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***Thrust Stand Calibration and Thrust  
Correction Procedures for an F404  
Engine Installation***

M. F. Mulligan and J. D. MacLeod

Laboratory Memorandum

Mémoire de laboratoire

1990/08

LM-ENG-028

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**THRUST STAND CALIBRATION AND THRUST CORRECTION  
PROCEDURES FOR AN F404 ENGINE INSTALLATION**

**ÉTALONNAGE D'UN BANC DE POUSSÉE ET PROCÉDURES DE  
CORRECTION DE LA POUSSÉE POUR L'INSTALLATION D'UN MOTEUR F404**

**M.F. Mulligan**  
**J.D. MacLeod**

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## ABSTRACT

Measurement of scale thrust and a procedure for obtaining engine gross thrust for a F404 gas turbine are described in this report. Calibration of a thrust bed (a structure for measuring the scale thrust), corrections for test stand tare, and test cell aerodynamic effects are discussed. Thrust calculations for a test run are also presented. Furthermore, software utilized for the thrust bed calibration is included in Appendix A.

## RÉSUMÉ

Le présent rapport donne les mesures de poussée à l'échelle ainsi qu'une procédure pour obtenir la poussée brute du moteur d'une turbine à gaz F404. L'étalonnage d'un banc de poussée (dispositif servant à mesurer la poussée à l'échelle), les corrections à apporter pour la tare du banc d'essai et les effets aérodynamiques du module d'essai sont aussi traités de même que les calculs de poussée pour un essai de fonctionnement. De plus, le logiciel utilisé pour l'étalonnage du banc de poussée est donné à l'annexe A.

## CONTENTS

	<b>Page</b>
ABSTRACT .....	i
RÉSUMÉ .....	i
LIST OF APPENDICES .....	iii
LIST OF FIGURES .....	iii
LIST OF SYMBOLS .....	iv
1.0 INTRODUCTION .....	1
2.0 CENTRE-LINE PULL CALIBRATION .....	1
2.1 Description of Centre-Line Pull Equipment .....	1
2.2 Description of Thrust Bed .....	1
2.3 Description of Test Procedure .....	2
2.4 Test Results .....	2
3.0 TEST STAND TARE COMPENSATION .....	3
4.0 RATIONALIZATION OF GROSS THRUST .....	3
4.1 Scale Force .....	4
4.2 Intrinsic Inlet Momentum .....	5
4.3 Bypass Pressure Drag .....	5
4.4 Thrust Frame Drag .....	5
4.5 Skin Friction Drag .....	6
4.6 Boattail Drag .....	6
4.7 Secondary Flow Calculations .....	6
4.8 Summary .....	7
5.0 CONCLUSIONS AND RECOMMENDATIONS .....	7
6.0 ACKNOWLEDGEMENTS .....	8
7.0 REFERENCES .....	8

## CONTENTS (Cont'd)

### LIST OF APPENDICES

Appendix		Page
A	Centre-line Pull Code . . . . .	A-1
B	Centre-line Pull Test Data . . . . .	B-1
C	Estimation of Boattail Drag . . . . .	C-1
D	Determination of Cell Airflow and Bypass Area . . . . .	D-1
E	F404 Thrust Calculations . . . . .	E-1

### LIST OF FIGURES

Figure		Page
1	No. 5 test cell - Engine Laboratory - NRCC . . . . .	9
2	Test cell wall mounting for centre-line pull rig . . . . .	10
3	Hydraulic jack mounting for centre-line pull rig . . . . .	11
4	Engine mounting points for centre-line pull rig . . . . .	12
5	Thrust bed layout . . . . .	13
6	Engine/test cell control volume . . . . .	14
7	Cell airflow vs. nozzle pressure ratio . . . . .	15
C1	Nozzle fairing static pressure taps . . . . .	C-6
C2	Nozzle geometry . . . . .	C-7

## LIST OF SYMBOLS

Symbol		Page
A	Area	$\text{in}^2, \text{ft}^2$
ABASE	Nozzle base area	$\text{in}^2$
A8A9	Nozzle throat to exit area ratio	
BPR	Bypass ratio	
C	Coefficient	
D	Diameter	in.
$\delta$	Boundary layer thickness	in.
dHF	Increment of fuel enthalpy from standard day temperature	
F	Force	$\text{lb}_f$
FAR	Fuel/air ratio	
H	Enthalpy	$\text{BTU}/\text{lb}_m$
L	Length	in.
NHC	Net heat of combustion	$\text{BTU}/\text{lb}_m$
NPI	Nozzle position indicator	deg
$\eta$	Efficiency	
P	Static pressure	psi
PAMB	Nozzle exit static pressure	psi
P5T	Nozzle inlet static pressure	psi
$R_e$	Reynold's number	
SQRT	Square root	
TH	Thrust	$\text{lb}_f$
$\rho$	Density	$\text{lb}_m/\text{ft}^3$
q	Dynamic pressure	
$\nu$	absolute viscosity	$\text{ft}^2/\text{s}$
VEL	Velocity	ft/s
W	Airflow	$\text{lb}_m/\text{s}$
WARO	water-air ratio	
WF	Fuel flow	$\text{lb}_m/\text{s}$
X	Nozzle axial length	in.

## Subscripts

b	Bypass
bt	Boattail
c	Combustion
d	Drag
e	Nozzle exit
exc	Excitation
f	Force
fr	Friction
g	Gross
im	Inlet momentum
md	Measured
p	Projected

**CONTENTS (Cont'd)****LIST OF SYMBOLS (Cont'd)**

<b>Symbol</b>		<b>Units</b>
ref	Reference	
stack	Exhaust stack	
tf	Thrust frame	
wet	Wetted	
0	Reference plane in test section	
$\infty$	Ambient	
8	Nozzle throat	
10	Nozzle exit outer fairing	

## THRUST STAND CALIBRATION AND THRUST CORRECTION PROCEDURES FOR AN F404 ENGINE INSTALLATION

### 1.0 INTRODUCTION

Gas turbines must pass a number of performance tests before entering or returning to service. For aircraft applications, these tests often include the verification of a performance parameter known as gross thrust. The gross thrust, a calculated quantity, is evaluated from a number of aerodynamic measurements made, most often, in an indoor test cell. Scale force, the dominant factor in the calculation, is measured directly in the test cell through the use of strain gauge devices commonly called "load cells". In most cases, these load cells are mounted, horizontally, in an engine support structure or "thrust bed" off centre to the axis along where the engine thrust is being applied. This offset introduces an error in the scale force measurement process. As a result, a calibration of the thrust bed must be done before attempting to make any engine thrust measurements.

This report describes a method for calibrating a thrust bed used for measuring the scale thrust of an F404 turbofan engine located in No. 5 test cell [Fig. 1] of building M-7. In addition, a procedure for deriving engine gross thrust and a method employed to compensate for test stand tare will also be described.

This report incorporates the Imperial system of units which is generally used by the manufacturer for describing engine performance. As a result, units relevant to the Syst me International (SI) will not appear.

### 2.0 CENTRE-LINE PULL CALIBRATION

A centre-line pull should be performed for any test program where the scale thrust is to be measured accurately. In this experiment the scale thrust was measured using two strain gauge load cells referred to as "measurement" cells. In addition, a third cell was incorporated for controlling a hydraulic ram that was used for preloading and maintaining the position of the thrust bed. A fourth cell or "reference" cell was introduced for measuring the loads applied by the centre line pull apparatus. The reference cell, acting as a transfer standard, was calibrated in a dead weight force machine located at the Structures Laboratory within NRC (Blais 1989).

#### 2.1 Description of Centre-Line Pull Equipment

The centre-line pull apparatus consisted of a reference cell (LC4) and a number of steel structural components for applying a force to the thrust bed, along the centre-line of the engine. The structural components included two rods that extended from the test cell wall [Fig. 2] to a hydraulic ram, located near the engine [Fig. 3]. The reference cell was connected to the ram and to two rods which extended to the engine mounts [Fig. 4]. A centre-line force up to a maximum of 25000 pounds could be applied through the use of a hand operated hydraulic pump. The outputs of the load cell (two bridges) and its excitation voltage were read by a precision voltmeter (HP3456A) and a data acquisition system (NEFF), both located in the control room of the test cell. The data acquisition system was controlled by a MicroVax II computer which was used to store and reduce the recorded data.

A computer program (Appendix A), written in FORTRAN 77, was coded to control the data system and to curvefit the recorded data during the calibration.

#### 2.2 Description of Thrust Bed

Thrust beds, in their simplest form, are constructed with a movable section which is restrained through a thrust measurement cell by a firmly mounted stationary structure. The moveable portion of the test bed, which also supports the engine, is connected to the stationary section with flexure plates. These flexures inhibit the movement of the test bed which causes an error in the thrust measurement process. Further errors are generated through bed bending and length changes caused by thermal expansion. To overcome these errors, a new method for measuring thrust was introduced which resulted in the manufacture and installation of a new thrust bed in No. 5 test cell.

The new bed (Fig. 5) was constructed from a number of structural components large enough to minimize the effects of bending. A multi-directional, low resistance, flexure support system was installed which allowed the bed to move freely in two directions. Control of the bed was managed through a system comprising three temperature controlled load cells, a hydraulic ram (MTS) and a hydraulic ram controller (MTS). One load cell (LC1) was connected to the thrust bed at the front and to the hydraulic ram that was anchored to a restraining beam at the front of the test cell. Two other cells were connected in series to the aft end of the thrust bed and to another restraining beam towards the rear of the test cell. The hydraulic system, controlled by one of the cells (LC2) at the rear, provided the capability to set and maintain a stand tension or preload. This preload, set at approximately 22000 pounds force, was measured by a second cell (LC3). As engine thrust increased the force generated by the hydraulic ram was reduced to maintain a constant preload and bed position. Engine scale force was computed from the difference between the force measured by LC3 and that measured by LC1. The thrust values recorded during engine operation were modified by subtracting out the stand tare after a test run.

The outputs of each cell and their excitation voltages were sampled by the NEFF.

### 2.3 Description of Test Procedure

The hydraulic ram controller was set up according to the steps outlined in the operating manuals (MTS, 1989) supplied with the system. Several calibration runs were carried out for stand preloads of 20000 and 22000 pounds force. An optimum preload of 22000 pounds force was selected which allowed LC1 to operate out of the non-linear portion (<5000 pounds force) in the low end of its operational range. Reference cell electrical zero readings were taken with the cell disconnected from the pulling apparatus prior to applying any load. The reference cell was reconnected and loaded to the its full scale value and then unloaded to exercise and stabilize both the reference and measurement cells before each calibration. During the calibrations, the load on the cells was increased in steps to the full scale value of the cells and then decreased in equal increments. Cell outputs and excitation readings were recorded throughout the range at each step. At the end of each calibration, the reference load cell was disconnected and electrical zero readings were taken.

### 2.4 Test Results

The results of each test sequence are given in Appendix B. A curvefit was done between the true force, as measured by the reference cell, and the difference between the output of measurement cells LC3 and LC1. Data from calibration runs 4, 5, 6, 7, and 11 were combined and curvefitted. The true force, measured by the reference cell, was adjusted to compensate for the average of the electrical offset read before and after each pull. Since the preload and the electrical zero for the measurement cells were treated as a combined term, no electrical zero was subtracted before curvefitting. The results show that the 'B' and 'C' coefficients from the curvefits were independent of preload and remained constant (i.e. constant slope) while the 'A' coefficient varied, slightly. In the form of the general quadratic expression:

$$F = A + BX + CX^2$$

an equation for bridge 'A' for the measurement cell was produced from the calibration values and curvefitting procedure.

$$F = 152.35 + 5920.43 X + 1.3 X^2 \quad (1)$$

where:  $X = mV/V_{exc}$   
 $mV$  = millivolt output of thrust cell  
 $V_{exc}$  = excitation voltage of thrust cell

A,B,C = quadratic curve coefficients

Likewise, the following equation for bridge 'B' was obtained.

$$F = 245.83 + 5913.03 X + 1.9 X^2 \quad (2)$$

An error of 0.4% of reading was found between the centre line force and that recorded by the measurement cells for loads ranging from 10000 to 19000 lb<sub>f</sub>. Loads between 1600 and 10000 lb<sub>f</sub> were found to be in error by 0.3% increasing to 0.9% at 1600 lb<sub>f</sub>.

### 3.0 TEST STAND TARE COMPENSATION

Temperature changes in the test cell affect the test stand tare in day- to-day test operations. To compensate for this tare, a scan of the thrust cells is done before and after each engine test run. The final value is used to correct the thrust readings taken during the test.

### 4.0 RATIONALIZATION OF GROSS THRUST

The gross thrust of an engine is affected by a combination of aerodynamic forces that act on the engine during operation and are specific to each installation. These forces include terms such as scale force, intrinsic inlet momentum, bypass pressure drag, thrust frame drag, skin friction drag, boattail drag, and in some cases wall friction drag. The terms which were found to be applicable for tests carried out in No. 5 test cell will be discussed in the following sections. The derivation of gross thrust, which is covered in another report by MacLeod (1988), has been included for explanatory purposes only.

Consider the engine/test cell control volume as shown in Figure 6. In this installation, the bellmouth is mechanically coupled to the engine stand. The sum of the forces acting on the control volume, under steady-state conditions, is equal to the rate of change in axial momentum across the control volume:

$$F_{md} + A_o P_o - A_b P_b - A_{bx} P_{bx} - A_e P_e + F_g + F_{fr} - W_e VEL_e + W_b VEL_b - W_o VEL_o \quad (3)$$

Given that the bypass ratio is defined as,

$$BPR = \frac{W_b}{(W_o - W_b)}$$

$$\text{then } W_b = \frac{BPR}{(BPR+1)} W_O \text{ and,} \quad (4)$$

$$VEL_b = \frac{BPR}{(BPR+1)} \frac{A_O}{A_b} VEL_O \quad \text{assuming } \rho_O = \rho_b \text{ and,} \quad (5)$$

$$A_b = A_O + A_{bx} + A_e \quad (6)$$

Substituting Equations (4), (5) and (6) into Equation (3), and solving for  $F_{md}$  gives:

$$\begin{aligned} F_{md} = W_e VEL_e + \left[ \left( \frac{BPR}{BPR+1} \right)^2 \frac{A_O}{A_b} - 1 \right] W_O VEL_O + A_O (P_b - P_O) \\ + A_{bx} (P_{bx} - P_b) + A_e (P_e - P_b) - F_{TF} - F_{fr} \end{aligned} \quad (7)$$

From Equation (7), the force measured in the test cell is equivalent to the intrinsic or engine generated thrust, plus some additional terms which result from the flow of secondary air over the external carcass of the engine. The locations of the planes of accounting, except for the exhaust exit plane, could be chosen arbitrarily. However, these planes are selected to facilitate measurements. The requirements for locating planes 0 and b are uniform static pressure and velocity. Therefore, definition of planes 0 and b might prove difficult in test cells with distorted flow fields. If the gross thrust is defined as,

$$TH_g = W_e VEL_e + A_e (P_e - P_O) \text{ ,or} \quad (8)$$

$$TH_g = W_e VEL_e + A_e (P_e - P_b) + A_e (P_b - P_O) \text{ and,} \quad (9)$$

$$A_e = A_O + A_b + A_{bx} \quad (10)$$

then,

$$\begin{aligned} TH_g = F_{md} + \left[ 1 - \left( \frac{BPR}{BPR+1} \right)^2 \frac{A_O}{A_b} \right] W_O VEL_O + [A_b (P_O - P_b) \\ + A_{bx} (P_O - P_b)] + A_{bx} (P_O - P_{bx}) + F_{ff} + F_{fr} \end{aligned} \quad (11)$$

These six terms are referred to as scale force, intrinsic inlet momentum, bypass pressure drag, boattail drag, thrust frame drag, and skin friction drag. Each term will be described below.

#### 4.1 Scale Force

With the definition the gross thrust of an engine, the first step is to determine what thrust is being measured in the test cell. The measured quantity in the test cell is known as the scale force. This force, corrected for test stand tare, is calculated from the relationship obtained from performing the centre-line pull.

## 4.2 Intrinsic Inlet Momentum

The most significant aerodynamic effect on the measurement of thrust, in indoor static engine testing, is attributed to the intrinsic inlet momentum. It is a fraction of the total momentum and is produced by the acceleration of air into the engine inlet. The remainder of the total momentum, which does not affect the measured thrust, is generated by the engine exhausting into the collector. The intrinsic inlet momentum change produces a drag force on the engine and, hence, must be added to the measured thrust. The magnitude of the force can be evaluated from:

$$F_{im} = [1 - (\frac{BPR}{BPR+1})^2 \frac{A_o}{A_b}] W_o VEL_o$$

This expression shows that the intrinsic inlet momentum is a function of the engine airflow and the bypass secondary flow, which are governed by the size of the engine and the aerodynamic characteristics of the test cell.

## 4.3 Bypass Pressure Drag

The bypass pressure drag is that force generated by a pressure drop 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:

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

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.

## 4.4 Thrust Frame Drag

The thrust frame drag is defined as the pressure force generated by the bypass flow acting on the exposed structure which supports the engine on the thrust measurement device. The magnitude of this drag is rather small, since most modern thrust frames are reasonably well streamlined and velocities are usually low. The drag is calculated from 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

The bypass velocity  $VEL_b$ , required for the calculation of  $q_b$ , may be computed by:

$$VEL_b = \frac{BPR}{(BPR+1)} \frac{A_o}{A_b} VEL_o$$

The bypass flow air 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 (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 and consequently will vary from one installation and configuration to another.

#### 4.5 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 the size of this force as:

$$F_{fr} = C_{fr} * A_{wet} * q_b$$

The effective skin friction coefficient,  $C_{fr}$ , for turbulent flow over a rough flat plate is approximately 0.005.

The magnitude of the skin friction force is a function of the bypass flow velocity and depends on the aerodynamic conditions in the cell. The dynamic pressure of the bypass flow,  $q_b$ , is computed from  $VEL_b$ , as in Section 4.4.

#### 4.6 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. The 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 drag component is very sensitive to the size and shape of the variable nozzle and the collector insert, and the spacing between the exhaust nozzle and the collector. The magnitude of the thrust component may be calculated by:

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

A more detailed analysis has been carried out for the variable nozzle on the F404 engine (Appendix C). Thrust corrections for boattail drag were found to be in the order of 0.03 to 0.2 percent of the scale force, depending on the engine power setting.

#### 4.7 Secondary Flow Calculations

As noted in the previous sections, most of the thrust corrections for an indoor test facility are attributed to the secondary airflow around the engine. The secondary airflow is incorporated into the correction equations through the calculation of the bypass ratio. It is therefore very important to estimate, as accurately as possible, the magnitude of the bypass ratio, by measuring the engine and total cell airflow. The engine airflow is normally easy to obtain with an engine airmeter, while it is more difficult to measure the cell airflow. The cell airflow can be estimated by performing an energy balance between the inlet and outlet of the test cell. The energy balance method (General Electric, 1979) comprises a calculation of the change in enthalpy, accounting for the energy input of the fuel consumed by the engine. The cell flow is then found by:

$$W_O = WF * [NHC * \eta_c + H_{ref} + dHF - H_{stack}] / (H_{stack} - H_i)$$

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

$$FAR_{stack} = WF/W_O * (1 + WAR_O)$$

The enthalpy of the exhaust stack,  $H_{stack}$ , is then computed from the 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 uniform temperature and velocity profiles, which make the measurement of the average temperature very difficult, if not impossible. An additional problem occurs during afterburner operation. Because the exhaust stack may not withstand the high gas temperatures, water is often injected, which makes the energy balance calculation much more difficult. It was found that the exhaust profile in No. 5 cell was not uniform and an alternative method was incorporated for determining the total cell airflow (Appendix D). The method involved making velocity measurements by traversing the test cell inlet. The inlet was divided into a number of cross sectional sub-areas. Measured velocities at each area and a constant density were used to calculate individual airflows. Total cell inlet airflow was calculated by summing the individual airflows. The process was repeated to obtain the bypass airflow. Total cell airflow was sought by the addition of the bypass and engine airflow. In both cases, an estimation of the boundary layer was made in an attempt to estimate the true flow area. A relationship of cell airflow and nozzle pressure ratio (P5T/PAMB) was used for obtaining cell airflow during test runs [Fig. 7].

#### 4.8 Summary

Sample hand calculations to verify the computer code for the various forces described in Section 4 are presented in Appendix E. The magnitude of the forces, at military power or maximum dry thrust for run 72 point No. 6, were found to be:

a) scale force( $F_{md}$ )	= 10536.0 lbf
b) inlet momentum( $F_{im}$ )	= 134.6 lbf (1.28% $F_{md}$ )
c) bypass pressure drag( $F_b$ )	= -56.6 lbf (-0.54% $F_{md}$ )
d) thrust frame drag( $F_{tf}$ )	= 2.3 lbf (0.02% $F_{md}$ )
e) skin friction drag( $F_{fr}$ )	= 0.18 lbf (-)
f) boattail drag( $F_{bt}$ )	= 25.5 lbf (0.24% $F_{md}$ )

The total correction is thus 106.0 lb<sub>f</sub> for this example which amounts to 1.0% of the measured thrust.

#### 5.0 CONCLUSIONS AND RECOMMENDATIONS

1. In any test arrangement where the thrust measuring device is offset from the engine centre-line, a pull must be done to correlate the force applied along the engine centre-line to that sensed by the measuring device.
2. Thrust correction factors, accounting for test cell aerodynamic effects, must be applied to obtain the gross thrust of an engine. Inlet momentum, bypass pressure drag, and boattail drag are the dominant factors effecting the computation of gross thrust. The combination of these factors attribute to 0.98% of the total correction of 1.0%. Thrust frame and skin friction drag corrections are insignificant.
3. An evaluation of each test installation must be done to determine the magnitude and direction of forces which contribute to the calculation of the gross thrust of an engine. Detailed cell velocity surveys are likely necessary.

## 6.0 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of Mr. W. Grabe in providing a method for calculating boattail drag and of Mr. B.C. Barry in assisting in the centre-line pull calibration.

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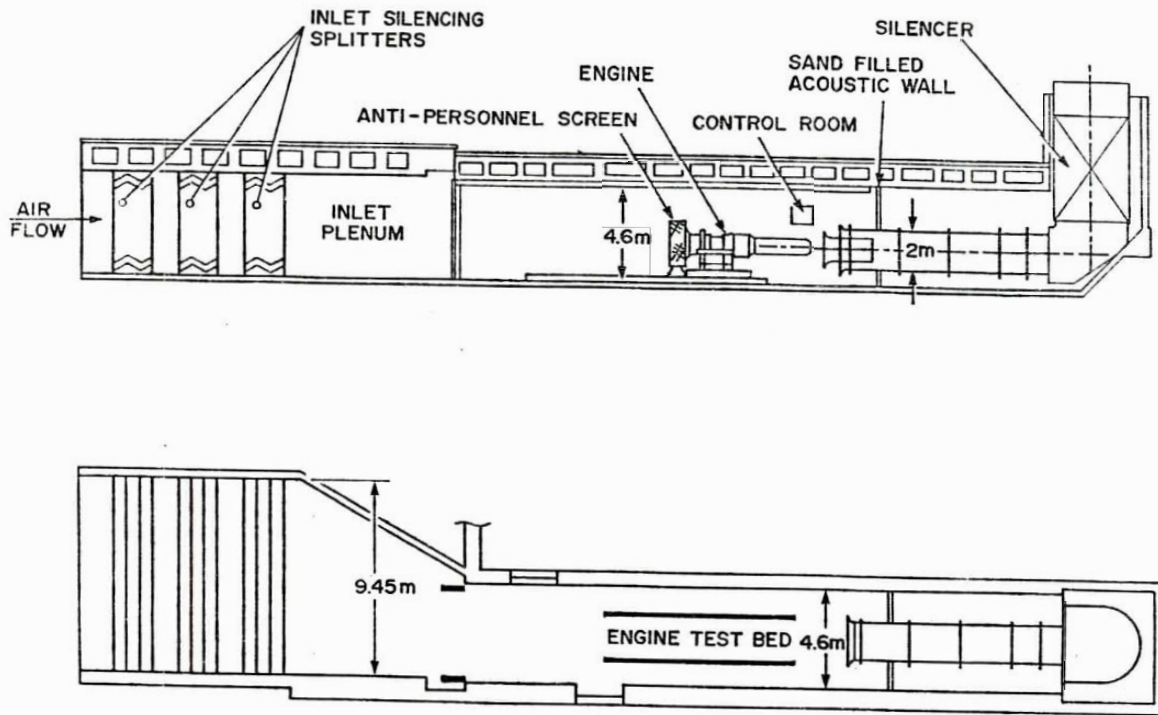


Figure 1. No. 5 test cell - Engine Laboratory - NRCC

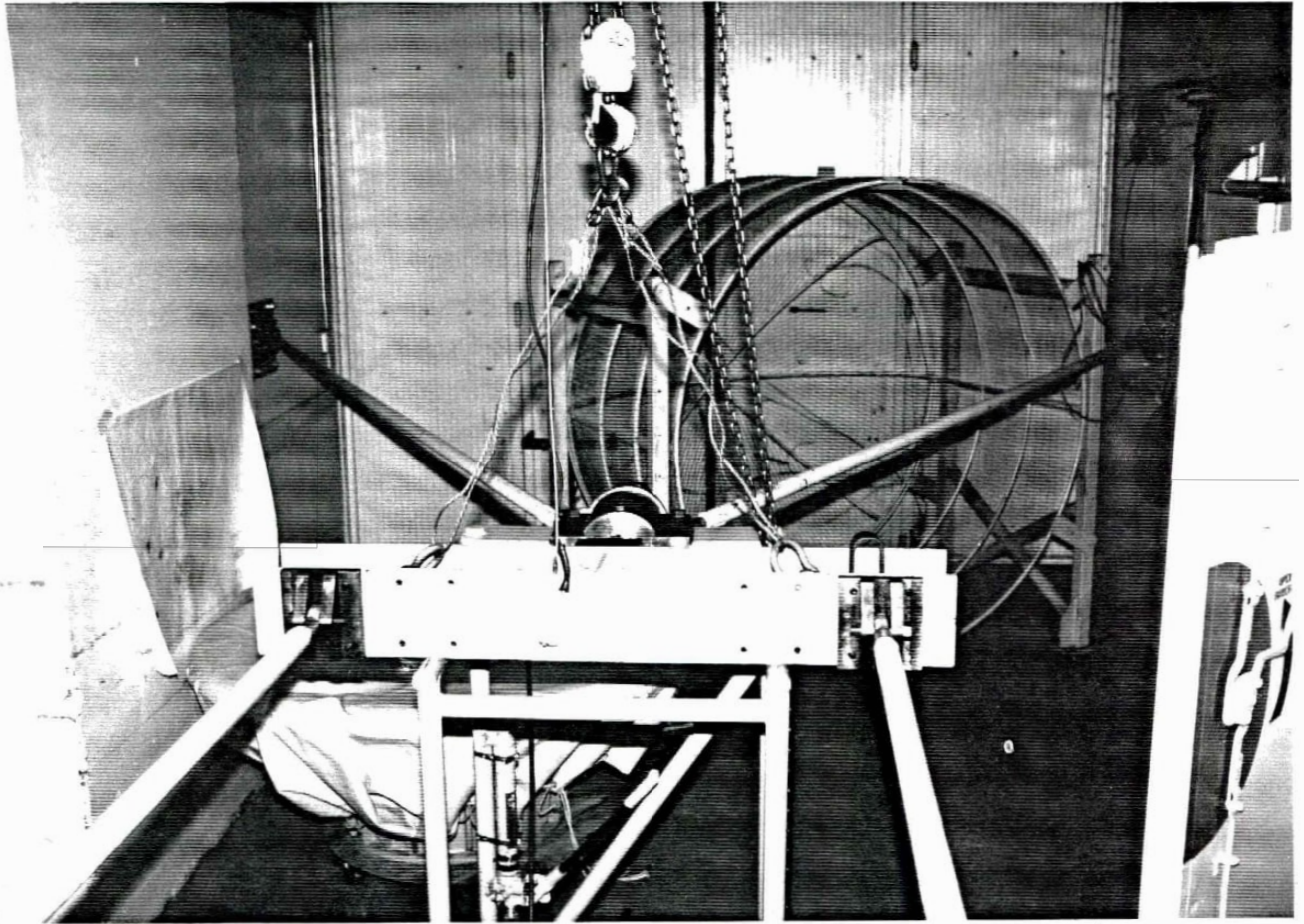


Figure 2. Test cell wall mounting for centre-line pull rig

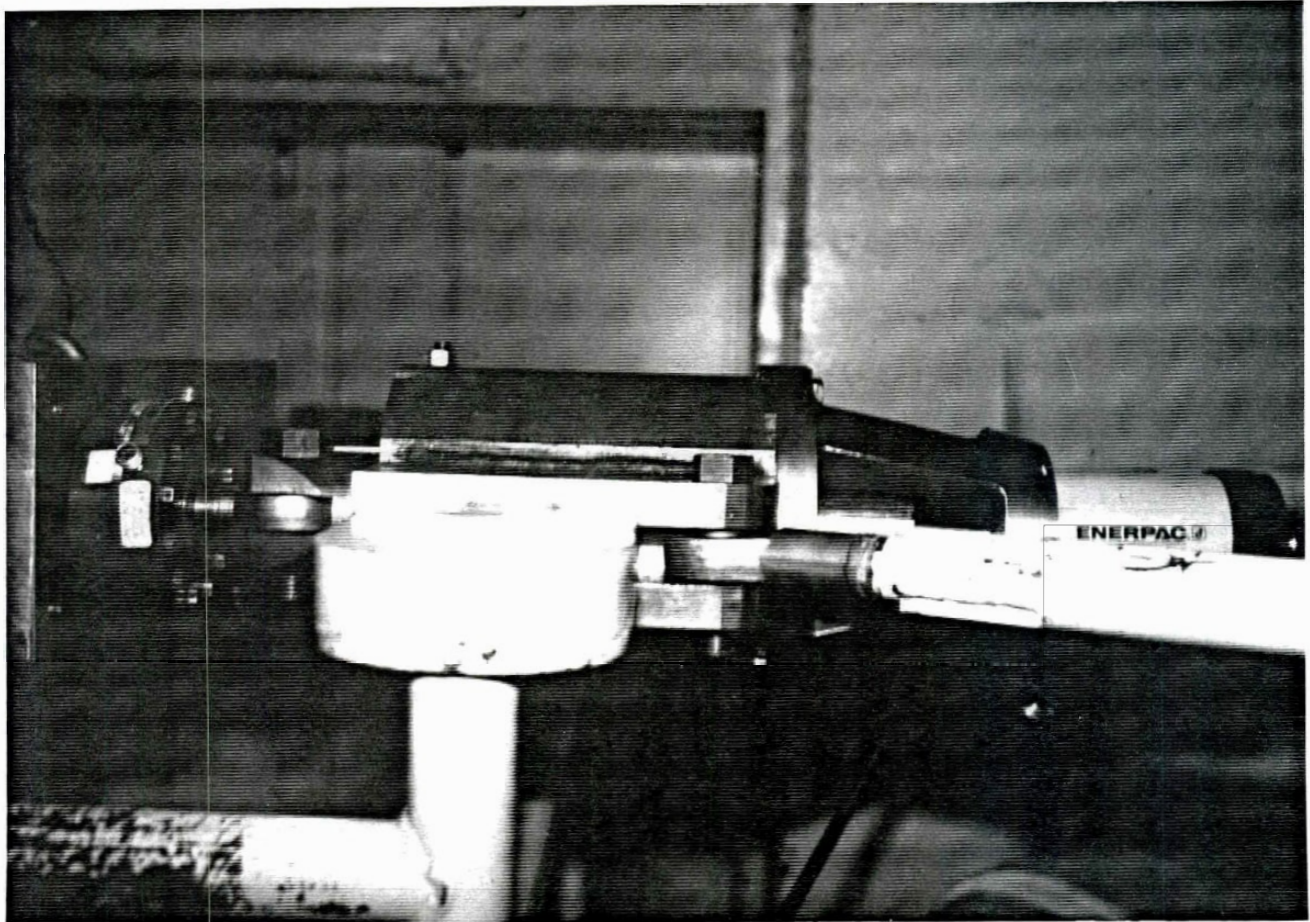


Figure 3. Hydraulic jack mounting for centre-line pull rig

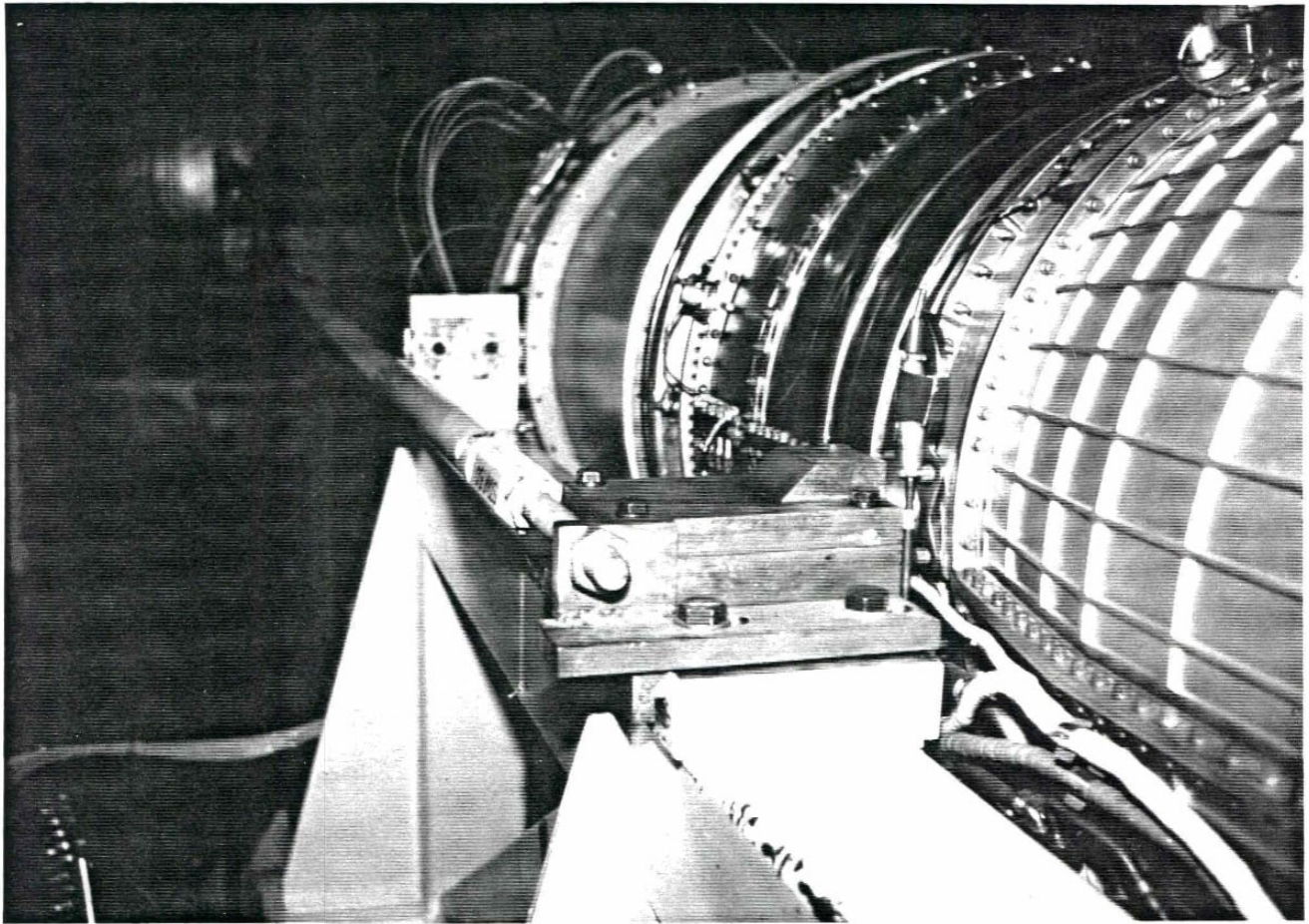


Figure 4. Engine mounting points for centre-line pull rig

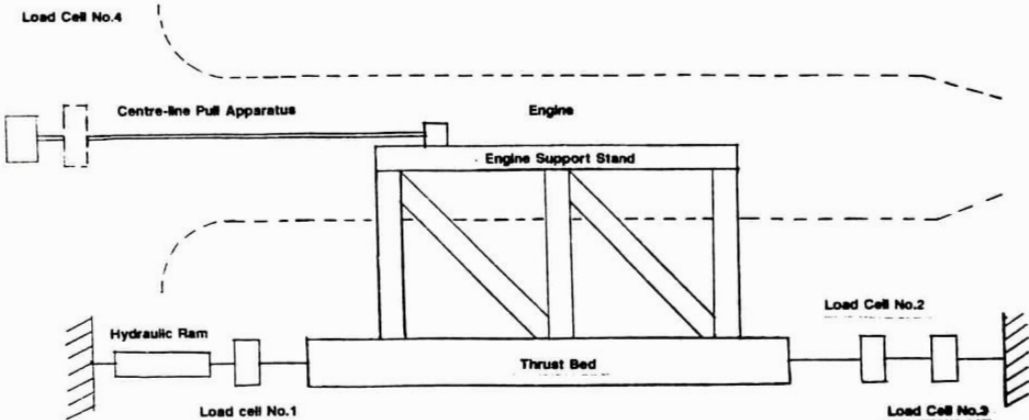


Figure 5. Thrust bed layout

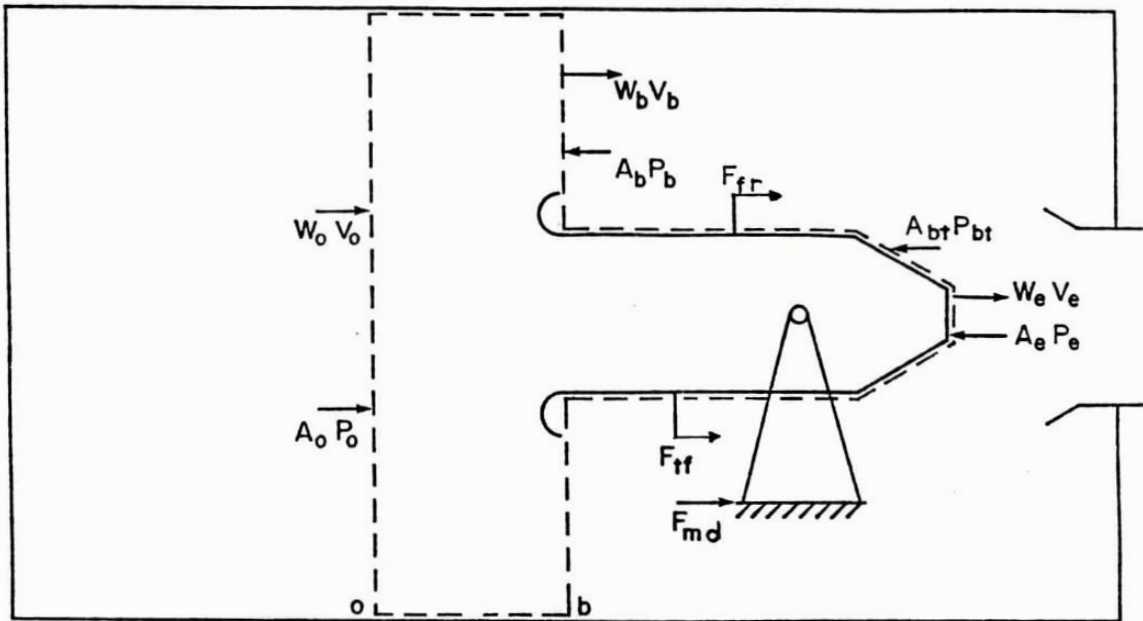


Figure 6. Engine/test cell control volume

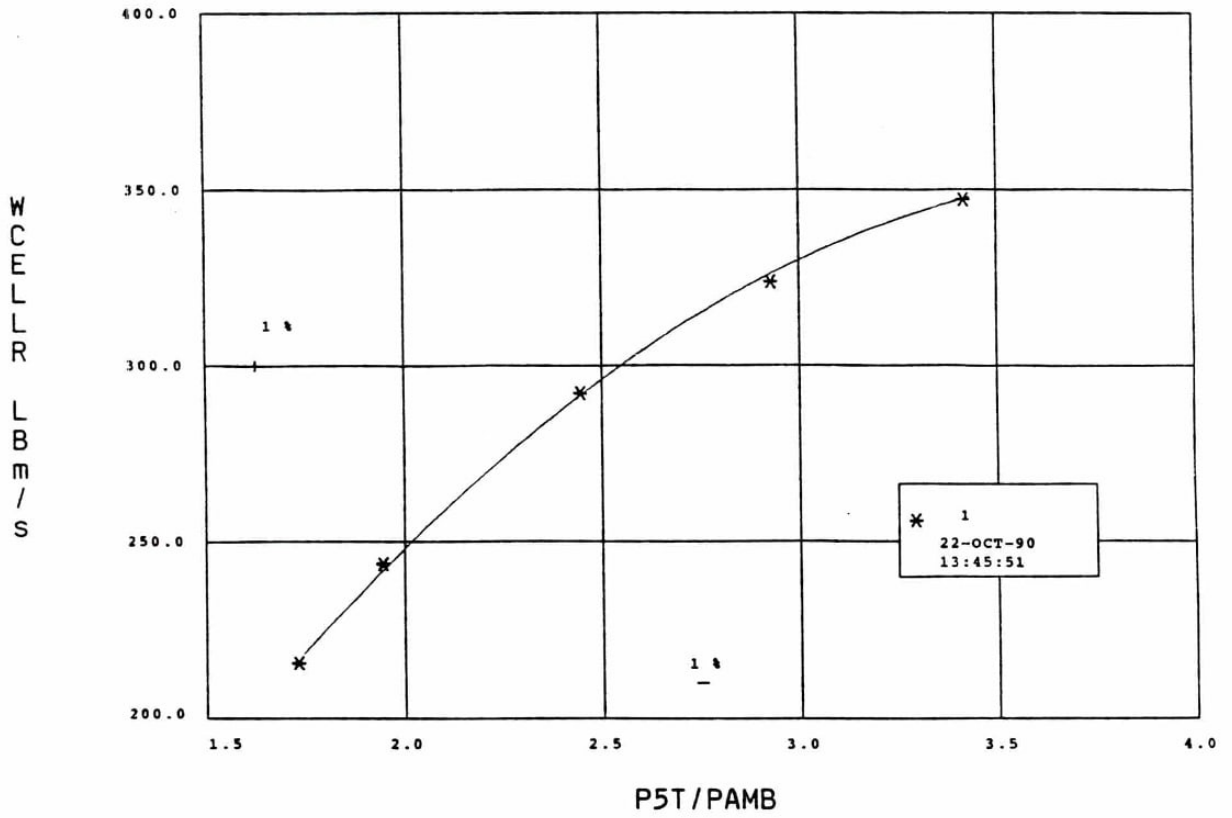


Figure 7. Cell airflow vs. nozzle pressure ratio

APPENDIX A  
Centre-line Pull Code

Appendix A contains the linker command file, NEFF instruction file, and Fortran 77 computer code that was used for the calibration.

#### A.1 Linker Command File

```
$ LINK CLPEX, CLPDRD, CLP_DATA_OUT,-
CLPDAS, CLPRED, CLPPOLY, NEFADC,-
CLPTAB, CLPCOM, NFLOAD, VMS_NEFF_DRIVER, NFCLDL,-
SCREEN, VTERAS
```

#### A.2 NEFF Instruction File

LABEL	CONFIGURATION DATA	RAM ALLOCATION	
		START	END
100	READ ADC	1	14
101	96 8 !LOAD CELL 1 BRIDGE A	5	5 DATA
102	97 8 ! BRIDGE B	6	6 DATA
103	98 8 !LOAD CELL 3 BRIDGE A	7	7 DATA
104	99 8 ! BRIDGE B	8	8 DATA
105	106 8 !LOAD CELL 4 BRIDGE A	9	9 DATA
106	107 8 ! BRIDGE B	10	10 DATA
107	158 0 !LOAD CELL 1 EXCITATION VOLTAG	11	11 DATA
108	159 0 !LOAD CELL 3 EXCITATION VOLTAG	12	12 DATA
109	163 0 !LOAD CELL 4 EXCITATION VOLTAG	13	13 DATA
200	SET TIMER	15	18
201	100.0	15	18
300	START CLOCK	19	19
301	READ CLOCK	20	20 DATA
9000	END		

## A.3 Centre Line Pull Source Code

C CLPEX\_DEFINE.COMMON

```
CHARACTER*23 DAYTIME, DATA_DAYTIME
CHARACTER*40 FILE1, FILE2, FILE3
CHARACTER*40 TITLE, DATA_FILE, DATA_TITLE
```

```
INTEGER*2IBUFF(10), IXBUFR(100), INSTRC(10), NAVG, ID
```

```
+ REAL*4RMVA1, RMVB1, RMVA3, RMVB3, RMVA4, RMVB4,
    EXTVT1, EXTVT3, EXTVT4, RVBUFF(100), RVFBUF(100)
```

```
COMMON /TIME/ DAYTIME, DATA_DAYTIME
```

```
COMMON /RUNID/ TITLE, ID, DATA_TITLE
```

```
COMMON /COUNT/ NAVG
```

```
COMMON /BUFF/ RVBUFF, RVFBUF, IXBUFR, IBUFF, INSTRC
```

```
COMMON /FILES/ FILE1, FILE2, FILE3, DATA_FILE
```

```
+ COMMON /CONST/ RMVA1, RMVB1, RMVA3, RMVB3, RMVA4, RMVB4,
    EXTVT1, EXTVT3, EXTVT4
```

C

C CLPEX\_DEFINE.COMMON

```
C      PROGRAM CLPEX
C      MAIN LINE CENTRE LINE PULL CALIBRATION
C      CHOOSE TO ACQUIRE DATA OR REDUCE AND CURVEFIT
C
      CALL LOAD
10     CALL VTERAS(1)
      TYPE 1000
      TYPE 1001
      ACCEPT 100, IC
      IF (IC .EQ. 'D') CALL CLPDAS
      IF (IC .EQ. 'R') CALL CLPRED
      IF (IC .EQ. 'A') CALL CLPCOM
      IF (IC .EQ. 'E') GOTO 20
      GOTO 10
1000  FORMAT(//25X, '*** CELL FIVE CENTRE LINE FORCE CALIBRATION ***')
1001  FORMAT(/$5X' D FOR DATA ACQUISITION ,R FOR REDUCTION,',
      1    ' A FOR FILE CONSOLIDATION ,E FOR EXIT ')
100   FORMAT(A1)
20    CONTINUE
      STOP
      END
```

```

SUBROUTINE VTERAS(IMODE)                ! FILE: VTERAS.FOR
C
C**** ROUTINE TO CLEAR THE SCREEN OF THE GRAPHICS TERMINAL
C****
C**** IF IMODE = 0 ... ONLY THE VT-100 MEMORY IS ERASED
C**** IF IMODE = 1 ... BOTH VT-100 & GRAPHICS MEMORIES ARE ERASED
C**** IF IMODE = 2 ... ONLY THE GRAPHICS MEMORY IS ERASED
C
      character esc, o200, gs, ff, can, nul
      parameter ( esc=char("33"), o200=char("200"), gs=char("35") )
      parameter ( ff=char("14"), can=char("30"), nul=char(0) )

      character ERASVT*7,ERASAL*6,ERASGR*6,EXIT*2,BVECTR*10

      equivalence (bvectr(1:2),iyleft)
      equivalence (bvectr(3:4),ixleft)
      equivalence (bvectr(5:6),iyrite)
      equivalence (bvectr(7:8),ixrite)
C
      erasvt = esc//'[2J'//esc//[H'
      erasal = gs//esc//ff//can//o200//nul
      erasgr = gs//esc//[1d'//o200
      exit = can//o200
      bvectr = o200//o200//o200//o200//o200
1      //o200//o200//o200//o200//o200

      call get_raw_iochan

      if (imode.ne.2) call rawput(erasvt)
      if (imode.eq.1) call rawput(erasal)
      IF(IMODE.NE.2) GO TO 300                !ERASE GRAPHICS
C
C**** TO ERASE THE GRAPHICS MEMORY THE ENTIRE SCREEN MUST BE FILLED
C**** WITH BLANK VECTORS
C
      call rawput(erasgr)
      IXLEFT = "40040                !INITIALIZE X AND Y
      IXRITE = "57477                !COORDINATE BYTES
      IYLEFT = "57437
C
      DO 200 I = 1,25                !REPEATEDLY INCREMENT
      IYLEFT = IYLEFT + "1                !THE Y COORDINATES
      DO 100 J = 1,32
      IYLEFT = IYLEFT + "400
      IYRITE = IYLEFT
      call rawput(bvectr)                !PLOT THE BLANK VECTOR
100 CONTINUE
      IYLEFT = IYLEFT - "20000
200 CONTINUE
      call rawput (exit)                !EXIT GRAPHICS MODE
C

```

```

300 call free_raw_iochan
      RETURN
END

```

```

C> File:Screen.for
      subroutine rawput( ch )
C
C      This routine outputs a variable length character string to the
C display.
C      Absolutely no formatting is done on the string, it is output in the
C same form it is received. The output is done using a SYS$QIOW
C system call and if the operation fails, the library routine
C LIB$SIGNAL is used to inform the user and stop the program if a
C fatal error occurs.
C
C      NOTE, an I/O channel must be opened using the "get_raw_iochan"
C routine, before a single character can be output with this
C routine.
C<

```

```

      character ch*(*)

      integer*2 Raw_lun
      integer*4 Iocode

      common / com_raw_lun / Raw_lun, Iocode

      integer*2 iosb(4)
      integer*4 sys$qiow, istat, lbuf

      lbuf = len( ch )

      istat = sys$qiow(, %VAL(Raw_lun), %VAL(Iocode),
+      iosb(1),, %REF(ch), %VAL(lbuf),,,)
      if (.not.istat) call lib$signal(%VAL(istat))

      return
end! rawput

```

```

C>
      subroutine get_raw_iochan
C
C      This routine makes a request for an I/O channel to be used with
C the "rawput" routine. If the request fails, the library routine
C LIB$SIGNAL is used to inform the user and stop the program if a
C fatal error occurs.
C
C      This routine must be called before using the routine "rawput".
C<

```

```
implicit none

include '($IODEF)'
integer*2 Raw_lun
integer*4 Iocode

common / com_raw_lun / Raw_lun, Iocode

integer istat, sys$assign

istat = sys$assign('SYS$OUTPUT:',Raw_lun,,)
if ( .not. istat ) call lib$signal(%val(istat))
Iocode = io$_writevblk .or. io$m_noformat

return
end! get_raw_iochan
```

```
C>
subroutine free_raw_iochan
C
C   This routine frees the I/O channel requested by the
C   "get_raw_iochan" routine.
C<
```

```
implicit none

integer*2 Raw_lun
integer*4 Iocode

common / com_raw_lun / Raw_lun, Iocode

integer istat, sys$dassgn

istat = sys$dassgn(%val(Raw_lun))
if ( .not. istat ) call lib$signal(%val(istat))

return
end! free_raw_iochan
```

```
      SUBROUTINE LOAD                                !FILE: NFLOAD.FOR
C
C**** ROUTINE TO TRANSFER A STORED LIST OF INSTRUCTIONS TO THE NEFF RAM
C
      INTEGER IERR(4)
      INTEGER * 2 IBUFFR(1000,2)
C
C**** OPEN DISK FILE AND READ IN ALL INSTRUCTIONS
C
      OPEN (UNIT=1,NAME='NFRAM.DAT',TYPE='OLD')
      NINST = 0
C
      DO 100 I=1,1000
      READ(1,1000,END=200) IBUFFR(I,1),IBUFFR(I,2)
100  NINST = NINST+1
1000 FORMAT(O5,4X,I1)
C
200  CLOSE (UNIT=1)
C
C**** INITIALIZE NEFF DRIVER, RESET NEFF BUS, AND CHECK NEFF STATUS
C
      CALL VMS_NFINIT
      CALL VMS_NFRSET(IERR)
      CALL VMS_NFSTAT(ISTAT,IERR)
C
C**** LOAD THE NEFF RAM - START AT LOCATION 1
C
      CALL VMS_NFWRAM(IBUFFR(1,1),NINST,1,IERR)
C
      RETURN
      END
```

## SUBROUTINE CLPDRD

```
C      THIS SUBROUTINE READS MV FROM THE
C      LOAD CELL BRIDGES.

      INCLUDE 'CLPEX.DEF'

C      THRUST DESIGNATIONS

C      RMVA1  RMV(1)! LOAD CELL # 1, FRONT
C      RMVB1  RMV(2)

C      RMVA3  RMV(3)! LOAD CELL # 3, REAR
C      RMVB3  RMV(4)

C      RMVA4  RMV(5)! REFERENCE LOAD CELL, #4
C      RMVB4  RMV(6)

C      EXTVT1 EXTVT1! LOAD CELL # 1, FRONT
C      EXTVT2 EXTVT3! LOAD CELL # 3, REAR
C      EXTVT3 EXTVT4! REFERENCE LOAD CELL # 4

C      CONSTANTS

      DO 302 I=1,100
      RVFBUF(I)=0.0
      RVBUFF(I)=0.0
302    CONTINUE

      CALL NEFADC(NAVG,1,6,5)!ALL SIX BRIDGES
      CALL NEFADC(NAVG,7,1,11)!VEXCT1
      CALL NEFADC(NAVG,8,1,12)!VEXCT3
      CALL NEFADC(NAVG,9,1,13)!VEXCT4

C      AVERAGE READS

      DO 20 I=1,9
      RVFBUF(I)=RVFBUF(I)/NAVG/4
20    CONTINUE

C      AVG READS AND CONV. TO MV.

      DO 50 I=1,6
50    RVFBUF(I)=RVFBUF(I)/256/800.098*1000.0

C      AVG READS AND CONV. TO VOLTS

      DO 60 I=7,9
60    RVFBUF(I)=RVFBUF(I)/800.098
```

RMVA1=RVFBUF(1)!FRONT  
RMB1=RVFBUF(2)

RMVA3=RVFBUF(3)!REAR  
RMB3=RVFBUF(4)

RMVA4=RVFBUF(5)!REF  
RMB4=RVFBUF(6)

EXTVT1=RVFBUF(7)!FRONT  
EXTVT3=RVFBUF(8)!REAR  
EXTVT4=RVFBUF(9)!REF

RETURN  
END

```
C.....NEFADC.FOR.....
      SUBROUTINE NEFADC(ICREAD,INDEX,ICHAN,ISTART)
C
C This subroutine is used to perform a/d conversions.
C The arguments are as follows:
C
C       ICREAD....Number of reads
C
C       INDEX. ...Starting address in RVBUFF to
C               store reads.
C
C       ICHAN.....The number of channels to be
C               converted.
C
C       ISTART....The ram address of the first
C               channel.
C
C       COMMON BLOCKS
C
C       INCLUDE 'CLPEX.DEF'
C
C       DO 5 I=1,ICREAD
C
C           Set clock for period mode
C
C           CALL VMS_NFHAND(IBUFF(1),4,15,IERR)
C
C           Start clock
C
C           CALL VMS_NFHAND(IBUFF(1),1,19,IERR)
C
C           Set up A/D function
C
C           CALL VMS_NFHAND(IBUFF(1),4,1,IERR)
C
C           Read channels
C
C           CALL VMS_NFHAND(IXBUFR(INDEX),ICHAN,ISTART,IERR)
C           CALL VMS_NFSTAT(ISTAT,IERR)
C
C           Terminate A/D function
C
C           CALL VMS_NFHAND(IBUFF(1),1,14,IERR)
C
C           Stop and read clock
C
C           CALL VMS_NFHAND(ITIME,1,20,IERR)
C           CALL VMS_NFSTAT(ISTAT,IERR)
C
C           Calculating elapsed time and frequency
C
C           RELAP = ITIME * 0.00001 * 4
C           RFREQ = 1.0/RELAP
```

```
IF(RELAP.GE.0.010)GO TO 10
C
C If RELAP<0.010 calculate required delay
C
RDELTA = 0.010 - RELAP
RWAIT = RDELTA * 1000.0
RTOTAL = RDELTA + RELAP
RFREQ = 1.0/RTOTAL
C
C Generate instructions and set clock to delay mode
C
CALL CLDLAY(RWAIT,INSTRC,IWORDS)
CALL VMS_NFDIRECT(INSTRC,IWORDS)
C
C Start and stop clock
C
CALL VMS_NFHAND(IBUFF(1),2,19,IERR)
C
C Calculate array indices and store reads
C
10 K=INDEX+ICHAN-1
DO 15 J=INDEX,K
RVFBUF(J)=RVFBUF(J)+IXBUFR(J)
15 CONTINUE
5 CONTINUE
C
RETURN
END
```

```

SUBROUTINE CLDLAY (RDELAY,INSTRC,IWORDS)    !FILE:NFCCLDL.FOR
C
C**** Routine to generate the NEFF S-500 control instructions required
C**** to set up the clock for the delay mode
C****
C****   Where:  RDELAY = The exact delay period in millisec
C****
C****           INSTRC = A 4 word array to receive the
C****                   generated instructions
C****
C****           IWORDS = The number of instruction words
C
      INTEGER INSTRC(1)
      REAL RANGE(5)
      DATA RANGE /5.E6, 1.E6, 100.E3, 10.E3, 1.E3/
C
C**** Set the static portion of the instruction words
C**** The assumed card location is BOX 0, CARD 9
C
      DATA ICONRG /"220/           !Control register addr
      DATA IRATRG /"221/           !Rate register addr
      DATA IMODE /"10020/          !Mode data mask
      DATA IRATE /"10000/          !Rate data mask
C
C**** Configure the instruction to set mode and range
C
      INSTRC(1) = ICONRG
C
C**** Configure the instructions to set the exact delay period
C**** choosing the range with the highest resolution
C
      DO 100 IRANGE = 1,5
      RCOUNT = ((RDELAY*0.001)-10.E-6)*RANGE(IRANGE)
      IF (RCOUNT .LT. 4096.) GOTO 200
100 CONTINUE
C
200 ICOUNT = RCOUNT
      INSTRC(2) = IMODE + (IRANGE -1)
      INSTRC(3) = IRATRG
      INSTRC(4) = IRATE + (-ICOUNT .AND. "7777)
      IWORDS = 4
C
      RETURN
      END

```

```
      SUBROUTINE CLP_DATA_OUT(IPRINT,LUN)

C      THIS SUBROUTINE WRITES DATA TO SCREEN, PRINTER, AND/OR DISC
C      AFTER EACH READ IS TAKEN.

      INCLUDE 'CLPEX.DEF'

      CALL LIB$DATE_TIME(DAYTIME)

5      FORMAT(////' File: ',A40/)
10     FORMAT(' ',A40/)
20     FORMAT(' Run date/time: ',a23/)
30     FORMAT(' Number of reads: ',I5/)
40     FORMAT(' ID  A1 MV  B1 MV  A3 MV  B3 MV  ',
+          'A4 MV  B4 MV  EXCIT 1 EXCIT 3 EXCIT 4')

50     FORMAT(' ', i2, 1x, 6f8.3, 1x, 3f9.4)

60     FORMAT('      FRONT CELL  REAR CELL  REF CELL',
+          '      EXCITATION VOLTAGES')
70     FORMAT('      _____  _____  _____',
+          '      _____')

      IF (IPRINT .EQ. 2) GOTO 100!PRINTER AND DISC
      IF (IPRINT .EQ. 6) GOTO 90!SCREEN
      WRITE (LUN,5) FILE1
      WRITE (LUN,10) TITLE
      WRITE (LUN,20) DAYTIME
      WRITE (LUN,30) NAVG

      WRITE (LUN,60)
      WRITE (LUN,70)

90     WRITE (LUN,40)

100    WRITE (LUN,50) ID, RMVA1, RMVB1, RMVA3, RMVB3, RMVA4, RMVB4,
+          EXTVT1, EXTVT3, EXTVT4

      RETURN
      END
```

```

SUBROUTINE CLPDAS

C      THIS PROG. READS IN THE DATA FOR THE
C      ENGINE CENTRE LINE PULL (CLP) TEST.

C      CELL FIVE VERSION APRIL, 1990
      -

C      COMMON BLOCKS

      INCLUDE 'CLPEX.DEF'

      CALL VTERAS (1)

50     FORMAT(A1)
51     FORMAT()
100    FORMAT(/15X,' ----ENGINE CENTRE LINE PULL TEST----')
105    FORMAT(/$5X' ENTER NAME OF OUTPUT FILE = ')
110    FORMAT(/$5X' ENTER A TITLE = ')
112    FORMAT(/$5X' ENTER THE NUMBER OF READS = ')
115    FORMAT(I5)
117    FORMAT(/5X' * NOTE: START WITH ID. # 0 , NO LOAD ')
119    FORMAT(F10.0)
120    FORMAT(A40)
121    FORMAT(A80)
130    FORMAT($5X' DATRD ID # (99 FOR FINAL ZERO) = ')
140    FORMAT(I5)
170    FORMAT($5X' READ MORE POINTS ? Y/N ')
180    FORMAT(/5X' HAVE YOU TAKEN THE FINAL ZERO (ID # = 99)? Y/N')
190    FORMAT(/5X' TEST COMPLETED')
C
      TYPE 100
      TYPE 105
      READ(5,121) FILE1
      OPEN( UNIT=2, NAME= FILE1, TYPE= 'NEW')
      OPEN( UNIT=7, NAME= '$PRINTER:', TYPE= 'NEW')
      TYPE 110
      READ(5,120) TITLE
      TYPE 112
      READ(5,115) NAVG
      TYPE 117

      IPRINT= !OUTPUT INCLUDE HEADER
1000   TYPE 130
      READ(5,140) ID
      TYPE 51

C      READ BRIDGE AND EXCITATION VOLTAGES

      CALL CLPDRD
```

```
CALL CLP_DATA_OUT(6,6)!PRINT TO SCREEN, NO HEADER
CALL CLP_DATA_OUT(IPRINT,7)!AND TO PRINTER
CALL CLP_DATA_OUT(IPRINT,2)!SAVE TO DISC
```

C READ MORE POINTS

```
TYPE 51
TYPE 170
IPRINT=2
READ(5,50) ISAVE
IF(ISAVE.EQ.'N')GO TO 500
GO TO 1000
500 TYPE 180
READ(5,50) ISAVE
IF(ISAVE.EQ.'N')GO TO 1000
TYPE 190
```

```
CLOSE(UNIT=2)
CLOSE(UNIT=7)
```

```
RETURN
END
```

```

SUBROUTINE CLPRED

C      LOAD CELL CALIBRATION REDUCTION PROGRAM

      INCLUDE 'CLPEX.DEF'
      CHARACTER*23 CTMP

      REAL*4 F1A(50), F1B(50), F4AV(50)  !X,Y ARRAYS TO CLPOLY
      REAL*8 SEE, ERR2, R2

      DIMENSION F4A(50), F4B(50), VS1(50),VS3(50),VS4(50),
+         R1A(50),R1B(50),R3A(50),R3B(50),
+         COEFA(16),COEFB(16),R4A(50),R4B(50),
+         DELA(50),DELB(50),RCAA(4),RCAB(4),RCAC(4),
+         RCBA(4),RCBB(4),RCBC(4),RVV(4)

C      CENTRE LINE LOAD CELL CALIBRATION DATA COEFFICIENTS
C      F=CX**2 +BX +A, X IS MV/V

C      TENSION 10K SN 22797
C      DATA RCAC(1)/-0.103238/,RCAB(1)/2262.41/,RCAA(1)/3.05656/,
C +     RCBC(1)/-0.390124/,RCBB(1)/2297.33/,RCBA(1)/0.0328487/

C      COMPRESSION 10K SN 22797
C      DATA RCAC(2)/8.7232/,RCAB(2)/2216.59/,RCAA(2)/35.872/,
C +     RCBC(2)/8.67726/,RCBB(2)/2251.22/,RCBA(2)/45.3785/

C      TENSION 25K SN 18734 NAE CAL CRS-322 17-MAY-89
C      DATA RCAC(3)/-2.344713/,RCAB(3)/5814.640256/,RCAA(3)/0.0/,
+     RCBC(3)/-2.042592/,RCBB(3)/5838.652904/,RCBA(3)/0.0/

C      COMPRESSION 25K SN 18734 NAE CAL CRS-322 17-MAY-89
C      DATA RCAC(4)/-1.5399/,RCAB(4)/5788.141/,RCAA(4)/0.0/,
+     RCBC(4)/-2.1486/,RCBB(4)/5819.475/,RCBA(4)/0.0/

      CALL VTERAS(1)

      TYPE 1000
1000  FORMAT(/15X, '*****DATA REDUCTION FOR CENTRE LINE CALIBRATION*****')
      TYPE 1001
1001  FORMAT(/$5X' ENTER FILE SPECS.FOR CALIBRATION DATA  ')
      READ(5,199) FILE1

      OPEN(UNIT=2, NAME = FILE1, TYPE='OLD', READONLY)
      TYPE 1002
1002  FORMAT($5X' ENTER FILE SPECS. FOR REDUCED DATA  ')
      READ(5,199) FILE2

```

```
OPEN(UNIT=3, NAME = FILE2, TYPE='NEW')
199  FORMAT(A80)
200  FORMAT(I2)

ICAL=3
C

OPEN(UNIT=7, NAME = '$PRINTER:', TYPE='UNKNOWN')
C  READ DATA

READ(2,'(///6X,A40)')DATA_FILE
READ(2,'(/,A40)')DATA_TITLE
READ(2,'(/,16X,A23)')DATA_DAYTIME
READ(2,'(/,18X,I5)')NAVG
READ(2,*)
READ(2,*)
READ(2,*)
READ(2,*)
NUM_DATA = 1
DO 30 I=1,100
READ (2, *, END=705 ) ID, RVA, RVB, RVC, RVD, RVE, RVF,
+      RVV(1), RVV(3), RVV(4)
C  INITIAL ZERO

IF ( ID .NE. 0 ) GOTO 10
ZF4A=RVE
ZF4B=RVF

GOTO 30
C  FINAL ZERO

10  IF ( ID .NE. 99 ) GOTO 20
ZZF4A=RVE
ZZF4B=RVF

GOTO 30
C  DATA POINT

20  R1A(NUM_DATA)=RVA!CELL 1
R1B(NUM_DATA)=RVB
R3A(NUM_DATA)=RVC!CELL 3
R3B(NUM_DATA)=RVD
R4A(NUM_DATA)=RVE!REF CELL
R4B(NUM_DATA)=RVF

VS1(NUM_DATA)=RVV(1)!CELL 1
VS3(NUM_DATA)=RVV(3)!CELL 3
```

```

        VS4(NUM_DATA)=RVV(4)!REF CELL

        NUM_DATA = NUM_DATA + 1
30  CONTINUE
705  CONTINUE

        NUM_DATA = NUM_DATA - 1

C      SELECT ZERO TO CORRECT DATA
C      INITIAL,FINAL OR AVERAGE IS POSSIBLE

        ZA1=(ZF4A+ZZF4A)/2.
        ZA2=(ZF4B+ZZF4B)/2.

        WRITE(6,1003)
        WRITE(6,1005) ZF4A, ZF4B
        WRITE(6,1006) ZZF4A, ZZF4B
        WRITE(6,1007) ZA1, ZA2
1003  FORMAT(/8X,'ZEROES DATA - FOR REFERENCE CELL ONLY')
1005  FORMAT(/8X,'FIRST A,B',10X,F8.3,5X,F8.3)
1006  FORMAT( 8X,'FINAL A,B',10X,F8.3,5X,F8.3)
1007  FORMAT( 8X,'AVERAGE A,B',8X,F8.3,5X,F8.3)

45    TYPE 46
46    FORMAT(/$7X'SELECT ZERO TO BE USED 1=FIRST, 2=AVG, 3=FINAL ')
        READ(5,300) IZ
300   FORMAT(I1)
        IF(IZ .NE. 1) GOTO 50
        Z1A=ZF4A
        Z1B=ZF4B
        GOTO 80
50    IF (IZ .NE. 2) GOTO 60
        Z1A=ZA1
        Z1B=ZA2
        GOTO 80
60    IF(IZ .NE. 3) GOTO 45
        Z1A=ZZF4A
        Z1B=ZZF4B
80    CONTINUE

C      STORE DATA

        WRITE(3,219) FILE2
        WRITE(3,220) DATA_TITLE
        WRITE(3,221) DATA_DAYTIME
        WRITE(3,222) NAVG
        WRITE(3,223)
        WRITE(3,224) ZF4A, ZF4B
        WRITE(3,225) ZZF4A, ZZF4B

```

```

WRITE(3,226) ZA1, ZA2
WRITE(3,227) Z1A, Z1B

WRITE(7,219) FILE2
WRITE(7,220) DATA_TITLE
WRITE(7,221) DATA_DAYTIME
WRITE(7,222) NAVG
WRITE(7,223)
WRITE(7,224) ZF4A, ZF4B
WRITE(7,225) ZZF4A, ZZF4B
WRITE(7,226) ZA1, ZA2
WRITE(7,227) Z1A, Z1B
219  FORMAT(7X,'FILE NAME: ',A40)
220  FORMAT(/7X,'TITLE: ',A40)
221  FORMAT(/7X,'DATA RECORDED ON :',A23)
222  FORMAT(/7X,'AVERAGE NUMBER OF READS :',I5)
223  FORMAT(/7X,'ZEROES DATA - FOR REFERENCE CELL ONLY',/
+    7X,'*****')
224  FORMAT(/7X,'FIRST A,B',10X,F8.3,5X,F8.3)
225  FORMAT( 7X,'FINAL A,B',10X,F8.3,5X,F8.3)
226  FORMAT( 7X,'AVERAGE A,B',8X,F8.3,5X,F8.3)
227  FORMAT( 7X,'ZERO USED A,B',6X,F8.3,5X,F8.3)

C    FOR EACH POINT CORRECT DATA AS MV-ZERO/SUPPLY VOLTAGE

      DO 90 J=1,NUM_DATA

      F1A(J) = (R3A(J) / VS3(J) - R1A(J) /VS1(J))
      F1B(J) = (R3B(J) / VS3(J) - R1B(J) /VS1(J))

      X4A=(R4A(J)-Z1A)/VS4(J)

      F4A(J)=RCAC(ICAL)*X4A**2+RCAB(ICAL)*X4A +RCAA(ICAL)

      X4B=(R4B(J)-Z1B)/VS4(J)

      F4B(J)=RCBC(ICAL)*X4B**2+RCBB(ICAL)*X4B +RCBA(ICAL)

      F4AV(J)=(F4A(J)+F4B(J))/2.

C    PRINT OUT RESULTS AND STORE

      IF(J.NE.1)GOTO 230
      WRITE(3,228)
      WRITE(7,228)
230  WRITE(3,229) F1A(J),F1B(J),F4A(J),F4B(J),F4AV(J)
      WRITE(7,229) F1A(J),F1B(J),F4A(J),F4B(J),F4AV(J)

228  FORMAT(/,'      RMVA(3-1)  RMVB(3-1)  Fa REF    Fb REF'
+    ',   Favg REF',7X,'*****'
+    ',*****')

```

```
229     FORMAT(2X,5F12.3)
90     CONTINUE

C       CURVE FIT WORKING CELLS (3-1) MV/V TO AVG. FORCE
C     FROM TWO CALIBRATION BRIDGES

C       BRIDGE A

        CALL CLPOLY(F1A,F4AV,NUM_DATA,2,COEFA,ERR2,R2,SEE)

        WRITE(3,400)
        WRITE(3,410)
        WRITE(3,420) COEFA(1)
        WRITE(3,430) COEFA(2)
        WRITE(3,440) COEFA(3)
        WRITE(3,450) ERR2
        WRITE(3,460) R2
        WRITE(3,470) SEE

        WRITE(7,400)
        WRITE(7,410)
        WRITE(7,420) COEFA(1)
        WRITE(7,430) COEFA(2)
        WRITE(7,440) COEFA(3)
        WRITE(7,450) ERR2
        WRITE(7,460) R2
        WRITE(7,470) SEE

400     FORMAT(/6X,' BRIDGE A CURVEFIT RESULTS, FORCE = A+BX+CX**2')
410     FORMAT(6X,' *****')
420     FORMAT(6X,' A = ',F14.5)
430     FORMAT(6X,' B = ',F14.5)
440     FORMAT(6X,' C = ',F14.5,/)
450     FORMAT(6X,' ERR2 = ',F14.5)
460     FORMAT(6X,' R2 = ',F14.5)
470     FORMAT(6X,' SEE = ',F14.5)

C       BRIDGE B

        CALL CLPOLY(F1B,F4AV,NUM_DATA,2,COEFB,ERR2,R2,SEE)

        WRITE(3,500)
        WRITE(3,510)
        WRITE(3,520) COEFB(1)
        WRITE(3,530) COEFB(2)
        WRITE(3,540) COEFB(3)
        WRITE(3,550) ERR2
        WRITE(3,560) R2
        WRITE(3,570) SEE

        WRITE(7,500)
```

```
WRITE(7,510)
WRITE(7,520) COEFB(1)
WRITE(7,530) COEFB(2)
WRITE(7,540) COEFB(3)
WRITE(7,550) ERR2
WRITE(7,560) R2
WRITE(7,570) SEE

500  FORMAT(/6X,' BRIDGE B CURVEFIT RESULTS, FORCE = A+BX+CX**2')
510  FORMAT(6X' *****')
520  FORMAT(6X,' A = ',F14.5)
530  FORMAT(6X,' B = ',F14.5)
540  FORMAT(6X,' C = ',F14.5,/)
550  FORMAT(6X,' ERR2 = ',F14.5)
560  FORMAT(6X,' R2 = ',F14.5)
570  FORMAT(6X,' SEE = ',F14.5)

C    PRODUCE COMPARISON TABLES OF MV/V,F CALIBRATION,

C    F CALCULATED AND DELTA (%)
CALL CLPTAB(NUM_DATA,F1A,F4AV,COEFA(3),COEFA(2),COEFA(1),'A ',DELA)
CALL CLPTAB(NUM_DATA,F1B,F4AV,COEFB(3),COEFB(2),COEFB(1),'B ',DELB)

CLOSE(UNIT=2)
CLOSE(UNIT=3)
CLOSE(UNIT=7)

RETURN
END
```

```

C*****
C****  LEAST SQUARES POLYNOMIAL CURVE FIT ROUTINE
C****  USING ORTHOGONAL POLYNOMIALS
C****
C****  CALLING SEQUENCE:
C****  X    X-DATA ARRAY
C****  Y    Y-DATA ARRAY
C****  X,Y MUST BE DECLARED DOUBLE PRECISION
C****  IN THE CALLING PROGRAM FOR PDP-11 SYSTEM
C****  M  NO. OF DATA POINTS
C****  NNN  FITTED DEGREE OF POLYNOMIAL
C****  0 < NNN < 16 AND MAXIMUM DEGREE= M - 1
C****  NOTE: IF NNN = M - 1 ---> EXACT FIT
C****  C    POLYNOMIAL COEFFICIENTS ARRAY
C****  D    DIFFERENCE (Y-YCALC) ARRAY
C****  ERR2  SUM OF SQUARE ERRORS (S[D**2])
C****  R2    MULTIPLE-DETERMINATION COEFFICIENT
C****  =1.0 IF M=NNN+1
C****  =1.0-ERR2/(S[Y**2]-S[Y]**2/M)
C****  SEE   STANDARD ERROR
C****  =SQRT(ERR2/M-NNN-1) FOR M>NNN+1
C****  =0.0   FOR M=NNN+1
C****
C****  Development Level 0  E.Politis  25-10-85
C*****
SUBROUTINE CLPOLY(X,Y,M,NNN,C,ERR2,R2,SEE)
DIMENSION X(150), Y(150),PI(150),PIM1(150)
1      ,S(150),YGQ(150), D(150)
DIMENSION ALPHA(16),BETA(16),C(16),G(16)
REAL*8 ERR,ERR2,SEE,DSQRT
ip=NNN
LP=NNN
LIM=LP+1
K=IP+1
100    IF(K.GT.LIM)RETURN
      ZER=0.0
      ONE=1.0
      IF(LP-IP)110,120,120
110    LP=IP
120    N=LP+1
      K=IP+1
      SY=0.0
      SY2=0.0
      DO 130 I=1,M
        PIM1(I)=ZER
        PI(I)=ONE
        SY=SY+Y(I)
        SY2=SY2+Y(I)*Y(I)
130    CONTINUE
      DO 140 I=1,16
        ALPHA(I)=ZER

```

```
BETA(I)=ZER
140 S(I)=ZER
    A1=ZER
    B1=ZER
    WII=M
    I=1
160 WI=ZER
    DO 170 L=1,M
170 WI=WI+Y(L)*PI(L)
    S(I)=WI/WII
    IF(I-N) 180,300,300
180 A1=ZER
    DO 190 L=1,M
190 A1=A1+X(L)*PI(L)*PI(L)
    A1=A1/WII
    ALPHA(I+1)=A1
    WI=ZER
    DO 210 L=1,M
    PIP1=(X(L)-A1)*PI(L)-B1*PIM1(L)
    PIM1(L)=PI(L)
    PI(L)=PIP1
    WI=WI+PIP1*PIP1
210 CONTINUE
    B1=WI/WII
    BETA(I+2)=B1
    WII=WI
    I=I+1
    GOTO 160
300 DO 310 L=2,16
310 G(L)=ZER
    G(1)=ONE
    G(2)=-ALPHA(2)
    DO 350 J=1,K
    S1=ZER
    DO 320 L=1,K
    IF(L.LT.3)GOTO 315
    G(L)=G(L)-ALPHA(L)*G(L-1)-BETA(L)*G(L-2)
315 S1=S1+S(L)*G(L)
320 CONTINUE
    C(J)=S1
    L=K
    DO 340 I2=2,K
    G(L)=G(L-1)
340 L=L-1
350 G(1)=ZER
    ERR2=ZER
430 DO 560 L=1,M
    YCALC=ZER
    J=K
    DO 440 I2=1,K
    YCALC=YCALC*X(L)+C(J)
```

```
440      J=J-1
        YGQ(L)=YCALC
        ERR=Y(L)-YCALC
        D(L)=ERR
        ERR2=ERR2+ERR*ERR
560      CONTINUE
        ERR=M-K
        IF(ERR.EQ.0)GOTO 570
        SEE=DSQRT(ERR2/ERR)
        ERR=M
        R2=1.0-ERR2/(SY2-SY*SY/ERR)
        GOTO 580
570      SEE=0.0
        R2=1.0
580      K=K+1
        IF(K-N)300,300,100
        END
```

```

SUBROUTINE CLPCOM

DIMENSION RX1(100),RX2(100),RY(100),COEFA(5),COEFB(5),
+   DELA(100),DELB(100),DFA(100),DFB(100),FCA(200),
+   FCB(200),CX(200)

INCLUDE 'CLPEX.DEF'

C   PROMPT FOR INPUT FILES AND REVIEW DATA FOR INCLUSION INTO
C   A LARGER FILE FOR SUBSEQUENT REDUCTION

CALL VTERAS (1)

WRITE(5,654)
654  FORMAT(1X,' WRITE TO DISK???)
      READ(5,1005) IAN
      IF(IAN.EQ.'Y'.OR.IAN.EQ.'y')GO TO 655
      GO TO 656
655  WRITE(5,1015)
      READ(5,222) FILE3
      OPEN( UNIT=7, NAME= FILE3, TYPE= 'NEW' )
      GO TO 667
656  OPEN( UNIT=7, NAME= '$PRINTER:', TYPE= 'NEW' )

667  IC=0
10   CONTINUE
      TYPE 1000
1000  FORMAT(/$' FILE SPECS FOR INPUT FILE TO BE REVIEWED  ')
222  FORMAT(A40)
      READ(5,222) FILE1
      OPEN( UNIT=2, NAME= FILE1, TYPE= 'OLD' )

      WRITE(7,223) FILE1
223  FORMAT(6X'INCLUDES DATA FROM FILE: ',A40/)

C   SKIP OVER HEADER INFO

      READ(2,'(//////////)')

C   READ LINES OF DATA FROM FILE FOR REVIEW

20   READ(2,*,ERR=40) X1,X2,XDUMMY,XDUMMY1,YAV
      WRITE(5,1004) X1,X2,YAV
1004  FORMAT($' INCLUDE ',3F10.3,' Y OR N ? ')
      ACCEPT 1005,INC
1005  FORMAT(A1)
      IF(INC .NE. 'Y') GOTO 30

C
C   INCLUDE THESE DATA
C
IC= IC + 1

```

```

RX1(IC)=X1
RX2(IC)=X2
RY(IC)=YAV
30  CONTINUE
    GOTO 20

C    FINISHED WITH FILE CLOSE TO START ANOTHER OR PROCESS
C
40  CLOSE(UNIT=2)
    TYPE 1006
1006 FORMAT(/$' ANOTHER FILE - Y OR PROCESS - P ? ')
    READ(5,1005) IAN
    IF(IAN .EQ. 'Y') GOTO 10

C    SEND RAW DATA TO PRINTER
    WRITE(7,390)
    WRITE(7,395)
390  FORMAT(6X,' BRIDGE A mV/V  BRIDGE B mV/V  AVG LOAD REF CELL')
395  FORMAT(6X,' *****')
    DO 600 I=1,IC
    WRITE(7,610) RX1(I),RX2(I),RY(I)
610  FORMAT(6X,F10.3,8X,F10.3,6X,F14.3)
600  CONTINUE

C    CURVE FIT WORKING CELL (1) CORRECTED MV/V TO AVG. FORCE
C    FROM TWO CALIBRATION BRIDGES

C    BRIDGE A

    CALL CLPOLY(RX1,RY,IC,2,COEFA,ERR2,R2,SEE)

    WRITE(7,400)
    WRITE(7,410)
    WRITE(7,420) COEFA(1)
    WRITE(7,430) COEFA(2)
    WRITE(7,440) COEFA(3)
    WRITE(7,450) ERR2
    WRITE(7,460) R2
    WRITE(7,470) SEE

400  FORMAT(/6X,' BRIDGE A CURVEFIT RESULTS, FORCE = A+BX+CX**2')
410  FORMAT(6X,' *****')
420  FORMAT(6X,' A = ',F20.5)
430  FORMAT(6X,' B = ',F20.5)
440  FORMAT(6X,' C = ',F20.5/)
450  FORMAT(6X,' ERR2 = ',F20.5)
460  FORMAT(6X,' R2 = ',F20.5)
470  FORMAT(6X,' SEE = ',F20.5)

```

```

C      BRIDGE B

      CALL CLPOLY(RX2,RY,IC,2,COEFB,ERR2,R2,SEE)

      WRITE(7,500)
      WRITE(7,510)
      WRITE(7,520) COEFB(1)
      WRITE(7,530) COEFB(2)
      WRITE(7,540) COEFB(3)
      WRITE(7,550) ERR2
      WRITE(7,560) R2
      WRITE(7,570) SEE

500    FORMAT(/6X,' BRIDGE B CURVEFIT RESULTS, FORCE = A+BX+CX**2')
510    FORMAT(6X' *****')
520    FORMAT(6X,' A = ',F20.5)
530    FORMAT(6X,' B = ',F20.5)
540    FORMAT(6X,' C = ',F20.5/)
550    FORMAT(6X,' ERR2 = ',F20.5)
560    FORMAT(6X,' R2 = ',F20.5)
570    FORMAT(6X,' SEE = ',F20.5)

C      PRODUCE COMPARISON TABLES OF MV/V,F CALIBRATION,
C      F CALCULATED AND DELTA (%)

      CALL CLPTAB(IC,RX1,RY,COEFA(3),COEFA(2),COEFA(1),'A ',DELA)
      CALL CLPTAB(IC,RX2,RY,COEFB(3),COEFB(2),COEFB(1),'B ',DELB)

1100   CONTINUE

C      SAVE ACCUMULATED DATA

      TYPE 1014
1014   FORMAT('$' SAVE ACCUMULATED DATA , Y OR N ')
      ACCEPT 1005, IS
      IF (IS .NE. 'Y') GOTO 1200
      TYPE 1015
1015   FORMAT('$' FILE SPECS. FOR DATA ')
      READ(5,222) FILE2
      OPEN( UNIT=3, NAME= FILE2, TYPE= 'NEW' )

      WRITE(3,390)
      WRITE(3,395)
      DO 50 I=1,IC
      WRITE(3,1016) RX1(I),RX2(I),RY(I)
1016   FORMAT(6X,F10.3,8X,F10.3,6X,F14.3)
50     CONTINUE
1200   CONTINUE

      CLOSE(UNIT=2)
      CLOSE(UNIT=3)

```

CLOSE(UNIT=7)

RETURN  
END

APPENDIX B  
Centre-line Pull Test Data

Appendix B comprises the test data used during the curvefitting process including data from calibration runs 4, 5, 6, 7, and 11. Also given are the quadratic equation coefficients produced by the curvefitting routine. The results of the curvefit procedure show a standard error of estimate of 3 to 4 lb<sub>f</sub> which is acceptable.

### B.1 Data Files

INCLUDES DATA FROM FILE: CLP\_5CELL\_4.RED

INCLUDES DATA FROM FILE: CLP\_5CELL\_5.RED

INCLUDES DATA FROM FILE: CLP\_5CELL\_6.RED

INCLUDES DATA FROM FILE: CLP\_5CELL\_7.RED

INCLUDES DATA FROM FILE: CLP\_5CELL\_11.RED

### B.2 Combined Data File

BRIDGE A mV/V    BRIDGE B mV/V    AVG LOAD REF CELL

\*\*\*\*\*

0.291	0.276	1875.840
0.432	0.417	2709.267
0.827	0.813	5046.287
1.224	1.210	7398.313
1.607	1.594	9673.206
1.995	1.981	11970.621
2.384	2.371	14278.688
2.797	2.784	16721.391
3.176	3.163	18969.359
2.785	2.772	16651.633
2.460	2.446	14726.736
2.060	2.046	12355.935
1.641	1.627	9875.019
1.232	1.217	7450.048
0.804	0.789	4915.439
0.443	0.428	2777.195
0.267	0.252	1738.415
0.240	0.225	1579.113
0.428	0.413	2690.395
0.829	0.814	5057.450
1.226	1.212	7411.267
1.616	1.602	9718.883
2.011	1.998	12063.520
2.414	2.401	14453.864
2.801	2.788	16742.900
3.185	3.172	19018.758
2.852	2.839	17047.514
2.443	2.429	14624.827
1.967	1.953	11804.960
1.649	1.635	9919.139

1.243	1.228	7511.592
0.801	0.787	4898.213
0.462	0.447	2885.199
0.261	0.246	1698.224
0.827	0.812	5044.642
1.610	1.597	9693.085
2.409	2.396	14428.135
3.184	3.171	19016.143
2.441	2.427	14613.487
1.649	1.635	9920.982
0.791	0.776	4835.090
0.832	0.818	5078.271
1.621	1.607	9749.819
2.376	2.363	14226.920
3.203	3.190	19122.779
2.444	2.430	14625.846
1.640	1.625	9858.241
0.799	0.784	4878.030
0.244	0.228	1600.485
0.424	0.408	2665.316
0.806	0.791	4924.377
1.197	1.183	7241.597
1.592	1.578	9575.873
1.990	1.977	11939.982
2.361	2.348	14138.050
2.784	2.771	16644.639
3.169	3.157	18926.053
2.862	2.849	17106.559
2.453	2.439	14682.704
2.042	2.027	12243.664
1.657	1.643	9969.263
1.233	1.218	7452.034
0.801	0.785	4891.475
0.455	0.439	2841.774
0.241	0.224	1576.271

### B.3 Curvefit Coefficients

BRIDGE A CURVEFIT RESULTS, FORCE = A+BX+CX\*\*2

\*\*\*\*\*

A = 152.35379  
 B = 5920.42969  
 C = 1.25425

ERR2 = 606.96252  
 R2 = 1.00000  
 SEE = 3.12885

## BRIDGE B CURVEFIT RESULTS, FORCE = A+BX+CX\*\*2

\*\*\*\*\*

A = 245.83151  
 B = 5913.03369  
 C = 1.87741

ERR2 = 825.29657  
 R2 = 1.00000  
 SEE = 3.64846

## B.4 Curvefit Comparison Data

## CURVEFIT COMPARISON TABLE FOR BRIDGE A

MV/V	F CALIBRATION	F CALCULATED	DF/F (%)
0.291	1875.8	1875.3	-0.03
0.432	2709.3	2710.2	0.03
0.827	5046.3	5049.4	0.06
1.224	7398.3	7400.8	0.03
1.607	9673.2	9669.7	-0.04
1.995	11970.6	11968.6	-0.02
2.384	14278.7	14273.8	-0.03
2.797	16721.4	16721.6	0.00
3.176	18969.4	18968.3	-0.01
2.785	16651.6	16650.5	-0.01
2.460	14726.7	14724.2	-0.02
2.060	12355.9	12353.8	-0.02
1.641	9875.0	9871.2	-0.04
1.232	7450.0	7448.2	-0.02
0.804	4915.4	4913.2	-0.05
0.443	2777.2	2775.4	-0.07
0.267	1738.4	1733.2	-0.30
0.240	1579.1	1573.3	-0.37
0.428	2690.4	2686.5	-0.14
0.829	5057.5	5061.3	0.08
1.226	7411.3	7412.7	0.02
1.616	9718.9	9723.0	0.04
2.011	12063.5	12063.4	0.00
2.414	14453.9	14451.6	-0.02
2.801	16742.9	16745.3	0.01
3.185	19018.8	19021.6	0.02
2.852	17047.5	17047.6	0.00
2.443	14624.8	14623.4	-0.01
1.967	11805.0	11802.7	-0.02
1.649	9919.1	9918.6	-0.01
1.243	7511.6	7513.4	0.02
0.801	4898.2	4895.4	-0.06
0.462	2885.2	2887.9	0.09
0.261	1698.2	1697.7	-0.03
0.827	5044.6	5049.4	0.09

1.610	9693.1	9687.5	-0.06
2.409	14428.1	14421.9	-0.04
3.184	19016.1	19015.7	0.00
2.441	14613.5	14611.6	-0.01
1.649	9921.0	9918.6	-0.02
0.791	4835.1	4836.2	0.02
0.832	5078.3	5079.0	0.01
1.621	9749.8	9752.7	0.03
2.376	14226.9	14226.4	0.00
3.203	19122.8	19128.4	0.03
2.444	14625.8	14629.4	0.02
1.640	9858.2	9865.2	0.07
0.799	4878.0	4883.6	0.11
0.244	1600.5	1597.0	-0.22
0.424	2665.3	2662.8	-0.09
0.806	4924.4	4925.0	0.01
1.197	7241.6	7240.9	-0.01
1.592	9575.9	9580.9	0.05
1.990	11940.0	11939.0	-0.01
2.361	14138.0	14137.5	0.00
2.784	16644.6	16644.6	0.00
3.169	18926.1	18926.8	0.00
2.862	17106.6	17106.9	0.00
2.453	14682.7	14682.7	0.00
2.042	12243.7	12247.1	0.03
1.657	9969.3	9965.9	-0.03
1.233	7452.0	7454.2	0.03
0.801	4891.5	4895.4	0.08
0.455	2841.8	2846.4	0.16
0.241	1576.3	1579.3	0.19

## CURVEFIT COMPARISON TABLE FOR BRIDGE B

MV/V	F CALIBRATION	F CALCULATED	DF/F (%)
0.276	1875.8	1878.0	0.11
0.417	2709.3	2711.9	0.10
0.813	5046.3	5054.4	0.16
1.210	7398.3	7403.4	0.07
1.594	9673.2	9676.0	0.03
1.981	11970.6	11966.9	-0.03
2.371	14278.7	14276.2	-0.02
2.784	16721.4	16722.3	0.01
3.163	18969.4	18967.5	-0.01
2.772	16651.6	16651.2	0.00
2.446	14726.7	14720.3	-0.04
2.046	12355.9	12351.8	-0.03
1.627	9875.0	9871.3	-0.04
1.217	7450.0	7444.8	-0.07
0.789	4915.4	4912.4	-0.06
0.428	2777.2	2777.0	-0.01
0.252	1738.4	1736.0	-0.14
0.225	1579.1	1576.4	-0.17
0.413	2690.4	2688.2	-0.08
0.814	5057.5	5060.3	0.06
1.212	7411.3	7415.2	0.05
1.602	9718.9	9723.3	0.05
1.998	12063.5	12067.6	0.03
2.401	14453.9	14453.8	0.00
2.788	16742.9	16746.0	0.02
3.172	19018.8	19020.9	0.01
2.839	17047.5	17048.1	0.00
2.429	14624.8	14619.7	-0.04
1.953	11805.0	11801.1	-0.03
1.635	9919.1	9918.7	0.00
1.228	7511.6	7509.9	-0.02
0.787	4898.2	4900.6	0.05
0.447	2885.2	2889.3	0.14
0.246	1698.2	1700.6	0.14
0.812	5044.6	5048.5	0.08
1.597	9693.1	9693.7	0.01
2.396	14428.1	14424.2	-0.03
3.171	19016.1	19014.9	-0.01
2.427	14613.5	14607.8	-0.04
1.635	9921.0	9918.7	-0.02
0.776	4835.1	4835.5	0.01
0.818	5078.3	5083.9	0.11
1.607	9749.8	9752.9	0.03
2.363	14226.9	14228.8	0.01
3.190	19122.8	19127.5	0.02
2.430	14625.8	14625.6	0.00

---

1.625	9858.2	9859.5	0.01
0.784	4878.0	4882.8	0.10
0.228	1600.5	1594.1	-0.40
0.408	2665.3	2658.7	-0.25
0.791	4924.4	4924.2	0.00
1.183	7241.6	7243.6	0.03
1.578	9575.9	9581.3	0.06
1.977	11940.0	11943.2	0.03
2.348	14138.0	14140.0	0.01
2.771	16644.6	16645.3	0.00
3.157	18926.1	18932.0	0.03
2.849	17106.6	17107.3	0.00
2.439	14682.7	14678.9	-0.03
2.027	12243.7	12239.3	-0.04
1.643	9969.3	9966.0	-0.03
1.218	7452.0	7450.7	-0.02
0.785	4891.5	4888.7	-0.06
0.439	2841.8	2842.0	0.01
0.224	1576.3	1570.4	-0.37

APPENDIX C  
Estimation of Boattail Drag

Boattail drag is a force acting on the engine nozzle surface parallel to, but opposite in direction of, the thrust. It is the result of the secondary air velocity being induced by the ejector effect from the nozzle efflux. The high velocity over the nozzle surface causes a depression of local static pressure, relative to test cell static pressure, which acts on the nozzle surface to produce a small, but measurable, drag force.

Static pressure taps were placed at the trailing edge of the nozzle fairing at 10°, 100°, 190°, and 280°, as seen in the direction of flight. Two rows of taps were extended along the nozzle fairing at 100° and 280° [Fig. C1]. Differential pressures were measured relative to the test cell wall static pressure in the plane of the engine inlet.

The axial force on the nozzle fairing was calculated by integrating the pressure force over the projected nozzle area. Pressures at each axial location were averaged and considered to act on a corresponding area. The areas are shown in Figure C2. A program written in Fortran 77 was used to calculate boattail drag.

The calculation of the boattail drag estimation is as follows:

- a) From the nozzle position indication (NPI) of a test point obtain the nozzle throat area, A8. The equation for A8 vs. NPI is given by:

$$A8 = 0.00856 \times NPI^2 + 1.8716 \times NPI + 220.0$$

- b) Calculate the nozzle exit area (A9) from the relationship of A9A8.  
(i.e.  $A9A8 = f(A8)$ )

$$A9 = A8 * A9A8$$

- c) The nozzle external fairing base area (ABASE) can be calculated from:

$$ABASE = 1.2 \times 3.14159 * \text{SQRT}(A9/3.14159)$$

- d) The nozzle fairing area (A10), nozzle exit diameter (D10), and Sine of the nozzle entry angle ( $\sin \theta$ ) are calculated from:

$$A10 = A9 + ABASE$$

$$D10 = \text{SQRT}(4.0 \times A10 / 3.14159)$$

$$\sin \theta = (34.852 - D10)/(2.0 \times 24.75)$$

- e) Calculate the radial lengths, nozzle areas, and projected areas from:

$$X_i = \sin \theta * L_i, \quad i=1,6$$

$$A_i = ((D10 + 2.0 \times X_i)^2 \times 3.14159 / 4.0) - A10, \quad i=1,6$$

$$A_{(i+1)p} = A_{(i+1)} - A_i, \quad i=0,5$$

- f) The average pressures at stations 1 to 6 are computed from differential pressure measurements, taken at stations located at equal distances from the nozzle exit. Forces acting on projected annuli are computed:

$$F_i = P_i \times A_{pi}, \quad i=1,6$$

and, finally, the total boattail drag is obtained from summation:

$$F_{\text{bt}} = \sum F_i, i=1,6$$

Sample Calculation

For a military power point (Run 72, point 6) sample calculations were carried out as summarized below:

$$P1 = 0.239 \text{ psi}$$

$$P2 = 0.121 \text{ psi}$$

$$P3 = 0.063 \text{ psi}$$

$$P4 = 0.045 \text{ psi}$$

$$P5 = 0.024 \text{ psi}$$

$$P6 = 0.024 \text{ psi}$$

Calculate A8 for NPI=15.7%.

$$\begin{aligned} A8 &= 0.00856 \times \text{NPI}^2 + 1.8716 \times \text{NPI} + 220.0 \\ &= 0.00856 \times (15.7)^2 + 1.8716 \times (15.7) + 220.0 \\ &= 251.5 \text{ in}^2 \end{aligned}$$

Calculate the nozzle exit area (A9) from the relationship of A9A8.  
(lookup table used of nozzle throat area vs. nozzle exit area)

$$\begin{aligned} A9 &= A8 \times A9A8 \\ &= 251.5 \times 1.2841 \\ &= 323.0 \text{ in}^2 \end{aligned}$$

Calculate the nozzle base area:

$$\begin{aligned} \text{ABASE} &= 1.2 \times 3.14159 \times \text{SQRT}(A9/3.14159) \\ &= 1.2 \times 3.14159 \times \text{SQRT}(323/3.14159) \\ &= 38.2 \text{ in}^2 \end{aligned}$$

Calculate the nozzle fairing area (A10), nozzle exit diameter (D10), and Sine of the nozzle entry angle (SIN  $\theta$ ):

$$\begin{aligned} A10 &= A9 + \text{ABASE} \\ &= 323.0 + 38.2 \\ &= 361.2 \text{ in}^2 \end{aligned}$$

$$\begin{aligned} D10 &= \text{SQRT}(4.0 \times A10 / 3.14159) \\ &= \text{SQRT}(4.0 \times 361.2 / 3.14159) \\ &= 21.44 \text{ in} \end{aligned}$$

$$\begin{aligned} \sin \theta &= (34.852 - D10)/(2.0 \times 24.75) \\ &= (34.852 - 21.44)/(2.0 \times 24.75) \\ &= 0.27095 \end{aligned}$$

Calculate the radial lengths, nozzle areas, and projected areas from:

$$X_i = \sin \theta \times L_i, i=1,6$$

$$\begin{aligned}
 L1 &= 0.594 \text{ in} \\
 L2 &= 2.50 \text{ in} \\
 L3 &= 6.00 \text{ in} \\
 L4 &= 12.00 \text{ in} \\
 L5 &= 20.13 \text{ in} \\
 L6 &= 24.75 \text{ in}
 \end{aligned}$$

$$\begin{aligned}
 X1 &= \sin \theta \times L1 \\
 &= 0.27095 \times 0.594 \\
 &= 0.161 \text{ in}
 \end{aligned}$$

Likewise:

$$\begin{aligned}
 X2 &= 0.677 \text{ in} \\
 X3 &= 1.626 \text{ in} \\
 X4 &= 3.251 \text{ in} \\
 X5 &= 5.453 \text{ in} \\
 X6 &= 6.706 \text{ in}
 \end{aligned}$$

Calculate the areas at each length from:

$$A_i = ((D10 + 2.0 \times X_i)^2 \times 3.14159 / 4.0) - A_{10}, i=1,6$$

$$\begin{aligned}
 A1 &= ((D10 + 2.0 \times X1)^2 \times 3.14159 / 4.0) - A_{10} \\
 &= ((21.44 + 2.0 \times 0.161)^2 \times 3.14159 / 4.0) - 361.2 \\
 &= 10.75 \text{ in}^2
 \end{aligned}$$

Likewise:

$$\begin{aligned}
 A2 &= 46.87 \text{ in}^2 \\
 A3 &= 117.58 \text{ in}^2 \\
 A4 &= 252.0 \text{ in}^2 \\
 A5 &= 460.53 \text{ in}^2 \\
 A6 &= 592.79 \text{ in}^2
 \end{aligned}$$

Calculate the nozzle projected areas:

$$A_{p(i+1)} = A_p(i+1) - A_{p,i}, i=0,5$$

$$\begin{aligned}
 A_{p1} &= A1 \\
 &= 10.75 \text{ in}^2
 \end{aligned}$$

Likewise:

$$\begin{aligned}
 A_{p2} &= 36.12 \text{ in}^2 \\
 A_{p3} &= 70.71 \text{ in}^2 \\
 A_{p4} &= 134.42 \text{ in}^2 \\
 A_{p5} &= 208.53 \text{ in}^2 \\
 A_{p6} &= 132.26 \text{ in}^2
 \end{aligned}$$

The forces acting on projected annuli are computed:

$$F_i = P_i \times A_{p,i}, i=1,6$$

$$\begin{aligned} F_1 &= P_1 \times A_{p,1} \\ &= 0.239 \times 10.75 \\ &= 2.57 \text{ LB}_f \end{aligned}$$

Likewise:

$$\begin{aligned} F_2 &= 4.37 \text{ LB}_f \\ F_3 &= 4.45 \text{ LB}_f \\ F_4 &= 6.05 \text{ LB}_f \\ F_5 &= 5.00 \text{ LB}_f \\ F_6 &= 3.18 \text{ LB}_f \end{aligned}$$

and, finally, the total boattail drag is obtained from summation:

$$\begin{aligned} F_{bx} &= \sum F_i, i=1,6 \\ &= 2.57 + 4.37 + 4.45 + 6.05 + 5.00 + 3.18 \\ &= 25.62 \text{ LB}_f \end{aligned}$$

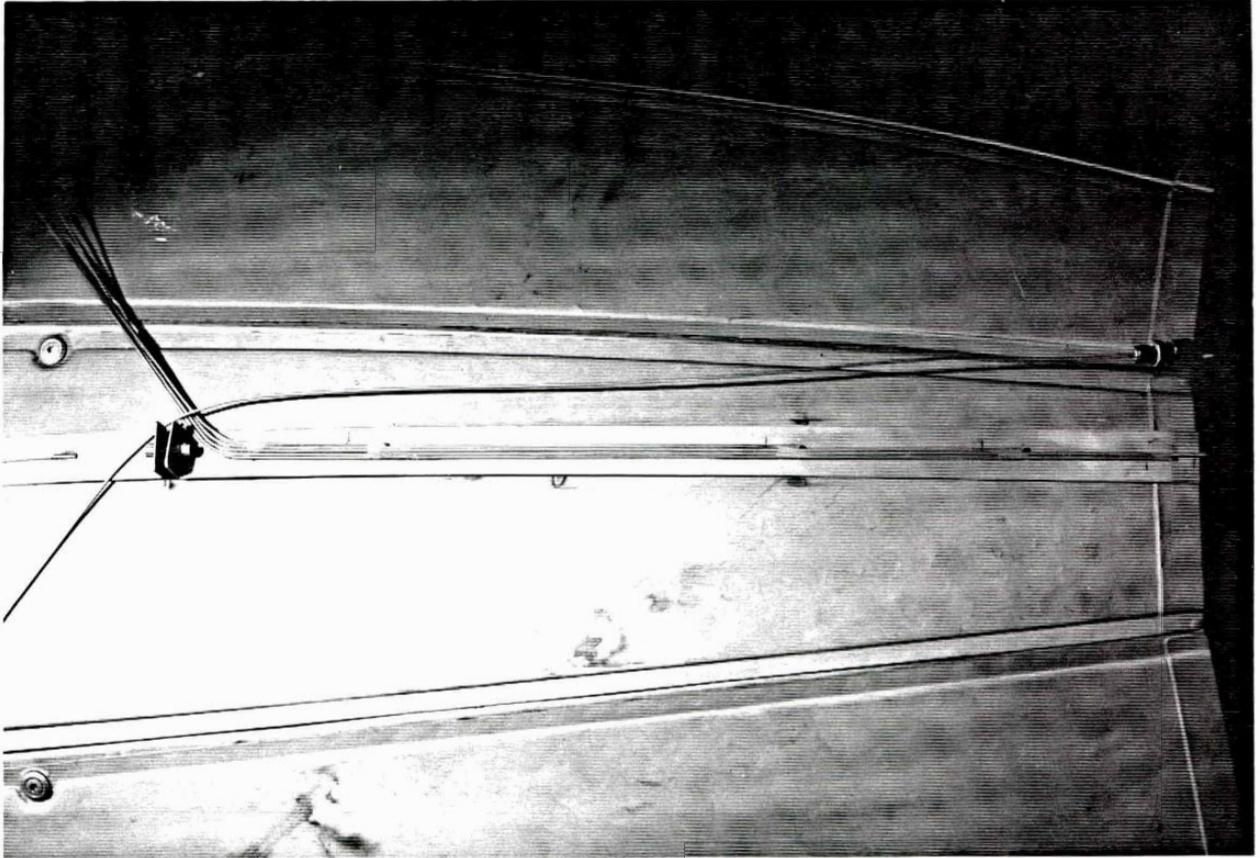


Figure C1. Nozzle Fairing Static Pressure Taps

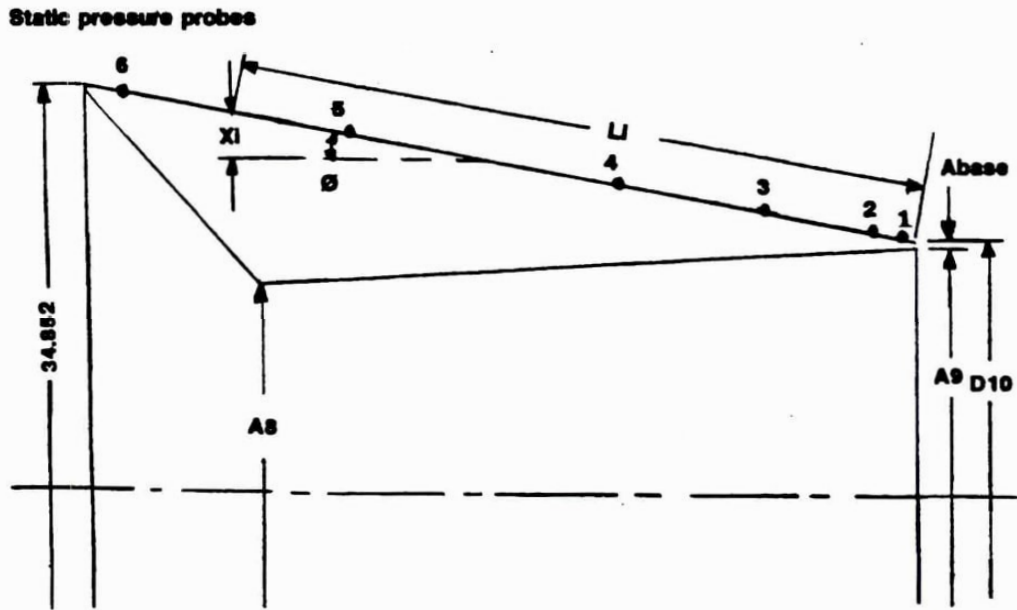


Figure C2. Nozzle Geometry

APPENDIX D  
Determination of Cell Airflow and Bypass Area

The traditional method for determining the cell airflow by energy balance, outlined in Section 4.7, was found to be unreliable for the NRC Engine Laboratory No. 5 test cell. Non uniform exhaust flow forced the disqualification of the energy balance method. An attempt to estimate the cell inlet airflow was done through direct measurements. The cross sectional area of the inlet was divided into 81 sub-areas. Velocity measurements were made in order to calculate the flow in each sub-area. Velocities near the walls, floor and ceiling, were adjusted (area weighted) to incorporate the effect of a boundary layer. The boundary thickness was estimated by calculating the Reynolds number (equation D1) at the cell inlet and by using a simplified formula (equation D2) for turbulent flow (Streeter and Wylie 1979). The Reynolds number was calculated from an average cell inlet velocity of 8 ft/s, an absolute air viscosity of  $1.572 \times 10^{-4}$  ft<sup>2</sup>/s, and a cell inlet length of 28 ft. This calculation resulted in a Reynolds number of  $1.43 \times 10^6$  which indicated turbulent flow for a flat plate (ie.  $R_e > 1.0 \times 10^5$ ). A boundary layer thickness of 7.3 inches was then calculated through equation D2. The total cell airflow was obtained by summing the individual airflows calculated in each subarea.

The procedure was repeated for the measurement of engine bypass airflow. Again, velocities were measured at several locations beside the engine bellmouth. An adjustment for the boundary layer was also included in the calculation for airflow passing near the walls, floor and ceiling of the cell. A Reynolds number of  $5.11 \times 10^6$  and boundary layer thickness of 10 inches was calculated for turbulent flow over a flat plate. As a result, a blockage of 5 inches was assumed and used to adjust the cross sectional areas adjacent to the test cell walls in the bypass. The airflows in each area were summed and added to the engine airflow measurement to obtain the total cell flow.

The total cell flow calculated from the inlet measurements compared to that used for the bypass method was found to be within 0.2 percent.

To simplify the calculation of cell airflow, a function of cell flow and nozzle pressure ratio is used during engine test runs. The co-efficients for the function are given in equation D3. Data for the curvefit were obtained from test run No. 60.

$$R_e = \frac{VEL \times L}{\nu} \quad (D1)$$

$$\delta = \frac{0.37L}{R_e^{0.2}} \quad (D2)$$

$$W_0 = -27.955 \times X^2 + 221.489 \times X - 80.1125 \quad (D3)$$

where: X = engine nozzle pressure ratio (P5T/PAMB)

The bypass area was approximated from physical measurements made in the test cell and was found to be 203.5 ft<sup>2</sup>.

APPENDIX E  
F404 Thrust Calculations

This Appendix gives a sample calculation of terms associated with thrust, as discussed in Section 4. Reference is made to the variable names used by a computer program for calculating thrust. The sample data were obtained from the data set of Run 72 (Point No. 6).

Calculate inlet air density:

$$\begin{aligned} \text{RV DEN} &= \text{RVBARO} / (\text{RCR} * \text{RVT1A}) * 144 \\ &= 14.5928 / (53.35 * 515.061) * 144 \\ &= 0.076473 \text{ lb}_m/\text{ft}^3 \end{aligned}$$

Calculate nozzle pressure ratio:

$$\begin{aligned} \text{XXPR5} &= \text{P5NRC} / \text{RVPAMB} \\ &= 50.364 / 14.354 \\ &= 3.50871 \end{aligned}$$

Calculate corrected cell airflow:

$$\begin{aligned} \text{RWCC} &= -27.9545 * \text{XXPR5}^2 + 221.4893 * \text{XXPR5} - 80.1123 \\ &= 352.9 \text{ lb}_m/\text{s} \end{aligned}$$

Uncorrect cell airflow based on test cell conditions:

$$\text{RWCC} = \text{RWCC} * \text{XXDEL T} / \text{RVRTHE}$$

$$\begin{aligned} \text{XXDEL T} &= \text{RVBARO} / 14.696 \\ &= 14.5928 / 14.696 \\ &= 0.992978 \end{aligned}$$

$$\begin{aligned} \text{RVRTHE} &= \text{SQRT}(\text{RVT1A}/518.67) \\ &= \text{SQRT}(515.061/518.67) \\ &= 0.996515 \end{aligned}$$

$$\begin{aligned} \text{RWCC} &= 352.9 * 0.992978 / 0.996515 \\ &= 351.6 \text{ lb}_m/\text{s} \end{aligned}$$

Calculate inlet air velocity:

$$\begin{aligned} \text{RVVCL} &= \text{RWCC} / (\text{RV DEN} * \text{A0}) \\ &= 351.6 / (0.076473 * 225.0) \\ &= 20.4 \text{ ft/s} \end{aligned}$$

Calculate bypass ratio:

$$\begin{aligned} \text{A} &= (\text{RWCC} - \text{RVW1T}) / \text{RVW1T} \\ &= (351.6 - 140.8) / 140.8 \\ &= 1.49716 \end{aligned}$$

Calculate momentum drag:

$$\begin{aligned} RVFIM &= [1 - (A/(A + 1))^2 * A0/AB] * RWCC * RVVCL / RCG \\ &= [1 - (1.49716/(1.49716 + 1))^2 * 225.0/203.5] \\ &\quad * 351.6 * 20.4 / 32.174 \\ &= 134.3 \text{ lb}_f \end{aligned}$$

Calculate bypass velocity:

$$\begin{aligned} RVVCLS &= A / (A + 1) * A0 / AB * RVVCL \\ &= 1.49716 / (1.49716 + 1) * 225.0 / 203.5 * 20.4 \\ &= 13.5 \text{ ft/s} \end{aligned}$$

Calculate thrust frame drag:

$$\begin{aligned} RVFTF &= 0.5 * RVDEN * RVVCLS^2 * RCCDTF * RCATF / RCG \\ &= 0.5 * 0.076473 * 13.5^2 * 1.17 * 8.82 / 32.174 \\ &= 2.2 \text{ lb}_f \end{aligned}$$

Calculate engine skin friction drag:

$$\begin{aligned} RVFFR &= 0.5 * RVDEN * RVVCLS^2 * RCCDFR * RCAFRR / RCG \\ &= 0.5 * 0.076473 * 13.5^2 * 0.005 * 165.87 / 32.174 \\ &= 0.18 \text{ lb}_f \end{aligned}$$

Calculate bypass pressure drag:

inlet static pressure:

$$\begin{aligned} PS0 &= PTB - 0.5 * RVDEN * RVVCL^2 / RCG / 144 \\ &= 14.5928 - 0.5 * 0.076473 * 20.4^2 / 32.174 / 144 \\ &= 14.5894 \text{ lb/in}^2 \end{aligned}$$

static pressure (PSB) in bypass:

$$\begin{aligned} PSB &= PTB - 0.5 * RVDEN * RVVCLS^2 / RCG / 144 \\ &= 14.5928 - 0.5 * 0.076473 * 13.5^2 / 32.174 / 144 \\ &= 14.5913 \text{ lb/in}^2 \end{aligned}$$

Calculate bypass drag:

$$\begin{aligned} RVFB &= (P0 + PSB) * RCABP \\ &= (14.5894 - 14.5913) * 203.5 * 144 \\ &= -55.7 \text{ lb}_f \end{aligned}$$

Calculate boattail drag (example given in appendix C)

$$RVFBT = 25.62 \text{ lb}_f$$

Calculate scale thrust:

$$RVFSCA = RCTH1A + RCTH1B * X + RCTH1C * X^2$$

$$\text{Where: } X = (RVMVA / RVEXCT)_{LC3} - (RVMVA / RVEXCT)_{LC1}$$

$$X = 1.754 \text{ mV/V (Calculated by program)}$$

$$\begin{aligned} RVFSCA &= 152.35 + 5920.43 * 1.754 + 1.25 * 1.754^2 \\ &= 10540.6 \text{ lb}_f \end{aligned}$$

Likewise:

$$RVFSCB = RCTH2A + RCTH2B * X + RCTH2C * X^2$$

$$\text{Where: } X = (RVMVA / RVEXCT)_{LC3} - (RVMVA / RVEXCT)_{LC1}$$

$$X = 1.737 \text{ mV/V (Calculated by program)}$$

$$\begin{aligned} RVFSCB &= 245.83 + 5913.03 * 1.737 + 1.88 * 1.737^2 \\ &= 10522.4 \text{ lb}_f \end{aligned}$$

Calculate the thrust bed tare in the same manner:

$$\begin{aligned} \text{Yields: } RVZERA &= 9.0 \text{ lb}_f \\ RVZERB &= -17.0 \text{ lb}_f \end{aligned}$$

Calculate average scale thrust:

$$\begin{aligned} RVF &= [(RVFSCA - RVZERA) + (RVFSCB - RVZERB)] / 2 \\ &= [(10540.6 - 9) + 10522.4 - (-17)] / 2 \\ &= 10536.0 \text{ lb}_f \end{aligned}$$

Calculate gross thrust:

$$\begin{aligned} RVFG &= RVF + RVFIM + RVFTF + RVFFR + RVFBT + RVFB \\ &= 10536.0 + 134.3 + 2.2 + 0.18 + 25.6 + -55.7 \\ &= 10642.6 \text{ lb}_f \end{aligned}$$

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