous forces which are inherently smaller than the momentum and pressure forces. The thrust frame drag (Figure 13), and the wall friction drag (Figure 15), are approximately 0.03 and 0.01 percent of the scale force respectively. The skin friction drag (Figure 14), is extremely small, at 0.0015 percent of the measured scale force.

5.2 Test Cell Corrections

It is apparent that the effect of the forces generated by the bypass flow are measurable. The combination of all the thrust contributions is a significant percentage of the scale force, even in a well designed test cell, and thus cannot be ignored. The overall correction factor that must be applied to the scale force measured in the NRC No. 5 indoor test cell to derive the actual gross thrust of the engine is given in Figure 16. The magnitude of this overall correction factor ranges from 1.8 to 2.4 percent of the measured thrust. The individual contributions of each of the correction terms to the overall correction factor are shown in Figure 17. Figure 18, illustrates the distinction between the scale force and the gross thrust at NRC. The gross thrust measured in the NRC indoor test cell can then be compared to a reference outdoor test stand, which should confirm that all the forces generated by the engine have been included.

CHAPTER 6

6.0 INDOOR/OUTDOOR TEST COMPARISON

To properly compare the test results of the indoor and outdoor testing of the J57 engine at the NRC Engine Laboratory and the Naval Air Propulsion Center, it is first important to establish the quality of the data recorded. The next step is to verify that the performance signature of the gas generator portion of test engine has not altered between the two tests. Once data quality and performance retention have been determined, a direct comparison of the thrust measurements can be made.

6.1 Data Quality

There are many indicators of the quality in any given set of engine test data. Influences of the test facility or the engine configuration are most noticeable by plotting the inlet and exhaust pressures as a function of power setting. Indications of engine thermal stability may be detected by observing the behavior of the

engine spool speeds and the temperature and pressure ratios throughout the engine.

The quality of the NRC indoor test data appears to be very good. A useful indicator of data quality is the ram pressure ratio, which is defined as the ratio of the pressure at the engine inlet to that of the exhaust plane. The ram pressure ratio establishes the pressure conditions to which the engine was exposed during the test. From Figure 19, the ram pressure ratio is slightly above 1.0, with a small increase over the operating range of the engine. This increase is a result of the static pressure depression at the exhaust exit plane caused by the increased secondary flow past the engine (Figure 9). The small change in ram pressure ratio implies that the inlet pressure has remained relatively constant during the test, which is indicative of a very low screen pressure loss. Data scatter is extremely small, which suggests constant, steady flow conditions at both the entry and exit of the test section.

The NRC data indicate that the engine was operating in a very stable manner throughout the testing period. This is evident from the spool speeds. For greater accuracy, the spool speeds are shown (Figure 20) as a ratio of the low pressure spool speed to the high pressure spool speed.

The relationship between the compressor temperature and pressure ratios is referred to as the compressor pumping characteristic. Figure 21 illustrates the consistency of the compressor pumping characteristic,

during the NRC testing. The back-to-back repeatability of the data suggests that sufficient time (five minutes) was given to allow the engine to stabilize thermodynamically, and that the scanning sequence of the data acquisition system (six minutes) was indeed long enough to average out any minor hunting that the engine might undergo. The only parameter which exhibited any noticeable scatter in the NRC data was the compressor efficiency (Figure 22). However, since the efficiency is calculated from several averaged measurements by,

$$E_c = \frac{P3Q2^\epsilon - 1}{T3Q2 - 1}$$

where $\epsilon = \frac{\gamma - 1}{\gamma}$,

with γ approximated by the average specific heat ratio inside the compressor, this amount of scatter is not unexpected.

The quality of the NAPC outdoor test stand data is good, but with noticeable scatter. In Figure 19, the ram pressure ratio is less than one. It is also evident that the ram ratio is decreasing with an increase in power, which indicates that a fairly dense, high-loss screen was used, as the pressure loss across the screen increases with the square of the intake velocity. The lack of back-to-back repeatability on several of the data points is significantly higher than expected. The scatter may be attributed to gusting wind conditions, which were reported during the testing. Since the engine stand was

fixed in one angular position during the testing, the changing direction of the wind would affect both the inlet and exhaust pressures.

The scatter in the NAPC data is also evident in the spool speed ratio (Figure 20), and to a lesser extent in the compressor pumping characteristics (Figure 21). It is possible that the scatter in the spool speed ratio is the result of the wind causing inlet pressure distortion which in turn could rematch the compressors. It is known, however, that the NAPC data were recorded during 45 second scans, as opposed to approximately six minute scans for the NRC data. If the engine was hunting more because of the wind conditions, it is more likely the NAPC data acquisition would not average out the fluctuations, thus reducing the precision of the results.

As expected, the compressor efficiency, Figure 22, shows a large amount of scatter, in some cases as much as 0.5 percent. If the fluctuating wind conditions are causing the compressor spools to shift their operating speeds, the compressor discharge pressure and temperature would naturally shift as well. The engine airflow (Figure 23), and fuel flow (Figure 24) also show minor scatter, since the airflow is governed by the low pressure compressor speed, and the fuel flow is governed by the high pressure compressor speed, for this particular engine.

Overall, the test data recorded by both the NRC Engine Laboratory and the NAPC are considered to be of sufficiently good quality to be used for an accurate comparison.

6.2 Performance Retention

The purpose of examining performance retention is to verify that engine performance had not deteriorated between the time it was tested at NRC and NAPC, nearly five years later. The J57 engine was tested first at the NRC Engine Laboratory in the summer of 1982. The NAPC tested the engine in April, 1987. In the intervening years, the engine was tested at several other ground level and altitude test facilities involved in the UETP. However, during that testing period, the engine accumulated less than two hundred operating hours.

Deterioration might take the form of compressor fouling, or wearing of compressor or turbine blades, vanes, or seals. Testing done on one of the two engines used in the UETP near the completion of the program showed that a water wash performed on the engine did not significantly change its performance, thus reducing any suspicion of compressor fouling.

To assess the performance retention of the engine is relatively straightforward for this particular case. The emphasis is on the performance of the gas generator. This simplification is possible because the engine has a fixed geometry final exhaust nozzle. Such a nozzle would produce the same amount of thrust, at a given nozzle pressure ratio, during any test, provided that it has the same nozzle inlet conditions, which depend entirely on the behavior of the gas generator.

The procedure for quantifying the performance of the gas generator is to divide it up into its individual components, where possible, and compare the performance of each. Any shifts in the performance of these components must also be judged relative to the associated uncertainties of the parameters. These uncertainties have been declared by both of the test facilities, and are given in Table 5. If the magnitudes of the performance shifts were larger than the estimated overall uncertainties (bias plus twice the precision), then the gas generator would be considered to be operating differently from one facility to the other, and a direct correlation of the thrust results would be more difficult.

The performance of the compressors is observed in the spool speed ratio (Figure 20), the compressor pumping characteristic (Figure 21), the compressor efficiency (Figure 22), and the airflow (Figure 23). The spool speed ratio shows a reduction of 0.2 percent, from NRC to NAPC. However, the uncertainty in the corrected rotor speed measurement is large enough to overlap both sets of data.

The compressor pumping characteristics show very good agreement between the two facilities, with NAPC slightly above the NRC at lower pressure ratios, and slightly below at high pressure ratios. Since the differences are much less than the uncertainties of the individual parameters used in the comparison, there is considered to be no change in the pumping characteristics.

The calculation of the compressor efficiency comes directly from the pumping characteristics, and the results are similar. The large scatter in the NAPC data accentuates the differences in the actual efficiency curves. However, since the curves of the two facilities cross, and the combined uncertainty on the compressor efficiency is nearly two percent, the compressor performance is likely unchanged.

The airflow comparison confirms the compressor efficiency results. The shift in the airflow is less than 0.5 percent, which is well within the measurement uncertainty. Based on the combined results of the compressor performance, it is reasonable to assume that the compressor had not deteriorated between the NRC and the NAPC testing.

The performance of the remainder of the gas generator may be determined by comparing the fuel flow data (Figure 24), and the engine temperature and pressure ratios (Figure 25). The engine temperature ratio is defined as the turbine exit temperature divided by the engine inlet temperature, while the engine pressure ratio is the turbine exit pressure divided by the engine inlet pressure. The fuel flow comparison shows excellent agreement between the two facilities, with the measurement uncertainty being larger than any perceived performance shift. The engine temperature and pressure ratios also demonstrate very close agreement at lower power settings, with some divergence at higher power. However, even at the maximum deviation, the difference between the NRC and NAPC data is less than the declared uncertainty.

The results of performance retention comparisons indicate that while some parameters exhibit minor scatter, the gas generator, as a whole, has not developed any measurable deterioration in its performance between testing at NRC and NAPC.

6.3 Thrust Correlation

Having shown that the performance of the gas generator has not shifted during the time between the NRC and NAPC testing, it is now possible to directly compare the thrust results, which should determine whether all of the forces generated in the indoor test cell have been counted. For one-dimensional analysis, if a fixed geometry exhaust nozzle is supplied with the same entry conditions, it will produce the same amount of thrust, at a given nozzle pressure ratio. In actual fact, the flow through the nozzle is three-dimensional, which means that even if the average flow conditions at the nozzle entry were equivalent, the performance of the nozzle may be altered by swirl and probe blockage affects. These will be discussed in greater detail later. Another problem encountered when using nozzle pressure ratio for data comparison is the measurement of the nozzle exit pressure. For an outdoor stand, the nozzle exhausts to the ambient barometric pressure. In an indoor cell, the pressure around the nozzle is depressed by the bypass flow over the external surface of the boattail. Measurement of the pressure the nozzle actually exhausts to may be difficult. For purposes of this analysis, most of the thrust comparisons will be performed using the engine pressure ratio, as recommended by the engine manufacturer (Pratt & Whitney, 1974).

The comparison of the gross thrust results are given in Figures 26 through 30. The corrected gross thrust (Figure 26), compares very favorably, with NRC slightly lower at low engine pressure ratios, and slightly high at the highest power setting. Figure 27 illustrates the deviation between the NAPC and NRCC gross thrust results. The uncertainty involved in measuring thrust (0.4 to 0.6 percent) is large enough to encompass all of the data. The same can be said for the comparison of two important thrust functions. The FAP function is defined as the gross thrust divided by nozzle exit area and nozzle entry or exit pressure. This non-dimensional function relates the thrust output of the nozzle to the existing nozzle entry or exit pressure conditions. In Figure 28, the FAP function (based on nozzle entry pressure) shows very good agreement over most of the power range. The NAPC data indicate a slight drop-off at the highest power condition. The FAP function (based on the nozzle exit pressure) plotted against nozzle pressure ratio, in Figure 29, shows good agreement between the two facilities. In this case, any difficulties in the measurement of the nozzle exit pressure are eliminated. The minor differences between the two facilities are within the overall uncertainty in the measurements.

The final comparison of the thrust measured at the two test facilities, is the specific fuel consumption (Figure 30). While the NAPC data display a lot of scatter, the differences between the two tests are indeed within the overall uncertainty.

6.4 Nozzle Effects

Any divergence observed in the thrust functions may be the influence of real nozzle effects. These effects include non-uniform nozzle inlet flow in the axial, circumferential, and radial directions. Coupled with real gas effects such as viscosity and variable specific heat properties, the performance of the exhaust nozzle used on this engine may be altered.

During the UETP testing, it was discovered that the measurement of the average nozzle entry total pressure was not very accurate because of faulty instrumentation. Coupled with the instrumentation problems was the observation that a slight change in the swirl pattern in the tailpipe would alter the calculation of the average pressure. Thus for the comparison of nozzle thrust data, the nozzle entry static pressure was used, since it was proven by NASA (Biesiedny, 1982) that the static pressure in the tailpipe was insensitive to the swirl.

CHAPTER 7

7.0 CONCLUSIONS

The derivation of gross thrust for a ground level jet engine test cell has been presented. The effect of the test cell on the performance of an engine has been quantified. Comparison between indoor and outdoor test results have been made to confirm the validity of the indoor thrust measurement corrections. Given the chosen thrust accounting scheme, these correction forces have been identified and derived individually and collectively. In support, a discussion of the quality of the test data and the performance continuity of the J57 engine used for this thesis has been presented.

Conclusions can be drawn regarding the significance of the test cell design on thrust measurement, the corrections which must be made to the scale force, and the use of cell correlation factors for various types of jet engine test facilities.

7.1 Influence of Test Cell Design

The design of the indoor ground level test cell has a significant influence on the measurement of thrust. The "test cell effect" is governed by the aerodynamic conditions inside the cell. All of the thrust corrections are a function of the average cell velocity, which is related to the cell bypass ratio. The bypass ratio is controlled by the exhaust collector geometry.

7.2 Thrust Measurement

For the calculation of the corrections which must be applied to the scale force to obtain the "true" gross thrust, it is important that certain vital parameters be measured or calculated accurately. These parameters include test cell airflow, average cell velocity, static pressure in planes 0 and b, and the external boattail pressure. In addition, precise measurement of the projected and wetted areas must be done, so that the magnitudes of the pressure and friction forces can be calculated correctly.

Once the flow conditions inside the test cell are quantified, all of the correction factors for momentum, pressure, and friction forces may be calculated. The corrected thrust value represents the "true gross thrust" of an engine as if it were operating in "free-air" conditions.

For a J57 engine run in the NRC Engine Laboratory's No. 5 test cell, the corrected gross thrust agrees very well with the thrust measurements made with the same engine at the NAPC outdoor test stand. Thus, the derivation and the magnitude of the cell corrections which, in this case, are approximately two percent, are considered to be valid.

7.3. Use of Cell Correlation Factors

For a research test facility capable of accurately measuring scale force and certain auxiliary parameters, the need for a test cell correlation factor to some reference outdoor test stand should, in general, be unnecessary. If all of the forces being generated in or on the test cell have been accounted for, then the gross thrust of the engine in an indoor cell would indeed be the "true" gross thrust.

For an overhaul facility or an engine run-up stand, which is incapable of measuring the auxiliary parameters needed to correct the scale force for the "test cell effects", then the use of a thrust correlation factor is warranted. However, if such a facility were to frequently modify the configuration of its cell, new correlation factors would have to be determined for each configuration, since the cell factor is strongly dependent on the aerodynamic performance of the test cell.

7.4 Summary

With future engines growing in terms of thrust and airflow, the importance of the test cell design and the thrust corrections needed to account for the "test cell effect" will increase dramatically. A better understanding of the interaction between the engine and its immediate surroundings will enhance the quality and efficiency of engine testing in the future.

CHAPTER 8

8.0 RECOMMENDATIONS FOR FUTURE WORK

Concerning the thrust corrections which must be made to the measured scale force, there are several small refinements that should be made to provide more accurate results. These refinements pertain to the calculation of the axial pressure forces on the engine control volume. For this study, these forces were approximated using average pressures and total projected areas for the boattail and bypass pressure drag. These forces are, in reality, surface integrals of incremental areas and pressure differences over the engine carcass and planes 0 and b. To better approximate these forces, measurements of the static pressure variation over these areas should be made, and the magnitude of the surface integrated force compared to the average force method used in this thesis.

In the comparison of the indoor and outdoor test data, it became apparent that the effects of the wind conditions on the measurements made on the outdoor stand were not accounted for. Attempts to quantify

the wind contribution to the thrust measurements, should be done to reduce the scatter, and provide better confidence in the results.

Regarding the use of gross thrust calculations such as those presented in the thesis, a rigorous uncertainty analysis should be performed to estimate the contribution that uncertainty in the correction factors make to the overall uncertainty in thrust and specific fuel consumption. In previous work the additional uncertainty accorded by a correction factor was considered a second order effect. Since the magnitude of these corrections is not insignificant, the overall uncertainty in the gross thrust could be affected.

Another approach which would prove helpful in correlating indoor and outdoor thrust data would be to calculate the gross thrust using a calibrated nozzle. This would require special instrumentation to measure the momentum and pressure forces in the exit plane of the nozzle. The advantage of this correlation method is that it eliminates the need for correction factors to compensate for aerodynamic forces acting external to the engine. An alternative method would be to compare thrust calculated using various planes of accounting.

REFERENCES

- 1) ASHWOOD, P. 1984. Operation and Performance Measurement on Engines in Sea-Level Test Facilities. AGARD-LS-132.
- 2) BIESIEDNY, T., et al. 1982. Uniform Engine Testing Program Phase I: NASA LeRC Participation. NASA TM 82978.
- 3) COVERT, E.E. 1985. Thrust and Drag: Its Prediction and Verification. AIAA Series Vol. 98.
- 4) DUNCOMBE, E., SMITH, E.. 1951. Note on the Effect of Various Intake Ducts on the Indicated Thrust of Turbojet Engines. National Research Council Laboratory Note ET-1-51.
- 5) ESDU 69006, 1981. Introduction to the Measurement of Thrust in Flight.
- 6) FREULER, R., DICKMAN, R. 1982. Current Techniques for Jet Engine Test Cell Modeling. AIAA-82-1272.
- 7) General Electric. 1979. F404-GE-400 Engine Qualification Test Phase - Performance Verification. R79AEG096.
- 8) HASTINGS, R.R., 1983. A Simulation of a Jet Engine Test Cell. NRC/DME report LTR-ENG-110.
- 9) HAYES, J.D. 1975. An Investigation of the Flow in Turbojet Test Cell Augmentors. Master's Thesis, Naval Postgraduate School.
- 10) HOERNER, S.F. 1965. Fluid-Dynamic Drag.
- 11) KARAMANLIS, T., et al. 1985. A Universal Turboshaft Engine Test Cell - Design Considerations and Model Test Results. AIAA-85-0382.
- 12) KARAMANLIS, T., et al. 1986. Theoretical and Experimental Investigation of Test Cell Aerodynamics for Turbofan Applications. AIAA-86-1732.
- 13) KROMER, S., DIETRICH, D. 1985. Flowfield Analysis of Low Bypass Ratio Test Cells. Journal of Aircraft, Vol. 22, No.2.
- 14) LEE, J., FREULER, R. 1985. Engine Simulator Techniques for Scaled Test Cell Studies. AIAA-85-1282.
- 15) OATES, G.C. 1984. The Aerothermodynamics of Aircraft Gas Turbine Engine and Rocket Propulsion. AIAA Education Series.
- 16) Pratt & Whitney Group. 1974. The Aircraft Gas Turbine Engine and Its Operation, PWA 182408.

- 17) SAE ARP 741. 1976. Gas Turbine Engine Test Cell Correlation.
- 18) SAE ARP 755A. Revised 1974: Gas Turbine Engine Performance Station Identification and Nomenclature.
- 19) SAPP, C., NETZER, D. 1978. Experimental Investigation of Turbojet Test Cell Augmentors. NPS-67-78009.
- 20) Uniform Engine Test Program, General Test Plan. Revised 1982. Propulsion and Energetics Panel, Working Group 15.

BIBLIOGRAPHY

- 1) ASHWOOD, P. 1987. AGARD: The Uniform Engine Test Programme Report of PEP Working Group 15, Issue No. 3.
- 2) RUDNITSKI, D., et al. 1983. A Detailed Procedure for Measuring Turbojet Performance in an Enclosed Sea-level Test Facility. LTR-ENG-120.
- 3) SARAVANAMUTTOO, H.I.H., et al. 1987. Gas Turbine Theory. 3rd Edition.
- 4) ZUCROW, M.J. 1958. Aircraft and Missile Propulsion, Volume II.
- 5) ABERNATHY, R.B., THOMPSON, J.W. 1973. Handbook of Uncertainty in Gas Turbine Measurements. AEDC-TR-73-5.
- 6) BERGMAN, D. 1971. Effects of Engine Exhaust Flow on Boattail Drag. Journal of Aircraft. Vol. 8, No. 6.
- 7) L'ECUYER, M. 1970. Correlation of Turbofan Engine Thrust Performance with Compound Nozzle Flow Theory. AIAA-70-612.
- 8) Guide to In-Flight Thrust Measurement of Turbojet and Fan Engines. 1979. AGARD-AG-237. MIDAP Study Group.
- 9) CHAPPELL, M.S., COCKSHUTT, E.P. 1974. Gas Turbine Cycle Calculations: Thermodynamic Data Tables for Air and Combustion Products for Three Systems of Units, NRC-LR-579.
- 10) OSBORN, A.R. 1987. A Comparison of Gross Thrust Determination Between UETP test Facilities, RAE Technical Memo P1011.
- 11) SIMPSON, P.A. 1986. Aerodynamics of Monitoring Engine Thrust Measurement on Indoor Sea-Level Test Beds, AIAA-86-1734.
- 12) Operation and Performance Measurement on Engines in Sea-Level Test Facilities. 1984. AGARD-LS-132.
- 13) BERGMAN, D. 1970. Effects of Engine Exhaust Flow on Boattail Drag, AIAA-70-132.
- 14) SMITH, J. 1971. Experimental Techniques for Evaluating Steady-State Jet Engine Performance in an Altitude Facility. NASA TMX-2398.
- 15) The Determination of Gross Thrust and Mass Flow in Flight. 1981. ESDU 69007.
- 16) Definitions of the Thrust of a Jet Engine and of the Internal Drag of a Ducted Body. 1955. ARC CP 190.

- 17) SPEAKMAN, G., et al. 1976. Internal Aerodynamics of Turbojet Test Cells, NPS-67NT76121.
- 18) Jet Flow Parameters. 1981. ESDU 67035.
- 19) JAKOBSSON, B. 1951. Definition and Measurement of Jet Engine Thrust. Journal of the Royal Aeronautical Society.
- 20) DEJNEKA, R. 1980. Decoupled Bellmouth - an Alternate Method of Measuring Thrust in the Sea-Level Test Cell. NAPC- PE-155.
- 21) BLAZEY, D. 1983. F404-400 Engine ESN 376044-1A Test Cell Correlation Results from Lynn Cell 108 and NRC Ottawa Canada Test Cell. G.E. Document.
- 22) TELERICO, J. 1961. Evaluation of a Proposed Method of Determining In-Flight Net Thrust. NATTS-ATL-65.
- 23) ASCOUGH, J. 1978. A Test Code for Contract Performance Measurements Made in Cell 3 of the NGTE Engine Test Facility. NGTE M78020.
- 24) Blockage Corrections for Bluff Bodies in Confined Flows. 1980. ESDU 80024.
- 25) Mass Flow and Momentum Functions for One-Dimensional Flow of Gas in Ducts. 1981. ESDU 81004. 1981.
- 26) SAMUELS, J., GALE, B. 1950. Effect of Humidity on Performance of Turbojet Engines. NACA TN 2119.
- 27) WALTERS, J., NETZER, D. 1978. A Validation of Mathematical Models for Turbojet Test Cells. NPS-67NT78061.
- 28) HEWLETT, H., et al. 1977. A Sub-Scale Turbojet Test Cell for Design Evaluations and Analytical Model Validation. NPS-67NT77091, 1977.
- 29) GOLDSMITH, E.L., CARTER, E.C. 1972. A Review of Methods Used for the Representation of Engine Flows in High Speed Wind Tunnel Testing, RAE TR 72012.

TABLE 1

NAPC AMBIENT TEST CONDITIONS					
Pamb (kPa)	Tamb (K)	Wind Velocity (m/s)	Wind Direction (Deg)	Stand Position (Deg)	Relative Humidity (%)
101.8	286-290	1.6-9.9	15-121	20	43

TABLE 2

NRC AMBIENT TEST CONDITIONS			
Pamb (kPa)	Tamb (K)	Cell Velocity (m/s)	Relative Humidity (%)
99.8	288-294	5 - 7	65

TABLE 3

NRC TEST CELL OPERATING CONDITIONS					
P_0 (kPa)	V_0 (m/s)	W_0 (kg/s)	WA2R (kg/s)	α	F_m (kN)
99.718	6.85	151.546	73.498	1.090	43.973
99.735	6.85	151.531	73.889	1.093	44.026
99.774	5.89	130.341	63.363	1.099	30.842
99.762	5.86	130.228	63.348	1.097	30.802
99.841	5.58	123.041	57.003	1.201	24.423
99.838	5.53	122.071	56.933	1.188	24.350
99.781	6.47	142.110	68.562	1.115	37.174
99.777	6.45	141.771	68.439	1.113	37.061
99.805	5.62	123.489	59.216	1.126	26.714
99.793	5.65	123.781	59.139	1.134	26.665
99.817	5.23	114.555	53.293	1.195	21.165
99.810	5.21	114.157	53.185	1.191	21.033
99.741	6.25	136.934	65.282	1.140	33.498
99.734	6.22	136.140	65.284	1.127	33.387
99.707	6.63	144.097	70.075	1.098	39.263
99.690	6.57	143.194	69.764	1.094	39.164

TABLE 4

THRUST CORRECTIONS							
F_m	$\frac{F_{tf}}{F_m}$	$\frac{F_f}{F_m}$	$\frac{F_{bt}}{F_m}$	$\frac{F_{im}}{F_m}$	$\frac{F_b}{F_m}$	$\frac{F_{fw}}{F_m}$	$\frac{\Sigma F_{tot}}{F_m}$
(kN)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
43.973	.0241	.0014	.372	1.702	-.313	.0118	1.829
44.026	.0241	.0014	.368	1.698	-.312	.0118	1.823
30.842	.0256	.0015	.476	1.789	-.178	.0124	2.012
30.802	.0256	.0015	.477	1.789	-.178	.0124	2.012
24.423	.0314	.0018	.550	1.951	-.225	.0140	2.283
24.350	.0307	.0018	.548	1.934	-.226	.0139	2.259
37.174	.0258	.0015	.428	1.767	-.333	.0124	1.954
37.061	.0257	.0015	.415	1.765	-.333	.0123	1.937
26.714	.0273	.0016	.526	1.849	-.206	.0130	2.128
26.665	.0278	.0016	.517	1.863	-.206	.0131	2.135
21.165	.0314	.0019	.587	1.969	-.195	.0142	2.333
21.032	.0313	.0018	.582	1.970	-.195	.0141	2.327
33.498	.0272	.0016	.457	1.812	-.164	.0128	2.035
33.387	.0267	.0016	.458	1.805	-.164	.0127	2.022
39.263	.0250	.0015	.392	1.749	-.315	.0122	1.893
39.164	.0246	.0014	.399	1.729	-.316	.0120	1.881

TABLE 5

ESTIMATED DATA UNCERTAINTIES						
PARAMETER	ERROR, PERCENT OF READING					
	NAPC			NRC		
	BIAS	PRECIS.	UNCERT.	BIAS	PRECIS.	UNCERT.
NLQNH	.01	.01	.02	.09	.00	.09
NHR	.23	.05	.32	.22	.09	.40
NLR	.23	.05	.32	.22	.09	.40
T5Q2	.43	.08	.61	.53	.19	.91
P5Q2	.02	.03	.08	.13	.06	.25
WA2R	.29	.11	.50	.60	.04	.68
FGR	.19	.12	.42	.43	.10	.63
WFR	.21	.31	.82	.45	.13	.71
SFCR	.28	.33	.93	.60	.14	.88
PS7QAMB	.03	.07	.18	.13	.06	.25
T3Q2	.43	.08	.61	.51	.19	.89
P3Q2	.02	.03	.08	.15	.06	.27

FIGURE 1: GENERAL TEST CELL

FIGURE 2: ENGINE / TEST CELL CONTROL VOLUME

FIGURE 3: ENGINE STATION DESIGNATIONS

FIGURE 4: NAPC TEST SITE LAYOUT

FIGURE 5: ENGINE INSTALLATION AT NAPC OUTDOOR TEST SITE

FIGURE 6: NO. 5 TEST CELL - ENGINE LABORATORY - NRCC

* WALL STATICS
(4 LOCATIONS)

EXHAUST COLLECTOR

PROPELLER
ANEMOMETER

*

ENGINE MOUNT
SUPPORT FRAMES

*

ENGINE INLET
BELLMOUTH

*

INLET SCREEN

THRUST STAND FLEXURES

THRUST STAND

THRUST CELL

FIGURE 7: SCHEMATIC OF J57 TURBOJET ENGINE ON TEST STAND

FIGURE 8: BYPASS RATIO VS AIRFLOW

TEST CELL CONDITIONS

FIGURE 9: CELL VELOCITY VS CELL AIRFLOW

FIGURE 10: INTRINSIC INLET MOMENTUM

FIGURE 11: BOATTAIL DRAG

FIGURE 12: BYPASS PRESSURE DRAG

FIGURE 13: THRUST FRAME DRAG

FIGURE 14: SKIN FRICTION DRAG

FIGURE 15: WALL FRICTION DRAG

• FIGURE 16: TOTAL THRUST CORRECTION

FIGURE 17: CORRECTION FACTOR COMPARISON

2 of/de 2

MicroD

FIGURE 18: SCALE FORCE TO GROSS THRUST COMPARISON

FIGURE 19 : RAM PRESSURE RATIO VS
CORRECTED COMPRESSOR ROTOR SPEED

FIGURE 20: SPOOL SPEED RATIO VS
CORRECTED COMPRESSOR ROTOR SPEED

INDOOR / OUTDOOR DATA COMPARISON

FIGURE 21: COMPRESSOR PUMPING CHARACTERISTIC

INDOOR / OUTDOOR DATA COMPARISON

FIGURE 22: COMPRESSOR EFFICIENCY VS
CORRECTED COMPRESSOR ROTOR SPEED

FIGURE 23: CORRECTED ENGINE AIRFLOW VS
CORRECTED COMPRESSOR ROTOR SPEED

INDOOR / OUTDOOR DATA COMPARISON

FIGURE 24: CORRECTED ENGINE FUEL FLOW VS
CORRECTED COMPRESSOR ROTOR SPEED

FIGURE 25: ENGINE TEMPERATURE RATIO VS
ENGINE PRESSURE RATIO

INDOOR / OUTDOOR DATA COMPARISON

FIGURE 26: CORRECTED GROSS THRUST VS
ENGINE PRESSURE RATIO

FIGURE 27: THRUST COMPARISON VS
ENGINE PRESSURE RATIO

FIGURE 28: FAP FUNCTION VS ENGINE PRESSURE RATIO

FIGURE 29: FAP FUNCTION VS
NOZZLE STATIC PRESSURE RATIO

INDOOR / OUTDOOR DATA COMPARISON

FIGURE 30: CORRECTED SPECIFIC FUEL CONSUMPTION VS CORRECTED GROSS THRUST

APPENDIX A

DERIVATION OF THE MOMENTUM EQUATION

The development of the momentum equation for a control volume is based on Newton's Second Law of Motion, which states that the sum of the external forces acting on a body in a given direction is proportional to the rate of change of momentum in the given direction, or

$$\Sigma F_x = \frac{d}{dt} (WV) \quad (1)$$

Expanding the right side of Equation (1) gives,

$$\frac{d}{dt} (WV) = W \frac{dV}{dt} + V \frac{dW}{dt}$$

where (since $W = \rho AV$),

$$W \frac{dV}{dt} = \frac{(WV)_{t+dt} - (WV)_t}{dt} = \frac{d}{dt} \int_V \rho V dv$$

and,

$$V \frac{dW}{dt} = \frac{(WdW)_{out} - (VdW)_{in}}{dt} = \int_A \rho V^2 dA$$

thus,

$$\Sigma F_x = \frac{d}{dt} \int_V \rho V dv + \int_A \rho V^2 dA$$

For steady-state, steady-flow conditions,

$$\frac{d}{dt} \int_V \rho V dv = 0$$

and considering only uniform properties in and out of the control volume, results in

$$\int_A \rho V^2 dA = \Sigma(WV)_{out} - \Sigma(WV)_{in}$$

therefore,

$$\Sigma F_x = \Sigma(WV)_{out} - \Sigma(WV)_{in} \quad (2)$$

Applying equation 2 to the control volume shown in Figure 2 results in (assuming positive forces are acting to the right),

$$\begin{aligned} F_m + A_o P_o - A_b P_b - A_{pbt} P_{bt} - A_e P_e + F_{tf} + F_f - F_{fw} \\ = W_e V_e + W_b V_b - W_o V_o \end{aligned}$$

where

F_{tf} = drag force on the thrust frame

F_f = friction force on the engine,

F_{fw} = friction force on the walls

APPENDIX B

DERIVATION OF THE TEST CELL ENERGY BALANCE

For the derivation of the energy balance across the test cell, the control volume shown in Figure A1 was chosen. The energy balance method comprises a calculation of the change in enthalpy from the cell intake, to the exhaust outlet, accounting for the energy input of the fuel consumed by the engine.

FIGURE A-1: CONTROL VOLUME FOR ENERGY BALANCE

From the First Law of Thermodynamics, the energy balance may be described by,

$$H_{in} + \dot{Q}_{in} = H_{out} + \dot{W}_{out} \quad (A1)$$

where: H_{in} = total enthalpy entering the control volume

$\dot{Q}_{in}$ = rate of heat added to the control volume

H_{out} = total enthalpy exiting the control volume

$\dot{W}_{out}$ = rate of work done by the control volume

Since the work output of the test cell control volume is, in this case, equal to zero, ie. $\dot{W}_{out} = 0$, Equation A1 reduces to:

$$\dot{H}_{out} - \dot{H}_{in} = \dot{Q}_{in} \quad (A2)$$

For the test cell control volume,

$$\dot{H}_{out} = (\dot{W}_0 + \dot{W}_F) * h_{stack} \quad (A3)$$

$$\dot{H}_{in} = \dot{W}_0 * h_{\infty} \quad (A4)$$

$$\dot{Q}_{in} = \dot{W}_F * (LHV * \eta_c + h_{ref} + dhf) \quad (A5)$$

where $\dot{W}_0$ = total test cell airflow

$\dot{W}_F$ = engine fuel flow

LHV = fuel lower heating value

η_c = combustion efficiency

h_{ref} = fuel reference enthalpy at standard day temperature

dhf = increment of fuel enthalpy from standard day temperature

h_{stack} = specific enthalpy in the exhaust stack

h_{∞} = specific enthalpy at the cell intake.

By substituting Equations A3, A4, and A5, into Equation A2,

$$(\dot{W}_0 + \dot{W}_F) * h_{stack} - \dot{W}_0 * h_{\infty} = \dot{W}_F * (LHV * \eta_c + h_{ref} + dhf)$$

or,

$$\dot{W}_0(h_{stack} - h_{\infty}) = \dot{W}_F * (LHV * \eta_c + h_{ref} + dhf - h_{stack})$$

The cell flow is then found by

$$W_0 = WF * [LHV * n_c + h_{ref} + dh_f - h_{stack}] / (h_{stack} - h_{\infty}).$$

In order to calculate the specific enthalpy in the exhaust, the fuel-air ratio in the exhaust stack must first be determined from,

$$FAR_{stack} = WF / (W_0 * (1 + WAR_0)),$$

where WAR_0 is inlet water-air ratio, which is a correction for humidity in the air.

The enthalpy of the exhaust stack is then computed using the exhaust stack temperature, the stack fuel-air ratio, and the inlet water-air ratio.

END

0|8·0|8·88

FIN