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Excrescence drag levels on aircraft

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EXCRESCENCE DRAG LEVELS ON AIRCRAFT

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EXCRESCENCE DRAG LEVELS ON AIRCRAFT

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
a	speed of sound	m/s	ft/s
b	span	m	ft
C_F	mean skin friction coefficient	—	—
C_f	local skin friction coefficient	—	—
D	drag	N	lbf
$f_{H_p, M}$	factor to account for variation of excrescence drag with H_p and M , see Section 6 and Appendix B	—	—
H_p	pressure height	m	ft
h_{fin}	fin height, measured from root chord	m	ft
k	sand roughness height	m	ft
M	Mach number, V/a	—	—
m	aircraft mass	kg	slug
q	kinetic pressure, $\rho V^2/2$	N/m ²	lbf/ft ²
S	wing reference area	m ²	ft ²
S_{wet}	aircraft wetted area	m ²	ft ²
s	fraction of semi span (or fin height) occupied by movable aerodynamic surfaces (controls, flaps, slats, spoilers)	—	—
V	true airspeed	m/s	ft/s
W	aircraft weight	N	lbf
$\Delta[D/q]_e$	increment in (parasite) “drag area” due to excrescences	m ²	ft ²
ρ	density of air	kg/m ³	slug/ft ³

Subscripts

<i>datum</i>	denotes datum condition, <i>i.e.</i> $H_p = 36\,089$ ft (11 000 m) and $M = 0.8$
<i>e</i>	denotes excrescence
<i>fin</i>	denotes fin
<i>le</i>	denotes leading edge
<i>tail</i>	denotes tail
<i>te</i>	denotes trailing edge
<i>wing</i>	denotes wing

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2. INTRODUCTION

This Data Item gives excrescence drag data based on values for a large number of aircraft and so provides a guide to standards that have been achieved and a first approximation for estimation purposes. The term “excrescence” is defined in **Section 3**.

Most of the data are presented as values of the parameter $\Delta[D/q]_{e, datum}$ for the datum flight condition: $H_p = 36\,089\text{ ft (11\,000 m)}$ and $M = 0.8$. Adjustments to other values of H_p and M are made using the method of **Section 6** which provides values of the factor $f_{H_p, M}$ so that

$$\Delta\left[\frac{D}{q}\right]_e = \Delta\left[\frac{D}{q}\right]_{e, datum} \times f_{H_p, M} \quad (2.1)$$

Section 4 presents values of $\Delta[D/q]_{e, datum}$ for complete aircraft; **Section 5** provides an estimation method based on the breakdown of excrescence drag into various contributions. **Section 7** provides data on the extent to which excrescence drag “clean up” has proved possible on several aircraft.

The data used in compiling **Sections 4, 5 and 7** are manufacturers’ estimated values for the aircraft as manufactured (and, in **Section 7**, as subsequently modified); **Section 8** gives background information regarding these data. The use of estimated data is unavoidable because in most cases the drag due to an individual excrescence is not identifiable from flight-test measurements. However, **Reference 8** shows how the combined effect on aircraft performance of several small airframe changes may be identified by the application of statistical principles to a set of flight-test measurements. Effects of airframe deterioration in service or of non-standard build are not considered. The effects on performance of airframe variability are considered on a statistical basis in **Reference 7**.

This Data Item deals only with airframe drag, but small surface features can affect both lift and moment characteristics – particularly if they influence shock wave development or boundary layer separation. In addition to influencing handling characteristics, these features can also result in noise and vibration – with implications for crew fatigue and passenger comfort. Excrescences can also affect significantly the radar cross section of an aircraft – particular examples are the presence of access panels, auxiliary intakes and drain holes or masts on surfaces liable to be “illuminated” by radar.

3. DEFINITION OF “EXCRESCENCE” FOR THIS DATA ITEM

The term excrescence *could* be used to signify “all deviations from a smooth, sealed external surface” of an aircraft. For practical reasons this definition is modified to, “anything that appears on the aircraft but is not represented on the wind-tunnel model”. However, if uniformly distributed roughness (corresponding to painted, metallic or other surface finishes) is dealt with as indicated in **Section 8.1.3**, the definition of “excrescence” becomes, “*anything other than distributed (or “sand grain”) roughness that appears on the aircraft but is not represented on a wind-tunnel model or equivalent theoretical model*”. The data given in this Item are consistent with this definition. The categories of excrescences in **Section 5** provide amplification of this definition while **Appendix A** lists individual excrescences.

The following items are **EXCLUDED** from the estimation methods of this Data Item:

- | | |
|------------------------------------|--|
| Vortex generators, fences | – but see Section 5.4 , |
| Flap tracks, engine, stores pylons | – treat as separate items, |
| Thrust reversers | – if turning vanes are exposed, treat as separate items, |
| Refuelling probe | – treat as separate item. |

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4. OVERALL LEVELS OF EXCRESCENCE DRAG ON COMPLETE AIRCRAFT

Figure 1 gives an approximate guide to overall excrescence drag levels for a wide range of aircraft. The characteristics of the aircraft for which data were available are summarised in Table 8.1. Where possible, the data have been adjusted to accord with the definition of Section 3, for example by the deletion of components that are excluded there. No further attempt has been made to allow for differences between what constitute excrescences for the various manufacturers concerned. Greater certainty as to *what* excrescences are included can be obtained by using the method of Section 5.

5. CONTRIBUTIONS TO EXCRESCENCE DRAG ON AIRCRAFT

Figures 2 to 7 give values of contributions to $\Delta[D/q]_{e, datum}$ for the following categories of excrescence.

Category of excrescence			see Section	see Figure	see Appendix A Section
Basic airframe	1.	Airframe-build surface imperfections.	5.1	2	A.1
	2.	Imperfections associated with movable aerodynamic surfaces.	5.1	3	A.2
Fixed external components of aircraft systems	3.	Air data sensors.	5.2	4(a)	A.3
	4.	Lights and beacons.	5.2	4(b)	A.4
	5.	Antennae.	5.2	4(c)	A.5
	6.	Static discharge wicks.	5.2	4(d)	A.6
	7.	Rain dispersal: screen wipers/blowing/fluid; gutters over doors.	5.2	4(e)	A.7
	8.	Drains.	5.2	4(f)	A.8
	9.	Fuel system.	5.2	4(g)	A.9
Internal Airflow Systems	10.	Ventilation/cooling.	5.3	5	A.10
	11.	Air conditioning/pressurisation.	5.3	6	A.11
	12.	Auxiliary power unit.	5.3	7	A.12
	13.	Miscellaneous airframe features.	5.4	—	—

Appendix A gives a detailed listing of excrescences included in the categories identified in the above Table. The categories are close to those used for several aircraft for which data were available but are chosen to take maximum advantage of data for a wider range of aircraft where no common set of categories has been used. The inclusion in the list of several very small items is justified by the possibility that for some classes of aircraft one or more of such items may not be present.

Table 8.2 describes the aircraft for which detailed excrescence drag data were available.

5.1 Excrescence Drag Associated with Basic Airframe (Categories 1, 2)

Figures 2 and 3 give data, respectively, for airframe-build surface imperfections and for imperfections associated with movable aerodynamic surfaces. These are the most numerous sources of excrescence drag and are directly related to the standards of airframe design and construction. Drag improvements in these categories can be very significant but are likely to take much time, effort and expense to achieve. The quantity of data available was greatest in these Categories but the standards of construction represented are correspondingly wide.

In Figure 3 the independent variable is the parameter

$$b_{wing}[s_{le} + s_{te}]_{wing} + b_{tail} s_{te_{tail}} + h_{fin} s_{te_{fin}}.$$

The spanwise fractions, s , are evaluated for all slots, steps and gaps for each relevant surface, *e.g.* control, slat, flap, spoiler.

5.2 Excrescence Drag Due to Fixed External Components of Aircraft Systems (Categories 3 to 9)

These Categories cover the bulk of external features not associated with the basic airframe. Some are relatively large – at least as compared with typical boundary layer thicknesses.

Air Data Sensors, Figure 4(a): The data apply to typical installations of pitot, pitot-static, static pressure sensors, outside air temperature sensors and flow direction sensors.

Lights and Beacons, Figure 4(b): Anti-collision beacons predominate on current aircraft; navigation lights are generally flush and give little drag. Landing lights are not considered; they are usually flush mounted in a forward facing surface or mounted on the undercarriage.

Antennae, Figure 4(c): The following trends are illustrated:

- (i) improved antenna design can reduce drag dramatically,
- (ii) higher maximum speeds necessitate lower-drag installations,
- (iii) an empirical, but fairly consistent, increase in drag with range.

Static Discharge Wicks, Figure 4(d): The data apply to modern, rigid static discharge wicks; older, flexible types tend to be larger but no data are available. Static wicks are located on the relatively-sharp tip and trailing surfaces of the airframe, primarily to avoid intermittent and sudden electric discharges which can interfere with electronic and communications equipment. Advantages in terms of safety (*e.g.* at refuelling) and comfort (*e.g.* at unloading) are recognised but many aircraft have no static wicks. The mechanism of static electricity generation is friction and so airframe wetted area might seem a relevant parameter. The use of frontal area in the figure was suggested by a manufacturer and found advantageous.

Rain Dispersal, Figure 4(e): A wide range of drag values is quoted for screen wipers. The “low drag dispersal systems” in the Figure include both low drag and/or faired wipers and cases where dispersal is accomplished by air blast from nozzles (contributions due to screen washers are included in the quoted values). The installation of screen wipers or air blast systems is part of a larger (certification) issue of pilot clear vision which includes the effects of rain, snow, ice and other contaminants and debris, *e.g.* following a bird strike. Other factors include the provision of clear-view (openable) panels, screen washers, water repellent coatings and screen geometry, especially sweep angles. Most large transport-category aircraft are equipped with screen wipers;

air-blast systems can be used but equivalent performance is required. On some smaller transport types, certification may be possible without either wipers or air blast systems. Most combat aircraft have some form of screen clearance system; air-blast systems are often used.

Drains, Figure 4(f): This encompasses all forms of masts and holes for rain, fuel, oil and other fluids. The relevant components from the systems considered in Section 5.3 are included. The use of aircraft maximum weight as the independent variable in Figure 4(f) implies only that no other relevant parameter has been identified.

Fuel System, Figure 4(g): This category does not include drag due to fuel tank access panels – which often occur in large numbers on the wing lower surface (and occasionally on upper surfaces). It was convenient to include the drag due to such panels in Category 1 because this involved the least adjustment of the available data.

5.3 Excrescence Drag Associated with Internal Airflow Systems (Categories 10, 11, 12)

Ventilation/cooling, air conditioning and auxiliary power unit systems involve inlets and outlets/exhausts in the airframe surface – not all of which will be in use during all (or even any) flight phases. These categories have proved to be the most difficult to generalise. The values quoted apply to the en-route or cruise configuration and include, where appropriate, system internal momentum losses. Much depends on the location and forms of the inlets and outlets and on whether either (particularly inlets) can be sealed when not in use.

The following paragraphs treat Categories 10, 11, 12 separately. However, the distinction between ventilation/cooling and air conditioning is by no means the same on all aircraft. Whatever the precise sub-division of these functions may be in a particular aircraft, it is suggested that contributions from categories 10 and 11 should be included in any overall estimate.

Ventilation/Cooling, Figure 5: These terms imply the exposure of airframe, engine and systems components to atmosphere air conditions. This may be achieved passively using ventilation holes, grills *etc.*, or by the use of dedicated scoop or flush inlets (with or without power assistance) or as part of larger systems such as the (boundary layer) bleeds and (engine) bypass or spill airflows on many high performance aircraft.

Cooling Airflows for piston engines are *not* included – whether the engine is “air” or “liquid” cooled. This is a major drag component in its own right and should be treated as such. No data are included in Figure 5 for aircraft with turbo-prop engines.

Air Conditioning/Pressurisation, Figure 6: The term implies a system providing large quantities of air at conditions of temperature, pressure and humidity which may be far removed from ambient. In most modern systems this air is bled initially from one or more stages of the engine compressor and subsequently “conditioned” by passage through heat exchanger and water separator and injector stages.

The primary effect of compressor air bleed on performance is taken into account as a loss of engine thrust (or power). Subsequent thrust recovery from the exhausting of cabin air is considered here as a negative contribution to excrescence drag. Maximum achieved values of thrust recovery are quoted but these imply the provision of suitable exhaust vents and a well-sealed fuselage. The other major direct effect of the air conditioning system is the drag ascribed to leakage where the fuselage is not sealed. Figure 6 quotes only maximum values.

The remaining effects on excrescence drag arise from pressure relief valves and the inlets and outlets for the cooling air used in the system heat exchangers and similar comments apply to those mentioned under “Ventilation/cooling”.

Auxiliary Power Unit, Figure 7: The main functions are, typically, to provide

- compressed air for the air conditioning system when on the ground,
- compressed air for main engine start up,
- shaft power for ground or emergency in-flight electrical power generation.

In many cases all three functions apply but for the purpose of this Data Item it has been found useful to consider only the air bleed capabilities of the unit.

Excrescence drag arises primarily due to the inlet and exhaust systems. On some installations the inlet(s) can be blanked off or retracted so that only the exhaust contributes to drag. If the exhaust is located in a rearward facing surface – usually the fuselage tailcone – its presence will not change whatever base drag has already been allowed. If a unit is to be used in flight it may be necessary to remove (divert) the airframe boundary layer ahead of the inlet – with an attendant drag penalty. This is particularly important if a unit is certificated to provide in-flight electrical power and/or bleed air when one of the main engines is inoperative.

5.4 Miscellaneous Drag Producing Features

Many aircraft carry features that do not fit easily into Categories 1 to 12. Alternatively, while a feature might fit into one of the categories, its occurrence might be so infrequent as to make its inclusion in that category of no practical value. This final Category presents some of the limited available data while adhering as closely as possible to the definition in Section 3.

Vortex generators: The flight conditions at which aircraft can operate are frequently constrained by the effects of boundary layer separation. Vortex generators provide an effective means of alleviating these effects while entailing only minor changes to the airframe.

In flow conditions where vortex generators are required to be effective, there may be an overall reduction in the drag of the airframe component on which they are installed – due to the separation control they provide. In such cases they should not be regarded as excrescences but as part of the basic wing, *etc.* For flow conditions where the vortex generators are not required to control separation (and these could include normal cruise conditions), information given in References 21 and 22 may be used to predict the “direct” drag of vane vortex generators. Section 8.1.1 of Reference 21 describes the estimation procedure in detail but the data of Reference 22 alone can be used to estimate the drag contribution due to a single vane, of height h_v , as

$$\left[\frac{\Delta D}{q} \right]_e = \frac{\frac{1}{2} \rho_v U_v^2}{q} h_v^2 [k_D \cos \sigma \pm k_v \sin \sigma] . \quad (5.1)$$

k_D, k_v : vane drag and vortex strength (lift) parameters, relative to local flow direction; Figure 2 of Reference 22 gives values as function of planform and incidence.

U_v, ρ_v : velocity and density at edge of boundary layer at vane location.

σ : angle between freestream and flow at vane; Figure 4 of Reference 22 gives values.

Gun installation: For a single barrel gun (20 mm or 30 mm) installed within the fuselage

$$\Delta[D/q]_{e, datum} = 0.03 \text{ to } 0.04 \text{ ft}^2. \quad (5.2)$$

This includes the drag due to the “break out” in the fuselage surface and an allowance for inlet/outlet of purging air and holes for the ejection of spent cartridges.

Arrester hook: Depending on the hook size and installation, values lie in the range

$$\Delta[D/q]_{e, datum} = 0.025 \text{ to } 0.1 \text{ ft}^2. \quad (5.3)$$

Open holes with transverse vanes (or cascades): Some exhausts (including some older-style thrust-reverser outlets) take this form and the limited data available suggest that

$$\Delta[D/q]_{e, datum} = 0.075 + 0.25 \times 10^{-3} \left[\begin{array}{l} \text{design airflow through} \\ \text{hole, in lbf/s} \end{array} \right] \text{ft}^2. \quad (5.4)$$

6. EFFECT OF CHANGES IN H_p AND M ON EXCRESCENCE DRAG

Figure 8 gives an approximate method for adjusting the summation of the values of $\Delta[D/q]_{e, datum}$ obtained from Figures 1 to 7, (and applicable to $H_p = 36\,089$ ft (11 000 m) and $M = 0.8$) to other combinations of H_p and M . These data are deduced from the typical variation with Mach and Reynolds numbers of drag data for excrescences where the mean height is of the order 0.1 of the boundary layer thickness. While this approach is clearly incorrect for relatively large excrescences such as antennae or air data sensors, it is acceptable when applied to the overall level of excrescence drag on an aircraft because of the relatively small average height of excrescences. In Figure 8 values are given of the parameter $f_{H_p, M}$, where

$$f_{H_p, M} = \frac{\Delta[D/q]_e}{\Delta[D/q]_{e, datum}}, \quad (6.1)$$

and $\Delta[D/q]_{e, datum}$ is the datum value, estimated using Sections 4 or 5, for $H_p = 36\,089$ ft and $M = 0.8$. The Figure includes data for three forms of excrescence, as follows

- (a) aft facing steps,
- (b) forward facing steps,
- (c) grooves transverse to flow.

A value of $f_{H_p, M}$ can be assessed as some combination of the values given in Figures 8(a) to 8(c). It is recommended that,

for conservative results, use Figure 8(a) (aft facing steps),
for typical airframe, use average of values from Figures 8(a) and 8(b),
use Figure 8(c) only in circumstances where it is obviously relevant.

Appendix B gives a derivation of the relationships presented in Figure 8.

7. EXCRESCENCE DRAG CLEAN-UP

The level of excrescence drag on an airframe is, at least in principle, optional – although much detail-design effort is required if a low excrescence drag is to be achieved. Figure 9 shows examples of the extent to which airframe “clean-up” has reduced the level of excrescence drag between different versions of particular aircraft types. The examples include

changes between prototype and initial production standard,
changes between early production standard and improved standard,
changes between “basic” aircraft and a derivative thereof.

Information regarding time, cost and effort required to bring about these improvements is not available although the times range between one and ten years for the extreme cases.

8. NOTES ON DATA USED IN PREPARING THIS DATA ITEM

In preparing this Data Item a large number of diverse topics has been considered and many of these are addressed in Section 5 and Appendices A and B. This Section deals with two areas that remain. Section 8.1 summarises the methods used to treat several aerodynamic phenomena so as to distinguish them (by implication, at least) from “excrescence drag” as treated here. Section 8.2 summarises the methods likely to have been used in generating the aircraft excrescence drag data upon which Figures 1 to 9 are based. It also provides a guide to the types of aircraft for which data were available.

8.1 Distinctions Between Treatments of Skin Friction, Surface Roughness and Excrescences

8.1.1 Skin friction on smooth flat plate

In viscous flow over a smooth flat plate, skin friction arises from the shear stress at the fluid/surface interface and is represented as either a local skin friction coefficient, C_f , or a mean skin friction coefficient, C_F . The latter of these represents an integration of values of the former over the relevant streamwise distance. References 3 and 4 give data for laminar and turbulent boundary layers. Appendix B gives equations for C_f and C_F for a turbulent boundary layer.

8.1.2 Effect of surface roughness and waviness on transition

Boundary layer transition from laminar to turbulent flow is affected by the presence of surface roughness. References 1 and 2 give estimates of roughness height (uniformly distributed or discrete), and of surface waviness, below which laminar flow boundary layer development, transition position (and hence drag) are unaffected.

8.1.3 Skin friction on uniformly rough flat plate

Values of skin friction coefficient for a turbulent boundary layer on a uniformly rough flat plate can be estimated using Reference 5 which follows the widely-used practice of characterising a uniform surface roughness by an *equivalent sand roughness height*, k , – defined as the value of k required to produce the same mean skin friction coefficient as the actual roughness.

8.1.4 Non-uniformly distributed roughness

Non-uniformly distributed roughness may also be represented by an equivalent sand roughness height – *i.e.* as the value of k required, for uniform surface roughness, to produce the same mean skin friction as the actual, non-uniform, roughness. This concept has been used to characterise excrescence drag levels on some aircraft. **Excrescence drag is not represented in this way in this Data Item.**

8.1.5 Drag due to individual excrescences

For a laminar boundary layer, if an excrescence is so small as to have no effect on transition, it can have only negligible effect on drag. If an excrescence is of sufficient height to influence transition of a laminar boundary layer (see Reference 2), increased drag will result due to higher skin friction levels associated with a turbulent boundary layer (References 4 and 5).

References 9 to 16 give drag values for particular types of excrescence, mounted on a flat plate (zero streamwise pressure gradient) and immersed in a turbulent boundary layer. These drag values are converted to values appropriate to airframe components in the presence of finite pressure gradients by use of an excrescence drag magnification factor, see References 17 and 18.