# Boeing 747-121, N739PA: Appendix G

**Aircraft Accident Report No 2/90 (EW/C1094)**

## Report on the accident to Boeing 747-121, N739PA at Lockerbie, Dumfriesshire, Scotland on 21 December 1988

**APPENDIX G**

**MACH STEM SHOCK WAVE EFFECTS**

### 1. Introduction

An explosive detonation within a fuselage, in reasonably closeproximity to the skin, will produce a high intensity shock wavewhich will propagate outwards from the centre of detonation. On reaching the inner surface of the fuselage skin, energy willpartially be absorbed in shattering, deforming and acceleratingthe skin and stringer material in its path. Much of the remainingenergy will be transmitted, as a shock wave, through the skinand into the atmosphere but a significant amount of energy willbe returned as a reflected shock wave, which will travel backinto the fuselage interior where it will interact with the incidentshock to produce Mach stem shocks - re-combination shock waveswhich can have pressures and velocities of propagation greaterthan the incident shock.

The Mach stem phenomenon is significant for two reasons. Firstly,it gives rise (for relatively small charge sizes) to a geometriclimitation on the area of skin material which the incident shockwave can shatter. This geometric limitation occurs irrespectiveof charge size (within the range of charge sizes considered realisticfor the Flight PA103 scenario), and thus provides a means of calculatingthe standoff distance of the explosive charge from the fuselageskin. Secondly, the Mach stem may have been a significant factorin transmitting explosive energy through the fuselage cavities,producing damage at a number of separate sites remote from thesource of the explosion.

### 2. Mach stem shock wave formation

A Mach stem shock is formed by the interaction between the incidentand reflected shock waves, resulting in a coalescing of the twowaves to produce a new, single, shock wave. If an explosive chargeis detonated in a free field at some standoff distance from areflective surface, then the incident shock wave expands sphericallyuntil the wave front contacts the reflective surface, when thatelement of the wave surface will be reflected back (Figure G-1). The local angle between the spherical wave front and the reflectingsurface is zero at the point where the reflecting surface intersectsthe normal axis, resulting in wave reflection directly back towardsthe source and maximum reflected overpressure at the reflectivesurface. The angle between the wave front and the reflectingsurface at other locations increases with distance from the normalaxis, producing a corresponding increase in the oblique angleof reflection of the wave element, with a corresponding reductionin the reflected overpressure. (To a first order of approximation,explosive shock waves can be considered to follow similar reflectionand refraction paths to light waves, ref: "Geometric ShockInitiation of Pyrotechnics and Explosives", R Weinheimer,McDonnel Douglas Aerospace Co.) Beyond some critical (conical)angle about the normal axis, typically around 40 degrees, thereflected and incident waves coalesce to form Mach stem shockwaves which, effectively, bisect the angle between the incidentand reflected waves, and thus travel approximately at right anglesto the normal axis, i.e.parallel with the reflective surface (detail"A", figure G-1).

**3. Estimation of charge standoff distance from the fuselageskin**

Within the constraint of the likely charge size used on FlightPA103, calculations suggested that the initial Mach stem shockwave pressure close to the region of Mach stem formation (i.e.the shock wave face-on pressure, acting at right angles to theskin), was likely to be more than twice that of the incident shockwave, with a velocity of propagation perhaps 25% greater. However,the Mach stem out-of-plane pressure, i.e.the pressure felt bythe reflecting surface where the Mach stem touches it, would havebeen relatively low and insufficient to shatter the skin material. Therefore, provided that the charge had sufficient energy toproduce skin shatter within the conical central region where noMach stems form, the size of the shattered region would be a functionmainly of charge standoff distance, and charge weight would havehad little influence. Consequently, it was possible to calculatethe charge standoff distance required to produce a given sizeof shattered skin from geometric considerations alone. On thisbasis, a charge standoff distance of approximately 25 to 27 incheswould have resulted in a shattered region of some 18 to 20 inchesin diameter, broadly comparable to the size of the shattered regionevident on the three-dimensional wreckage reconstruction.

Whilst the analytical method makes no allowance for the effectof the IED casing, or any other baggage or container structureinterposed between the charge and the fuselage skin, the presenceof such a barrier would have tended to absorb energy rather thanre-direct the transmitted shock wave; therefore its presence wouldhave been more critical in terms of charge size than of position. Certainly, the standoff distance predicted by this method wasstrikingly similar to the figure of 25 inches derived independentlyfrom the container and fuselage reconstructions.