

Estimation of take-off thrust using generalised data for turbo-jet and turbo-fan engines

Endorsed by
The Royal Aeronautical Society

ESDU DATA ITEMS

Data Items provide validated information in engineering design and analysis for use by, or under the supervision of, professionally qualified engineers. The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants. The whole process is subject to independent review for which crucial support is provided by industrial companies, government research laboratories, universities and others from around the world through the participation of some of their leading experts on ESDU Technical Committees. This process ensures that the results of much valuable work (theoretical, experimental and operational), which may not be widely available or in a readily usable form, can be communicated concisely and accurately to the engineering community.

We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Performance Committee. This Committee first met in 1946 and now has the following membership:

Chairman

Mr D.H. Peckham — Ministry of Defence, Procurement Executive

Vice-Chairman

Mr H.Y. Ratcliffe — Cranfield Institute of Technology

Members

Mr E.N. Brailsford	— British Aircraft Corporation Ltd, Filton
Mr W.R.B. Bryder	— Civil Aviation Authority, Airworthiness Division
Mr T.S.R. Jordan	— Hawker Siddeley Aviation Ltd, Kingston
Mr J.R.D. Kenward	— British Airways, European Division
Mr D.W. Kew	— Loughborough University of Technology
Mr J.A. Lawford	— Aeroplane and Armament Experimental Establishment
Mr P. Robinson	— Hawker Siddeley Aviation Ltd
Mr R. Thornhill	— Rolls-Royce (1971) Ltd, Derby Engine Division
Mr P.C.H. White	— British Aircraft Corporation Ltd, Preston
Mr H. Wickardt*	— Fokker-VFW BV., Schiphol-Oost.

* Corresponding Member

The performance Committee and ESDU gratefully acknowledge the very considerable assistance given by Rolls-Royce (1971) Ltd, Bristol Engine Division in the form of the computed data presented in this Item. Particular help and advice were given during the preparation of the Item by

Mr E.A. White
Mr T.J. Jordan

of the Engine Project Studies Department.

The work on this Item was carried out in the Aircraft Motion Group of the Engineering Sciences Data Unit under the supervision of Mr P.D. Chappell, Group Head. The member of staff who undertook the technical work involved in the initial assessment of the available information and the construction and subsequent development of the Item was

Mr D. J. Mitchell — Senior Engineer.

ESTIMATION OF TAKE-OFF THRUST USING GENERALISED DATA FOR TURBO-JET AND TURBO-FAN ENGINES

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	3
3. NET THRUST VARIATION WITH FORWARD SPEED	3
3.1 Notes on the Use of the Figures	4
3.1.1 Engine reference thrust	4
3.1.2 Design specific thrust	4
3.1.3 Method of engine control	5
3.1.4 Effect of ambient conditions	5
3.1.5 Flat rating	6
4. ALLOWANCES TO NET THRUST FOR INSTALLATION EFFECTS	7
5. REFERENCES	8
6. EXAMPLES	9
6.1 Subsonic Transport Aeroplane with Non-Flat-Rated Engines	9
6.2 Flat-Rated Turbo-Fan Engine	10
6.3 Fighter-Type Aeroplane With and Without Reheat	13
FIGURES 1 TO 10	16 to 25
APPENDIX A BASIS OF COMPUTED UNINSTALLED ENGINE THRUST DATA	
A1. ENGINE CORE (PRIMARY STREAM) DESIGN PARAMETERS	26
A2. MIXED-FLOW ENGINES	26
A3. UNMIXED-FLOW TURBO-FAN ENGINES	26
A4. ENGINE CONTROL LAWS	27
A5. INTAKE	27
A6. NOZZLES AND EXHAUSTS	27
A7. OFFTAKES	27
A8. DUCT LENGTHS	27
A9. OTHER LOSSES	27

ESTIMATION OF TAKE-OFF THRUST USING GENERALISED DATA FOR TURBO-JET AND TURBO-FAN ENGINES

1. NOTATION AND UNITS^{*†}

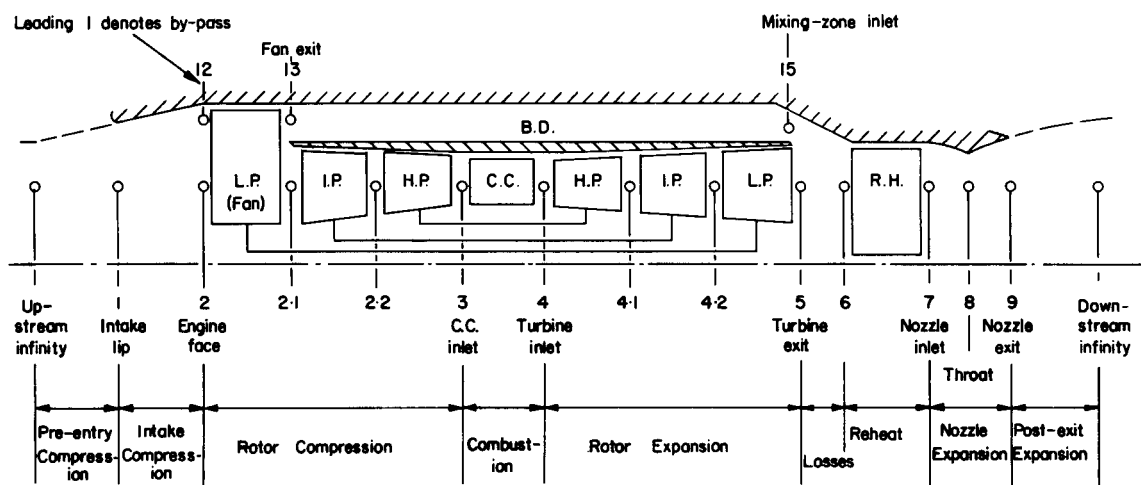
		<i>SI</i>	<i>British</i>
f_N	uninstalled net thrust of one engine (see Section 4)	N	lbf
Δf_N	increment in net thrust	N	lbf
g	acceleration due to gravity	m/s ²	ft/s ²
H_p	pressure height	m	ft
M	Mach number [*]		
$\dot{m}$	mass airflow [†]	kg/s	slug/s
N_F	fan or low pressure compressor rotational speed	rev/min	rev/min
p	pressure [*]	N/m ²	lbf/ft ²
T	temperature [*]	K	K
T_f	flat-rating limit (see Section 3.1.5)	K	K
$\dot{w}$	weight airflow [†]	N/s	lbf/s
λ	bypass ratio, (secondary stream airflow)/(primary stream airflow)		
δ	relative pressure, p/p_0		
Subscripts			
<i>avg</i>	denotes average value		
<i>f</i>	denotes value at flat-rating limit, T_f		
<i>intake</i>	denotes value at intake		
<i>rated</i>	denotes engine rated value at sea level		
<i>ref</i>	denotes reference value		
<i>reheat</i>	denotes value with reheat in operation		
<i>s</i>	denotes static value		

^{*} No subscript is used when considering ambient, free stream or upstream-infinity conditions.

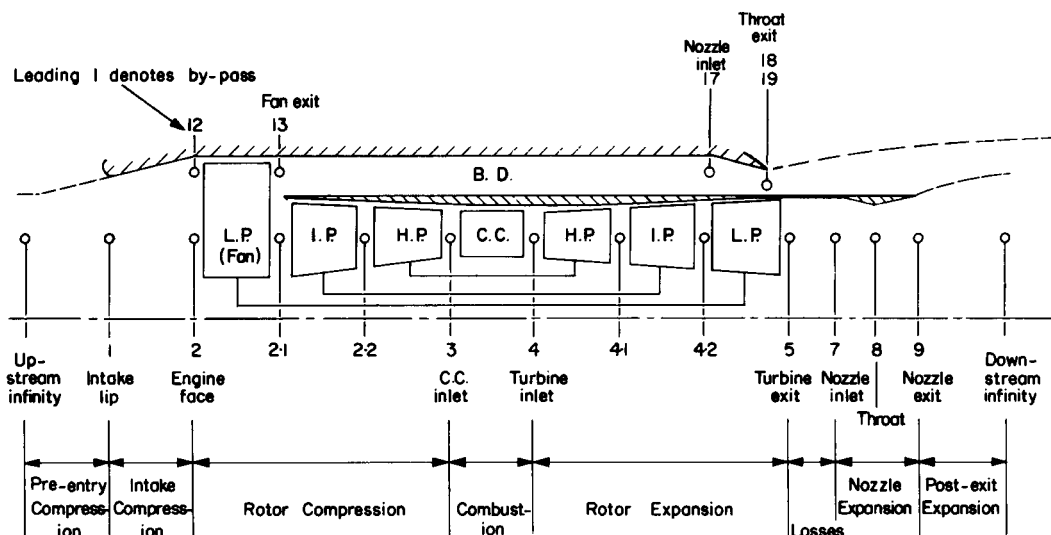
[†] Airflow is considered here in terms of *weight* flow in both British and SI systems of units since the engine specific thrust, *i.e.* thrust per unit airflow, is then expressed in the same units (seconds) in both systems. Although this procedure differs from the practice of considering flow in mass units in the SI system (see, for example Item Nos 70020–22 and 73018–19), it is felt to be justified by the resulting simplification of the Figures of this Item. In either system the corresponding mass flow can of course be obtained by making the substitution $\dot{m} = \dot{w}/g$.

- T denotes value at temperature $^* T$
- t denotes total value
- 0 denotes value at sea level in International Standard Atmosphere
(Item Nos 68046 and 72018 give numerical values)
- 1, 2, 3, . } denote engine station designations * , see Sketch 1.1
12, 13, . }

* No subscript is used when considering ambient, free stream or upstream-infinity conditions.



(a) Mixed-flow design



(b) Unmixed-flow design
(Three-quarter length fan duct)

B.D. By-pass (or fan) duct I.P. Intermediate Pressure
C.C. Combustor L.P. Low Pressure
H.P. High Pressure R.H. Reheat

Sketch 1.1 ENGINE PERFORMANCE STATION DESIGNATION

2. INTRODUCTION

To estimate the take-off performance of an aeroplane (see Item Nos Perf EG 5/1 and 76011), a knowledge is required of the thrust available and, in particular, of the variation of thrust with forward speed. For the purposes of initial design calculations this Item presents data that relate the uninstalled net thrust, f_N , of an engine during take-off to a static, sea-level reference thrust, $f_{N_{ref}}$ (see Section 3.1.1). The data apply to turbo-jet and turbo-fan engines operating in a range of ambient conditions and include the effects of three alternative methods of engine control. The effects of using reheat are considered for turbo-jet engines and for mixed-exhaust-flow turbo-fan engines of relatively low bypass ratio. Procedures are included for considering the effect of engine flat-rating (see Section 3.1.5).

The thrust available from an engine when installed in an aeroplane is usually less than that of the uninstalled engine. The term “uninstalled”, as applied to the thrust data in this Item, is defined briefly in Section 4. Note, however, that when using these data the only installation correction that must always be made is the allowance for the effect on net thrust of the intake total pressure recovery. In particular cases, other losses may be avoidable, or included in the uninstalled thrust data, or negligible, see Section 4.

The Item includes several worked examples to illustrate the application of the data.

3. NET THRUST VARIATION WITH FORWARD SPEED

Figures 1 to 8 of this Item present data for use in estimating the variation of net thrust with forward speed for uninstalled turbo-jet and turbo-fan engines; a guide to the contents of each Figure is given in Table 3.1

TABLE 3.1 Guide to Engine Data in Figures 1 to 8

	Cases considered	Figures
Engine configuration, see Appendix A	Medium to high bypass ratio, two stream (i.e. unmixed-flow) turbo-fans; approximate range of values of $(f_N/\dot{w})_{s,0}$: 25 to 50 seconds	1, 2, 3, 4
	Unreheated turbo-jet and single stream (i.e. mixed-flow) low bypass ratio turbo-fans; approximate range of values of $(f_N/\dot{w})_{s,0}$: 50 to 90 seconds	1, 2, 3, 4
	Reheated turbo-jet and single stream (i.e. mixed-flow) low bypass ratio turbo-fans; approximate range of values of $(f_N/\dot{w})_{s,0}$: 90 to 125 seconds	5, 6, 7, 8
Ambient conditions, see Section 3.1.4	$\left. \begin{array}{l} T = 268.15 \text{ K} \\ T = 288.15 \text{ K} \\ T = 298.15 \text{ K} \\ T = 308.15 \text{ K} \end{array} \right\} \text{corresponding to } \left\{ \begin{array}{l} \text{ISA} - 20 \text{ K} \\ \text{ISA} \\ \text{ISA} + 10 \text{ K} \\ \text{ISA} + 20 \text{ K} \end{array} \right\} \text{at sea level,}$ see Figure 10 for interpretation of values of T at other heights	1, 5 2, 6 3, 7 4, 8
Method of engine control, see Section 3.1.3	Constant temperature, T_{t_4}	1 to 8
	Constant fan or low pressure compressor rotational speed, N_F	1 to 8
	Constant $N_F/\sqrt{T_{t_2}}$ or $N_F/\sqrt{T_{t_{12}}}$	1 to 8

These data have been computed for a group of engines considered typical of current design and detailed descriptions of the selected engine configurations and values of the principal design parameters are given in Appendix A. In addition, the relationship between the design values of specific thrust*, $(f_N/\dot{w})_{s,0}$, and bypass ratio, λ , for these engines is shown by the solid lines in Figure 9. In Figures 1 to 8 values of $(f_N/\delta)/f_{N_{ref}}$ are plotted against freestream Mach number, M , and $(f_N/\dot{w})_{s,0}$ for three methods of engine control and a range of ambient temperatures. Note that the use of design specific thrust as an independent variable in these Figures permits reliable estimates to be obtained of the variation of thrust with forward speed for any engine for which $(f_N/\dot{w})_{s,0}$ is known. For cases where the value of $(f_N/\dot{w})_{s,0}$ is not known, Figure 9 gives advice on the variation of this parameter with bypass ratio, see Section 3.1.2.

3.1 Notes on the Use of the Figures

3.1.1 Engine reference thrust

The reference thrust, $f_{N_{ref}}$, used in this Item is related to the static, sea-level rated thrust, $f_{N_{rated}}$, of the uninstalled engine (*i.e.* the maximum static thrust by which the engine is customarily “known”). However, there is more than one method of rating an engine and so $f_{N_{ref}}$ is not always equal to $f_{N_{rated}}$. The principal cases of interest are as follows.

- (i) For an engine whose static, sea-level rated thrust is quoted at ISA conditions, *i.e.* $T = 288.15$ K,

$$f_{N_{ref}} = f_{N_{rated}} = f_{N_{s,0}} \quad (3.1)$$

- (ii) For an engine whose static, sea-level ($\delta = 1.0$) rated thrust is quoted at an ambient temperature, T ,

$$f_{N_{ref}} = \frac{f_{N_{rated}}}{\left[\frac{f_N}{\delta} \frac{1}{f_{N_{ref}}} \right]_{s,T}} \quad (3.2)$$

The quantity in square brackets in Equation (3.2) is the static value, at temperature T , of the thrust ratio given in Figures 1 to 8 and obtained if necessary by interpolation.

- (iii) For a “flat-rated” engine (see Section 3.1.5) the value of $f_{N_{ref}}$ is obtained as in Equation (3.2) with the temperature T taken as the sea-level flat-rating limit, $T_{f_{rated}}^{ref}$.

3.1.2 Design specific thrust

To use Figures 1 to 8 a value of $(f_N/\dot{w})_{s,0}$ is required. For the engines defined in Appendix A, values of this parameter are related to bypass ratio by the solid lines in Figure 9 while values for existing engines can usually be obtained from sources such as References 3, 8 and 11. For other cases involving unheated engines the user may refer to the broken lines in the main part of Figure 9 which give an approximate correlation of values of $(f_N/\dot{w})_{s,0}$, λ and T_{t_4} for a nominal overall pressure ratio, p_{t_3}/p_{t_2} , of 20. This approximate correlation is based on data taken from theoretical studies reported in References 1, 2, 4, 5, 7, 10, 12, 13 and 14 and has been found to predict values of $(f_N/\dot{w})_{s,0}$ for existing engines to within ± 10 per cent in most cases[†]. It is considered that any additional effects on the correlation of other combinations of values of p_{t_3}/p_{t_2} and T_{t_4} likely to be encountered in practice will be negligibly small.

* Expressed in seconds, see second footnote to Section 1.

† When considering a flat-rated engine (see Section 3.1.5) the specific thrust in sea-level ISA conditions *must* be associated with the value of T_{t_4} in those conditions and not with the value of T_{t_4} which applies at the flat-rating limit.

For the reheated engines defined in Appendix A, i.e. with a reheat temperature, $T_{t_{7, \text{reheat}}} = 2100 \text{ K}$, the relationship between $(f_N/\dot{w})_{s,0, \text{reheat}}$ and λ is shown by the upper solid line in Figure 9. For cases where the design specific thrust is not known, for example if other values of $T_{t_{7, \text{reheat}}}$ are considered, an approximate value may be obtained by using the expression

$$\left[\frac{f_{N, \text{reheat}}}{f_N} \right]_{s,0} \cong \left[\frac{T_{t_{7, \text{reheat}}}}{T_{t_7}} \right]^{1/2}, \quad (3.3)$$

where T_{t_7} is the un-reheated exhaust gas temperature. For cases where T_{t_7} is not known the inset diagram in Figure 9 gives approximate values of $(f_N/\dot{w})_{s,0, \text{reheat}}$ for ranges of values of T_{t_4} and $T_{t_{7, \text{reheat}}}$.

3.1.3 Method of engine control

The three methods of engine control noted in Table 3.1 are largely self-explanatory. During initial design calculations the user must choose between the three types of control law offered. In general it can be assumed that for the “simpler” types of engines and most civil transport engines either constant T_{t_4} or constant N_F control is used. Constant $N_F/\sqrt{T_{t_4}}$ control tends to be used on the more advanced types of military engine.

3.1.4 Effect of ambient conditions

Figures 1 to 8 can be used to determine thrusts for a wide range of ambient conditions. The effect of pressure height, H_p , is accounted for by the use of the relative pressure, δ , in the ordinate of the Figures. The effect of ambient temperature is considered independently by interpolation between Figures 1 to 4 for unreheated engines and Figures 5 to 8 for reheated engines. The relationships between T , H_p and δ for conditions in the range ISA – 20 K to ISA + 30 K are given in Figure 10.

To estimate thrust at height H_p and ambient temperature T , adopt the following procedure.

- (i) Determine the value of the reference thrust, $f_{N_{ref}}$, using the method given in Section 3.1.1, Equation (3.1) or (3.2). (In general, for a non-flat-rated engine, Equation (3.1) will apply.)
- (ii) Determine the value of δ at H_p .
- (iii) At the required temperature and Mach numbers, determine values of the thrust ratio

$$\left[\frac{f_N}{\delta f_{N_{ref}}} \right]. \quad (3.4)$$

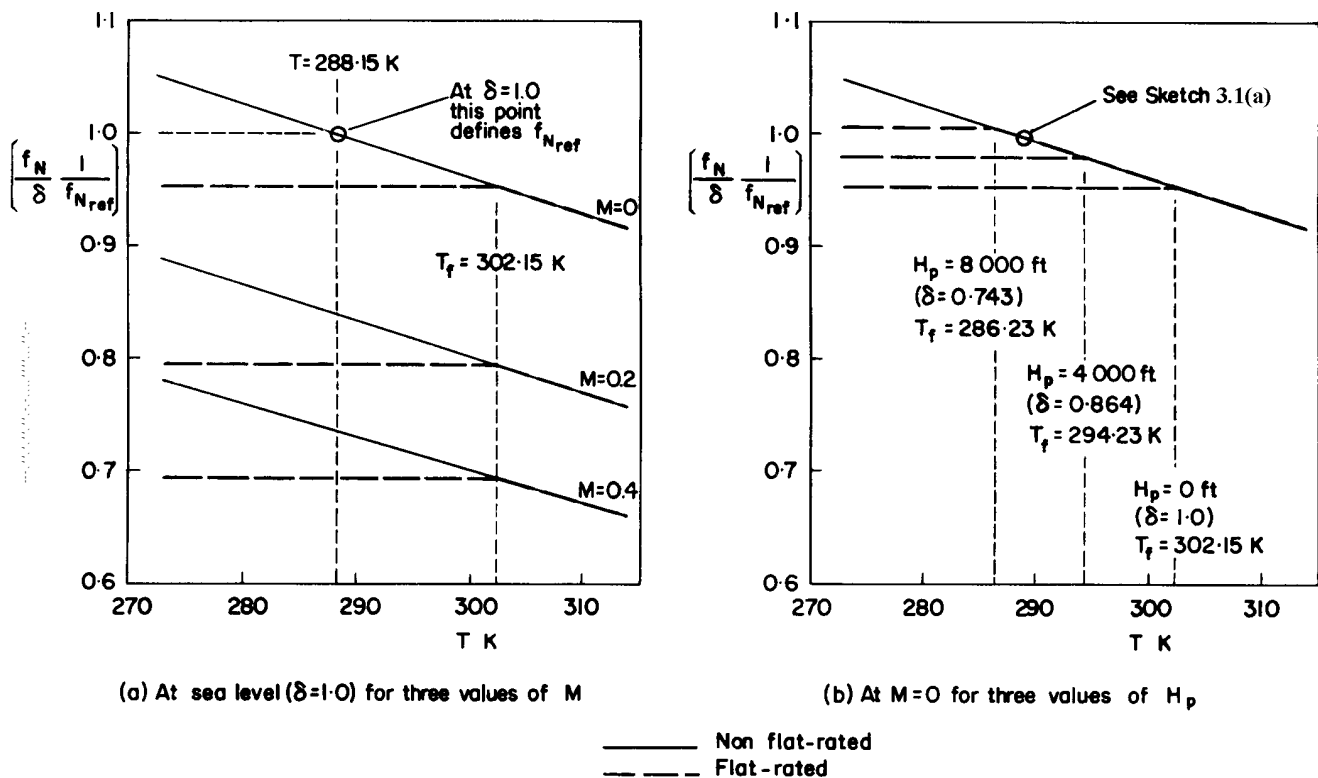
- (iv) Obtain the net thrust from

$$f_N = \left[\frac{f_N}{\delta f_{N_{ref}}} \right] \times f_{N_{ref}} \times \delta. \quad (3.5)$$

3.1.5 Flat rating

It is current practice for many engines to be “flat-rated” at take-off, *i.e.* to be controlled so as to give the same take-off thrust performance over a range of ambient temperatures up to a “flat-rating limit”, T_f . For a flat-rated engine the usual system of control operates such that T_f is a fixed increment above ISA temperatures and typically in the range ISA + 10 K to ISA + 15 K. At temperatures below T_f the engine is controlled so that the thrust varies with speed only. Above T_f the engine operates under constant T_{t4} or N_F control and thrust varies with both speed and ambient temperature, see Sketch 3.1.

Flat-rating is used mainly for the engines of transport aeroplanes with the objective of improving the overall operating economics as compared with non-flat-rated engines. Sketch 3.1 shows that a non-flat-rated engine that produces the same take-off thrust as a flat-rated one at a temperature T_f , produces greater thrusts at lower temperatures. However, the consequent decrease in take-off field length and increase in climb gradient may not be required and such apparent advantages must be set against the increased weight and cost associated with the higher design thrust of the non-flat-rated engine. In addition, when the flat-rated engine operates at temperatures below T_f , the engine temperatures are reduced from their maximum values with a consequent improvement in component life. Note that where an engine is designed to be flat-rated at take-off, it usually cannot be “de-flat rated” to give higher thrusts at temperatures below T_f by changing the control system alone.



Sketch 3.1 Illustration of Effect of Flat-rating a Turbo-Fan Engine To $T_f = \text{ISA} + 14 \text{ K}$

To use Figures 1 to 8 to estimate the thrust of an engine that is flat-rated, adopt the following procedure.

- (i) Determine the value of the reference thrust, $f_{N_{ref}}$, using the method given in Section 3.1.1, item (iii) and Equation (3.2). (Note that this requires the sea-level value of the flat-rating limit, $T_{f_{rated}}$, which is associated with $f_{N_{rated}}$.)
- (ii) Determine the values of δ and T_f for the height at which the thrust is required.

- (iii) For ambient temperatures at or below the flat-rating limit, read Figures 1 to 8 at temperature T_f to determine values of $[(f_N/\delta)/f_{N_{ref}}]$ at the required Mach numbers. For ambient temperatures above T_f , read values at the required temperature.
- (iv) The net thrust is

$$f_N = \left[\frac{f_N}{\delta f_{N_{ref}}} \right] \times f_{N_{ref}} \times \delta. \quad (3.6)$$

4. ALLOWANCES TO NET THRUST FOR INSTALLATION EFFECTS

In general installing an engine in an aeroplane produces changes in both thrust and drag and the task of satisfactorily accounting for these often-interrelated effects can be complex. Following Item No. 69006 and Reference 9, net thrust is taken as the streamwise force applied by the engine internal flow to the surfaces that bound it (before, during and after passage through the engine). For given ambient conditions and engine internal flow, any parts of the internal-flow boundaries in the installed configuration that differ from those assumed to apply to the uninstalled engine are considered to produce changes in engine thrust. Thrust losses also arise due to offtakes of engine airflow and/or shaft power. The various types of installation effect may be conveniently grouped in the categories: intake, ducts and exhaust, and offtakes.

The data given in Figures 1 to 8 apply to uninstalled engines. However, since the term “uninstalled” can have a variety of meanings, the following Table briefly summarises both the allowances that are included and those that are excluded from the data. For further definition of the engine configurations, see Appendix A.

Installation category	Data in Figures 1 to 8 INCLUDE allowances for the effects of	Data in Figures 1 to 8 EXCLUDE allowances for the effects of
Intake		Intake total pressure loss.
Ducts and Exhaust	Duct losses for basic engine; full length fan ducts on unmixed-flow engines; representative exhaust and nozzle losses for primary and fan streams.	Variation of fan-duct length on unmixed-flow engines; variation of tailpipe length; free surfaces such as pylons or a “bullet” fairing in exhaust flow; thrust reverser (when not in use) and noise suppression treatment.
Offtakes		Air offtakes for air conditioning, anti-icing, boundary layer or other control; shaft power offtakes for aeroplane accessories.

The only correction that must *always* be made to the uninstalled-engine data when obtaining installed thrust is the allowance arising from the intake total pressure loss which changes the absolute value of thrust and, since it varies with speed, can effectively change the thrust ratio, $[(f_N/\delta)/f_{N_{ref}}]$, see Example of Section 6.3. The effect of other changes from the defined standard of losses on the *thrust ratio* are usually negligible. However, the effect of such changes should be included in the *absolute* values of thrust.