1. INTRODUCTION

Base drag, that due to flow separation on a blunt afterbody base or lifting surface trailing edge can contribute a very large proportion, typically 30% to 40% of the total drag on a weapon. The topic is familiar, however the development of a reliable technique for estimating the magnitude of this component continues to pose difficult problems.

The problem discussed here is the base drag (pressure) on a blunt base body of revolution at mainly supersonic speeds, with or without a single axisymmetric cold jet exhausting from a motor nozzle whose exit plane is in the plane of the base. This lecture, deals with three topics (i) physical flow mechanism and configuration design aspects, (ii) empirical prediction methods and (iii) theoretical methods, including a review and preliminary assessment of a theoretical flow model, developed recently in Redstone Arsenal of USA.

The background to this presentation is the experience being gained at BAC Bristol, much of which stems from past work on analysis of experimental data and the continuing investigations into the development of improved prediction techniques.

2. FLOW FIELD BEHIND BLUNT BASES - THE BASE DRAG PROBLEM

2.1. Motor Off

Base drag arises through flow separation and the generation of a zone of re-circulating fluid behind the base. The effect of this flow separation is to bring about a reduction of the base pressure P_B below the external value P_1 just upstream of the base, and hence below the free stream value P_o. The drag coefficient is proportional to the pressure difference $P_B - P_o$ acting on the base area A_b; the flow mechanism for supersonic speeds is illustrated for a parrallel afterbody in the first diagram (Fig. 1a).

The diagram illustrates the complexity of the flow, the main characteristics of which are an expansion fan at the corner, laminar or turbulent mixing on the edge of the recirculating fluid, and a recompression shock separating the mixing zone from the wake. At subsonic speeds, the flow pattern is not so complicated as the expansion fan and shock system do not, of course, exist.

2.2. Motor On

When an axisymmetric jet is present, for the single nozzle motor geometry considered here, the flow field is more complex due to mixing on the jet and external stream boundaries. (Fig. 1b).

2.3. Base pressure versus motor exit pressure ratio

Figure 2 illustrates a typical plot for motor burning, when the exit to atmospheric pressure ratio P_I/P_o is progressively increased. Points to note are

1. an initial value of the base pressure point A for motor off.
2. the beneficial effect of low velocity air, or base bleed, with P_B reaching a maximum level at B
3. A minimum corresponding to maximum drag at the point C
4. Point D where the jet is "perfectly expanded" giving $P_I = P_o$
5. a progressive recovery of base pressure with P_I/P_o increasing above design pressure ratio i.e. nozzle under expanded.

The work reviewed herein has concentrated on attempts to predict the base pressure for motor off, point A, and the motor on pressure level from C upwards.

3. AFTERBODY DESIGN ASPECTS

The importance of base drag raises the question of what options are available for reducing its magnitude to a more acceptable level.

Possible options are:

1. the use of afterbody boat tailling, motor on or motor off, disadvantage, increased afterbody drag and a negative lift on the tapered afterbody,
2. low velocity base bleed, injection of air into the wake.
3. choice of favourable motor exit characteristics, such as maximising the ratio D_J/D_B or minimising the area on which the base pressure can act - disadvantage possible loss of motor thrust.

To illustrate an effect of the possible benefits of a suitable choice of afterbody shape Figure 3 illustrates the variation of total afterbody drag including base, and for the motor off. The diagram demonstrates how it is possible to use an optimum shape and achieve a considerable reduction in drag, these results were obtained with the aid of the BAC empirical methods discussed in these notes.

All these aspects make it necessary to formulate prediction methods that will evaluate base drag, and correctly estimate the effects of varying afterbody and motor exit geometry. The next sections comment on current problems and some work that has been done within BAC.

4. EMPIRICAL PREDICTION METHODS

This section outlines the work done at BAC Bristol in an attempt to derive reasonably accurate engineering techniques for the estimation of drag on a weapon project. Most of the experimental data were drawn from American sources, as published during the 1950-1960 decade.

4.1. Base drag at supersonic speeds, motor off

For parallel afterbodies it seems reasonable to assume that the base pressure is a function of Reynolds Number and the parameters M_1 and P_1 just upstream of the base. An examination of some experimental data from tests in which the Reynolds Number, based on body length varied from 10^6 to 10^8 (Fig. 4) suggested that, provided the boundary layer is turbulent at the instance separation commences, the effect of Reynolds Number is small.

Following correlation techniques by Chapman[1] and Fraenkel[2], it was found that the data fall close to a single curve of the form $P_B/P_2 = F(M_2)$ where the pressure P_2 is the external pressure evaluated at a point of a hypothetical extension of the cylindrical length of the body, of one base diameter. Fig.5 shows the correlation[3] that was achieved. The technique was extended to boat tail bodies by postulating a hypothetical shock at the end of the boat tail, and then evaluating P_2, for a hypothetical parallel extension, having a length equal to one base diameter. The parameter P_2/P_o was evaluated by an approximate method given in reference 2. Though it is difficult to justify this correlation technique on physical grounds, the collapse of the data were considered sufficiently encouraging to recommend an empirical method on this basis.

4.2. Effect of motor burn - cold jet

When a motor exhausts from a base, base drag becomes a function of many parameters, such as:-

$$P_B/P_o = f(P_{1_E}, M_{1_E}, P_{1_I}, M_{1_I}, \beta_E, \beta_I; A_J/A_B) \qquad \ldots(1)$$

where P and M denote pressure and Mach Number; the symbol 1 denotes initial conditions; i.e. jet exit, the symbols E and I denote external stream and internal jet stream.

$\beta_E ; \beta_I$ are boat tail and nozzle divergence angles.

A_J/A_B is the ratio of jet to base diameter ratio.

In the BAC correlation a jet expansion angle parameter ϕ is introduced such that

$$\phi = f(P_{1_I}/P_o; \quad M_{1_I}) \qquad \ldots. \ (2)$$

The function was evaluated using simple two dimensional relationships and it was further assumed that provided β_I is $< 5^\circ$ its effect could be neglected. This reduced the problem to the form

$$P_B/P_o = f(P_{1_E}, M_{1_E}, \beta_E; \phi ; A_J/A_B) \qquad \ldots. \ (3)$$

An early attempt to correlate experimental data, and a correlation of some theoretical results by BAC Warton (Fig. 6) tend to justify this type of approach, although the theoretical data suggest some dependence on Mach Number M_{1_I}. The theoretical results are of interest as the inviscid part of the flow model used resembles that which will be outlined in the next section. However a simpler empirical criterion was used to relate the pressures downstream of the wake shock to the pressures upstream and a solution to the base pressure problem determined on this basis. The next step was to explore the effect of the jet on base drag by formulating a function of the form

$$\frac{C_{D_{B(\text{JET ON})}}}{C_{D_{B(\text{JET OFF})}}} = f(M_{1_E} ; \phi ; A_J/A_B) \qquad \ldots. \ (4)$$

The function was arrived by assuming that boat tailling would not effect this ratio as defined, although the terms $C_{D_{B(\text{JET ON})}}$ and $C_{D_{B(\text{JET OFF})}}$ are of course functions of boat tail angle.