Assessment of the Lethality of Direct Hitting Anti-Air Missiles

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SUMMARY

Traditional methods of anti-air lethality assessment have tended to concentrate on the damage to the target caused by fragments and blast from the intercepting missile's warhead. With the development of more effective seeker hardware and guidance algorithms the miss distances achieved by missiles have tended to reduce. This has led to a general reduction in the size of missile warheads and a greater reliance on the damage caused to the target by the impact of the missile body itself. In order to assess experimentally the damage inflicted upon an air target it is necessary to replicate the dynamics of the endgame as closely as possible. This paper describes the various experimental and numerical simulation methods that can be employed to achieve this goal.

1.0 INTRODUCTION

Traditional methods of lethality assessment for anti-air guided weapons, ranging from simple "engineering judgement" through detailed computer modeling to the conduct of full scale live firing trials have tended to concentrate on the effects of blast and fragment damage to the target. This is as would be expected for missiles equipped with large warheads with lots of fragments and high explosive content. Direct hits, with these large missiles, were considered to result in kills, i.e. P_K=1.0, in (almost) all cases. This methodology is still prevalent in the vulnerability/lethality assessment communities of the world.

With the development of more effective seeker hardware and guidance algorithms, the miss distances achievable by modern anti-air missiles (and systems likely to enter service in the future) has decreased; this has led to a number of significant changes related to the lethality of the missile system:

- The size of the warhead has tended to decrease. This in turn has led to a smaller damage radius for the warhead resulting in a smaller probability of blast damage and a lower level of "mechanical" damage due to the impact of fragments.
- A new phenomenon has been observed, termed the "close burst" effect, resulting from synergy between the simultaneous impact of blast and fragments on the target.
- A high percentage of engagements result in a direct hit on the target.

Reliance on the subjective assessment of lethality by expert practitioners is becoming more and more difficult to justify, particularly as the opportunities for staff to observe full-scale trials are reducing. In addition the cost of conducting full-scale live firing trials is considerable: a price for the conversion of a USAF F-4 aircraft to QF-4 drone standard of around $ 2 million has been quoted in the press [1]. Whilst dynamic engagements of real targets remain the ultimate measure of weapon effectiveness it is

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difficult to obtain data when the target aircraft is invariably destroyed upon impact with the ground. The use of a high-speed test track goes some way to simulating the true dynamics of the engagement. With the increase in available computer power and the huge advances in simulation fidelity that have taken place over the past decade, the use of numerical methods to assess the outcome of direct hits is becoming increasingly more viable.

Currently the preferred route is via a combination of all three of the above using a limited trial programme to support development and validation of computer models containing robust algorithms, which in turn are interpreted by expert users [2].

This paper describes the various experimental and numerical simulation methods that can be employed to provide an effective assessment of the lethality of direct hitting missiles.

2.0 KILL MECHANISMS

Before describing the methods used to assess direct hits in detail, it is valuable to review the kill mechanisms by which a conventional warhead may inflict damage on its target. These are described in the following paragraphs.

- Fragment Damage
- Close Burst effects
- Direct Hit

↓ Decreasing Miss Distance

Fragment Damage, for warheads that burst at some distance (typically more than 2 metres) from the target, the primary kill mechanism is fragment penetration of the structure and underlying systems. At 2 metres stand-off it is unlikely that more than 10% of the fragments on the warhead will strike the target. Considerable data exists on the penetration capability of a wide range of fragment materials (for typically compact fragments) into most traditional aircraft materials with the exception of advanced composites: A separate paper to be presented at this conference describes work funded by the UK MOD to address this shortfall.

Close Burst effects, where the missile detonates at close range to the target and damage is caused by a combination of fragment impacts and the arrival of the blast wave from the warhead. The time of arrival of the two has a marked effect on the damage inflicted to the aircraft. If the blast arrives before the fragment swathe the damage is typically less severe than if the two arrive simultaneously or if the fragments arrive first. Figure 1 illustrates typical close burst damage.

Direct Hit of the missile onto the target, generally leads to a combination of structural failure and disruption/destruction of aircraft systems components situated in the vicinity of the impact point. There is also the possibility of additional damage mechanisms leading to a structural failure including hydraulic shock damage to structures containing (full or part full) fuel tanks, explosions of empty (or part full) fuel tanks and secondary damage from disintegration of engines or detonation of on-board munitions. Very limited data is available on the effects of direct hitting missiles, particularly against modern aircraft structures.

In order to accurately simulate the behaviour of a target to direct hitting missiles it is essential to replicate the dynamics of the engagement as closely as possible. Direct hit trials require the missile to be travelling at a representative velocity, this is currently accomplished by using a high-speed test track. The cost of using these facilities is considerable although two orders of magnitude less than conducting full-scale live firings and again they fail to fully replicate the engagement taking no account of the motion of the target aircraft, airflow or flight loads.

Figure 1: Typical Close Burst Damage to a Mig 23 Aircraft. The fragment swathe struck the intake first, weakening the structure, which was then distorted by the blast loading. The photograph was taken during a joint Dstl/DSTO trial conducted at the Port Wakefield test range in South Australia.

Figure 2: Damage inflicted on a Jaguar Aircraft during the Gulf War by a small SAM (MANPAD). Typical missiles of this type have warheads of less than 1kg and an “all burnt” mass of less than 10kg. Photograph courtesy of RAF ABDR Flight, St Athan.

3.0 ASSESSMENT OPTIONS

Four sources of potentially useful data have been identified, these are:

- Literature search of aircraft accident reports (multiple sources)
- High-Speed Test Track trial programme
- Hydrocode modelling programme
- Data gathering from full scale live firing trials

3.1 Literature Search

It is believed that much can be learned regarding the levels of survivable structural damage by studying aircraft accident reports relating to mid-air collisions. Although these do not represent actual impacts from missiles, they do provide an illustration of the levels of damage that can be survived. The most graphic illustration of this being an Israeli F-15 which was involved in a mid air collision with an A-4, which resulted in the entire starboard wing being lost. The aircraft flew back to base and landed safely. Several similar incidents have been recorded, a typical example is shown in figure 3.

Figure 3: "Survivable" Damage as a result of a Mid Air Collision. Approximately 50% of the port wing has been removed along with a large section of the port tail fin. The fin has also suffered severe damage to its primary structure.

To further illustrate this point a brief survey has been made of military "fast jet" aircraft accidents for a single year; Table 1 provides a summary of the findings. This period was chosen at random and it is not known whether this represents anything other than an "average" year from a flight safety point of view. It can be seen that from a total of 28 aircraft (discounting the 19.03.90 entry), 4 aircraft survived (approx. 14%). The comments relating to landings "badly damaged" or "minus 1.5m from one wing" are noteworthy.

Table 1: Summary of “Fast Jet” Mid Air Collisions for 1990

Date	Aircraft types	Outcome	Fast Jet Survivors
12.12.89	2 x Mirage 2000	Both aircraft crashed	
18.12.89	2 x F16	Both aircraft crashed	
09.01.90	Jaguar & Tornado	Tornado crashed, Jaguar landed minus 1.5m from one wing.	1
23.01.90	2 x F18	One crashed the other made emergency landing, badly damaged.	1
19.03.90	F15	Struck by a “live” Sidewinder missile fired from an F15 during an exercise. Port tailplane was removed and the Starboard rudder badly damaged. The aircraft landed safely.	(1)
22.03.90	2 x F16	Both aircraft crashed	
17.04.90	2 x CF-18	Both aircraft crashed	
10.05.90	2 x F16	Both aircraft crashed	
30.05.90	2 x A7	Both aircraft crashed	
07.06.90	F16 & Glider	Glider crashed killing the pilot, the F16 sustained only minor damage	1
26.07.90	2 x F4	Both aircraft crashed	
01.08.90	2 x Jaguar	Both aircraft crashed	
02.08.90	2 x F18	One crashed the other made a safe landing minus several feet of the port wing.	1
06.08.90	T38 & Cessna	T 38 crashed, Cessna landed on a nearby road.	
14.08.90	2 x Tornado	Both aircraft crashed	
10.12.90	2 x A4	Both aircraft crashed	

3.2 High-Speed Test Track Trial Programme

The use of high-speed test tracks allows for a high level of control of the missile impacting the target, it does not, however, allow all of the engagement parameters to be accurately represented. Whilst the dynamics of the missile can be simulated on the track, the target will usually be statically mounted and not subject to either airflow or flight loads. These may be applied if required but the increased cost of including them is generally prohibitive. A number of test tracks are in use around the world as detailed in Table 2. The cost of using these facilities is considerable. Limitations of conducting trials of this type with a static target include the omission of flight loads applied to the target and the effects of airflow.

Table 2: High-Speed Test Track Facilities Worldwide

Country Operator, Location	**Length**	**Maximum Speed**
UK		
QinetiQ, Pendine	1503m	M 3.2
France		
DGA, Biscarosse	390m	M 2.5
	1998m	M 3.0
USA		
USAF, Eglin AFB	610m	M 3.0
USAF, Holloman AFB	15480m	M 9.0
USN, NSWC China Lake	914m	?
	6568m	M 3.3
Sandia National Lab.	3048m	M 6.0
Russia		
GosNIIAS, Faustovo	2500m	?
LII, Ramenskoye	?	?

The UK initiated a programme [3] to investigate the effects of direct hitting missiles on aircraft structure during the early 1980s using the high-speed test track at Pendine on the South Wales coast. Over a period of several years a total of 47 inert missiles of four different types have been fired at a selection of aircraft structures including wings, jet engines and helicopter and fixed wing aircraft fuselages.

The missiles (less warheads, propellants, etc.), mounted on a specially designed sled were driven along the test track by a combination of booster and sustainer rocket motors. On reaching the target situated at the end of the track, the missiles were released from the sled by either a knife severance of restraining tapes or by activating explosive bolts, leaving the missile to free fly on to the target. The sled is diverted away from the target into an underground “catcher butt” using a downward curved rail at the end of the track.

The missile impact velocity was controlled by varying the type of propulsion system (number and arrangement of rocket motors) and point of rocket initiation along the test track. The desired variations in impact angle with the target were obtained by mounting the missile on the sled at various pitch and roll angles, and by suitable choice of target orientation relative to the track.

During the course of these trials missile weights of between 5 and 50kg, impact velocities from 200 to 800m/s and impact energies up to almost 6 MJ have been trialled. Results were assessed in terms of the likely kill category for the target following the engagement.

The UK kill categories consider that an engagement can result in either no damage, damage that will render the target incapable of continuing with its mission within a time “t” (C kill) and damage that will render the target permanently incapable of controlled flight within time “t” (F kill).

Figure 4 illustrates typical damage to an aircraft structure, in this case a retired Hunter aircraft. The missile had a mass of approximately 5kg and impacted at 800m/s. In this instance the missile passed right through the fuselage and exited on the opposite side. No residual velocity was measured so the actual absorbed energy within the target is difficult to quantify. An assessment made at the time predicted that the results of this engagement would be a permanent loss of controlled flight capability within 5 minutes of the impact occurring (UK F_{5MIN} kill). This level of kill is generally associated with loss of hydraulic fluid leading to loss of control, loss of fuel leading to fuel starvation or the onset of an uncontainable fire within the aircraft.

Figure 4: Direct Hit Damage to Aircraft Fuselage. This level of damage was assessed as causing a permanent loss of flight capability within 5 minutes (UK F_{5MIN} kill category).

The data obtained from these trials was adequate for the needs of the time but did not lend itself to support the development of an algorithm suitable for incorporation into the vulnerability assessment tools which have been developed over the past 20 years. A generic methodology was required which expressed penetration of a missile into the target as a function of target density, missile energy and engagement geometry [4]. The use of this data to develop a capability within the UK's detailed vulnerability assessment model is described later in this paper.

3.3 Hydrocode Modeling Programme

The cost of conducting truly representative trials is considerable and as a consequence it is unlikely that sufficient can be done to provide a truly statistically valid answer. It is believed that the use of hydrocode modelling, although not yet sufficiently developed to make the conduct of trials redundant, is nevertheless capable of providing evidence to support the development of algorithms for the assessment tools used in the UK.

Knowledge of work being carried out in the US [5] has indicated that there is considerable interest in assessing the vulnerability of aircraft to direct hitting missiles, although the threat missiles considered are very different. The decision was made to replicate some of the work being conducted in the US but to consider a more representative (to the UK) missile. Initial work has concentrated on the design of a generic missile using engineering materials for which suitable material characterisations exist. The internal components are mass representative of real missile hardware and the missile is symmetrical about its centre line. As a consequence a half model has been produced incorporating in excess of 68000 elements. Figure 5 illustrates the missile model that has been developed.

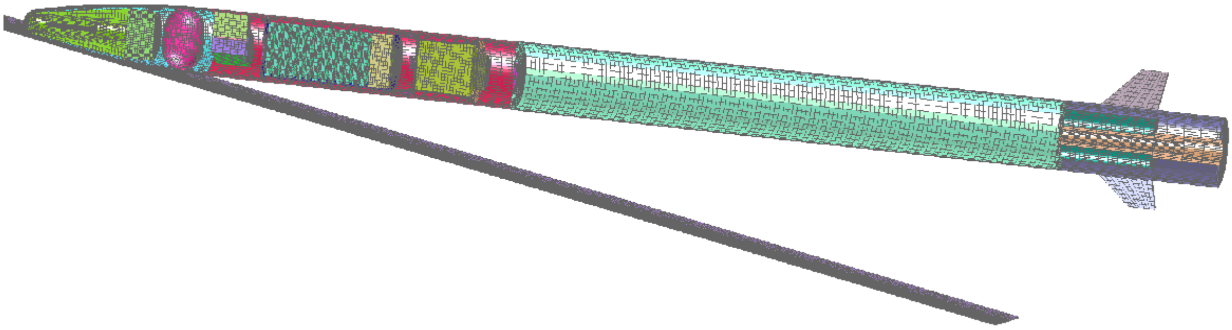


Figure 5: Internal details of Generic Missile used in UK Hydrocode Modelling Programme.

A limited number of hydrocode runs have been completed using a ductile void growth (Goldthorpe) failure model for both the missile body and the target. The nose of the missile incorporates a ceramic "dome" for which a plastic strain failure model is used. It is intended to thoroughly explore the ricochet limit for a range of velocities and target characteristics during the coming year.

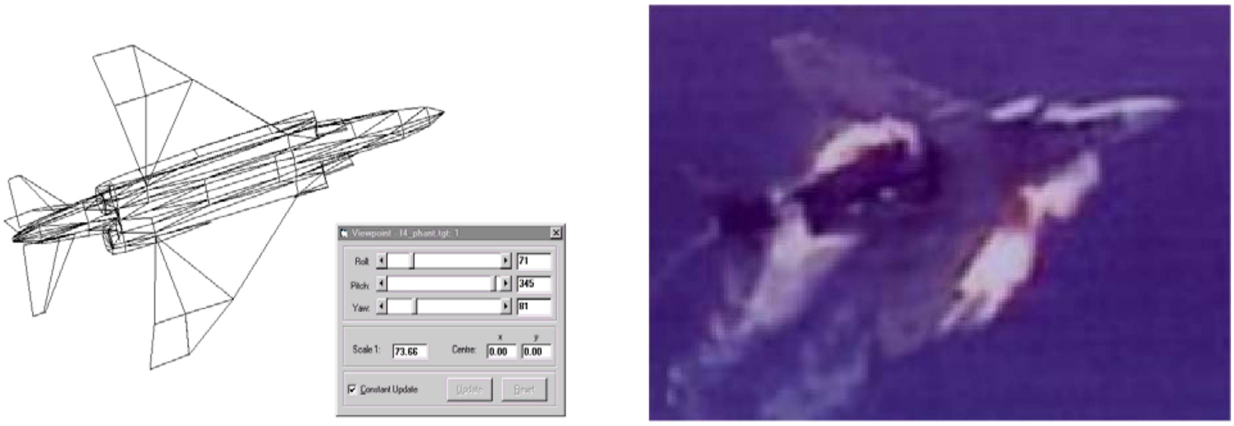
3.4 Data Gathering from Full-scale Live Firing Trials

During the development cycle of an anti-air missile it is customary to conduct a number of full-scale live firing trials against representative targets. A large number of firings are also carried out each year in order to train aircrew in the use of air-to-air missiles. Whilst the majority of these firings are conducted against sub-scale drones, there are a number where full size aircraft targets are used. In recent years the number of these trials has reduced to the point that today only the US have the facility to carry out truly representative engagements.

The UK have been involved in a number of full-scale trials in recent years where missiles have been fired against QF-4 target drones in the US. During preparations for the most recent of these trials programmes [6], consideration was given to data gathering to support the development of an improved methodology for the assessment of direct hit. A number of options were considered to record the engagement and provide a measure of the actual damage inflicted upon the target aircraft, these included:

- Data gathering on the aircraft itself (e.g. control positions, engine parameters, hydraulic and electrical system states, etc).
- Photographic evidence relating to damage to the target using cameras mounted on either the target aircraft itself, a second unmanned aircraft flying nearby, a second manned aircraft flying at a greater range (2-3 km), or on the ground.
- Recovery of the target aircraft if damage inflicted by the missile did not result in an immediate kill.

Unclassified imagery of the engagement of a QF-4 target aircraft by an AIM-9X missile were obtained from Raytheon [7]. It was considered that by superimposing a wire frame depiction of the aircraft over the image, a reasonable assessment of the damage caused by the impact could be obtained. The wire frame allows accurate estimates of pitch roll and yaw of the targets image to be made and as a consequence superimposition of target structural and systems configuration. Figure 6 shows a single frame from the AIM-9X promotional video together with a wire frame depiction of the target. The missile impacted from above the aircraft striking the starboard engine and exiting through the starboard main undercarriage bay. Extensive damage to the wing skin including probable severance of the rear spar has occurred. The light coloured patches are believed to be un-burned fuel exiting the engine bay and intake.



Viewpoint - f4_phant.tgt: 1

Roll: 71

Pitch: 345

Yaw: 81

Scale 1: 73.66

Centre: x 0.00 y 0.00

☑ Constant Update

Figure 6: Imagery of QF-4 Target Aircraft immediately after Impact from AIM-9X Missile. The wire frame has been rotated to mimic the appearance of the aircraft. A more detailed wire frame could include structural and system details to allow accurate damage assessment to be carried out. Photograph courtesy of Raytheon Missile Systems.

4.0 LETHALITY MODELLING

The UK maintains an independent capability to assess the vulnerability of air, land, and sea (above and below surface) vehicles. Use of these models also allows the lethality of current and future weapons systems to be assessed against these targets. Separate modelling suites are employed in each scenario although a degree of commonality runs through all of them.

4.1 The INTAVAL Model

The INTAVAL (Integrated Air target Vulnerability Assessment Library) suite of computer programmes has been used for the past 20 years in the assessment of air target vulnerability and anti-air weapon lethality. Separate modules exist to assess the effects of inert projectiles (fragments and bullets) and shells (both internally and externally bursting). A shot line approach is employed where individual fragments are passed through a geometric representation of the target and damage to individual systems assessed.

A typical target will consist of between 1500 and 2000 components which are either critical to maintaining flight or mission capability or provide shielding to those components. Figure 7 illustrates a section of a typical target description. Each component is modelled in terms of its physical dimensions, location within the target and its material composition. Component damage algorithms are assigned to each vulnerable component, which express the degradation to its functionality as a result of fragment mass and (typically) impact velocity. Failure logic (fault tree) analysis is used to calculate whole target vulnerability by summing the individual component vulnerabilities whilst taking account of the duplication and redundancy present within the system.

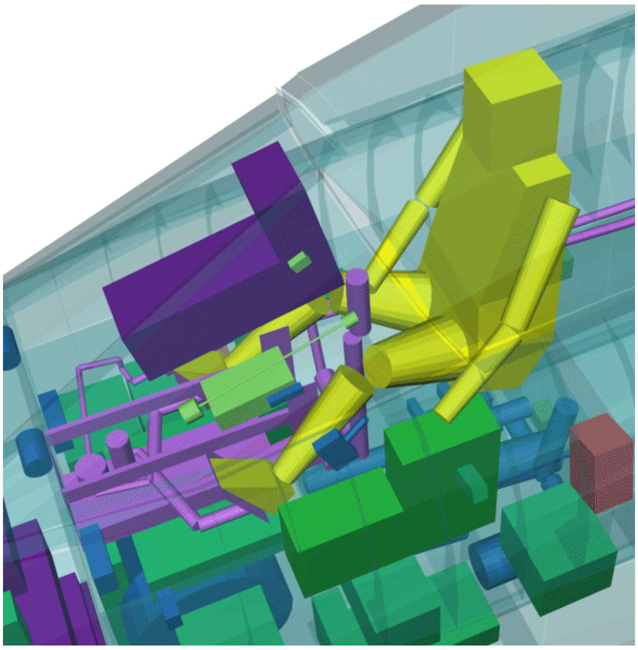


Figure 7: Detail from a Typical INTAVAL Target Description of a Combat Aircraft.

4.2 Direct Hit Lethality Modelling

The trials data obtained from the high-speed test track trials programme was re-assessed to determine which of the data points would be useable for the development of a new methodology. Several of the firings resulted in complete penetration of the target with the missile body exiting the target; these were discounted as there was no record of the exit velocity and hence the absorbed energy within the target could not be estimated. Similarly, a number of firings were made against fluid filled fuel tanks. Considerable hydraulic ram damage resulted in these cases which masked the actual damage from the missile penetration, these results were also discounted.

Estimates were made of the average density of the target at the point of impact. Density was initially categorised into light, medium and heavy although this was subsequently determined to be too coarse a measure and intermediate densities were added. The initial stage in the development of the methodology was to plot depth of penetration against target density.

The next step was to identify a relationship between the points on the graph and parameters relating to the impacting missile, for example momentum, energy, etc. A wide range of parameters were calculated for each data point and their values were shown alongside each corresponding point on the graph. For each of these parameters in turn, the graph was used to determine whether a correlation existed between the parameter values and graph points by looking for a consistent set of lines of “constant parameter value”. In this context “consistent” is used to describe lines that are progressively ordered and do not cross over each other. After examining a large number of missile parameters, the best correlation was found to be that shown in Figure 8a.

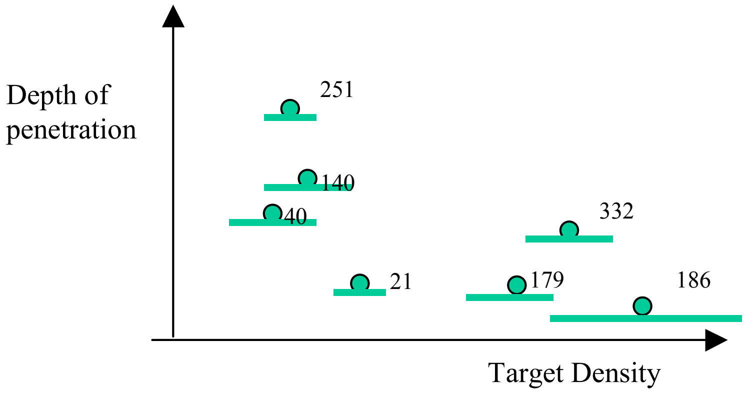


Figure 8a: Plot of Missile Penetration vs Target Density.

The figures next to each data point represent the absorbed energy per unit area, calculated using the missile "signature" on the target when projected in the missile's relative velocity direction. For normal impacts the area will be the same as the missile cross section, for other impacts this will obviously vary. Error bars have been applied to take account of the uncertainty in estimating target density; the error bars are considerably larger for high-density targets than they are for low density ones.

The limited data set available (19 useable points) together with the presence of error bars on the target density values required a degree of interpretation to produce these curves. The general shape of the curve is consistent with a theoretical assessment carried out by airframe structure specialists. Curves that define penetration Vs target density for a constant level of absorbed energy per unit are shown in Figure 8b.

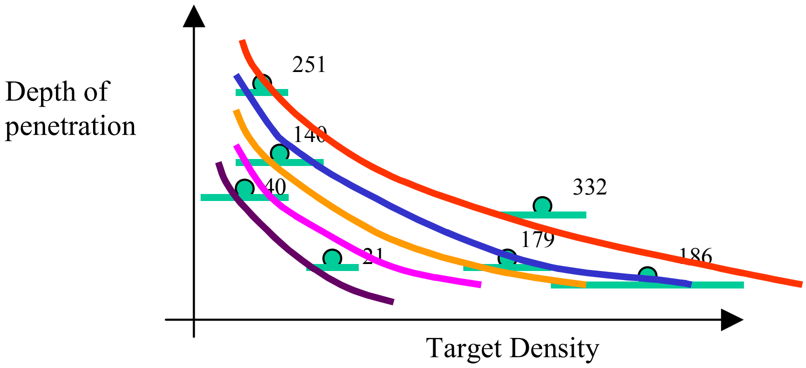


Figure 8b: Curves of constant Absorbed Energy per unit area of Impacting Missile.

The final stage is to transform the curves from the form derived from the trial into a series of "iso-density" curves relating penetration to absorbed energy within the target per unit area of the impacting missile. This provides penetration data in a form that can be used "off line" with the detailed vulnerability model to determine penetration. The form of these curves is shown in figure 8c.

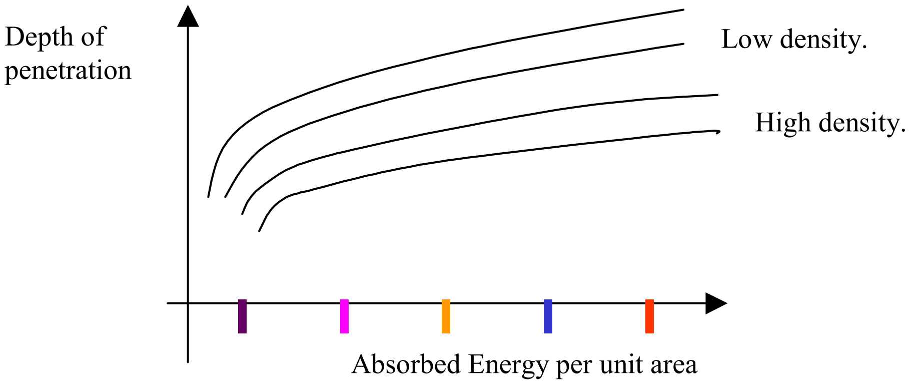


Figure 8c: Iso-Density Curves

The area of damage caused to a target by the impact of a missile is not confined to the signature of the missile's area. Extended damage to both the target's structure and its internal sub-systems will result from the impact of a missile body. To take account of this a number of zones around the missile body are considered. These take account of the distortion to the structure caused by the passage of the missile and secondary effects from break up of the missile and the penetrated structure. The zones currently considered in UK assessments are illustrated in Figure 9. The volume of these zones is dependant upon the mass, velocity and construction of the missile together with the density, construction and content of the section of the target that is impacted. Derivation of these zones is typically achieved by reference to the direct hit trials database, a degree of extrapolation being necessary to account for systems for which no trials data is currently available.

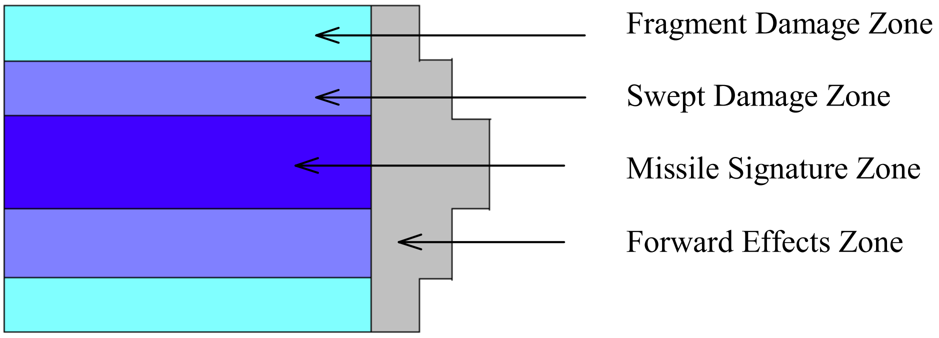


Figure 9: Direct Damage Zones within Target.
Note that the volume of the zones is not typically representative.

Prior to the creation of the penetration graph in Figure 8b, an INTAVAL module had been produced with intentional flexibility so that it would have a high likelihood of representing any future penetration relationship. The module chosen was based on the following rule:

The total mass of material displaced from the target is proportional to the missile's mass and impact velocity, raised to powers that can be pre-defined.

Based upon the graph in Figure 8c, best values for the constant of proportionality and the power terms were established by analysis and input into INTAVAL. Although the INTAVAL module introduces some constraint on the accuracy with which the graph is embodied, the errors are considered to be acceptable.

The INTAVAL module works as follows. An initial depth of penetration of the missile body into the target is assumed, and the mass of the target encroached by the missile at this position is registered by INTAVAL's standard shot-lining technique. In effect INTAVAL registers material volume, however, because it also has knowledge of the material density it can calculate the target mass. This encroached mass is then compared to the final mass, as calculated by the INTAVAL module for the particular conditions of the impacting missile under consideration. If the encroached mass is less than the final mass, INTAVAL increases the depth of penetration from the initial value and repeats the process, whereas, if the converse is true, the depth of penetration is reduced. By repeated iterations, it is possible to arrive at a solution within a user-defined tolerance of the final mass, and hence obtain a penetration estimate where the missile comes to rest.

The next stage involves superimposing the zones of additional damage around the position where the missile comes to rest. This is to identify target components damaged by the missile penetration. Different component kill probabilities are assigned according to the location of the components within the various damage zones. INTAVAL automatically registers which components are in which damage zone and calculates their kill probability. These kill probabilities are then passed through INTAVAL's component survival logic tree (which identifies critical components and systems) to obtain the total kill probability of the target.

5.0 FUTURE PLANS

A programme of numerical simulation supported by high-speed test track firings is proposed. The modelling described earlier in this paper will be continued to determine the penetration characteristics and ricochet limit for the generic missile impacting a range of typical target structures. In parallel a number of firings of the generic missile into "plate array" targets will be conducted. The missile used for the firing programme will be based upon the design used for the hydrocode modelling, the generic missile having been designed using materials for which good material characterisation data already exists. This represents a significant reduction in the level of work required.

The firings, against largely homogeneous targets, will remove the error bars present in the previous trials and are expected to provide a high level of confidence in the hydrocode predictions. Once this has been achieved the hydrocode will be used to populate a graph similar to that shown in figure 8c, this in turn will form the basis of a new direct hit algorithm within the INTAVAL model.

Additional firings will be made against aircraft structures in order to validate the hydrocode predictions of ricochet limit.

6.0 CONCLUSIONS

A large amount of data relating to the level of damage inflicted upon conventional aircraft structures by direct hitting missiles is available from high-speed test track firings carried out over the past 20 years in the UK.

Anecdotal evidence from actual air combat, mid-air collisions between fast jet aircraft and observation of trials against target drones suggests that the outcome of a direct hit is not always a kill.

The advances made in numerical simulation techniques over the past 10 years have now reached a stage where hydrocode modelling can provide accurate data on the behaviour of both the target aircraft and the missile following an engagement. This reduces the requirement for full-scale trials and effectively paves the way for an affordable assessment capability.

An overview of the UK capability in this area has been described and outline plans for the future direction presented.

7.0 REFERENCES

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8.0 ACKNOWLEDGEMENT

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SYMPOSIA DISCUSSION – PAPER NO: 22

Discusser's Name: Greg Czarnecki

Question:
When a warhead is included in the missile model, I suspect detonation will assist penetration and the richochet (as modeled) will not occur. Do you plan on adding a warhead component to your missile model?

Author's Name: Collins

Author's Response:
The warhead may well detonate prior to impact with the target. The objective of this work is to look at the level of damage from direct hit alone. The fragment damage will be taken account of usually within the lethality model either by the traditional fragment/shot line approach or by the use of structural/systems close burst envelopes.

Discusser's Name: Doug Wright

Question:
Do you compute the energy lost in missile impact due to structural collapse of missile?

Author's Name: Collins

Author's Response:
The current model uses a trials-based methodology, therefore the collapse of missile and target (if they occurred) would have been taken into account. The hydrocode uses a Goldthorpe erosion model to take account of the disintegration of the missile body.

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