



ESDU 00007

Issued July 2001
With Amendments A and B
October 2011

Drag of a rectangular planform cavity in a flat plate with a turbulent boundary layer for Mach numbers up to 3. Part II: Open and transitional flows



Endorsed by
The Royal Aeronautical Society

AVA Documents
Document Sharing Hub

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 The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants.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 Aerodynamics Committee. This Committee first met in 1942 and now has the following membership:

Chairman

Mr H.C. Garner — Independent

Members

Dr M.Z. Bouter*	— Raytheon Aircraft Co., Wichita, Kansas, USA
Mr P.D. Chappell	— Independent
Dr P.C. Dexter	— BAE SYSTEMS, Advanced Technology Centre, Sowerby
Mr J.R.J. Dovey	— Independent
Dr K.P. Garry	— Cranfield University
Mr D.H. Graham*	— Northrop Grumman Corp., El Segundo, CA, USA
Mr M.J. Green	— Independent
Dr H.P. Horton	— Queen Mary and Westfield College, University of London
Mr M. Jager*	— Boeing, Long Beach, CA, USA
Dr E.H. Kitchen	— Rolls-Royce Commercial Aero Engines Ltd, Derby
Miss M. Maina	— Aircraft Research Association Ltd
Mr M. Maurel	— EADS AIRBUS SA, Toulouse, France
Mr C.M. Newbold	— QinetiQ, Farnborough
Mr J.B. Newton	— BAE SYSTEMS, Military Aircraft and Aerostructures, Warton
Mr M.J. Pow	— BAE SYSTEMS, Airbus, Filton
Mr R. Sanderson	— Daimler-Benz Aerospace Airbus, GmbH, Bremen, Germany
Mr E. Totland*	— Saab AB, Linköping, Sweden
Mr J. Tweedie	— Short Brothers plc, Belfast
Mr A.J. Wells	— BAE SYSTEMS, Regional Aircraft, Woodford.

* Corresponding Member

The technical work involved in the assessment of the available information and the development and subsequent construction of the Data Item method was carried out under contract to ESDU by

Mr P.D. Chappell

The person with overall responsibility for the work in this subject area is Mr R.W. Gilbey, Head of Aircraft Aerodynamics Group.

DRAG OF A RECTANGULAR PLANFORM CAVITY IN A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER FOR MACH NUMBERS UP TO 3. PART II: OPEN AND TRANSITIONAL FLOWS

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	4
3. FLOW BOUNDARIES	7
3.1 Open Flow Boundary	7
4. DRAG PREDICTION METHOD FOR OPEN AND TRANSITIONAL FLOWS	9
4.1 Determination of d	9
4.2 Determination of c	10
4.2.1 Low speeds : $M_1 \leq 0.5$	10
4.2.2 High speeds : $M_1 > 0.5$	11
4.3 Flat Plate Local Skin Friction Coefficient	11
5. APPLICABILITY AND ACCURACY	12
5.1 Applicability	12
5.1.1 Overall ranges of applicability	13
5.1.2 Low speeds : $M_1 \leq 0.5$	14
5.1.3 High speeds : $M_1 > 0.5$	16
5.2 Accuracy	19
6. DERIVATION AND REFERENCES	25
6.1 Derivation	25
6.2 References	27
7. EXAMPLES	28
7.1 Example 1	28
7.2 Example 2	32
FIGURES 1 to 6	36-45
APPENDIX A DEVELOPMENT OF PREDICTION METHOD FOR d	46
A1. NOTATION	46
A2. METHOD	47

APPENDIX B INTERFACE BETWEEN THIS DATA ITEM AND ESDU 00006:	
Illustration by means of an extension to Example 2	49
B1. NOTATION	49
B2. INTRODUCTION	49
B3. EXTENSION TO EXAMPLE 2	49

ESDU Copyright material. For current status contact ESDU.

DRAG OF A RECTANGULAR PLANFORM CAVITY IN A FLAT PLATE WITH A TURBULENT BOUNDARY LAYER FOR MACH NUMBERS UP TO 3. PART II: OPEN AND TRANSITIONAL FLOWS

1. NOTATION AND UNITS

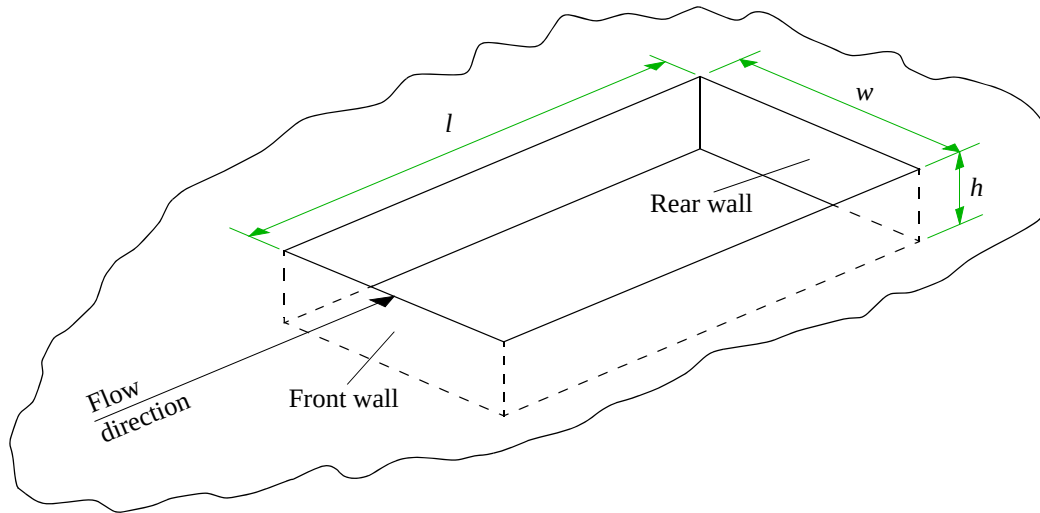
		SI	British
C_D	increment in drag coefficient due to presence of cavity, based on planform (floor) area wl and q_{1m}		
C_{Dref}	cavity drag coefficient based on wing reference area S_{ref} and q_∞ , Equations (5.3) to (5.5)		
C_f	local skin friction coefficient on flat plate, in absence of cavity, based on q_1		
C_{fm}	value of C_f at cavity mid-length, see Figure 5 (or Section 4.5 of ESDU 00006)		
c	term in Equation (4.1), see Figures 4a to 4d		
d	coefficient in Equation (4.1), see Figure 3		
h	cavity depth, see Sketch 1.1	m	ft
l	length of rectangular cavity, see Sketch 1.1	m	ft
M_1	Mach number at edge of boundary layer at cavity mid-length, in absence of cavity		
M_∞	free-stream Mach number		
m_d	drag magnification factor in Equation (5.3)		
q_1	local kinetic pressure at edge of boundary layer, in absence of cavity, $\frac{1}{2}\rho_1 U_1^2$	N/m ²	lbf/ft ²
q_{1m}	value of q_1 at cavity mid-length	N/m ²	lbf/ft ²
q_∞	free-stream kinetic pressure	N/m ²	lbf/ft ²
R_{fl}	friction Reynolds number based on l , $u_\tau l/\nu_w$, see Equation (4.2)		
R_l	Reynolds number based on l and R_{1m} , $R_{1m}l$		
$R_{x'm}$	Reynolds number based on x'_m and R_{1m} , $R_{1m}x'_m$		

Issued July 2001 – 51 pages
With Amendments A and B, October 2011 – 51 pages
This page Amendment B

R_1	local unit Reynolds number based on conditions at edge of boundary layer, in absence of cavity	m^{-1}	ft^{-1}
R_{1m}	value of R_1 at cavity mid-length	m^{-1}	ft^{-1}
$R_{1\infty}$	free-stream unit Reynolds number	m^{-1}	ft^{-1}
R_{δ_m}	Reynolds number based on δ_m and R_{1m} , $R_{1m}\delta_m$, see Figure 6 or Equation (5.2)		
S_{ref}	wing reference area	m^2	ft^2
U_1	local velocity at edge of boundary layer, in absence of cavity	m/s	ft/s
u_τ	friction velocity, $(\tau_w/\rho_w)^{1/2}$	m/s	ft/s
w	width of rectangular cavity, see Sketch 1.1	m	ft
x'_m	length of fully-turbulent flow from origin of turbulent boundary layer to cavity mid-length, in absence of cavity	m	ft
δ_m	boundary-layer thickness (at $0.99U_1$) at cavity mid-length, in absence of cavity, obtained via Figure 6 or Equation (5.2)	m	ft
ν_w	kinematic viscosity at wall	m^2/s	ft^2/s
ρ_1	local density at edge of boundary layer, in absence of cavity	kg/m^3	$slug/ft^3$
ρ_w	density at wall	kg/m^3	$slug/ft^3$
τ_w	shear stress at wall	N/m^2	lbf/ft^2

Subscripts

$expt$	denotes experimental value
$pred$	denotes predicted value
w	denotes wall conditions (taken here as conditions on flat plate at cavity mid-length, in absence of cavity)



Sketch 1.1 Cavity geometry

2. INTRODUCTION

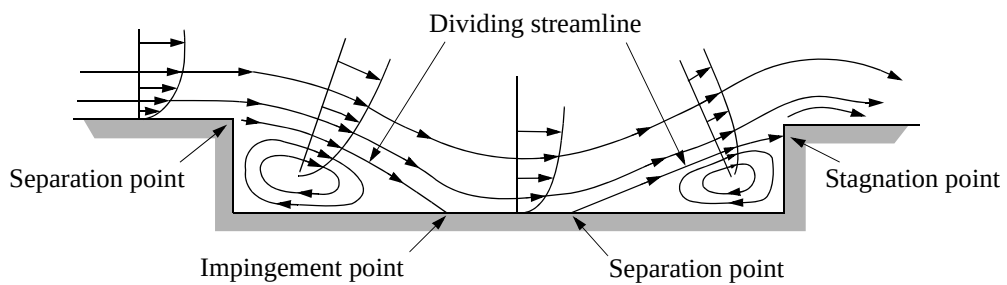
The flow patterns associated with a rectangular planform cavity are traditionally divided into three categories, termed *closed*, *transitional* and *open*, as described in Section 3.1 of ESDU 00006 (Derivation 24) and covered in more detail in ESDU 02008 (Reference 28). Sketches 2.1 and 2.2 illustrate the flow patterns typical of closed and open flow, respectively. Each sketch shows the patterns for (a) subsonic speeds and (b) supersonic speeds. In the transitional flow regime the shear flow enters the cavity over the front wall but does not attach to the cavity floor before passing over the rear wall. The drag of rectangular planform cavities arises primarily from the pressures that the flow generates on the front and rear walls, dominated by the latter. Secondary effects arise from the skin friction on the floor and side walls, together with the effects of the disturbed flow on the flat plate skin friction around the cavity, especially aft of it, for up to half the cavity length downstream.

This Data Item provides an empirical method for predicting the drag of rectangular planform cavities with open or transitional flow for Mach numbers up to 3, and is a companion to ESDU 00006 which deals with closed flows. The two Items therefore cover the complete range of flows for rectangular planform cavities. The method in the present Data Item applies only to cavities without doors. For the effect on cavity drag of a pair of doors open at 90° see ESDU 10016 (Reference 29).

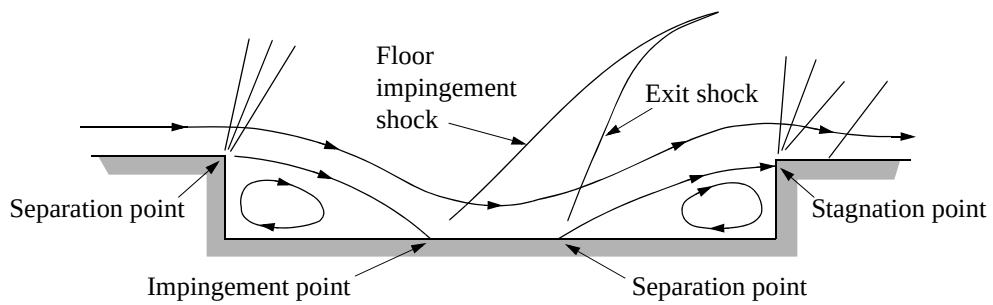
ESDU 00006 provides an approximate estimation of the range of conditions for closed flow in terms of cavity geometry and Mach number. The present Data Item provides a similar method for the identification of open flow, see Section 3. A knowledge of the closed and open flow boundaries therefore allows the extent of the transitional flow region to be deduced.

The drag prediction method for open or transitional flow, which is presented in Section 4, applies to cavities in a flat plate with a fully-turbulent boundary layer. Section 5 addresses the applicability and accuracy of the method, Section 6 lists the Derivation and References and Section 7 presents two worked examples, one relating to a low-speed light aircraft and the other to the supersonic combat aircraft considered in Example 2 of ESDU 00006. Appendix A gives background information on the development of that part of the drag prediction method relating to the effect of friction Reynolds number. Appendix B provides information on the treatment of the interface between the closed flow method of ESDU 00006 and the method of the present Data Item for transitional flow.

The drag prediction method in Section 4 was developed using wind-tunnel data for cavities in flat plates at zero angle of attack, *i.e.* in uniform flows. In order to apply the method to a practical situation in which a cavity is in a non-uniform flow, an artifice employed in the application of other excrescence drag data is used, see ESDU 90029 (Reference 26). In essence, that involves the use of local flow values for Mach number, unit Reynolds number and kinetic pressure at the edge of the boundary layer at the cavity mid-length, but in the absence of the cavity, and that is detailed in Section 5.1.

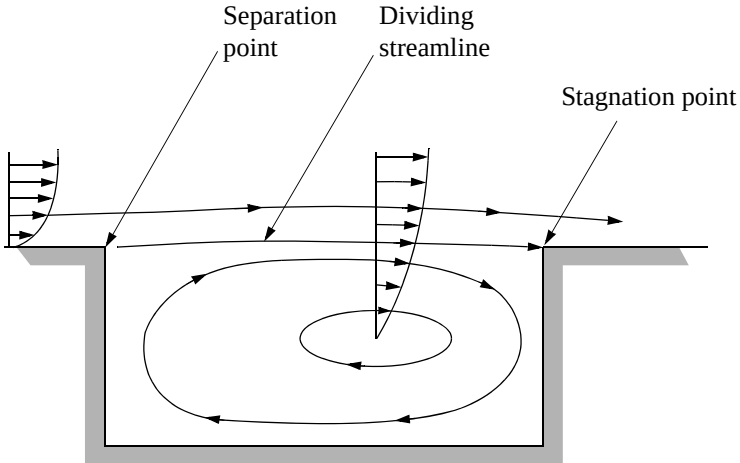


(a) Subsonic speeds

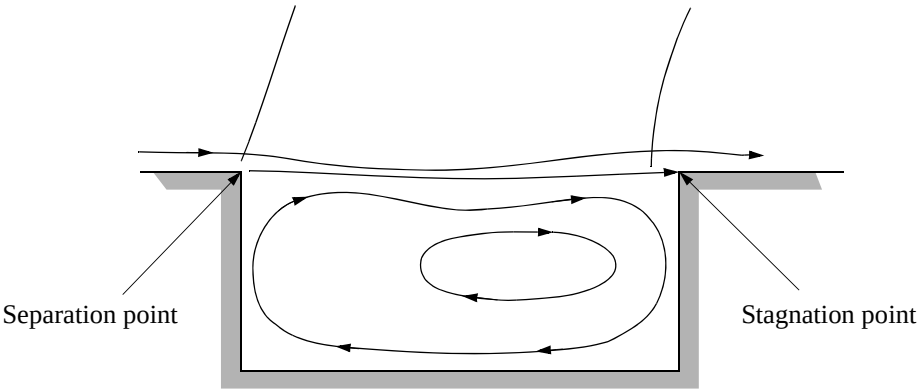


(b) Supersonic speeds

Sketch 2.1 Closed flow



(a) Subsonic speeds



(b) Supersonic speeds

Sketch 2.2 Open flow

3. FLOW BOUNDARIES

This Data Item applies to both open and transitional flows. Therefore, a knowledge of the closed flow boundary is all that is required to separate its range of applicability from that of ESDU 00006. Figure 1, taken from ESDU 00006, indicates that closed flow is likely for values of h/l below a boundary which depends on Mach number. For values of h/l above the boundary, transitional or open flow is likely and the present Data Item is applicable. Below the boundary the method of ESDU 00006 is appropriate.

The uncertainty of the exact flow pattern in the transitional flow region and its effect on drag makes it desirable also to know the likely location of the boundary separating transitional and open flow, see Section 3.1. All other considerations aside, there are far more test data for clearly open or clearly closed flow and so the corresponding drag predictions are more soundly based than that for transitional flow.

As conditions change between open and transitional flow the single method of this Data Item predicts a smooth and continuous variation of drag across the open flow boundary. The interface at the closed flow boundary between the predicted variation of drag in the transitional flow region and the prediction for closed flow from ESDU 00006 is less exact and may require the construction of a short fairing for continuity, as discussed in detail, by way of an example, in Appendix B.

3.1 Open Flow Boundary

In order to obtain an approximation to the lower limit in h/l for open flow, the data of Derivations 9, 11, 14 and 19 were analysed.

The data of Derivation 19 for $M_1 = 0.2$ to 0.95 and $w/h = 1, 4, 8$ and 16 are comprehensive enough to allow a reasonable estimate to be made of the open flow boundary for subsonic speeds (see Section 3 of ESDU 00006 for the means by which that was done in Derivation 19). Even so, as was the case in establishing the closed flow boundary, in order to provide a smooth variation with M_1 , for a given w/h , a local deviation between about $M_1 = 0.6$ and 0.8 for $w/h = 4$ had to be ignored. The result of the analysis is shown in Figure 2a in which the lower limit in h/l for open flow is plotted against w/l for a family of Mach number values from 0 to 1.

The available data for supersonic speeds in Derivations 9, 11 and 14 are restricted almost wholly to $w/h = 5$ and 5.3 for $M_1 = 1.5$ to 2.86 . However, the determination of open flow boundaries from those data is very problematical. The work reported in Derivation 11 concentrated on the task of establishing how the transitional-closed and transitional-open flow boundaries (see Section 3.1 of ESDU 00006) varied with Mach number for $w/h = 5$. In Derivation 14 cavities typifying both of these transitional flow types for $w/h = 5.3$ are identified, together with others typifying both closed and open flows. But no report has presented a properly established open flow boundary for supersonic flow. Therefore, for the purposes of this Data Item, the following process was used to arrive at an open flow boundary. If the drag data of Derivation 14 are replotted using C_D/C_{fm} , as for the prediction method of this Data Item in which C_D is based on floor area rather than rear wall area (see Section 4), it is seen that over the l/h range tested (about 4 to 17.5) a minimum occurs at $l/h \approx 8$, independent of Mach number over the range 1.6 to 2.86. There is also a maximum somewhere in the range $l/h \approx 14$ to 16, varying with Mach number. Since the values of l/h for the maximum accord well with the closed flow boundary data of Figure 1, it is assumed that the open flow boundary is close to the l/h values at which the minima occur. This assumption is supported by the fact that the cavities with $l/h = 8$ were identified as having open flow. Based on this cautious hypothesis the drag data of Derivation 9 for $w/h = 5$ and 2.5 and Derivation 14 for $w/h = 5.3$ were used to produce the lowest curve in Figure 2b, giving the open flow boundaries for supersonic speeds. The curve for $M_1 = 1$ was taken from Figure 2a and the curves for M_1 between $M_1 = 1$ and 1.5 were obtained from a smooth fairing linking the data for $M_1 \leq 1$ and $M_1 > 1.5$.

As with Figure 1, the curves for constant Mach number in Figure 2b are shown broken to indicate the uncertainty in their derivation. Furthermore, the curves for $M_1 > 1.3$ in Figure 2b have been restricted to a lower limit of $w/h = 1$ due to conflict with the closed flow boundaries of Figure 1. This is symptomatic of the tentative nature of both Figures 1 and 2b for supersonic speeds.

In Figures 1 and 2a and 2b the dashed lines of constant w/h are given for two reasons. Firstly, they are a reminder that the boundaries were originally constructed in terms of w/h . Secondly, and more importantly, the drag prediction method for low speeds ($M_1 \leq 0.5$) is based on the use of w/l , while that for higher speeds is based on w/h , see Section 4.

In the use of Figures 1 and 2a and 2b it should be recognised that the h/l values are not definitive. In ESDU 00006 it is suggested that, with regard to Figure 1, an accuracy of about ± 0.005 on h/l might be appropriate for low speeds, rising to ± 0.01 for high subsonic and supersonic speeds. The boundaries for open flow are even less accurate, with errors of, say, ± 0.01 on h/l for low speeds, rising to perhaps ± 0.02 for high subsonic and especially supersonic speeds.

4. DRAG PREDICTION METHOD FOR OPEN AND TRANSITIONAL FLOWS

The method developed here is for cavities without doors. For the effect on cavity drag of a pair of doors open at 90° see ESDU 10016. Analysis of experimental data (Derivations 7 and 8) for the drag of an *ad hoc* selection of small-scale rectangular planform cavities with open flow over a wide range of friction Reynolds numbers for Mach numbers up to 2.8 (see Appendix A) showed that, to a reasonable approximation,

$$C_D / C_{fm} = d \log_{10}(R_{fl}) - c, \quad (4.1)$$

which is of the same form as that derived for closed flow in ESDU 00006.

In Equation (4.1), C_D is the increment in drag coefficient due to the presence of the cavity, based on the planform (floor) area (wl) and is normalised with respect to C_{fm} , the local skin friction coefficient on the flat plate at the cavity mid-length, in the absence of the cavity. The first term on the right-hand side is the component due to the friction Reynolds number, R_{fl} , based on cavity length (l), given to a good approximation by

$$R_{fl} = (C_{fm}/2)^{1/2} R_l (1 + 0.178 M_1^2)^{-1.3}, \quad (4.2)$$

in which R_l is a Reynolds number based on cavity length and edge of boundary-layer conditions at the cavity mid-length, and M_1 is the Mach number at the edge of the boundary layer at the cavity mid-length, all in the absence of the cavity.

In this Data Item, the drag predicted from Equation (4.1) is the drag due to the **presence** of the cavity, *i.e.* the gross drag of the cavity installed in a flat plate minus the drag due to that area of plate (wl) occupied by the cavity. Accordingly, the definition of C_D includes a reduction by C_{fm} . Thus, when $C_D = 0$ the drag of the installed cavity is equal to that of the area of flat plate it replaced, see Section A3 in Appendix A of ESDU 00006 for a justification of the use of C_{fm} for the calculation of flat plate drag.

With the form of Equation (4.1), it is possible for negative values of C_D/C_{fm} to be calculated for values of R_{fl} below a certain value, dependent on the values of d and c . Such values are considered to be unrealistic and should be taken as zero.

The parameters d and c in Equation (4.1) are functions of cavity geometry and Mach number, see Section 4.1 for the determination of d and Section 4.2 for c . The value of C_{fm} to be used in Equations (4.1) and (4.2) is evaluated as given in Section 4.3.

4.1 Determination of d

In Appendix A it is noted that the analysis of the test data of Derivations 7 and 8 showed that the coefficient d in Equation (4.1) is a function of w/h and M_1 , as given in Figure 3. The particular values of w/h were chosen so that linear interpolation between them would be satisfactory. Figure 3 shows that d is essentially independent of w/h for $w/h \geq 4$, with the implication that, as far as d is concerned, the open flow within the cavity can be considered to be largely two-dimensional under those conditions. This is somewhat less restrictive than the range, $w/h \geq 7$, deduced for closed flow. Figure 3 also implies that, for a given value of w/h , d is essentially independent of M_1 for $M_1 \geq 2$.

It is assumed that Figure 3 can be applied, independently of h/l , to both open and transitional flows. Although there is no contradictory evidence, there is insufficient information, either experimental or theoretical, to confirm that assumption conclusively.

4.2 Determination of c

In contrast to the situation for closed flow (see ESDU 00006), there is a considerable quantity of test data for open and transitional flows, particularly for high speeds, from which values of c may be deduced via Equation (4.1) with d given by Figure 3. Even so, there was a problem hampering the analysis. For largely historical reasons, there are differences in the way a variation in h/l was obtained for most of the tests at low speeds, compared to those at high speeds. In recent years, the work concerning transonic and supersonic speeds (and often even low speeds) has tended to concentrate on geometries typical of carriage bays for weapons, for which planform aspect ratios (w/l) and depth-to-length ratios (h/l) less than 1 are most usual. For such applications it is logical to vary l at fixed values of w and h . In contrast, most of the earlier work related to low speeds, mainly for cavities with $w/l \geq 1$, and h was varied at fixed values of w and l .

This situation led to the need to analyse the low-speed data, taken to be for $M_1 \leq 0.5$, in terms of w/l and h/l , see Section 4.2.1, and the high-speed data, for $M_1 > 0.5$, in terms of w/h and h/l , see Section 4.2.2. In practice, this has not created any difficulties in the use of the methods, see Section 7.2 for example.

With regard to the choice of test data, the preference in terms of accuracy was for wind-tunnel tests in which drag was measured by means of a balance, especially if the rig allowed the drag to include a large part of the effects of the wake aft of the cavity. Where further data were required, limited use was made of drags derived from suitable static pressure tests and the few available two-dimensional Navier-Stokes calculations.

4.2.1 Low speeds : $M_1 \leq 0.5$

The considerable number of test data for low speeds in Derivations 1 to 3, 5, 7, 8, 16 to 18, 22 and 23 were analysed using Equations (4.1) and (4.2), with Figure 3 for d and C_{fm} via Section 4.3, to determine values of c . The resulting data were used to establish a set of smoothed curves for c versus h/l , for constant values of w/l from 0.4 to 30, presented in Figure 4a. For constant h/l , c decreases more slowly against w/l (for $w/l \geq 8$) as w/l approaches 30. Consequently, in practice, it can be assumed that the bottom curve applies to $w/l \geq 30$. In order to interpolate between the curves for w/l it is recommended that linear interpolation in $\log_{10}(w/l)$ is used. In order to give some idea of the location and extent of the transitional flow region, the approximate open and closed flow boundaries are shown as cross-hatched bands, the widths of which indicate the spread due to the variation of w/l . If required, more detailed information can be obtained from Figures 1 and 2a.

The rapid convergence of the curves for constant w/l as the open flow boundary is approached and traversed, coupled with the scatter of the data, made it difficult to define the trends for a given w/l . Consequently, the curves in that area, and certainly within the transitional region, are greatly simplified, with possibly a small sacrifice in accuracy.

As with the flow boundary charts in Figures 1 and 2a, curves of constant w/h are cross-plotted on Figure 4a. In that respect, a small number of data within the transitional flow region allowed the tentative extensions of the curves for $w/l = 1$ and 2 to values of h/l below the curve for $w/l = 0.4$. However, it is recommended that the use of the Figure be based on w/l wherever possible.

There were no test data to the right of the curve for $w/l = 1$. Consequently, the curves in that area are shown broken to indicate their tentative nature.

4.2.2 High speeds : $M_1 > 0.5$

There are fewer data in the region $0.5 < M_1 < 1.5$, making it very difficult to cover that range. Here, the essentially two-dimensional data of Derivation 18, supported by the few data of Derivations 7, 8 and 13, were used. There are rather more data for supersonic speeds in the range $1.5 \leq M_1 \leq 3$, although even there the coverage in terms of h/l is patchy for $w/h < 2.5$. Indeed, the only systematic data, concerning $w/h \approx 5$ and 2.5, come from Derivations 9, 11 and 14, and they provide the foundation for the method when $M_1 \geq 1.5$.

Analysis of systematic data from Derivations 4, 9, 10, 11, 13, 14 and 18, supported by additional data from Derivations 7, 8, 12, 15, 20 and 21, were used to produce sets of curves for $M_1 = 1$ in Figure 4b, $M_1 = 1.5$ in Figure 4c and $2 \leq M_1 \leq 3$ in Figure 4d.

In Figures 4b to 4d it is seen that wide ranges of w/h values, from 1 upwards, are covered. Within the accuracy of the data it can be assumed that c is independent of w/h for $w/h \geq 4$, reflecting the trend in d in Figure 3. The extent of the solid curves in terms of h/l indicates the range of the available data, which is generally wider for the larger values of w/h . Short-dashed extensions to the solid lines are included as an aid to interpolation within the regions of applicability which are delineated by the long chain-dashed angled lines joining the curves for $w/h = 1$ and 2.5.

With regard to interpolation within the w/h values given, it is preferable to use linear interpolation in $\log_{10}(w/h)$. Linear interpolation in M_1 will suffice.

As with Figure 4a, the approximate boundaries for open and closed flow are shown on Figures 4b to 4d, cross-hatched where necessary to indicate the spread with w/h or M_1 values. Such boundaries are particularly difficult to show with any clarity in Figure 4d. For a more detailed picture it is advisable to use Figures 1, 2a and 2b.

For completeness, small extensions into the closed flow region are given for some of the curves; the drag of a cavity in these regions is better determined by the dedicated method of ESDU 00006 (Derivation 24), see also Appendix B.

4.3 Flat Plate Local Skin Friction Coefficient

The value of C_{fm} used in Equations (4.1) and (4.2) is obtainable from Figure 2 of ESDU 68020 (Derivation 6) as a function of Reynolds number $R_{x'm}$ for the cavity mid-length, in the absence of the cavity, for various values of M_1 . An excellent fit to the data, using a modified form of the Prandtl-Schlichting equation for fully-turbulent flow, is given via Equations (4.25) to (4.28) in Section 4.5 of ESDU 00006, to which the user is referred for more information. The results of the fit are given in Figure 13 of that Item, reproduced here as Figure 5, which presents C_{fm} against $R_{x'm}$ over the range $10^5 \leq R_{x'm} \leq 10^9$ for $M_1 = 0$ to 3 in increments of 0.5. The hatching indicates the approximate lower limit of C_{fm} for a fully-turbulent boundary layer, given by Equation (4.29) of ESDU 00006.

5. APPLICABILITY AND ACCURACY

5.1 Applicability

The method of Section 4 for cavity drag prediction applies to rectangular planform cavities with either open or transitional flow for Mach numbers up to 3. The cavities, which have no doors, lie in a flat plate with a fully-turbulent boundary layer at the cavity location. For the effect on cavity drag of a pair of doors open at 90° see ESDU 10016.

As explained in Appendix A, the form of Equation (4.1) and the parameters involved in it were derived from data for which the cavity dimensions are small compared to the thickness of the approach-flow boundary layer. Although there is a lack of extensive balance-measured data that could be used to demonstrate any effects of boundary-layer thickness on cavity drag, there is one source of useful information. In Derivation 3 a particular cavity ($w/l = 7.656$) is tested at low speeds over a range of h/l values from about 0.09 to 1.5, at two widely differing streamwise locations in a flat plate, yielding a considerable difference in boundary-layer properties, such that the thickness (δ_m) varied by a factor of more than 5.5 and h/δ_m varied from about 0.05 to 3.5. For those tests, even though the two locations produced corresponding drag coefficients (C_D) differing by a factor varying from 1.5 to 2, the use of the ratio C_D/C_{fm} provided an excellent correlation, to within about ± 0.5 . From this, albeit small, amount of evidence, it can be deduced that the use of C_D/C_{fm} should allow for most of the effect of boundary-layer thickness on cavity drag, for h/δ_m values up to 3.5 at least. This, in itself, is well beyond the range ($h/\delta_m \lesssim 0.1$) over which the law of the wall*, implied in the use of friction Reynolds number, might be expected to apply. However, the values of h/δ_m for the test data used in developing the method of Section 4 extend even further, up to 40 for low speeds and about 12 for high speeds (see Tables 5.2 and 5.3). Unlike the situation for closed flow (see Section 5.1 of ESDU 00006), such high values of h/δ_m do not seem to invalidate the use of the method (but see Section 5.2). Even so, it is helpful to be able to estimate the boundary-layer thickness parameter, h/δ_m , where δ_m is the boundary-layer thickness at the cavity mid-length, in the absence of the cavity. This can be accomplished through the equation

$$h/\delta_m = (h/l)(l/\delta_m) = (h/l)R_l/R_{\delta m} \quad (5.1)$$

Figure 6, derived from Figure 9 of ESDU 68020, presents $R_{\delta m}$ against $R_{x'm}$. The curve in Figure 6, which is independent of M_1 , is given by

$$R_{\delta m} = \frac{0.0641 R_{x'm} [\log_{10}(R_{x'm})]^{-1.06}}{1 - 3.03 [\log_{10}(R_{x'm})]^{-1.06}} \quad (5.2)$$

For closed flow, the method of ESDU 00006 (Derivation 24) should be used. If calculations around the closed flow boundary are carried out using the methods of both ESDU 00006 and the present Data Item, it is unlikely that the two sets of results will match well. The main reasons are, firstly, the different approaches adopted for the two methods and, secondly, the increasing scatter in the experimental data as the closed flow boundary is approached, especially for supersonic speeds, see Section 5.2. This is, therefore, a difficult region with regard to drag prediction and, in practice, a fairing will be required between the results from

* The velocity in the region between the outer edge of the viscous sub-layer and the inner edge of the wake region, at about $0.1\delta_m$ for a turbulent boundary layer in incompressible flow, is represented by "the law of the wall", of the form

$$u/u_\tau = C_1 \log_{10}(u_\tau z/\nu_w) + C_2,$$

where u is the local velocity at height z from the flat plate and C_1 and C_2 are constants, see page 303 of *The Mechanics of Fluids*, by W.J. Duncan, A.S. Thom and A.D. Young, published by Edward Arnold, 1960.

the two methods. It is not possible to give a generalised fairing that could be applied in every case and so the best solution is to illustrate the problem by way of an example. To that end, Example 2 (in Section 7.2) has been extended, with the additional material being supplied in Appendix B.

The method of this Data Item is based on cavities in flat plates at zero angle of attack, and as such it is applicable to uniform flow. As noted in the Introduction (Section 2), in order to allow the method to be applied to a practical situation in which a cavity is immersed in a non-uniform flow, an artifice previously used in the application of other excrescence drag data (see ESDU 90029) was also employed here. To that end, the cavity drag coefficient and all the flow parameters used in the prediction were based on local flow values at the edge of the boundary layer at the cavity mid-length, but in the absence of the cavity. The flow parameters used were therefore M_1 , R_{1m} and q_{1m} .

The principles in ESDU 90029 give the cavity drag coefficient C_{Dref} , based on free-stream kinetic pressure q_∞ , and reference area S_{ref} , as

$$C_{Dref} = C_D \frac{wl}{S_{ref}} m_d, \quad (5.3)$$

where C_D is based on the local value of kinetic pressure q_{1m} , as defined above, and the cavity planform area wl , and m_d is a drag magnification factor accounting for the effects of non-uniform pressure distribution. Section 3.3.3(b) of ESDU 90029 suggests that for non-lifting bodies, such as fuselages or nacelles, it is reasonable to assume that m_d is approximated by the kinetic pressure ratio q_{1m}/q_∞ , since the flows over non-lifting bodies are characterised by weak pressure gradients. So, for non-lifting bodies Equation (5.3) becomes

$$C_{Dref} = C_D \frac{wl}{S_{ref}} \frac{q_{1m}}{q_\infty}. \quad (5.4)$$

Equation (5.4) will usually apply equally well to the lower surface of lifting surfaces at low lift coefficients. In practice, in all such cases the value of q_{1m}/q_∞ will often be less than unity and so a conservative prediction would assume $q_{1m}/q_\infty = 1$, giving

$$C_{Dref} = C_D \frac{wl}{S_{ref}}, \quad (5.5)$$

where now C_D is derived using free-stream properties and is based on q_∞ and wl . So, for a weapons bay cavity in a fuselage lower surface, Equation (5.5) will usually be appropriate. For other types of cavity, the general forms of Equations (5.3) or (5.4) might be more appropriate, depending on the cavity location. On the upper surface of wings, for example, values of m_d can be as high as 2 or 3, see ESDU 93032 (Reference 27), so that Equation (5.3) would be required.

5.1.1 Overall ranges of applicability

Overall, the experimental data (Derivations 1 to 5, 7 to 18 and 20 to 23) used in the development of the method of this Data Item cover wide ranges of geometric and flow parameters. However, because of the *ad hoc* nature of the wind-tunnel tests, there are inevitably many gaps in the data ranges and this makes it difficult to give definitive ranges for the applicability of the method. Provided that is borne in mind, Table 5.1, which largely summarises the overall ranges of the experimental data, can be used as a rough guide to the ranges over which the method might be expected to apply, to the accuracy discussed in Section 5.2.

TABLE 5.1 Ranges of applicability

M_1	w/l	w/h	h/l	h/δ_m	R_{fl}
0 to 3	≥ 0.12	≥ 0.7	≥ 0.1	0.03 to 40	$\geq 1000^*$

* It is particularly difficult to define a lower limit in R_{fl} as it is dependent on a number of factors, see Section 5.2.

Because of the problems inherent in defining the simplified parameter ranges in Table 5.1, it was decided to include the details of the parameter ranges for each of the sets of test data for low and high speeds and these are discussed in Sections 5.1.2 and 5.1.3, respectively.

5.1.2 Low speeds : $M_1 \leq 0.5$

Table 5.2 summarises the parameter ranges covered by the experimental data of Derivations 1 to 3, 5, 7, 8, 16 to 18, 22 and 23 for low speeds, $M_1 \leq 0.5$.

In Derivations 1 to 3, 7, 8 and 16 the cavity drag was measured by means of a floating-element balance. The method used in Derivations 5, 17, 18, 22 and 23 was based on an integration of static pressures over the front and rear cavity walls. As discussed in Section 5.1 of ESDU 00006, balance-measured drags are preferable, but where there is a lack of data coverage, integrated-pressure drags provide useful guidance at the very least; in fact, it is possible to obtain very good correlation between balance-measured and integrated-pressure drags in cases where a dense matrix of pressure taps has been used, see Derivation 16, for example. The data in Derivations 22 and 23 were derived from such dense matrices of pressure taps and were preferable to those from Derivations 5, 17 and 18 which were derived from fewer lateral locations; three locations for Derivation 18 but only centre-line values for Derivations 5 and 17. Of the latter, Derivation 17 is the less contentious, relating to large w/h values. Derivation 5, involving $w/h = 1$, is rather more suspect, but the data do cover a large range of w/l values and they tie in quite well with the balance-measured data of Derivation 1 and so were included unmodified.