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L.V. Krishnamoorthy, D.R. Kirk and R. Glass

DSTO-TR-0554

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**Weapons Systems Division**
**Aeronautical and Maritime Research Laboratory**

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## ABSTRACT

The drag database of the Mk 82 General Purpose Low Drag bomb, the primary gravity weapon in the RAAF inventory, has some shortcomings in the quality and traceability of data, and in the variations due to configurational differences. Extensive testing of scaled models in a wind tunnel and an aeroballistic range facility have resulted in establishing estimates of the drag of a clean Mk 82 bomb as well as the incremental drag of add ons such as lugs and fuzes. These results, together with data obtained from full scale bomb drop trials, have been used to produce drag estimates for a full range of bomb configurations and release conditions. It is recommended that these data be incorporated into the mission computer of the weapon delivery system of the updated F111C aircraft. Furthermore it is recommended that the accuracy of these data be validated when the updated aircraft undergoes Ballistic Accuracy Verification flight trials.

## RELEASE LIMITATION

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# An Aerodynamic Database for the Mk 82 General Purpose Low Drag Bomb

## Executive Summary

The Mk 82 500-lb General Purpose (GP) is a high explosive bomb which can be configured in either a low drag, high drag, laser guided or shallow water mode depending upon the operational requirement. The store can be fitted with different fuzes such as M904 nose fuze, M905 tail fuze for initiation of detonation. Depending upon the type of aircraft, the Mk 82 bomb uses T type or D type suspension lugs.

The Mk 82 General Purpose Low Drag (GPLD) is the primary gravity drop weapon in RAAF's inventory. The trajectory and subsequent impact point of the bomb released by the aircraft weapon system depend on many factors: free stream aerodynamic characteristics, aircraft release parameters such as release speed, altitude, ejection velocity, aircraft flow field disturbance parameters, and atmospheric conditions. In the upgraded F111C aircraft the bombing solutions computed by the ballistic computer use a simple three degree of freedom point mass representation of the store. In this point mass representation, the store's aerodynamic characteristics are usually represented by fitted curves of the drag coefficient as a function of Mach number over the complete flight regime of the store. There are some shortcomings in the quality of data that RAAF has provided as part of their AUP commitments. For instance, the aerodynamic characteristics for the Mk 82 bomb have been derived by scaling Mk 83 bomb data, thereby introducing errors of scale. Further, the origin of the original database corresponding to the Mk 83 GPLD bomb is not known. This scaling approach is not necessarily valid for a RAAF weapon. Hence there is a need to establish a better quality database for Mk 82 GPLD bomb.

This report discusses in detail the aerodynamic database of Mk 82 GPLD stores as obtained from several sources: wind tunnel tests conducted by Air Operations Division (AOD) on scaled models (full scale, 1/6 scale) in both Melbourne and Salisbury facilities, aeroballistic range trials conducted by the Weapons Systems Division (WSD) using well tested photogrammetric techniques, and full scale bomb drop trials conduced by Aircraft Research and Development (ARDU) from F/A-18 aircraft in the Woomera instrumented Range facility.

It is hoped that this recommended database for Mk 82 GPLD stores will be used in the mission computer software of the post AUP F-111C aircraft, and that the new data will provide improved accuracy with the Mk 82 bomb releases. Further, this report will provide valuable data for exchanges with US and other TTCP countries.

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# Contents

# 1. Introduction

The F/RF-111C is a Royal Australian Air Force (RAAF) long-range, supersonic aircraft. The RF-111C is the reconnaissance version and F-111C is the attack version. The F-111C Avionics Update Program (AUP) involves replacing the existing analogue avionics system with a digital counterpart. This requires installation, development, and/or modification of the operational flight programs associated with the digital avionics processors. One system that will be replaced is the analogue ballistic computer unit which calculates the bombing solutions. The digital computer system will require a weapon aerodynamic database along with the aircraft release parameters and separation coefficients to compute the ballistic solutions. The improved weapon delivery system will provide increased accuracy of all the gravity weapons from the F-111 aircraft. The AUP will provide an improved aircraft with an extended service life.

Ballistic computers in the weapon delivery systems have an aerodynamic database for all the weapons in the aircraft's inventory. These databases consist of various aerodynamic force, moment and damping coefficients as functions of Mach number (M) and angle of attack ($\theta$). The aerodynamic coefficients required depend on the complexity of the trajectory model used in the mission computer (MC). This can vary from a simple three degrees of freedom point mass representation of the bomb to a more complex six degrees of freedom. The representation depends solely on the computational capability of the MC and the availability of reliable aerodynamic data. The F-111C AUP Mission Computer employs a three degree of freedom model which uses tabulated values of drag coefficient ( $C_D$ ) against Mach number (M) over the flight regime of the weapon.

Mk 82 General Purpose Low Drag (GPLD) bomb is the primary gravity (free fall) weapon in the RAAF's inventory. Even though the Mk 82 bomb has been widely used, it was discovered that very little data existed on its free-stream aerodynamics (ref 1). As a result there are shortcomings in the quality of data that RAAF has provided as Government Furnished Information (GFI) part of its AUP commitments. For instance, the aerodynamic characteristics for the Mk 82 bomb have been derived (ref 2) by scaling from a Mk 83 bomb of unknown configuration. Further the origin of the original database corresponding to Mk 83 General Purpose Low Drag (GPLD) bomb is not known. Hence there is a need to establish a better quality database for Mk 82 GPLD bomb.

There are many ways of obtaining estimates of the drag coefficient versus Mach number. The main ones are as follows:

(1) Theoretical estimation using fluid dynamic theory or empirical methods using data on similar bomb shapes.
(2) Wind tunnel testing using a scaled model.
(3) Aeroballistic range testing using either scaled or actual stores.
(4) Free flight full scale drops.

This report discusses in detail the aerodynamic database of Mk 82 GPLD stores as obtained from following sources:

(a) Wind tunnel tests conducted by Air Operations Division (AOD) on scaled models (full scale, 1/6 scale) in both Melbourne and Salisbury facilities.
(b) Aeroballistic range trials conducted by the Weapons Systems Division (WSD) using well tested photogrammetric techniques.
(c) Full scale bomb drop trials conduced by Aircraft Research and Development (ARDU) from F/A-18 aircraft in the instrumented Woomera Range facility.

The work reported here is in response to an Air Force Research Requirement (AFRR) 7/90, 'F-111C/RF-111C Modelling', Supplement 1. Amongst other things, AFRR sought assistance from the Defence Science and Technology Organisation (DSTO) to compile ballistic data of stores specified for use in the post-AUP F-111C aircraft system.

The following sections describe the work undertaken in response to the AFRR, and discuss the results obtained. Section 2 describes the Mk 82 GPLD configuration and its physical characteristics. Section 3 describes the wind tunnel tests carried out on scaled models by AOD. The aim of these tests was to produce the aerodynamic data of the bomb in free stream, and in the aircraft flow field in order to predict the weapon behaviour during separation. Section 4 discusses the drag characteristics as obtained from the analysis of the aeroballistic range trials conducted by WSD. Section 5 is devoted to the drag data as obtained from the full scale Mk 82 bomb drops from F/A-18 aircraft at the Woomera range during March 1994 and March 1995. Section 6 compares the drag data in order to arrive at a database for use in the post AUP F-111C aircraft system.

## 2. Mk82 GPLD Bomb Description

The 500 lb (225 Kg) General Purpose Low drag Bomb (Figure 1) has a slender body with a long tapered nose with a length to diameter ratio of about 9:1. A conical-type fin (MAU-93/B) is attached to the aft end of the bomb body. The fin assembly has a 1.5° cant to induce spin for stability. Figure 1 has been reproduced from Reference 3. Depending upon the aircraft type, the Mk 82 bomb can be configured with either a T-Lug (BRU rack in F-111C aircraft) or a D-Lug (F/A-18) for carriage attachment. The bomb can be used with proximity, mechanical or electrical fuzes. The type of fuzes used are the M904; an impact fuze designed to fit in the nose of the bomb, and the M905; an inertial type of fuze to fit in the tail section. The fin configuration of the tail fin assembly and the ATU-35A tail fuze drive assembly are found to depend on the type of aircraft. Figure 2 shows the differences between the F-111C (figure 2a) and F/A-18 aircraft configurations.

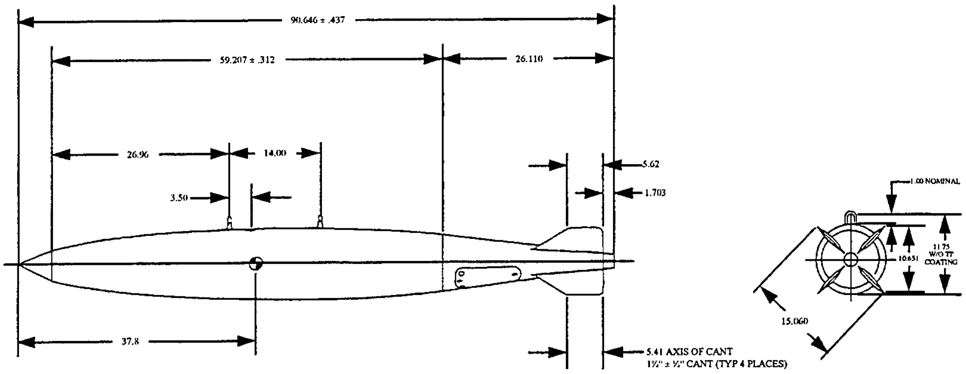


*Figure 1. Layout of Mk 82 General Purpose Low Drag (GPLD) 500 lb bomb (all dimensions in inches)*

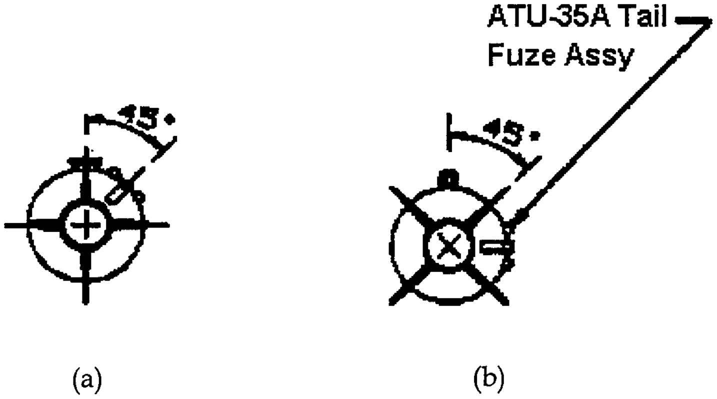


*Figure 2. End View showing the fin orientation of Mk 82 General Purpose Low Drag (GPLD) 500 lb bomb; (a) F-111C Configuration, (b) F/A-18 configuration.*

The physical characteristics of Mk 82 GPLD bomb are given in the reference 4 and are reproduced in Table 1.

The test programme on a Mk 82 GPLD store involved measuring aerodynamic forces and moments of its trajectory over many possible configurations. Table 2 indicates the various configurations tested.

*Table 1. Physical Characteristics of 500 lb (225 Kg) Mk82 GPLD Bomb*

| **Parameter** | **Imperial units** | **Metric units** |
|---|---|---|
| Length, assembled | 90.65 inches | 2.30 m |
| Body diameter | 10.65 inches | 0.27 m |
| Fin (conical type) | | |
| Span | 15.1 inches | 0.3835 m |
| Chord | 10.6 inches | 0.2692 m |
| Weight | 24 lb | 10.9 Kg |
| Total weight (nominal)[1] | 531 lb | 240.9 Kg |
| Explosive weight(nominal)[2] | 192 lb | 87.1 Kg |
| Case weight (nominal) | 311 lb | 141.1 Kg |
| Centre of Gravity (from nose) | 37.8 inches | 0.96 m |
| Moments of inertia | | |
| Pitch | 36.7 slug ft$^2$ | 49.8 Kg m$^2$ |
| Yaw | 36.7 slug ft$^2$ | 49.8 Kg m$^2$ |
| Roll | 1.5 slug ft$^2$ | 2.0 Kg m$^2$ |

*Table 2. Mk 82 GPLD Bomb test configurations*

| Config No | Fuzes | | Lugs | Fin angle ° | Tests Conducted at | | | | Description |
|---|---|---|---|---|---|---|---|---|---|
| | Nose | Tail | | | LSW[3] | HSW[4] | W[5] | A[6] | |
| 1 | - | - | - | 0 | y | y | | y | Clean |
| 2 | - | - | T | 0 | y | | | y | T-Lugs |
| 3 | - | ATU35 | - | 0 | y | | | | Tail Fuze |
| 4 | - | ATU35 | T | 0 | | y | | y | TF+TLugs |
| 5 | M904 | - | - | 0 | y | | | | NF |
| 6 | M904 | - | T | 0 | | y | | y | NF+Tlugs |
| 7 | M904 | ATU35 | T | 0 | y | y | | y | NF+TF+TLugs |
| 8 | - | - | - | 45 | y | | | | Clean |
| 9 | - | - | D | 45 | y | | y | y | D-Lugs |
| 10 | - | ATU35 | - | 45 | y | | | | Tail Fuze |
| 11 | - | ATU35 | D | 45 | | | | y | TF+DLugs |
| 12 | M904 | - | - | 45 | y | | | | NF |
| 13 | M904 | | D | 45 | | y | y | y | NF+Dlugs |
| 14 | M904 | ATU35 | D | 45 | y | | | | NF+TF+DLugs |

---

[1] Filled with H-6, Tritonal, or Minol II

[2] Filled with H-6 or Tritonal

[3] Low Speed Wind Tunnel Facility At DSTO Melbourne

[4] High Speed Wind Tunnel Facility At DSTO Salisbury

[5] Woomera Instrumented Range

[6] Aeroballistic Range facility at Port Wakefield

# 3. Wind Tunnel Testing

## 3.1 Low Speed Wind Tunnel Tests

Air Operations Division have undertaken a series of wind tunnel tests to determine the aerodynamic characteristics of Mk 82 GPLD stores in free-stream and in the aircraft flow field in order to predict the weapon separation behaviour. These tests were conducted at two different DSTO wind tunnel facilities. A full scale Mk 82 store has been tested in the closed return circuit low speed wind tunnel facility at Melbourne during October 1995.

The maximum air speed in the tunnel is about 100 m/s in the empty test section. Six component force and moment coefficients $C_x$ (axial force), $C_z$ (normal force), $C_y$ (side force), $C_l$ (rolling moment), $C_m$ (pitching moment), and $C_n$ (yawing moment), were measured over a pitch angles up to 26°, and roll angles between $\pm 180°$. Only a brief note on the tests (Table 2) and outcomes are presented in this report. Detailed information can be seen in reference 5.

Tests were conducted at a nominal speed of 50-60 m/s and the average test Reynolds Number based on the body diameter is $1 \times 10^6$. No corrections for tunnel interference or base pressure are applied to the measurements.

The tests indicate that all the measured coefficients remain relatively constant for small angles of incidence ($\theta$) and roll angles ($\varphi$). The measured drag coefficient at zero angle of incidence ($C_D = -C_x$ at $\theta = 0°$), which is the primary interest in this report, is independent of the fin orientation (F-111C or F/A-18 configuration). The $C_D$ of the fully armed store is found to be the sum of individual component increments from the clean store. The $C_D$ increases by about 90% between configurations 1 and 7 (F-111C) as compared to an increase of 70% in configurations 8 and 14. The other coefficients are found to have only minor variations.

The values of the drag coefficient for configurations 1, 7, 8 and 14 (Table 2) are shown in Table 3.

*Table 3. Drag Coefficient from Low Speed Wind Tunnel Tests.*

| Configuration | Mach Number | Drag coefficient |
|---|---|---|
| 1 | 0.176 | 0.1118 |
| 7 | 0.176 | 0.2134 |
| 8 | 0.176 | 0.1139 |
| 14 | 0.176 | 0.1917 |

## 3.2 Subsonic and Transonic tests at S1 wind tunnel

Wind tunnel tests on 1/6 scale Mk 82 GPLD stores were conducted in the continuous circuit S1 tunnel facility at DSTO Salisbury. The S1 tunnel is a variable pressure and variable Reynolds Number facility, which has an operating Mach number range of 0.35 to 2.8. The configurations tested in this facility are shown in Table 2 under the column heading HSW. Six component force and moment coefficients were measured over a pitch angle range of 0° to 30° in 2° increments and various roll angles. The test Mach number varies from 0.5 to 0.95. The strain gauge balance outputs from the tunnel data acquisition system were processed using standard S1 data reduction software. The axial force coefficients were corrected for skin friction contribution due to sub-scale Reynolds Number tests and base pressure changes to the presence of model mounts. No other correction for blockage effects and tunnel wall interference was applied to the data. Details of the test data and results can be found in references 6-11. Figure 3 shows the variation of drag coefficient with Mach number for zero incidence angle for all the tested configurations (1, 4, 6, 7 and 13). The data is also presented in Table 4.

*Table 4. Drag Coefficient from S1 wind tunnel tests.*

| Mach No. | Config 1 | Config 4 | Config 6 | Config 7 | Config 13 |
|---|---|---|---|---|---|
| 0.5 | 0.1744 | 0.2877 | 0.2722 | 0.2567 | 0.2754 |
| 0.6 | 0.1635 | 0.2876 | 0.2784 | 0.2599 | 0.2768 |
| 0.7 | 0.1508 | 0.2193 | 0.2840 | 0.2557 | 0.2744 |
| 0.8 | 0.1411 | 0.2853 | 0.2912 | 0.2599 | 0.2779 |
| 0.9 | 0.1434 | 0.2951 | 0.2888 | 0.2681 | 0.2793 |
| 0.95 | 0.1632 | 0.3117 | 0.2966 | 0.2890 | 0.2998 |

A series of tests was carried out on a 1/24 scale model (ref 12). The aim of the tests was to assess the quality of the data from scaled models used in store separation studies. During these tests, the axial force coefficient was not measured (only five component strain gauge balance was used in testing).

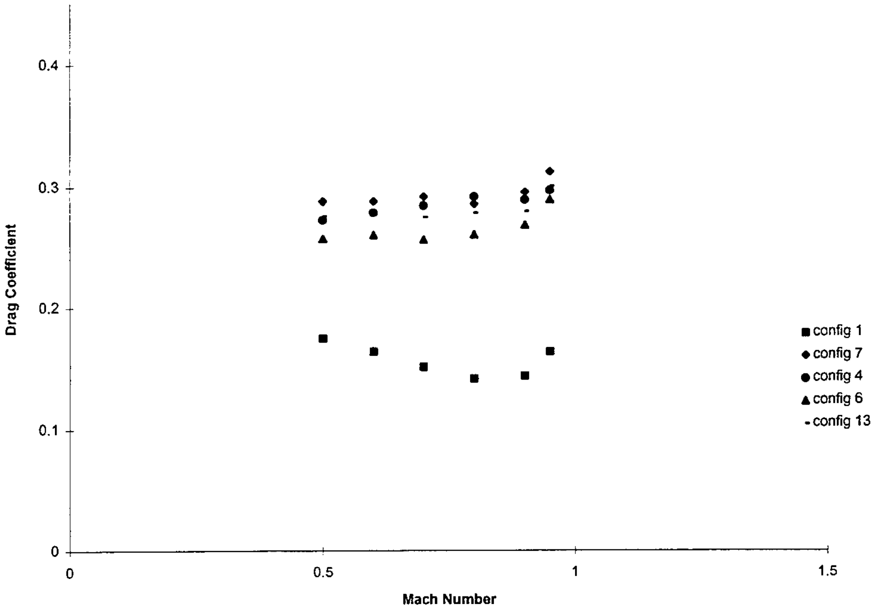


*Figure 3. The Drag Coefficient as a function of Mach number for various Mk 82 GPLD configurations as obtained from high speed wind tunnel tests.*

## 3.3 Transonic Tests in Melbourne Tunnel Facility

A 1/8 scale model of Mk82 GPLD bomb (config 1) has been tested in the transonic wind tunnel over the range of Mach numbers $0.95<M<1.2$, during December 1976. Six component force and moment coefficients were measured over a range of angle of incidences ($-2°<\theta<28°$) and roll angles ($-45°<\varphi<45°$). A complete set of this data can be found in Reference 13. Drag coefficient variation with Mach number corresponding to zero $\theta$ and zero $\varphi$ are given in Table 5.

*Table 5. Drag Coefficient from transonic wind tunnel tests.*

| Mach Number | Drag Coefficient |
|---|---|
| 0.95 | 0.1793 |
| 1.00 | 0.2178 |
| 1.05 | 0.3284 |
| 1.10 | 0.3487 |
| 1.15 | 0.3443 |
| 1.20 | 0.3574 |

## 3.4 Mk82CX Data Base - Collection of Wind Tunnel Test Data

Further there seems to exist a database for Mk82 GPLD stores with AMRL wind tunnel facility. The database is of historic nature and it is generated from the subsonic results of Salisbury tunnel tests and transonic results of Melbourne tunnel facility put together, smoothed, interpolated and extrapolated (ref 14). The data was extensively used for store separation studies. The data file has following information: $C_x$, $C_y$, $C_z$, $C_l$, $C_m$, $C_n$, $C_{l_p}$ (roll damping), $C_{m_q}$ (pitch damping), $C_{n_r}$ (yaw damping), $C_{n_p}$ (yawing moment coefficient due to roll rate) and $C_{y_p}$ (side force coefficient due to roll rate) as function of incidence angles ($0° < \theta < 30°$ at 2° increments), roll angles ($-45° < \varphi < 45°$ at 7.5° increments) and Mach numbers (M=0.4, 0.5, 0.6, 0.7, 0.8, 0.85, 0.9, 0.95, 1.0, 1.05, 1.1, 1.15, 1.2). The drag coefficient variations with Mach number for $\theta = 0°$ and $\varphi = 0°$ is presented in Table 6.

*Table 6. Drag coefficient from Mk 82 CX database.*

| *Mach Number* | Drag Coefficient |
|---|---|
| 0.40 | 0.1499 |
| 0.50 | 0.1508 |
| 0.60 | 0.1504 |
| 0.70 | 0.1509 |
| 0.80 | 0.1498 |
| 0.85 | 0.1506 |
| 0.90 | 0.1529 |
| 0.95 | 0.1607 |
| 1.00 | 0.1918 |
| 1.05 | 0.3173 |
| 1.10 | 0.3550 |
| 1.15 | 0.3514 |
| 1.20 | 0.3638 |

# 4. Testing at the Aeroballistic Range Facility

Free flight testing is generally necessary to confirm the accuracy of the aerodynamic coefficients measured from wind tunnel testing as they suffer from scale effects and flow modifications due to model mounting inside the test facility. Full scale flight tests are limited by the high costs. The aeroballistic range facility offers a compromise for the study of flying objects under free flight conditions. In aeroballistic ranges, we measure the position and angles of the projectile at consecutive intervals of time. By construction of the trajectory and solving the equations of motion with the well developed parameter estimation technique, aerodynamic coefficients can be evaluated.

The relative simplicity in the manufacturing the test vehicle, the use of relatively small ranges (indoor or outdoor) and the use of a simple (3 Degrees Of Freedom, 3dof) to the more complex models (6dof) for the solutions of the trajectory, has made this test method extremely useful. The following sections describe the Aeroballistic Range trials which were conducted by WSD during 1993-1995 on Mk 82 GPLD bomb.

## 4.1 Gas Gun facility

DSTO Salisbury has a number of smooth bore gas-operated guns, situated on two aeroballistic ranges, one located adjacent to the RAAF Base at Edinburgh and the other at the Army P&EE Establishment at Port Wakefield. The Edinburgh range uses a 384 mm bore gas gun for launching models at low subsonic velocities, while Port Wakefield range uses a 256 mm gun for launching at transonic and supersonic velocities. These were both used to launch a wide variety of models. Considerable variation in projectile model size can be accommodated by enclosing the model in cylindrical sabots confirming to the gun bore. The main features of these guns are summarised in Table 7.

*Table 7. Physical Characteristics of DSTO Gas Gun Facility.*

| | Subsonic | Transonic |
|---|---|---|
| Gun Calibre (mm) | 384 | 265 |
| Effective Barrel Length (m) | 5.8 | 6.5 |
| Maximum Operating Pressure (MPa) | 1.8 | 28.0 |
| Maximum Launch Velocity (m/s) | 270 | 550 |
| Maximum Acceleration (g) | 500 | 3000 |
| Gas used | air | nitrogen |
| Quadrant Elevation (°) | 0-90 | 0-30 |
| Type of loading | Breech | Front of Breech |
| Type of Valve | Sleeve | Piston ejected at each firing |

## 4.2 Range Layout

The layouts of the two aeroballistic ranges are similar and differ only in the locations of the cameras and reference lights. The Edinburgh Range was used only for early evaluation trials while the Mk 82 scaled models were launched at the Port Wakefield range. The Port Wakefield range has six cameras, giving a coverage of about 2 km downrange. The cameras are situated three on each side of the range centreline and arranged so that each point on the flight path can be seen by at least two cameras, usually more. Seven reference lights are also situated around the range to register their images on the cameras, so that each camera will see at least two reference lights, sometimes three. For reasonable coverage the cameras are at least 500 metres from the range centreline. The locations of cameras and reference lights are shown in Figure 4.

The cameras are purpose built kinetheodolites with large lenses and a slot to carry a light proof film case with an exposure slide to hold a negative approximately 215 x 190 mm. The reference lights consist of three powerful strobe lights, mounted on a cross bar about 3 metres long on a pole about 2 m high. The exact positions of the cameras and reference lights were all determined in three dimensions by a surveyor to within 10 mm. The firings were done at night and the camera shutters and slides were left open for the duration of the flight. The method of operation of these cameras is covered in reference 15.

## 4.3 Half Scale Mk 82 bomb instrumentation

The half scale models launched from the Port Wakefield gas gun are subjected to very high 'g' forces, (up to 3000) and needed to carry electronic circuitry to operate two flashing lights, or strobes, one at the nose and one at the tail of the test vehicle. These lights require electronic circuits to cause them to flash at approximately 30 Hz. The battery packs were installed just prior to launch to ensure that they would have adequate life. An inertia switch started the lights at launch, provided the electronic package survived the 'g' forces, there were some failures because of this. Various attachments could be applied to the models to simulate the different fuze and lug arrangements used by the RAAF. The configurations used in the trials are given in Table 2. The vehicles were recovered from the range the next day, if possible, for refurbishment and re-use of undamaged components. The gun elevation during launch was adjusted to land the models in a reasonably small recovery area. The launch elevation varied from 5° to a maximum of 20°.

## 4.4 Processing of Film Images

After an evening trial at Port Wakefield the film cases were delivered back to Salisbury and handed over to ARDU (Aircraft Research and Development Unit) for development. Later trials films were processed by 92 Wing Photographic at Edinburgh. After return of the negatives, they were examined on a Zeiss comparator machine, capable of 1 μm resolution, to determine the positions of the images of the flashing lights on the vehicle, the reference lights and the camera fiducial markers. The images were magnified with a miniature TV camera and displayed on a monitor. These data were stored on 3.5 inch diskettes and on a hard disk in a personal computer where purpose written software was used to convert the position of these images to time, azimuth and elevation tables for each camera. These tables were combined algebraically to produce a set of three dimensional coordinates representing the positions of the test vehicle at various times, relative to the range centreline. The time information is obtained from the flash rate of the strobe units, which are measured prior to the trials. These were checked on the recovered models for possible drift due to high launch impulses. In all cases the drift was found to be negligible. The trajectory data was used to compute drag coefficients at various times during the flight.

## 4.5 Data Analysis

A parameter estimation technique (refs 16-20) was used to compute the aerodynamic characteristics of Mk 82 configurations from their measured trajectory data. This technique attempts to find all the values of the parameters characterising the mathematical model such that the sum of the squares of the differences between model output (predicted response) and the input (observation vector) is minimum. The number of parameters to be determined depends on the complexity of the model which describes the equations of motion. This can be from a simple three degrees of freedom (3dof) to a complex six degrees (6dof). We have used a simple 3dof model in this analysis and its implementation to determine drag characteristics are discussed in reference 21.

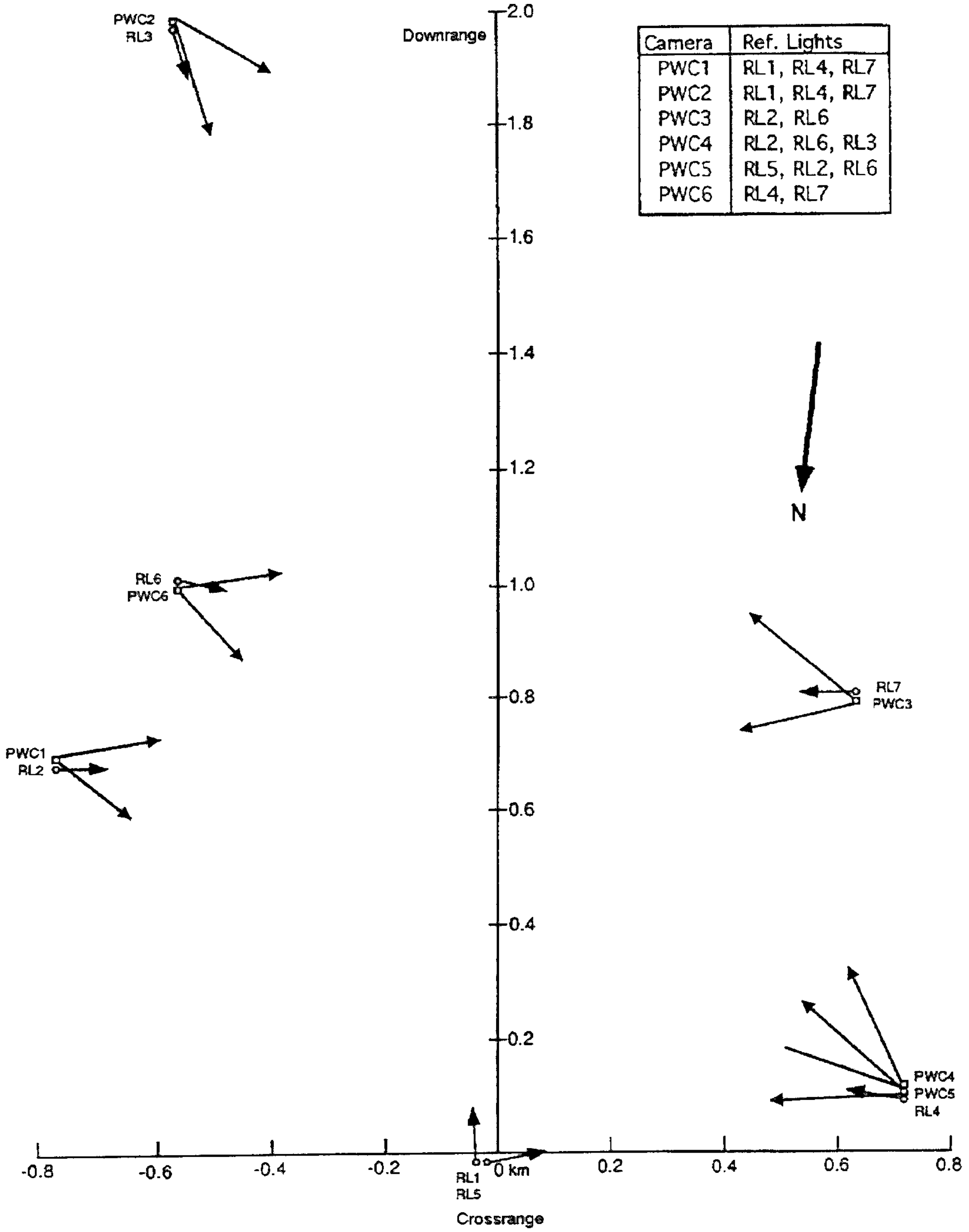
The six parameters used in the model are: the initial positions in x and z (x, down range; z, vertically down and y, horizontal to right in a right handed range co-ordinate system), their initial velocities ( $\dot{x}$ and $\dot{z}$ ) and two forces $C_x$ and $g$. The drag coefficient $C_D$ is negative of the axial force coefficient $C_x$ as the model assumes zero incidence angle (point mass). The converged values of $C_D$ will then correspond to the vector sum of velocity obtained from the converged $\dot{x}$ and $\dot{z}$. Thus the model derives a single value of $C_D$ for each trial.

The data analysis was carried out over flight ranges where the changes in the flight velocities were minimal, ensuring that the changes in $C_D$ over this section of the flight are small.

## 4.6 Drag Characteristics

The main objective of this trial was to establish the drag characteristics of Mk 82 GPLD stores in its operational configuration. Since the work was sponsored by F-111C AUP, much attention was given to the bomb configurations corresponding to F-111C aircraft. Further we were interested in characterising the incremental increase in drag coefficient due to add ons to the basic clean Mk 82 configuration (config 1). It is hoped that these efforts will allow determination of drag characteristics of new add ons (fuze/lug) with a limited number of trials.

The variation of drag coefficient against Mach number (M) of Mk 82 GPLD store configurations corresponding to F-111C and F/A-18 aircraft is shown in figures 5 and 6 respectively. The $C_D$ values are not corrected to account for the Reynolds number differences between full and half scale models. The reason for presenting uncorrected data was that the correction procedure as discussed in reference 22 is dependent on the boundary layer transition (laminar to turbulent) location. Further the correction is of empirical nature.



| Camera | Ref. Lights |
|---|---|
| PWC1 | RL1, RL4, RL7 |
| PWC2 | RL1, RL4, RL7 |
| PWC3 | RL2, RL6 |
| PWC4 | RL2, RL6, RL3 |
| PWC5 | RL5, RL2, RL6 |
| PWC6 | RL4, RL7 |

*Figure 4. Port Wakefield gas gun range camera and reference light locations.*

The variation $C_D$ of different F-111C Configuration over the Mach number range 0.5<M<0.95 can be summarise as follows:

$$\text{Config } 7 \cong \text{Config } 6 < \text{Config } 4 < \text{Config } 2$$

The $C_D$ of a fully configured store (Config 7) is about 100% more than the clean configuration. Similar conclusions can be deduced for F/A-18 configurations but the increase seem to be little less. This could be attributed to the streamlined D-type of suspension lugs on F/A-18 to the bluff T lugs of F-111C aircraft.

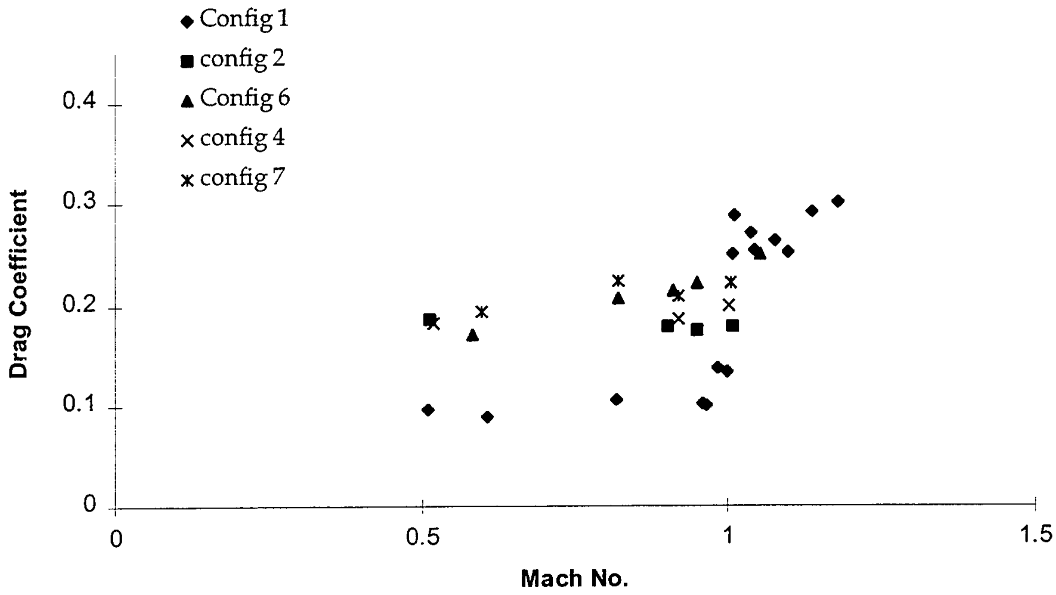


*Figure 5. The Drag Coefficient as a function of Mach number for various Mk 82 GPLD configurations related to F-111C aircraft obtained from aeroballistic range trials.*

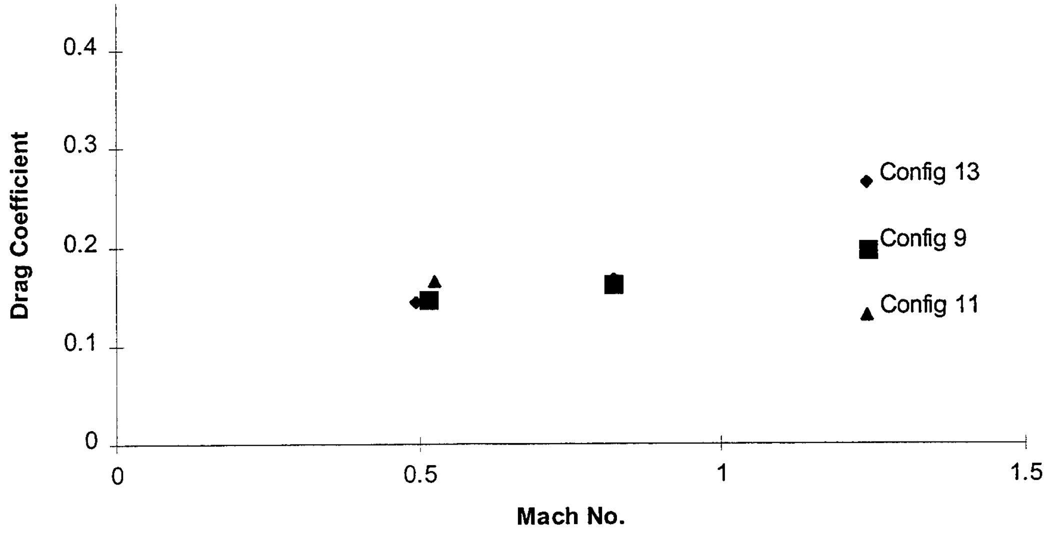


*Figure 6. The Drag Coefficient as a function of Mach number for various Mk 82 GPLD configurations related to F/A-18 aircraft obtained from aeroballistic range trials.*

# 5. Testing at Woomera Range Facility

The full scale drops of bombs usually serve in the assessment of safe separation of stores form the parent aircraft. Further these drops serve the purpose of deriving the separation coefficients present in the software of the bombing solutions of the mission computer. The measured bomb trajectory can also be used to assess the aerodynamic characteristics of the bomb, which can be compared with results obtained by tests explained in the previous sections to improve the confidence level. A number of Mk 82 GPLD bombs have been dropped from F/A-18 aircraft in the Woomera Instrumented Range (WIR). The main aim of this trial was to obtain the free stream aerodynamic characteristics of Mk 82 bomb in support of F-111C AUP project. Two trials were conducted, one in March 1994 and the other during March 1995. The following section describes briefly the trials scenario and the data collection to obtain the trajectory of the bomb. Finally the estimation of drag coefficient from the data using the 3dof parameter estimation model, as explained in reference 21, is discussed.

## 5.1 Range Axis System and Instrumentation

The Woomera Instrumented Range has a number of Kinetheodolites (5) and radars (2) to measure the trajectory of bomb. The range has been surveyed in AMG66 co-ordinates and its layout is given in Figure 7. A local right handed rectangular co-ordinate system is used to define the position of the range instruments and the measured trajectory. The origin, the range reference point and the axes system are defined as follows: X axis has a bearing of 34° 42′ 41″ relative to true north, Y axis has a bearing of 304° 42′ 41″ relative to true north and Z axis vertical. The range has two designated tracks. The track whose bearing is 272° relative to true north has been used in these trials.

The Kalman Filtering Technique has been used for processing the kinetheodolite data. A minimum of three kinetheodolite (K41, K36 and K8) were used to construct the trajectory of the bomb in space. Angular data from the contraves kinetheodolite was extracted at a rate of 20 points per second. The data was corrected for bore sight error and other systematic errors (ref 23). The position and velocity of the bomb was obtained by the Kalman Smoothing process and presented in Range Co-ordinate system (ref 24). The instant of release from the aircraft is determined from the earliest visual evidence on the ground based optical records. The bomb trajectory data is supplied to WSD for further processing to obtain the aerodynamic coefficients.

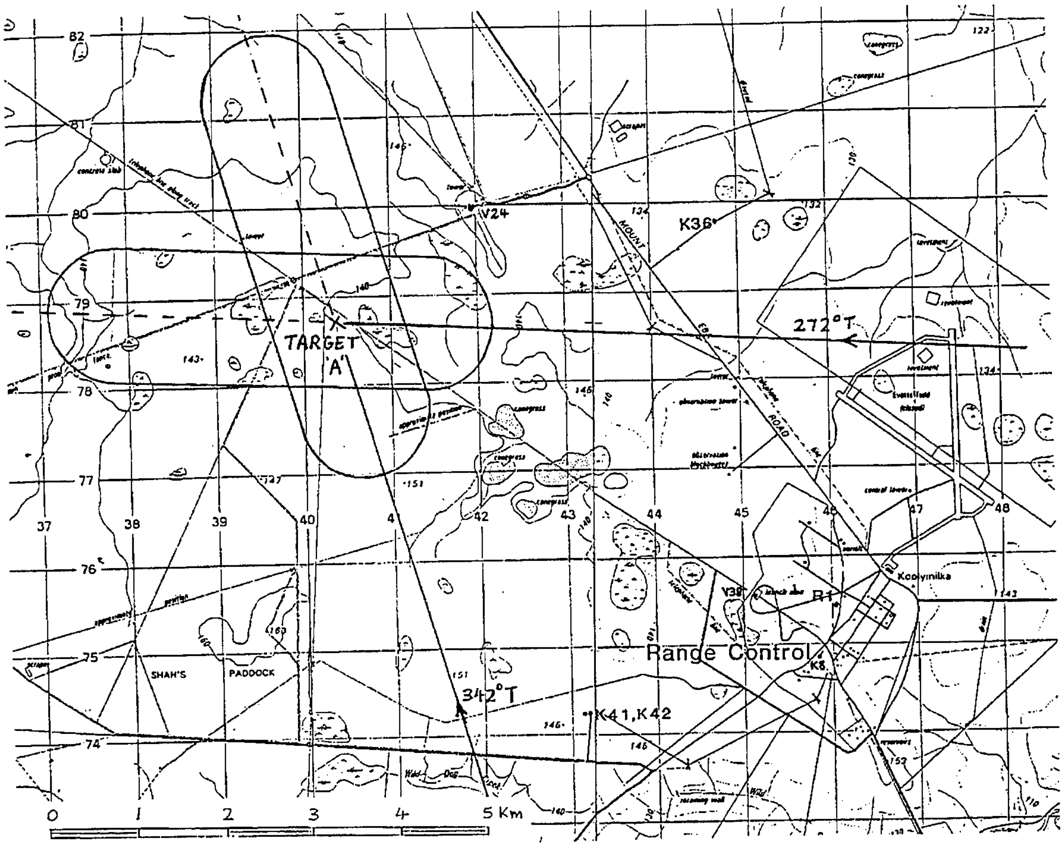


*Figure 7. Woomera Range Lay out.*

## 5.2 Trials Description

The Mk 82 GPLD bombs were dropped from an F/A-18 aircraft. They were released from different bomb release stations. The bomb configurations are shown in Table 2. The release position and velocity were varied to obtain the drag characteristics over a range of Mach numbers 0.6<M<1.3. Table 8 provides the relevant bomb release information. Reference 24 provides the full details of the two trials; IC 50 (March 1994) and IC 52 (March 1995).

## 5.3 Data Analysis

The data provided by ARDU is in the Range Co-ordinate system described in section 5.1 They consist of three files: one describing the bomb trajectory, the second containing the aircraft trajectory and the third, information about wind, temperature, pressure and some derived quantities such as Mach number and drag coefficient of the bomb. The method of analysis used to obtain the drag coefficient provided in the third file is described in reference 25 and the outcome of *release no.1* is presented in Figure 8. It can be seen that the analysis presents high values of $C_D$ for the initial part of the trajectory due to the bomb trajectory being influenced by aircraft flow filed disturbances. Further the $C_D$ shows an oscillating behaviour with Mach number, which can only be attributed to the drag estimation procedure.

A further data analysis based on the 3dof parameter estimation technique is performed on the data provided by ARDU. Each trial contains bomb trajectory for about 20 seconds. The initial portion of the data, corresponding to about 0.075 seconds of the bomb trajectory was removed as it is influenced by the flow field disturbances. Parameter estimation procedure is then applied to portions of the flight trajectory to obtain $C_D$ as a function of Mach number. Typically 6 to 7 seconds of data length are found to be sufficient to obtain drag coefficient to better than 99% confidence level, satisfying the conclusions made in Reference 26 in relation to precision of axial force ($C_D = -C_x$) coefficient estimation with the record length.

The Variation of $C_D$ with Mach number for the configuration 9 and 13 are shown in figure 9. It can be seen that the $C_D$ of configuration 13 is slightly more than that of configuration 9, which is attributable to the presence of M904 nose fuze. Even after meticulous planning in the release parameters, we are unable to obtain $C_D$ over a small range of Mach number 1.05<M<1.2.

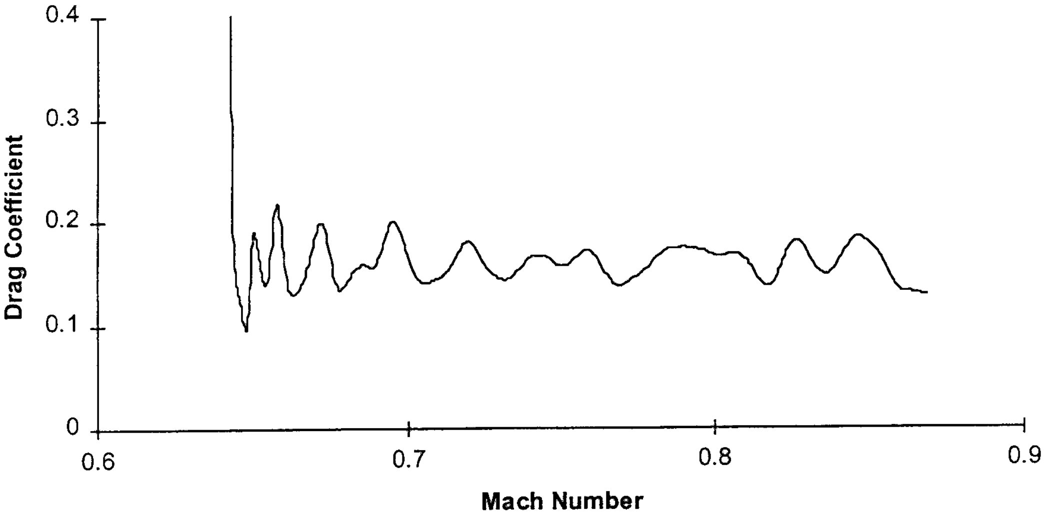


*Figure 8. Drag Coefficient estimation as described in ref 25.*

Table 8. Full scale bomb releases from F/A-18 aircraft; IC50 and IC52 trials.

| Release No. | Bomb No. | Config | Mass | Planned release | | |
|---|---|---|---|---|---|---|
| | | | | Altitude (ft) | Dive Angle (°) | Mach No./TAS (ft/s) |
| IC 50 trials (March 1994) | | | | | | |
| 1 | 12 | 13 | 227 | 10000(10053)[7] | 10 | 0.64 (412)[8] |
| 2 | 28 | 13 | 130 | 10000(10174) | 10 | 0.64(418) |
| 3 | 14 | 13 | 224 | 10000(10223) | 10 | 0.64 (419) |
| 4 | 27 | 13 | 229 | 10000(10176) | 10 | 0.64 (412) |
| 5 | 35 | 13 | 223 | 10000(13689) | 48 | 0.98 (617) |
| 6 | 16 | 13 | 229 | 10000(11593) | 44 | 0.98 (610) |
| 7 | 1 | 13 | 220 | 10000(10288) | 43 | 0.98 (617) |
| 8 | 5 | 13 | 218 | 10000(10462) | 45 | 0.98 (617) |
| 9 | 15 | 13 | 227 | 10000(10160) | 42 | 0.98 (630) |
| 10 | 33 | 13 | 226 | 10000(10327) | 44 | 0.98 (623) |
| 11 | 39 | 13 | 226 | 10000(10416) | 45 | 0.98 (626) |
| 12 | 13 | 13 | 224 | 10000(10802) | 46 | 0.98 (614) |
| 13 | 6 | 9 | 221 | 20000 | 60 | 1.3 |
| 14 | 26 | 9 | 228 | 20000 | 60 | 1.3 |
| 15 | 7 | 9 | 226 | 10000(10008) | 10 | 0.64 (423) |
| 16 | 9 | 9 | 226 | 10000(10056) | 10 | 0.64 (418) |
| 17 | 4 | 9 | 220 | 10000(10258) | 10 | 0.64 (419) |
| 18 | 29 | 9 | 225 | 10000(10211) | 10 | 0.64 (421) |
| 19 | 34 | 9 | 222 | 10000(10267) | 10 | 0.64 (417) |
| 20 | 24 | 9 | 229 | 20000(21046) | 65 | 1.3 (799) |
| 21 | 8 | 9 | 227 | 20000(20790) | 61 | 1.3 (806) |
| 22 | 25 | 9 | 229 | 10000(10388) | 10 | 0.64 (422) |
| 23 | 38 | 9 | 226 | 20000(20755) | 62 | 1.3 (805) |
| 24 | 10 | 9 | 226 | 20000(20720) | 61 | 1.3 (808) |
| 25 | 32 | 13 | 225 | 20000(20628) | 59 | 1.3 (783) |
| 26 | 11 | 13 | 227 | 20000(20400) | 64 | 1.3 (809) |
| 27 | 40 | 13 | 227 | 20000(20694) | 61 | 1.3 (820) |
| 28 | 36 | 13 | 221 | 10000 | 10 | 0.64 |
| 29 | 31 | 13 | 225 | 10000 | 10 | 0.64 |
| 30 | 3 | 13 | 220 | 10000 | 10 | 0.64 |
| 31 | 2 | 13 | 221 | 10000 | 10 | 0.64 |
| 32 | 22 | 9 | 229 | 10000 | 10 | 0.64 |
| 33 | 37 | 9 | 224 | 10000(10311) | 45 | 0.98 |
| 34 | 21 | 9 | 227 | 10000(10436) | 45 | 0.98 |
| 35 | 23 | 9 | 228 | 10000(10069) | 45 | 0.98 |
| 36 | 30 | 9 | 228 | 10000(9884) | 45 | 0.98 |
| IC 52 Trials (March 1995) | | | | | | |
| 9 | | 9 | 218 | 15102 | 44 | 1.0 |
| 10 | | 9 | 218 | 15176 | 44 | 0.8 |
| 11 | | 9 | 218 | 15489 | 44 | 0.6 |
| 12 | | 9 | 218 | 15335 | 44 | 0.6 |
| 13 | | 13 | 218 | 14926 | 44 | 1.0 |
| 45 | | 13 | 218 | 14510 | 45 | 0.8 |
| 46 | | 13 | 218 | 14343 | 45 | 0.6 |
| 47 | | 9 | 218 | 14292 | 45 | 0.7 |
| 48 | | 9 | 218 | 14449 | 45 | 0.8 |

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[7] values with in the bracket are actual release altitude

[8] values with in the bracket are actual release speed

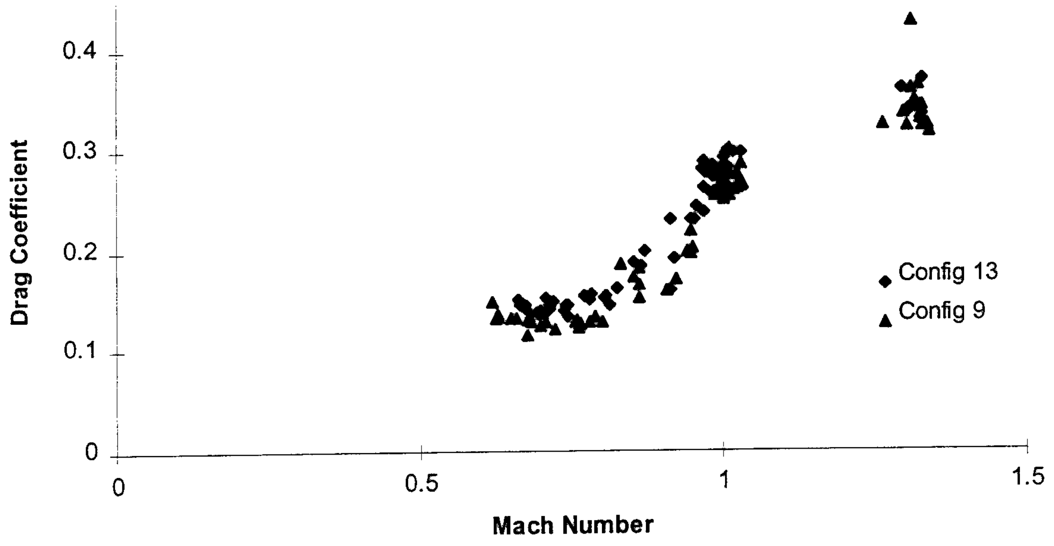

*Figure 9: Drag Coefficient as a function of Mach number as obtained from full scale bomb drops*

# 6. Database for Mk 82 GPLD store

The drag characteristics of Mk 82 GPLD stores used in the MC of the F-111C aircraft can be found in reference 2. This database was provided to AUP contractor to be incorporated into the bombing software. A discussion on the shortcomings of this database is contained in Section 1. The current section describes the construction of a new database using the results of the tests discussed in sections 3, 4 and 5.

A comparison of drag coefficient estimates obtained from various sources for a clean Mk 82 bomb with no fuze or lugs attached is shown in Figure 10. The agreement between them is poor. The discrepencies could only be attributed to the scale effects and correction methods applied to account for them.

As a bomb cannot be carried without a suspension lug on an aircraft, it is futile to spend time in assessing the correctness of $C_D$ for a clean configuration. Reference 1 suggested that for low-cost bombs such as Mk 82 GPLD stores, of which large numbers are in the inventory, flight testing will probably be the most efficient approach in establishing the drag characteristics.

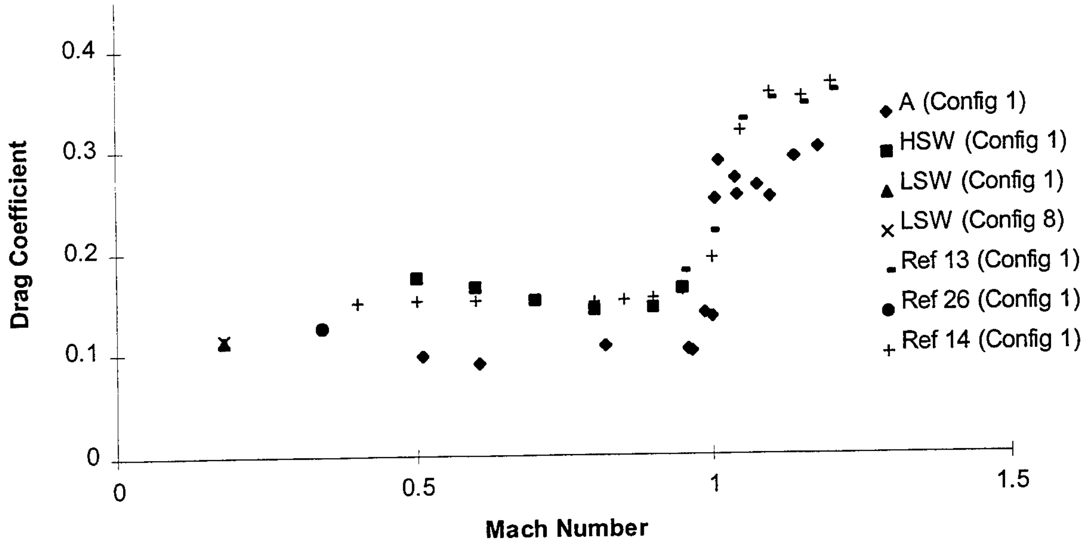

*Figure 10. Drag coefficient as function of Mach number for a clean Mk 82 GPLD stores with no fuze or lugs.*

Data for Mk 82 configurations released from F/A-18 aircraft are compared in figure 11 where the values $C_D$ obtained from full scale flight trials have been included. With the exception of the $C_D$ from the wind tunnel tests, the spread between different estimates is small. This small spread is attributable to the presence of nose fuze which will alter the flow characteristics principally by initiating a turbulent boundary layer. The error bars shown in the figure 11 represent the spread of the data at various Mach Numbers. The dotted line represents the average estimated $C_D$ distribution, referred to as $C_{D_{F/A-18}}$.

The differences in $C_D$ between T-lugs and D-lugs is small but not negligible even when M904 type of nose fuze was present. Hence $C_D$ variation for Mk 82 stores configured for carriage on F-111C aircraft will be more than the estimated $C_{D_{F/A-18}}$. Figure 12 is the plot of $C_D$ variations for F-111C aircraft. The drag characteristics provided to the AUP contractor and the drag data obtained from reference 1 are also shown for comparison. These values were produced by the Arnold Engineering Development Centre (AEDC) from full scale wind tunnel tests, flight tests and simulation.

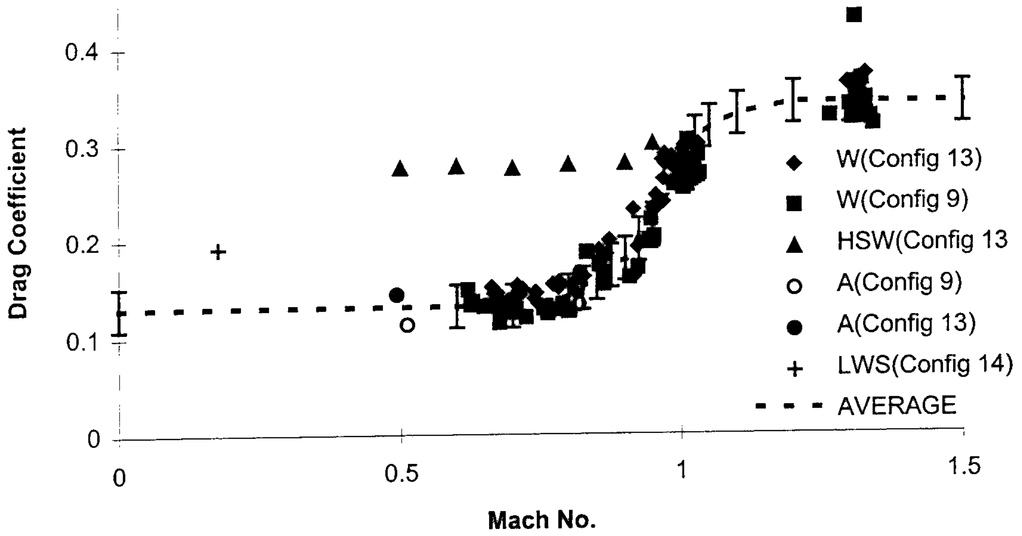

*Figure 11. Drag coefficient as function of Mach number for a Mk 82 GPLD stores configured for carriage on F/A-18 aircraft.*

It can be seen that the values obtained from wind tunnel tests are approximately double those obtained from aeroballistic range testing. For the Mach number range up to 0.9, the values of $C_D$ obtained by aeroballistic range facility fall around the AEDC results. The dotted line in the figure corresponds to $C_{D_{F/A-18}}$. The error bars correspond to ±20% of $C_D$ of that Mach number.

The study on the sensitivity of various parameters (ref 27) on the miss distance of Mk 82 GPLD bomb from aircraft showed that the aircraft variables such as velocity, altitude, and ejection velocity during release are the most dominant among other variables dependent on bomb and environment. Of all the bomb dependent variables, the study suggested that the drag coefficient has the greatest influence. Figure 13 shows the accuracy with which the drag characteristics have to be estimated to produce one mil error in the ground plane. It can be seen that the sensitivity depends on the type of release; toss manoeuvre requires only 5% change while 40% changes can be tolerated for level release. An average value of ±20% error about the mean estimated variation of $C_{D_{F/A-18}}$ encompasses all the estimates obtained from aeroballistic range testings. The $C_{D_{F/A-18}}$ distribution seems to be higher than those values given to the AUP contractors (GFI) over the Mach number region M<1.0 where the majority of bomb releases occur. The average $C_{D_{F/A-18}}$ will serve as an interim distribution for F-111C configurations. These values will be evaluated when the updated F-111C aircraft undergoes Ballistic Accuracy Verification (BAV) flight tests.

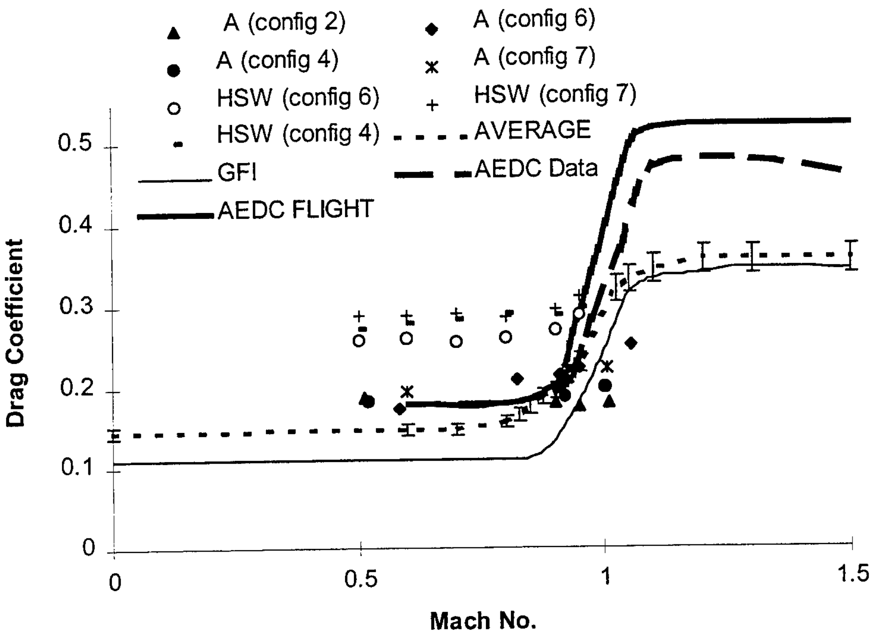

*Figure 12. Drag coefficient as function of Mach number for a Mk 82 GPLD stores configured for carriage on F-111C aircraft.*

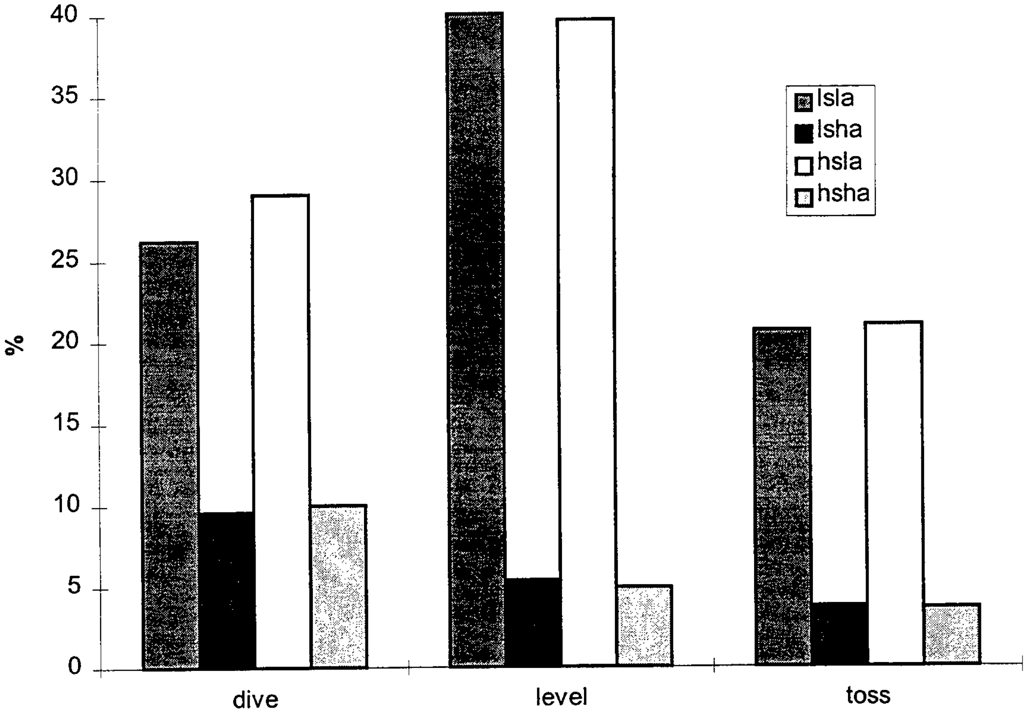

*Figure 13. Drag Coefficient Sensitivity for 1 mil error in ground plane*

# 7. Acknowledgment

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Mk-82 bombs, aerodynamic drag, F-111C aircraft

19. ABSTRACT

The drag database of the Mk 82 General Purpose Low Drag bomb, the primary gravity weapon in the RAAF inventory, has some shortcomings in the quality and traceability of data, and in the variations due to configurational differences. Extensive testing of scaled models in a wind tunnel and an aeroballistic range facility have resulted in establishing estimates of the drag of a clean Mk 82 bomb as well as the incremental drag of add ons such as lugs and fuzes. These results, together with data obtained from full scale bomb drop trials, have been used to produce drag estimates for a full range of bomb configurations and release conditions. It is recommended that these data be incorporated into the mission computer of the weapon delivery system of the updated F111C aircraft. Furthermore it is recommended that the accuracy of these data be validated when the updated aircraft undergoes Ballistic Accuracy Verification flight trials.