

ESTIMATION OF SPILLAGE DRAG FOR A WIDE RANGE OF AXISYMMETRIC INTAKES AT $M < 1$

1. NOTATION AND UNITS*

		SI	British
A	cross-sectional area*, far upstream, of streamtube entering cowl, see Sketch 1.1	m^2	ft^2
A_c	intake capture area (= A_1 for axisymmetric intake), see Sketch 1.1	m^2	ft^2
A_1	intake cross-sectional area at cowl lip (or highlight)	m^2	ft^2
$[A/A_c]$	mass flow ratio, $\dot{m}/\rho A_c V$		
$[A/A_c]_{datum}$	datum mass flow ratio, see Section 3.1 (= 1.0 in this Item)		
$[A/A_c]_{sep}$	separation mass flow ratio, see Sketch 3.1 and Section 3.2 for definition		
$[A/A_c]_{sep,basic}$	value of separation mass flow ratio at $M = 0.6$, $\sigma = 0$		
$C_{D_{spill}}$	spillage drag coefficient, D_{spill}/qA_c (= D_{spill}/qA_1 for axisymmetric intake)		
C_F	mean skin friction coefficient (flat plate)		
$C_{\phi_{pre}}$	pre-entry force coefficient for axisymmetric intake, ϕ_{pre}/qA_1 , see Section 5.2 (also known as additive drag coefficient)		
D_f	cowl forebody drag	N	lbf
$D_{f_{datum}}$	cowl forebody drag at datum mass flow ratio, $[A/A_c]_{datum}$	N	lbf
D_{max}	maximum diameter of axisymmetric cowl	m	ft
D_{spill}	spillage drag, per intake, see Section 3.1 for definition		
D_1	intake diameter at lip (or highlight) of axisymmetric cowl	m	ft
L_f	length of cowl forebody, see Sketch 1.2	m	ft
M	Mach number*		

* No subscript is used when considering ambient, freestream or upstream infinity conditions.

$\dot{m}$	mass airflow entering cowl, see Sketch 1.1	kg/s	slug/s
p	static pressure*	N/m ²	lbf/ft ²
q	kinetic pressure*, $\gamma p M^2/2$	N/m ²	lbf/ft ²
Re_f	Reynolds number based on cowl forebody length, L_f		
R_f	initial radius of curvature of cowl forebody, see Sketch 1.2 and Table 8.2	m	ft
S	reference wing area	m ²	ft ²
V	true airspeed	m/s	ft/s
x	cowl longitudinal co-ordinate with $x = 0$ at cowl lip (or highlight), see Sketch 1.2	m	ft
x/X	cowl non-dimensional longitudinal co-ordinate with $X = L_f$		
y	cowl co-ordinate normal to x direction, with $y = 0$ at cowl lip (or highlight), see Sketch 1.2	m	ft
y/Y	cowl non-dimensional co-ordinate with $Y = (D_{max} - D_1)/2$		
γ	ratio of specific heat capacity at constant pressure to that at constant volume (taken as 1.4 for air)		
$\Delta[A/A_c]_{sep, M}$	correction to $[A/A_c]_{sep}$ for Mach numbers other than 0.6		
$\Delta[A/A_c]_{sep, \sigma}$	correction to $[A/A_c]_{sep}$ for incidence angles other than $\sigma = 0$		
ΔC_D	contribution to aircraft drag coefficient due to spillage, per intake, ($= D_{spill}/qS$)		
$[\Delta C_D]_{spill, att}$	contribution to spillage drag coefficient associated with increasing thickness of attached boundary layer and evaluated at $[A/A_c]$ or $[A/A_c]_{sep}$, whichever is the greater, see Sketch 3.1		
$[\Delta C_D]_{spill, sep}$	contribution to spillage drag coefficient due to flow separation , when $[A/A_c] < [A/A_c]_{sep}$, see Sketch 3.1		
$\Delta(D/q)$	increment in aircraft drag parameter due to spillage, per intake, ($= D_{spill}/q$)	m ²	ft ²
$\Delta D_{spill, att}$	contribution to spillage drag associated with increasing thickness of attached boundary layer and evaluated at $[A/A_c]$ or $[A/A_c]_{sep}$, whichever is the greater, see Sketch 3.1, ($= [\Delta C_D]_{spill, att} \times q A_c$)	N	lbf

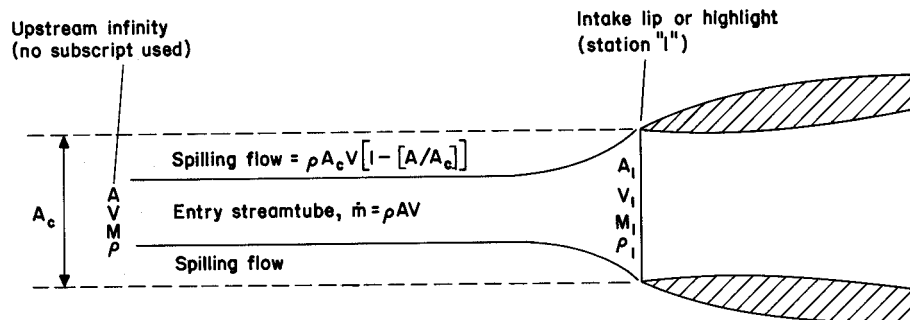
For footnote refer to end of Notation Section

$\Delta D_{spill,sep}$	contribution to spillage drag due to flow separation when $[A/A_c] < [A/A_c]_{sep}$, see Sketch 3.1, $(= [\Delta C_D]_{spill,sep} \times q A_c)$	N	lbf
δ_f	cowl forebody angle, defined between stations $x = 0.01D_1$ and $x = 0.05D_1$ aft of the cowl lip, see Sketch 1.2 and Table 8.2	deg	deg
ρ	density of air*	kg/m ³	slug/ft ³
σ	incidence angle, <i>i.e.</i> angle between local flow direction and cowl axis of symmetry $(= \sin^{-1}[1 - \cos^2\alpha \cos^2\beta]^{1/2})$, where α = angle of attack, β = angle of sideslip, see Item No. 79018 for definitions)	deg	deg
ϕ_{pre}	pre-entry stream force on outside of stream tube entering cowl, positive in downstream direction (also known as additive drag), see Section 5.2.	N	lbf

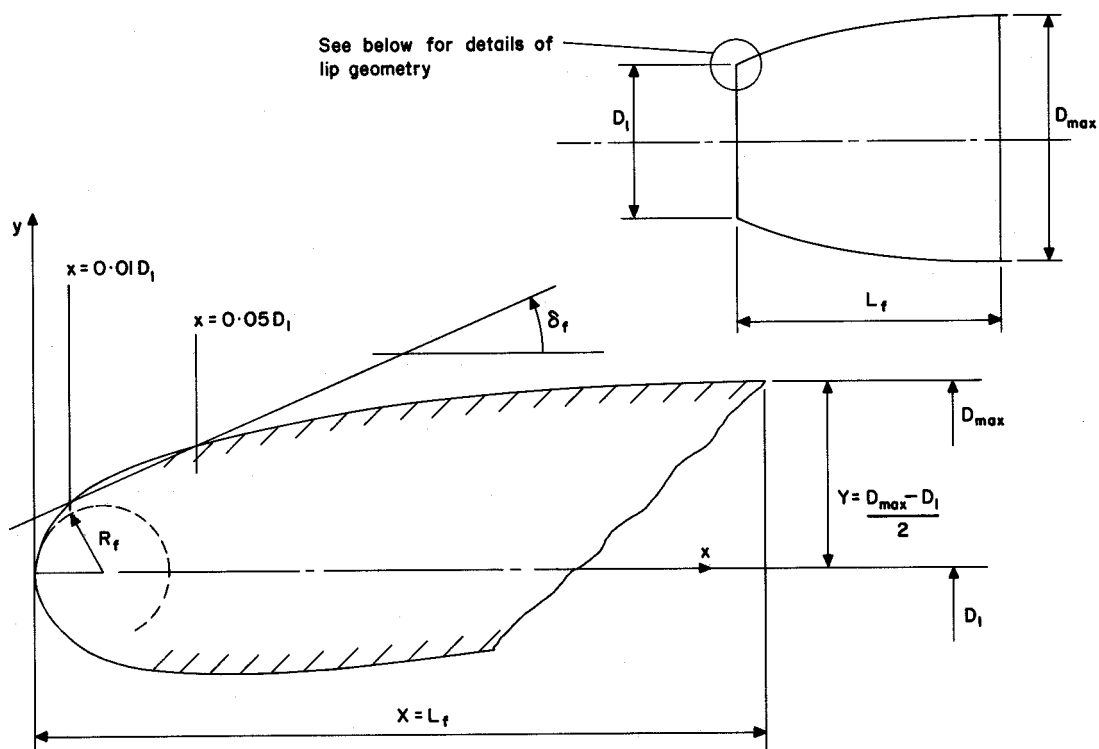
Subscripts *

f	denotes cowl forebody
σ	denotes value at incidence angle, σ
1	denotes value at cowl lip (or highlight)

* No subscript is used when considering ambient, freestream or upstream infinity conditions.



Sketch 1.1 Illustration of intake flow parameters for axisymmetric cowl



Sketch 1.2 Forebody and lip geometries for axisymmetric cowl

2. INTRODUCTION

This Item presents data for use in estimating values of spillage drag for axisymmetric intakes. The data are applicable at subsonic freestream Mach numbers and incidence angles up to twenty degrees are considered. A wide range of axisymmetric intake configurations is considered and data are included for the whole range of intake flow conditions at which spillage drag may be encountered, *i.e.* mass flow ratios in the range $0 \leq [A/A_c] < 1.0$.

The Item is suitable for use in aircraft project studies and one particular application is in providing spillage drag data at low values of intake mass flow ratio (≤ 0.4 , say) for use in conjunction with the “bare-engine” windmilling drag and airflow data given in Item No. 81009. The combined usage of the windmilling drag data of Item No. 81009 and the spillage drag data of the present Item to estimate the drag of an inoperative turbo-jet or turbo-fan engine is described in Item No. 84005. A method for estimating the total drag of cowlings having NACA 1-series forebodies is given in Aerodynamics Item No. 81024.

Before using this Item it is important that particular attention should be paid to Section 3 which gives definitions of spillage drag, D_{spill} , spillage drag coefficient, $C_{D_{spill}}$ and associated geometric and flow parameters. The estimation method is described in Section 4 and Figures 4 to 9 present values of the mass flow ratio, $[A/A_c]_{sep}$, for flow separation at or near the cowl lip and the associated values of $C_{D_{spill}}$. Section 5 indicates how the method was derived, discusses the likely accuracy and, by the combined use of Table 8.1 and the References of Section 6, indicates the range of data used. A more complete description of the derivation is given in Reference 38.

As with all calculations associated with the propulsion system, the estimation method of this Item should be used as part of a consistent system of thrust and drag accounting. This is particularly important where drag components are dependent on the engine operating conditions – in the present case intake mass flow ratio. The breakdown of the forces associated with a propulsion system into “thrust” and “drag” is to some extent arbitrary and is introduced in Item No. 69006 (Reference 24). Reference 32 gives an example of a comprehensive system of thrust and drag accounting avoiding inconsistencies in the definitions of forces.

3. DEFINITIONS

3.1 Spillage Drag and Drag Coefficient

For values of mass flow ratio, $[A/A_c]$, less than 1.0, intake spillage drag is defined as

$$D_{spill} = D_f - D_{f_{datum}} \quad (3.1)$$

In Equation (3.1), D_f is the cowl forebody drag* while $D_{f_{datum}}$ is a datum value associated with a value of mass flow ratio, $[A/A_c]_{datum}$, see Sketch 3.1. For the open-nose (or pitot) type axisymmetric intakes considered in this Item, $[A/A_c]_{datum} = 1.0$ so that

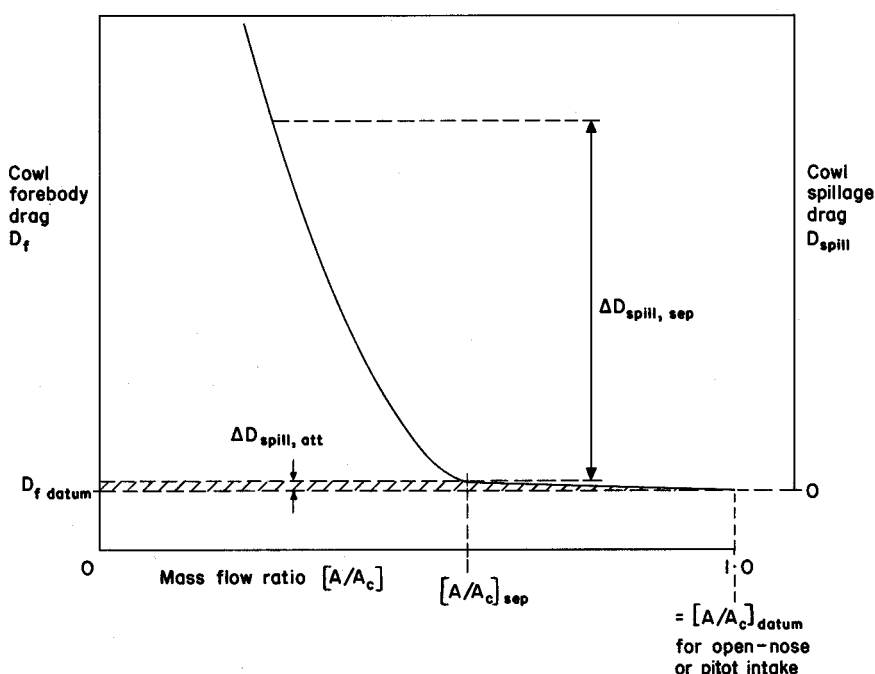
$$D_{spill} = D_f - [D_f]_{A/A_c = 1.0} \quad (3.2)$$

The spillage drag coefficient is defined on the basis of intake capture area as

$$C_{D_{spill}} = \frac{D_{spill}}{qA_c} \quad (3.3)$$

For axisymmetric cowls $A_c = A_1$.

The estimation method of this Item subdivides D_{spill} and $C_{D_{spill}}$ into two contributions, corresponding to flow conditions above and below the mass flow ratio at which flow separation occurs at or near the cowl lip, see Section 3.2.



Sketch 3.1 Definition of spillage drag for open-nose (or pitot) intake

* The precise meaning of D_f , i.e. the drag of a part of the cowl, and its distinction from the forces acting on that part of the cowl, is not considered here – see Reference 32.

3.2 Mass Flow Ratio for Flow Separation

The separation mass flow ratio, $[A/A_c]_{sep}$, is the value of $[A/A_c]$ below which a rapid increase in cowl forebody drag, and hence spillage drag, occurs as a result of flow separation at or near the cowl lip. The contribution to spillage drag corresponding to this flow condition is denoted $\Delta D_{spill,sep}$, see Sketch 3.1. The more gradual increase in drag shown in Sketch 3.1 in the range $1.0 > [A/A_c] \geq [A/A_c]_{sep}$ is associated with increasingly adverse pressure gradients and consequent thickening of the cowl boundary layer and is denoted $\Delta D_{spill,att}$. The respective contributions to the spillage drag coefficient are denoted $[\Delta C_D]_{spill,sep}$ and $[\Delta C_D]_{spill,att}$ and in this Item estimates of spillage drag coefficient are made by summing these, i.e.

$$C_{D_{spill}} = [\Delta C_D]_{spill,sep} + \Delta C_{D_{spill,att}}. \quad (3.4)$$

Values of $[A/A_c]_{sep}$ have been correlated here using two parameters to characterise the cowl forebody (see Sketch 1.2 and Section 5.1.1).

- (i) A cowl lip radius parameter, R_f/D_1 , where R_f is the initial radius of curvature at the cowl lip or highlight.
- (ii) A cowl forebody angle, δ_f , defined between points at distances $x = 0.01D_1$ and $x = 0.05D_1$ aft of the cowl lip.

The values of R_f/D_1 and δ_f for cowls used in developing the estimation method are given in Table 8.1 and Figure 1; methods of estimating R_f/D_1 and δ_f are given in Table 8.2.

3.3 Contribution of Spillage Drag to Total Airframe Drag

Values of $C_{D_{spill}}$ derived here may be treated* like any other aerodynamic contribution to airframe drag coefficient provided only that the appropriate reference areas are used, see Equations (4.6) and (4.7) in Section 4.

* See Section 3.1

4. ESTIMATION OF SPILLAGE DRAG COEFFICIENT AND DRAG

Cowl forebody geometric properties are given in Table 8.2 and Figures 1 to 3 while Figures 4 to 9 provide data from which values of $[A/A_c]_{sep}$ and C_{Dspill} are estimated.

The calculation sequence for given values of freestream Mach number, M , and incidence angle, σ , is as follows.

- (i) Calculate intake mass flow ratio either from known engine mass flow data,

$$\left[\frac{A}{A_c}\right] = \frac{\dot{m}}{\rho A_c V} \quad , \quad (4.1)$$

or, when using Item No. 81009 for windmilling airflow data, the flow area, A , may be obtained directly from Figure 3 and Equation (A4.12) of that Item.

- (ii) For the cowl configuration of interest, estimate values for the lip radius parameter, R_f/D_1 , and the cowl forebody angle, δ_f , using equations given in Table 8.2 and/or data given in Figures 1 to 3.
- (iii) Use Figure 4 to estimate $[A/A_c]_{sep,basic}$, i.e. the mass flow ratio for flow separation at freestream Mach number, $M = 0.6$, and incidence angle, $\sigma = 0$.
- (iv) Use Figure 5 to estimate a value of $\Delta[A/A_c]_{sep,M}$, i.e. a correction to the “basic” value for Mach numbers other than 0.6.
- (v) Use Figure 6 to estimate a value of $\Delta[A/A_c]_{sep,\sigma}$, i.e. a correction to the “basic” value for incidence angles other than $\sigma = 0$.
- (vi) Using the values estimated in steps (iii) to (v), calculate $[A/A_c]_{sep}$ from,

$$\left[\frac{A}{A_c}\right]_{sep} = \left[\frac{A}{A_c}\right]_{sep,basic} + \Delta\left[\frac{A}{A_c}\right]_{sep,M} + \Delta\left[\frac{A}{A_c}\right]_{sep,\sigma} \quad (4.2)$$

If the calculated value of $[A/A_c]_{sep}$ is greater than one or less than zero then values of one and zero respectively should be used, see Sections 5.1.2 and 5.1.3.

- (vii) Use Figures 7a to 7e to estimate $[\Delta C_D]_{spill,sep}$, the “separation” contribution to spillage drag coefficient, using the value of $[A/A_c]_{sep}$ calculated from Equation (4.2). For intermediate values of M , values of $[\Delta C_D]_{spill,sep}$ can be estimated by linear interpolation between Figures 7a to 7e. Note that for cases where $[A/A_c] > [A/A_c]_{sep}$, $[\Delta C_D]_{spill,sep} = 0$.
- (viii) Estimate $[\Delta C_D]_{spill,att}$, the “attached-flow” contribution to spillage drag coefficient using the relationship

$$[\Delta C_D]_{spill,att} = \left[\frac{[\Delta C_D]_{spill,att}}{C_F} \right] \times C_F \quad (4.3)$$

Values of the change in cowl form factor $\{[\Delta C_D]_{spill,att}/C_F\}$, with mass flow ratio are given in Figure 8 and values of the mean skin friction coefficient, C_F , in Figure 9. Values of $[\Delta C_D]_{spill,att}$ should be calculated at whichever is the greater of $[A/A_c]$ and $[A/A_c]_{sep}$ – see Sketch 3.1.

- (ix) Using the values obtained in steps (vii) and (viii) calculate,

$$C_{D_{spill}} = [\Delta C_D]_{spill,sep} + [\Delta C_D]_{spill,att}. \quad (4.4)$$

- (x) Spillage drag is given by the relationship

$$D_{spill} = C_{D_{spill}} q A_c = C_{D_{spill}} 0.7 p M^2 A_c. \quad (4.5)$$

The contribution, ΔC_D , to aeroplane drag coefficient is,

$$\Delta C_D = C_{D_{spill}} \frac{A_c}{S} \quad (4.6)$$

or, alternatively,

$$\Delta \left[\frac{D}{q} \right] = C_{D_{spill}} A_c. \quad (4.7)$$

5. NOTES ON THE CORRELATIONS

Measured data for a wide range of axisymmetric cowls, obtained using different measurement techniques and test facilities, were used to derive the estimation method of this Item. Table 8.1 gives geometric data and details of the ranges of experimental conditions from those References in Section 6 which provided numerical data while Figures 1 to 3 give graphical presentations of cowl geometric properties. This section describes the work done in producing the estimation method, with particular emphasis on those aspects likely to influence the user's interpretation of the data. Reference 38 gives a more complete description of the work and includes the data correlations.

5.1 Mass Flow Ratio for Flow Separation at Cowl Lip

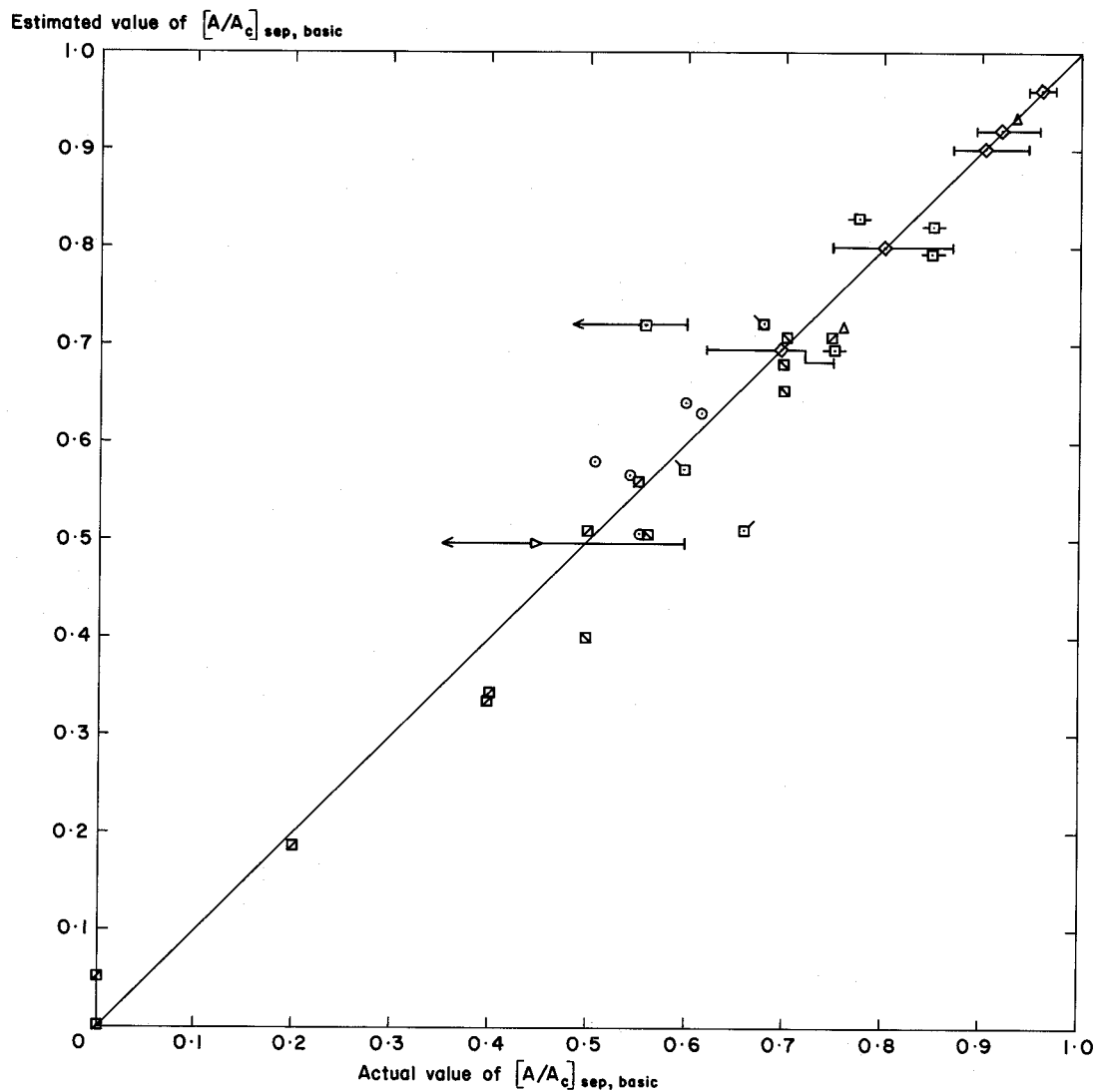
The use of $[A/A_c]_{sep}$ to analyse spillage drag data is usually associated with the "round-lip" cowls of subsonic aircraft, see References 19, 21 and 28. Here, however, this approach has been adopted to analyse data for all types of axisymmetric cowls, including those with sharp lips – the last-mentioned application finding theoretical support, for incompressible flow, in Reference 37, see Section 5.3.1. Advantages of this approach are:

- (i) all available data are used in a single correlation – so lending support to one another,
- (ii) effects of changes in M and σ can be taken into account as incremental effects on $[A/A_c]_{sep, basic}$.

5.1.1 Effect of cowl geometry

Cowl geometry is taken into account primarily through the values of $[A/A_c]_{sep, basic}$ (i.e. $[A/A_c]_{sep}$ at $M = 0.6$, $\sigma = 0$) which were correlated in terms of the cowl lip radius parameter, R_f/D_1 , and forebody angle, δ_f . The result of the correlation is presented as Figure 4 and the extent to which it represents the original data is illustrated in Sketch 5.1. The two parameters, R_f/D_1 and δ_f , were used to define forebody geometry so as to permit the widest possible range of cowl shapes to be incorporated in one correlation. For limited groups or families of cowl shapes, correlations can be obtained using only one or other of these (or related) parameters. For example, Figure 1 shows that for NACA 1-series cowls there is a close relationship between R_f/D_1 and δ_f so that either the former (References 21, 28 and 36), or the latter (Reference 19), can be used as a basis of correlation. On the other hand, in References 15 and 25, where cowls of nominally constant but small forebody angle were tested with different lip radii, little or no effect of R_f/D_1 was found except at low values of M . In the case of References 6, 15 and 34, where different lip geometries were applied to given forebody shapes, the rearwards extent of the (usually circular-arc) lip was often enough to affect the value of δ_f – see Section 5.3.2 regarding the use of Reference 34.

- ◊ Range of values needed to correlate spillage drag data for sharp lip cowls
(see Section 5.3.1 and Sketch 5.1)
- ← Indicates case where only an upper limit to the actual value is known



Sketch 5.1 Comparison of actual and estimated values of mass flow ratio for separation at
 $M = 0.6, \sigma = 0$

5.1.2 Effect of freestream Mach number

The effects of changes in freestream Mach number on the mass flow ratio for separation were examined in terms of $\Delta[A/A_c]_{sep,M}$, i.e. the difference between the value of $[A/A_c]_{sep}$ at a specified value of M and the value at $M = 0.6$. Best results were obtained by plotting $\Delta[A/A_c]_{sep,M}$ against δ_f although there was considerable scatter in the data so that the curves presented in Figure 5 are better regarded as a plausible interpretation of the data than a precise correlation. One result of the simple form of presentation used in Figure 5 is that Equation (4.2) can give values of $[A/A_c]_{sep}$ greater than 1.0 or less than 0. In such cases the value 1.0 or 0 should be used.

For $M < 0.4$, relatively few data were available and so the curves in this region were drawn in a conservative fashion and account taken of the data in Reference 34, see Section 5.4. In constructing the curves in Figure 5 for $M > 0.6$ it was decided to ignore those instances where an increase in M led to a suppression of the flow separation and a temporary reduction in $[A/A_c]_{sep}$. This suppression of flow separation occurs due to a change in the form of the pressure distribution just downstream of the cowl lip as the local Mach number becomes greater than 1.0 and shock waves form. With further increase in freestream mach number, $[A/A_c]_{sep}$ resumes its upward trend but the "spillage" drag then includes at least an element of wave drag and for some combinations of Mach number and mass flow ratio may consist almost wholly of wave drag. In this Item, no attempt is made to distinguish between the contributions to spillage drag due to flow separation and shock waves and no simple parametric approach could deal with their mutual interaction. By ignoring the temporary suppression of separation the method gives overestimates of spillage drag although the implications are unlikely to be significant in the context of project performance work.

5.1.3 Effect of angle of incidence

The effect of changes in the local angle of incidence, σ , on the mass flow ratio for separation was examined in terms of $\Delta[A/A_c]_{sep,\sigma}$, i.e. the difference between the value of $[A/A_c]_{sep}$ at a particular value of σ and the value at $\sigma = 0^\circ$. The results of this correlation are presented in Figure 6. As in Section 5.1.2, one result of this simple form of presentation is that Equation (4.2) can give values of $[A/A_c]_{sep}$ greater than 1.0. In such cases the value 1.0 should be used.

Data showing the effects of changes in σ were available in References 16, 21, 22 and 26 (σ up to 6° , wide range of M) and Reference 3 (σ up to 8° , low M). The extrapolation shown in Figure 6 was obtained by inference from data in References 9, 12, 14 and 39 on the angles of incidence for flow separation on cowls operating at $[A/A_c] = 1$. For each of the cowls in these references, the following procedure was adopted:

- (i) the value of σ for flow separation at $[A/A_c] = 1.0$ was deduced from curves of lift coefficient against σ .
- (ii) a value of $[A/A_c]_{sep,\sigma=0}$, i.e. at $\sigma = 0$, was estimated from Figures 4 and 5,
- (iii) a value of $\Delta[A/A_c]_{sep,\sigma}$ was calculated from

$$\Delta\left[\frac{A}{A_c}\right]_{sep,\sigma} = 1 - \left[\frac{A}{A_c}\right]_{sep,\sigma=0} \quad (5.1)$$

The resulting values of $\Delta[A/A_c]_{sep,\sigma}$ were plotted against their respective values of σ (from step (i)) to provide the basis of the extrapolation shown in Figure 6.

5.1.4 Effect of changes in Reynolds number

As with other separation-onset conditions, the value of $[A/A_c]_{sep}$ is likely to be sensitive to changes in Reynolds number. The values of Reynolds number (based on cowl forebody length) for the various sets of test data are included in Table 8.1. However, the available data do not permit a Reynolds number effect to be quantified. Full-scale Reynolds numbers will, in most cases, be greater than those of the model tests, in which case the values of $[A/A_c]_{sep}$ (and hence of $C_{D_{spill}}$) are likely to be lower than those predicted using the method of this Item.

5.2 Use of Pre-Entry Force as Upper limit to Spillage Drag

In analysing the spillage drag data, considerable use was made of the pre-entry force, ϕ_{pre} , and especially its coefficient form $C_{\phi_{pre}}$, to provide limiting values of $C_{D_{spill}}$. Values of $C_{\phi_{pre}}$ for $M \leq 1$ are given by the following expressions (taken from Reference 35 with $\gamma = 1.4$),

$$C_{\phi_{pre}} = \frac{1}{0.7M^2} \left[\left[\frac{5 + M^2}{5 + M_1^2} \right]^{3.5} (1 + 1.4M_1^2) - 1 \right] - 2 \left[\frac{A}{A_1} \right] \quad (5.2)$$

$$\left[\frac{A}{A_1} \right] = \frac{M_1}{M} \left[\frac{5 + M^2}{5 + M_1^2} \right]^3. \quad (5.3)$$

The concept arises from the need to separate thrust and drag forces and from the conventional definition of thrust. Section 4 of Item No. 69006 (Reference 24) shows the definition of standard net thrust to include a “pre-entry thrust”, i.e. the force acting on the inner surface of the entry streamtube between stations far upstream and at the intake plane. This force acts in the direction of the true airspeed vector and is zero when $[A/A_c] = [A/A_1] = 1.0$. A consistent system of thrust and drag accounting must then consider the “pre-entry force”, ϕ_{pre} , which acts on the outer surface of the entry stream-tube in the opposite direction to the pre-entry thrust.

When the external flow is considered in isolation, for **inviscid flow** the pressure distribution on the cowl forebody gives rise to a suction force that exactly cancels ϕ_{pre} . However, for **viscous flow**, boundary layer growth reduces the cowl suction force from that appropriate to inviscid flow and this loss increases progressively as mass flow ratio decreases and pressure gradients around the cowl lip become more severe. Eventually the boundary layer separates and there is a rapid increase in $(\phi_{pre} - \text{cowl suction})$.

Consequently, from Equation (3.2), and noting that $\phi_{pre} = 0$ when $[A/A_c] = 1.0$, the pre-entry force must represent the maximum possible value of spillage drag at any chosen values of M and $[A/A_c]$, see Sections 5.3 and 5.3.1.

5.3 Contribution to Spillage Drag Coefficient Due to Flow Separation

From each set of measured data, values of $[\Delta C_D]_{spill,sep}$ were derived using the same values of $[A/A_c]_{sep}$ as the correlations described in Section 5.1. Charts such as those shown in Sketch 5.1 were constructed in which all available values of $[\Delta C_D]_{spill,sep}$ were plotted against $[A/A_c]_{sep}$ for fixed values of M and $[A/A_c]$. Separate charts were constructed for all combinations of the values, $0 \leq [A/A_c] \leq 0.9$ and $0.2 \leq M \leq 0.9$, in steps of 0.1 (see Reference 38). Mean lines were faired through the data and subsequently adjusted to obtain consistent carpet plots across the whole range of values of $[A/A_c]$ and M . This process was made easier by use of the following two “end points” (see Sketch 5.1):

- (i) at $[A/A_c]_{sep} = 1.0$ the maximum value of $[\Delta C_D]_{spill,sep}$ is defined by the value of the pre-entry force coefficient, $C_{\phi_{pre}}$, at the specified values of M and $[A/A_c]$, see Section 5.2.