



Aerodynamics and aero-acoustics of rectangular planform cavities. Part IIIA: Alleviation of unsteady flow effects – Introduction

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AERODYNAMICS AND AERO-ACOUSTICS OF RECTANGULAR PLANFORM CAVITIES. Part IIIA: Alleviation of Unsteady Flow Effects – Introduction

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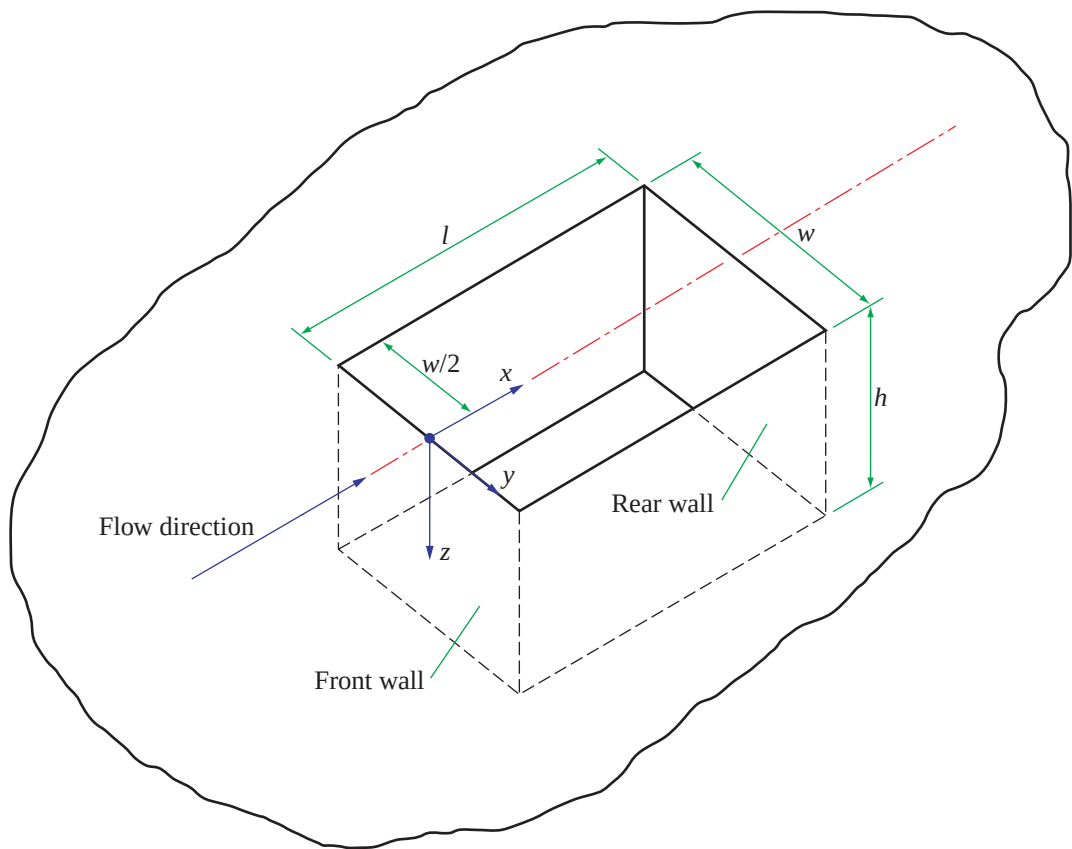
1. NOTATION AND UNITS

The dimensions are generally quoted in the units given in the original work, whether or not they conform to those given by ESDU in terms of SI or British units. Where they differ from these two sets, lengths are typically given in inches (1 in. = 25.4 mm or 0.0254 m) or millimetres. If required, a useful approximate conversion is 1 m $\approx$ 39.37 in. or 3.281 ft. Conversions for these and other units are given in ESDU CFA.

		SI	British
AEDC	Arnold Engineering Development Center		
AFFDL	Air Force Flight Dynamics Laboratory		
AFRL	Air Force Research Laboratory, successor to the Air Force Wright Laboratory and, earlier, AFWAL		
AFWAL	Air Force Wright Aeronautical Laboratories, formed in 1975 from the four Wright Field Research Laboratories for Materials, Aero Propulsion, Avionics and Flight Dynamics, plus the Air Force Aerospace Research Laboratories		
AMRAAM	Advanced Medium-Range Air-to-Air Missile		
ARA	Aircraft Research Association		
C_D	increment in drag coefficient due to presence of cavity (<i>i.e.</i> <i>net</i> drag), based on planform (floor) area (wl) and kinetic pressure at edge of boundary layer (q_1)		
$(C_D)_{baseline}$	gross drag coefficient due to cavity with no suppression device, based on area wl and kinetic pressure q_1 , see Section 6.2		
$(C_D)_{suppressed}$	gross drag coefficient due to cavity with suppression device		
CFD	Computational Fluid Dynamics		
C_f	flat plate local skin friction coefficient in absence of cavity, τ_w/q_1		
C_{fm}	value of C_f at cavity mid-length, calculated using $R_{x'}$		
DSP	Digital Signal Processing		
f	frequency	Hz	Hz
h	depth of rectangular planform cavity, see Sketch 1.1	m	ft
h_{ramp}	height of front or rear wall ramp, see Section 6.3.3	m	ft

h_{rw}	depth of irregular cavity rear wall, see Section 5.3	m	ft
$h_{0.5}$	mid-length depth of irregular cavity, see Sections 5.1 and 5.3	m	ft
k	kinetic energy of turbulent fluctuations (per unit mass) in turbulence model for CFD calculations (normally implemented in dimensionless form in CFD calculations)	m^2/s^2	ft^2/s^2
l	cavity length, see Sketch 1.1	m	ft
l_{ramp}	length of rear wall curved ramp, see Section 6.3.3	m	ft
M_1	Mach number at edge of boundary layer (<i>i.e.</i> free-stream Mach number as used in this Data Item)		
m	cavity length mode number, see Section 5 of ESDU 04023		
$OASPL$	Overall Sound Pressure Level	dB	dB
q_1	kinetic pressure at edge of boundary layer (<i>i.e.</i> free-stream kinetic pressure as used in this Data Item)	N/m^2	lbf/ft^2
R_1	unit Reynolds number based on conditions at edge of boundary layer	m^{-1}	ft^{-1}
$R_{x'}$	Reynolds number based on x' and conditions at edge of boundary layer, $R_1 x'$		
SPL	Sound Pressure Level	dB	dB
SRAM	Short Range Air Missile		
TRANS	Time-accurate Reynolds-Averaged Navier-Stokes (equations), now called URANS		
URANS	Unsteady Reynolds-Averaged Navier-Stokes (equations)		
WPAFB	Wright-Patterson Air Force Base		
w	width of rectangular planform cavity, see Sketch 1.1	m	ft
w_{rw}	width of irregular cavity rear wall, see Section 5.3	m	ft
$w_{0.5}$	mid-length width of irregular cavity, see Sections 5.1 and 5.3	m	ft
x, y, z	cavity coordinates from origin at mid-width of front wall top edge (lip); right-handed orthogonal set with x positive aft and z normal to surface, positive into cavity, as shown in Sketch 1.1	m	ft
x'	length of fully-turbulent flow from origin of turbulent boundary layer upstream of cavity	m	ft

θ_s	angle of slanted rear wall, see Section 6.3.3	deg	deg
τ_w	wall shear stress	N/m ²	lbf/ft ²
ω	specific dissipation rate of turbulent kinetic energy in turbulence model for CFD calculations (normally implemented in dimensionless form for CFD calculations)	s ⁻¹	s ⁻¹
2D, 3D	two-dimensional, three-dimensional (CFD simulations)		



Sketch 1.1 Cavity geometry and coordinate system

2. INTRODUCTION

This Data Item is the first in the series of four Items (Parts IIIA to IIID) comprising Part III of the wider five-part series (Parts I to V) dealing with the aerodynamics and aero-acoustics of rectangular planform cavities:

Part I: Time-averaged Flow – ESDU 02008 (Reference 31)

Part II: Unsteady Flow and Aero-acoustics – ESDU 04023 (Reference 32)

Part III: Alleviation of Unsteady Flow Effects,

IIIA Introduction – ESDU 08011 (This Data Item)

IIIB Acoustic suppression using passive devices – ESDU 08012 (Reference 33)

IIIC Acoustic suppression using active devices – ESDU 09001 (Reference 34 to be issued)

IIID Store deployment – ESDU 09002 (Reference 35, to be issued)

Part IV: Overview of CFD methods – Reference 37, (Data Item to be issued),

Part V: Bibliography and Tabular Survey – Reference 38, (Data Item to be issued).

The general subject area of Part III is the alleviation, or suppression, of unsteady flow effects and is introduced by the present Item (Part IIIA). Part IIIB (ESDU 08012) deals with acoustic suppression using passive devices. The use of active devices is considered in Part IIIC (ESDU 09001), while the improvement of store deployment conditions is dealt with in Part IIID (ESDU 09002).

Section 2.1, below, gives general background information behind the need for the alleviation of weapons bay noise and the improvement of store deployment conditions, two important problem areas concerning the internal carriage of weapons. It is noted that, ideally, the means to overcome those problems should not increase the drag of the aircraft; preferably, it should decrease it.

The general principles involved in the suppression of the effects of unsteady flow are discussed in Section 3. Sections 3.1 and 3.2 consider open or transitional flow and closed flow, respectively, with particular attention being paid to the possible alleviation strategies.

Section 4 deals with the classification of devices used to control cavity unsteady flow, whether related to noise or store deployment conditions. Of the two main categories, passive devices are usually not categorised further. On the other hand, active devices are commonly categorised as having either open-loop or closed-loop operation.

Many of the wind-tunnel tests or CFD simulations involving acoustic suppression devices concern simple rectangular box cavities, often with no doors fitted and usually with no stores installed. Therefore, Section 5 presents data giving some idea of the effects of cavity shaping (Section 5.1), doors (Section 5.2) and stores (Section 5.3) on the noise characteristics of cavities with no suppression devices. Such material can be used in a number of ways; for example, as a guide to the relative effectiveness of a given suppression device in different baseline (i.e. no suppression device fitted) situations.

Section 6 deals with drag considerations in the choice of an acoustic suppression device. The few instances which feature the effect of a suppression device on the drag, in addition to the acoustics, of a cavity are discussed in Section 6.1. In order to understand the effect on drag in the assessment of various passive devices, the concept of cavity baseline drag (gross drag) and its relationship with the drag (net drag) predicted using ESDU 00006 (Reference 29) and ESDU 00007 (Reference 30) is outlined in Section 6.2. Finally, the assessment of the installed drag of each of the passive devices dealt with in Sections 3 to 9 of ESDU 08012 is considered in Section 6.3.

2.1 Background

In the late 1940s and early 1950s there was an increasing awareness in the aircraft industry of the effects that the highly unsteady, and often oscillatory, airflow in and around cavities exposed to the free-stream, such as wheel wells and bomb bays, were having on the aerodynamics of such cavities and their contents, and even the aircraft itself. That is not to say that the problem had not previously been recognised; indeed, a significant effect on the bombing accuracy of World War II aircraft was caused in many cases by the tumbling of the bomb load immediately after release. As noted in Section 2.1 of ESDU 04023, early post-war work in this area was carried out in relation to the buffeting and periodicity of the airflow in and around the bomb bays of the English Electric Canberra and Boeing B47 (see References 1, 2 and 4, for example). In parallel with that work in the 1950s and 1960s many other wind-tunnel investigations and flight tests involving more general research into the unsteady flows and noise due to cavities were being carried out, and Section 2.1 of ESDU 04023 should be consulted for specific references to that work. Subsequent work, from the 1970s onwards, has increasingly concentrated on the noise aspect of cavity flows in relation to its potentially harmful effects on the cavity and its contents. Such work has been aided in no small measure by the rapid developments in flow measurement techniques, digital signal processing (DSP) and computational fluid dynamics (CFD).

Flight testing, backed up by a large number of research studies, has identified two crucial problem areas concerning the carriage of weapons in rectangular planform cavities.

- (a) Flow unsteadiness and the likelihood of self-sustained oscillations and associated acoustic phenomena for deep to moderately deep cavities with *open* or *transitional* flow^{*}. Cavities with open flow are particularly prone to the development of high intensity tones[†], which are capable of inflicting damage, see Section 3.1.
- (b) Weapon release difficulties from shallow cavities with *closed* flow^{*}. The difficulties arise mainly from the strong inflow (upwash) at the forward end of the cavity together with the equally strong outflow (downwash) at the rear.

Clearly, for internal weapons carriage in practice, some means of overcoming the problems outlined in (a) and (b) has to be found. At the same time, it would be advantageous if such means not only did not increase the cavity drag but actually decreased it. It is known that resonance in cavities with open flow is detrimental to drag (Reference 6). It is also known that for the practical length-to-depth range of weapons bays, the drag of those with closed flow tends to be much higher than those with open flow, for a given cavity depth, see for example Reference 4 and ESDU 00006 and 00007.

A very large range of noise and vibration suppression devices has been investigated in the last 50 years or so, mainly in wind-tunnel tests. They vary from add-on devices and simple geometry changes such as those applied to the Canberra bomb bay in 1951 (Reference 1) in an effort to improve the bomb separation characteristics, progressing with the development of systems of increasing sophistication and complexity through to current proposals for the use of DSP and CFD methods to control actively the severe tonal peaks as well as to lower the background noise level of cavities with open flow.

The primary aim of the present Data Item is to act as an introduction to the other three Items comprising Part III, described earlier. The overall objective of Part III is to provide a representative survey and assessment of the various devices used over the past 50 years in the quest for the satisfactory alleviation of unsteady flow effects. In the bibliography of Part V there are about 1000 references dealing with cavity

^{*} See ESDU 02008 for an explanation of the flow patterns corresponding to these terms and a treatment of the time-averaged characteristics.

[†] See ESDU 04023 for a treatment of the unsteady flow characteristics.

aerodynamics and aero-acoustics. Of those, about one third concern noise suppression or store deployment strategies. Moreover, interest in those areas is unabated, with reports currently being issued at a rate of between 10 and 20 annually.

Obviously, that is a large and ever increasing amount of information to try to assimilate – perhaps impossibly so in a reasonable timescale. That being so, the surveys in Parts IIIB to IIID are based on a scrutiny of about 60 per cent of the available material. The choice aimed to include much of the classic early work, together with reference to all of the important lines of research over the last 15 to 20 years. In that endeavour it is hoped that the work of all the principal individuals and groups of researchers in the field will have been taken into account. Finally, the various lines of research have been presented, wherever possible, in chronological order so that the user can assess the effect on the efficacy of the alleviation schemes emanating from the various developments, especially those made possible by the advances in testing techniques, digital analysis methods and computational capacity.

3. ALLEVIATION OF UNSTEADY FLOW EFFECTS

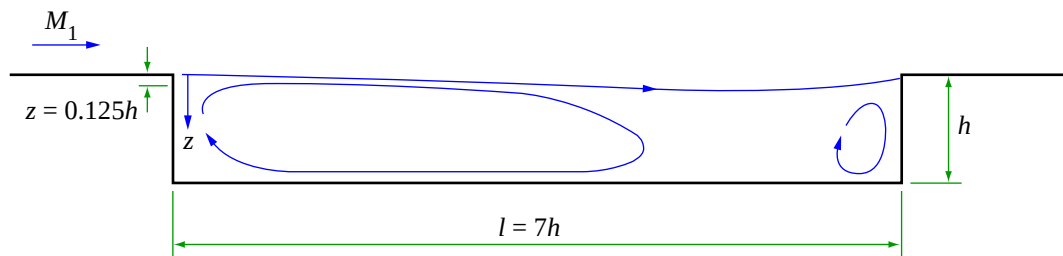
As outlined in Section 2.1, there are two main problem areas to be addressed with regard to the carriage of stores in rectangular planform cavities. In simple terms, the character of the problem is closely linked to the flow regime for the cavity in question, and ESDU 02008 should be consulted for more information on the various flow regimes.

3.1 Open or Transitional Flow

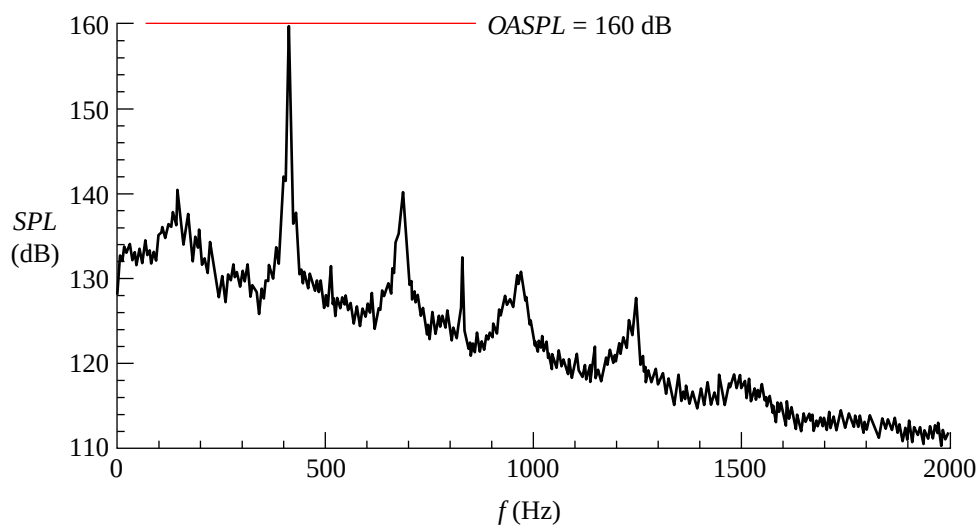
If the cavity has a depth (h) that is relatively large in comparison to the length (l), *i.e.* small to moderate l/h , then the flow regime is likely to be *open* or *transitional*. In ESDU 00007, Figures 1 and 2 provide guidance on the flow type likely to prevail for given cavity geometry and free-stream Mach number. The Figures define the boundaries across which the flow type is likely to change from open to transitional and from transitional to *closed*.

The open and transitional flow regimes are characterised by flow unsteadiness coupled with the likelihood of self-sustained oscillations, usually involving high intensity tones. ESDU 04023 should be consulted for more information on the unsteady flows and aero-acoustics associated with the various flow regimes of rectangular planform cavities. Sketch 3.1 presents a typical time-averaged flow pattern and acoustic spectrum, *i.e.* *Sound Pressure Level (SPL)* against frequency (f), for a cavity with transitional flow, taken from comprehensive tests by Tracy and Plentovich, reported in Reference 16*. The cavity dimensions are length (l) = 16.8 in., width (w) = 9.6 in. and depth (h) = 2.4 in., *i.e.* $l/h = 7$, $w/h = 4$ ($w/l = 0.571$), the flow Mach number is $M_1 = 0.8$ and the data were obtained from a transducer at $z = 0.125h$ on the cavity front wall centre line.

* The OASPL value in Sketch 3.1(b) is not given in Reference 16. It is an approximate value obtained from Equation (B3.5) in Appendix B of ESDU 04023.



(a) Time-averaged flow pattern (transitional flow)



(b) Acoustic spectrum at $z/h = 0.125$ on front wall centre line

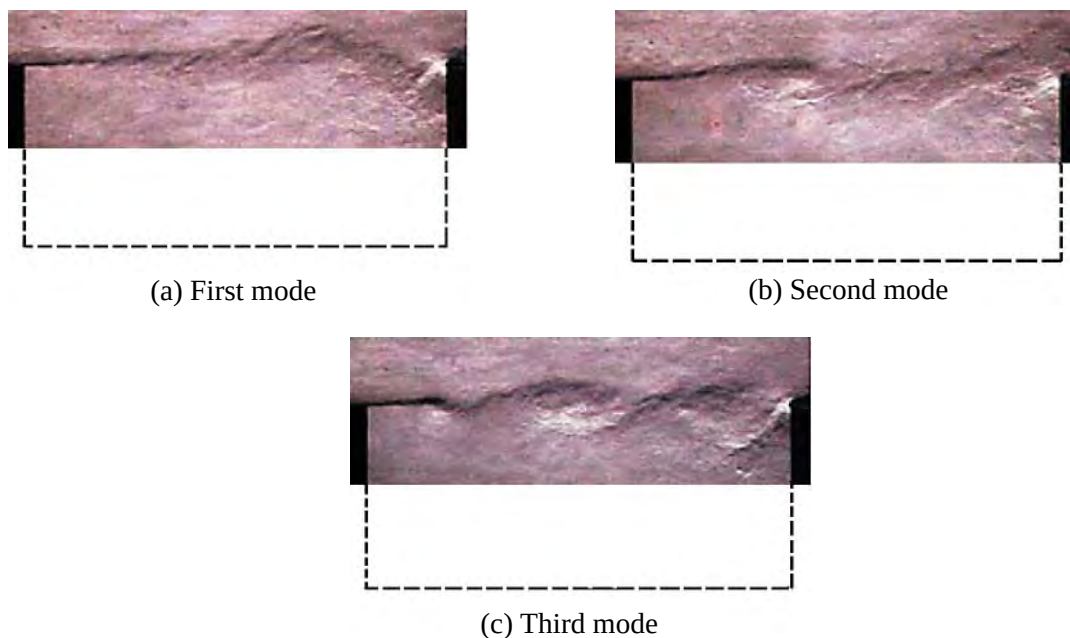
**Sketch 3.1 Flow pattern and acoustic spectrum for $l = 16.8$ in., $w = 9.6$ in. and $h = 2.4$ in.,
i.e. $l/h = 7$, $w/h = 4$ ($w/l = 0.571$), at $M_1 = 0.8$**
(Reproduced with additions from Reference 16)

The flow regime for the moderately deep cavity depicted in Sketch 3.1(a) is found from Figure 2a of ESDU 00007 to be just on the transitional side of the open/transitional boundary. If the cavity were to be used as a weapons bay and the spectrum for the full-scale cavity (with doors open) produced tonal peaks of similar amplitudes to those in Sketch 3.1(b), and within the range for structural resonance, then they could cause damage to the bay and its surrounding structure through acoustic fatigue. Equally importantly, damage could also be inflicted on the sensitive avionics systems (for control and navigation) of the weapons carried, due to the severe acoustic and vibrational environment in the bay. It is not possible to give precise levels for tonal peaks above which damage to sensitive electronic equipment would occur, but Steinberg (Reference 21) suggests structural damage is likely for an OASPL (see Appendix A of ESDU 04023) above about 150 dB. Of course, that figure would always imply lower tonal (SPL) values; in fact, a spectrum with multiple peaks of similar level, say, would involve much lower peak SPLs. Particular components, susceptible to microphony (electrolytic capacitors, for example), can fail at much lower OASPL values – Steinberg suggests as low as 125 dB. With regard to tonal levels, Shaw and Shimovetz (Reference 13) assert that a 155 dB tone is high enough to cause airframe damage in a short time, especially when it occurs at a frequency near that for a structural resonance. Some early work by Hess *et al.* (Reference 3) shows that, for a given OASPL, a rectangular test panel 11 in. by 13 in. by 0.032 in.

failed in under an hour when subjected to discrete frequency noise of under 145 dB (the fundamental frequency of the siren used being adjusted to that of the 1st natural mode of the panel). The use of a random noise, via an air jet, of the same *OASPL* resulted in an order of magnitude increase in fatigue life.

From the foregoing it is seen to be prudent to treat any *OASPL* greater than 150 dB, like that in Sketch 3.1(b), as a cause for concern. Stanek *et al.* (Reference 20) corroborate the use of that limit as “a reasonable goal for reliable weapons system performance”. Of course, depending upon the use of particular electronic components, *OASPL* values much lower than that might have to be taken into account.

Cavities with open flow are often thought to present no problems with regard to weapon deployment but, in practice, such problems are known to exist. The unsteady flow in the thick, oscillating shear layer, with its large-scale turbulent structures, see Sketch 3.2 (taken from work by Cattafesta *et al.* in Reference 18) and ESDU 04023, can often present problems in terms of the stability of a weapon as it traverses from the cavity to the free stream.



Sketch 3.2 Large-scale vortical structures in shear layer across open flow cavity $l = 6$ in., $w = 2$ in. and $h = 3$ in, i.e. $l/h = 2$, $w/h = 0.667$ ($w/l = 0.333$), at $M_1 = 0.4$
(Reproduced with modifications from Reference 18, with permission)

Sketch 3.2 presents Schlieren pictures of the vortical structures in the shear layer for a cavity with open flow resonating in the first, second and third Rossiter modes, see Section 5.1.1.1 of ESDU 04023. The structures are large compared to the cavity depth*. The number of vortical structures traversing the cavity is that of the mode number. In practice, the dominant mode largely dictates the number of such structures present at any instant.

The speed with which the shear layer is traversed during weapon deployment influences the weapon separation characteristics in situations like those depicted in Sketch 3.2. The length of the weapon in relation to the large-scale shear-layer structures, as well as its mass, mass distribution and dynamic response also affect the separation characteristics. So it is readily appreciated that the problem is a complex one, see ESDU 09002.

* The flow in the lower half of the cavity, shown dashed in outline, is not visualised in Sketch 3.2 due to the size of the viewing window, but the large scale of the vortical structures compared to the cavity depth is clear.