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HSE CONTRACT RESEARCH REPORT No. 90/1996

DEVELOPMENT OF A SOFTWARE MODEL FOR MISSILE IMPACT DAMAGE - FINAL REPORT

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Failures of pipework or vessels can be initiated in [illegible]o be taken into account when undertaking a risk assessment. One class of such [illegible]hich impact from a vehicle, item of plant or airborne missile may result in pen[illegible]nt. The work presented in this report considers the impact of flying debris, which may [illegible]ailure, and could lead to an escalation of the event. A missile of a specified mass and velocity is [illegible]ct on a target of steel, concrete or pipework. The various current methods for addressing this problem have been reviewed, and a selection of appropriate formulae have been incorporated into the Missile Impact Model (MIM) software.

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CONTENTS

1.0 INTRODUCTION

Most hazardous scenarios which would be identified as part of a risk assessment or safety report entail the release of either toxic or flammable material from pipework or vessels. One possible initiating event for such releases is rupture or perforation due to the impact of 'missiles', which may be dropped objects or fragments from a nearby piece of machinery or from a vessel which may have exploded as a result of a BLEVE. In a risk assessment application, the most likely cause of missile generation is an explosion. The first stage of any risk assesment would therefore be to determine the number, size, shape, range and velocity of the missiles likely to be generated. These issues are not addressed in this project, which concentrates on the next stage in the risk assessment, that is, the effect of the missile on a target object, such as a tank, vessel or barrier. Further, the effects have been limited to the primary causes of loss of containment, such as penetration or perforation; no consideration has been given to secondary effects such as weakening of supports, structural collapse, etc.

In order to determine whether such fragments, of specified mass and velocity, can cause loss of containment, the study reported here was undertaken, and appropriate models coded into a software tool developed specifically for use by the Major Hazards Assessment Unit, HSE. It should be noted that the terms of reference did not envisage a major review with a detailed critique of each method; rather the objective was to identify a range of models which would cover various missile and target types, and could easily be incorporated into a simple software tool for use by MHAU.

Section 2 details the literature search undertaken in the field of industrial missile impact, while Section 3 presents the assessment criteria, assessment methods and conclusions on the mathematical models derived from the literature. Section 4 outlines the software QA standard used to develop the Missile Impact Model (MIM) software. Section 5 presents the project conclusions and recommended methods and discusses the possibilities for further research and development.

Extensive verification and validation of the MIM software has been undertaken, and reported in detail in the internal document presented to HSE. These are not repeated here, but a sample selection of typical results is included in Appendix 1.

Contents

2.0 LITERATURE SEARCH

The COMPENDEX engineering database was searched on-line using the following criteria:

- Keyword search:
  `MISSILE AND (IMPACT OR PERFORATION OR PENETRATION)`

- Published in the time period 1983-1993.

- Published in the English language.

The online search returned 83 references. A further 15 references were drawn from other sources, giving a total of 98 references.

A review of the material produced the following results:

Initial rejections (no appropriate model included)	57
References received	35
References unavailable	1
References outstanding	5
Total number of references considered	**98**

The outstanding references are normally available from the BLDSC, but were on loan to other users during the lifetime of this project.

Of the 35 references received the following classification was developed:

References with well documented missile impact models	9
References with data relevant to missile impact modelling	9
References with poorly documented models or models containing inconsistencies.	5
References irrelevant to missile impact modelling	12

The 23 relevant references and 5 outstanding references are listed below in Section 6.

3.0 MODEL ASSESSMENT

The 9 references with missile impact models describe a total of 22 different models. All the models examined assume a rigid missile is impacting upon a continuous homogeneous target. These are significant assumptions since missiles do deform on impact and targets are heterogeneous structures.

3.1 Assessment Criteria

The criteria used for assessing the usefulness of a certain model were as follows:

- Use of SI units or ease of conversion to SI units.
- Documented ranges of validity.
- Correlation with other similar models.
- Application of model to a wide range of target and missile types.

3.2 Assessment Method

Those models that were poorly documented with respect to units or validity ranges were not considered further. The remaining models were tested with a range of input values on a computerised spreadsheet. This allowed models to be compared by inspecting the spreadsheet results. Those models whose results were inconsistent with the consensus of other similar models were rejected. Where two or more models produced consistent results, the best documented and most widely applicable was chosen for incorporation into the MIM software tool.

3.3 Results of Model Assessment

Four models were considered sufficiently useful and well enough validated to be utilised in the MIM software. These models are:

- High Pressure Safety Code (1975)[1]	Equation 1
- Miyamoto (1984)[4]	Equations 2 and 3
- Barr (1990)[5]	Equation 4
- SCI (1992)[6]	Equation 5.

Of the remaining 18 models, 6 were validated but not used in MIM and 12 were rejected as being invalid or poorly documented. The validated models that were not used have more restrictive validity ranges or are less flexible than those incorporated into MIM.

3.3.1 Validated Models Used in the MIM Software Tool

Four different types of target are considered within the MIM software tool, namely:

i) Mild steel targets;
ii) Hardened steel targets;
iii) Concrete targets;
iv) Pipework targets.

Contents

The models used for each type of target are summarised below

In each of the models it is possible either to specify the missile velocity (V) and hence determine the target thickness (T) that would just be perforated, or alternatively to specify the target thickness and determine the minimum missile velocity required for perforation.

i) <u>**Mild Steel Target** - High Pressure Safety Code (1975)[1]</u>

T	Plate thickness (m)
M	Missile mass (kg)
D	Missile diameter (m)
V	Missile velocity (m s^{-1})

For rod shaped steel missiles impacting on a mild steel target:

$$MV^2 = 3\times10^9 D^3 (\frac{T}{D})^{1.41} \tag{1}$$

Published validity ranges: None

ii) <u>**Hardened Steel Target** - Model from Miyamoto (1984)[4]</u>

T	Target Thickness (mm)
D	Missile Diameter (mm)
θ	Total Nose Angle of Conical Missiles (Degrees)
E	Perforation Energy (Joules), ½MV^2
M	Missile mass (kg)
V	Missile Velocity (m s^{-1})

Impact of stainless steel into hardened pressure vessel steel.
For blunt missiles:

$$E = 2.9T^{1.5}D^{1.5} \tag{2}$$

For conical missiles:

$$E = 2.9T^{1.5}(T\ [1+2.9(\tan(\theta/2))^{2.1}])^{1.5} \tag{3}$$

For almost-blunt missiles, θ approaches 180°, and Equation (3) would give E = ∞. Equation (2) should therefore be considered as an upper limit for E, thus defining a value of θ above which the missile is effectively blunt.

Published validity ranges:

T	7-38 mm
M	3-50 kg
V	25-170 m s^{-1}
D	66-160 mm

iii) **Concrete Target** - Model from Barr (1990)[5]

V_c	Critical perforation velocity (m s^{-1})
g	Density of concrete(kg m^{-3})
F_c	Characteristic compressive strength of concrete (Pa)
p	Perimeter of the missile (m)
T	Thickness of the concrete (m)
M	Mass of the missile (kg)
r	Reinforcement quantity in percent

$$V_c = 1.3g^{1/6}F_c^{1/2}\left(\frac{pT^2}{\pi M}\right)^{2/3}(r+0.3)^{1/2} \quad (4)$$

Published validity ranges:

V_c	11-300 m s^{-1}
F_c	15-37 MPa
r	0-0.75 percent
$p/(\pi M)$	0.2-3 m kg^{-1}
$M/(p^2T)$	150-10000 kg m^{-3}

This model does not include the effects of spalling (from the front surface) or scabbing (from the rear surface). However, these effects are discussed further in the paper and methods given for prediction of the onset of scabbing.

iv) **Pipework Target** - Model from SCI (1992)[6]

T	Pipe Wall Thickness (m)
D	Missile Diameter (m)
D_p	Pipe Diameter (m)
E	Perforation Energy (Joules), ½MV^2
M	Mass (kg)
V	Missile Velocity (m s^{-1})
Au	Empirically derived constant, 8 x 10^9 (J m^{-3})

$$\frac{E}{D^3} = Au(T/D)^{1.7}(D/D_p)^{0.5} \quad (5)$$

Published validity ranges:

M	4-50 kg
T	0.007-0.018 m
D	0.025-0.17 m
D_p	0.150 m

3.3.2 Validated Models Not Used in MIM Software Tool

Although the models outlined below were generally of sufficient quality to be used in the software, it was felt that they did not add anything to the set which has already been identified in Section 3.3.1.

(i) Models from High Pressure Safety Code (1975)[1]

The following quantities are used throughout the HPSC models:

T	Plate thickness (m)
M	Missile mass (kg)
D	Missile diameter (m)
A	Impact area presented by missile (m^2) (since most models are appropriate to normal incidence, this can be considered to be equivalent to $\pi D^2/4$)
V	Missile velocity ($m\ s^{-1}$)

For small (< 1 kg) blunt missiles impacting on a F_c=35 MPa concrete target:

$$T = 18\times10^{-6}M^{0.4}V^{1.5} \tag{6}$$

For small (< 1 kg) blunt missiles impacting on mild steel target:

$$T = 6\times10^{-5}M^{0.33}V \tag{7}$$

For larger missiles (> 1 kg) the following is proposed:

$$T = \frac{CM}{A}\log_{10}(1+5\times10^{-5}V^2) \tag{8}$$

Where values for C include:

Concrete (Unreinforced, Fc = 15 MPa)	10×10^{-4}
Concrete (1.4% Reinforced, Fc = 22 MPa)	6×10^{-4}
Concrete (1.4% Reinforced, Fc = 40 MPa)	3.5×10^{-4}
Mild steel	0.5×10^{-4}

For rod shaped steel missiles impacting on a concrete target:

$$T = \frac{2\times10^{-7}MV^{1.5}}{D^{1.8}} \tag{9}$$

(ii) Model from TNO Yellow Book (1979)[7] (Steel Plate)

V_c	Critical perforation velocity ($m\ s^{-1}$)
σ_{fr}	Ultimate tensile stress of vessel material (Pa)
T	Plate thickness (m)
τ_{fr}	Ultimate shearing stress of vessel material (Pa)

M Mass of missile (kg)
D Missile diameter (m)

$$V_c^2 = \frac{(11.3\sigma_{fr}T^3 + \pi D\tau_{fr}T^2)}{M} \qquad \textbf{(10)}$$

Derived versions of the above equation are given for both nozzles or manholes and valves.

Published validity ranges:
T 0.003-0.05m

(iii) Ipson Residual Velocity Model (Steel Perforation) - Shaaban (1984)[2]

Missile weight	W
Missile length	L
Plate thickness	T

Any self-consistent units are valid.

$$V_r = \frac{(V_o^2 - V_p^2)^{0.5}}{(1 + Wp/W)} \qquad \textbf{(11)}$$

Where V_r is the residual velocity (ie the velocity of the missile after passing through the target), V_o is the impact velocity and V_p is the perforation velocity, which may be calculated using one of equations 1 to 10 above. Wp is the weight of target material driven from the plate.

$$W_p = \frac{WZT}{L} \qquad \textbf{(12)}$$

Where Z is the ratio of target to projectile material density.

Published validity ranges:
None.

(iv) Healey and Weisman Residual Velocity Model (Concrete Perforation) - Shaaban (1984)[2]

Penetration depth in infinitely thick target (from eqn. 21 of the paper)	x
Target thickness	T
Target thickness that would just be perforated	T_p

Contents

Any self-consistent units are valid.

For x $\leq$ 2D

$$\frac{V_r}{V_o} = [1-(T/T_p)^2]^{0.555} \tag{13}$$

For x > 2D

$$\frac{V_r}{V_o} = [1-(T/T_p)]^{0.555} \tag{14}$$

Where V_r is the residual velocity of the missile after penetration and V_o is the impact velocity.

Published validity ranges:
None.

3.3.3 Rejected Models

In view of the very specific and limited objective of this study, it was necessary to reject all but a handful of models. This section describes briefly some of the models which were rejected at an early stage because of missing information, incorrect units, insufficient validation data or lack of ease of use.

Models from Shaaban (1984)

Shaaban describes 11 impact models. General symbols used by Shaaban are:

Penetration	x
Missile weight	W
Missile mass	M
Missile cross sectional area	A
Missile diameter	D
Missile length	L
Missile impact velocity	V
Perforation energy	E
Plate thickness	T

A variety of non-SI units are proposed by the models and are not always clearly defined. No validity ranges are published.

Baker (1984)[3] and Recht (1971)[8] describe the same models as or derivative models to those described by Shaaban.

Contents

a) **Concrete Penetration models**

1. Petry Model

$$x = 12\frac{kW}{A}Log_{10}[1+\frac{V^2}{215000}] \quad (15)$$

Where k is an empirically determined constant.

2. Beth Model

$$\frac{R}{A} = a(x)V^{2\lambda}+b(x)V^2 \quad (16)$$

Where a(x) is a constant, b(x) is the inertial resistance of the target material and R is resisting force to missile penetration.

3. BRL Model

$$x = \frac{427}{\sqrt{f_c}}\frac{W}{D^2}D^{1/5}(\frac{V}{1000})^{4/3} \quad (17)$$

Where f_c is the compression strength of reinforced concrete.

4. ACE Model

$$x = \frac{222}{\sqrt{f_c}}\frac{W}{A}D^{0.215}(\frac{V}{1000})^{1.5}+0.5D \quad (18)$$

Where f_c is the compression strength of reinforced concrete.

5. NDRC Model

$$x=\frac{282}{\sqrt{f_c}}\frac{W}{D^2}D^{0.215}(\frac{V}{1000})^{1.5}+0.5D \quad (19)$$

Where f_c is the compression strength of reinforced concrete.

b) **Steel Penetration models**

6. SRI Model

$$\frac{E}{D} = S(0.34T^2+0.032T) \quad (20)$$

Where S is the ultimate tensile strength of the target minus the tensile strength in the steel.

7. BRL Model (Steel Penetration)

$$T^{3/2} = \frac{0.5k_p^2WV}{8.975\times10^{-2}D^{3/2}} \tag{21}$$

Where k_p is the collapse stress.

8. DeMarre Model

$$V = 2.05\times10^4(\frac{T}{M^{1/3}})^{3/4} \tag{22}$$

9. Thor Model

$$V = 4.05\times10^4(\frac{T^{0.906}}{M^{0.359}}) \tag{23}$$

10. Ipson Recht Model

A complex model for penetration of steel utilising the acoustic wave velocities and relative densities of the missile and target.

11. Kar Model

A complex model for penetration of steel utilising several constants relating to the missile and the standard Charpy V-notch fracture test applied to the target.

c) Pipe Impact models

SCI (1992)[6]
For indentation of pipes which are not perforated the following is described.

$$E = 25T^2\sigma(x/D_p)^{1/2} \tag{24}$$

Where x is the indentation, D_p is the pipe diameter, T is the pipe wall thickness and σ is the yield stress. Although no units are specified, it is assumed that they are SI.

4.0 SOFTWARE METHODS AND DEVELOPMENT

The IEE Software Quality Assurance Model (1990) has been used as a framework for the development of MIM. The IEE Software Quality Assurance Model describes a standard for quality assurance for a broad range of software developments. For small stand-alone developments, such as MIM, the following stages and deliverables were performed. Deliverables 1-4 were provided to HSE during the development of the program; deliverable 5 is substantially covered by this final report, but also includes a User Guide which has already been submitted to HSE.

	Development Stage	Deliverable
1.	User Requirements Specification and Review	Requirements Specification
2.	Software Design and Design Review	Design Document
3.	Software Coding	Computer Code
4.	Module Testing and System Testing	Test Plan and Results
5.	System Handover and Support	User Documentation and Support service

5.0 CONCLUSIONS

5.1 Literature Search

A large quantity of published material is available on missile impact. The majority of this information deals with impact at ballistic velocities (> 1000 m s^{-1}) under the umbrella of military research. There is a smaller but significant body of knowledge on industrial missile impact at velocities up to 300 m s^{-1}. The literature survey undertaken enabled a substantial portion of this knowledge to be collected and collated.

5.2 Model Assessment

The assessment of the models extracted from the literature search identified 22 models in total, of which:

- 4 Models were used in the MIM v1.2 software.
- 6 Models, with demonstrable validity, were not used in MIM v1.2 software.
- 12 Models were rejected using various criteria as indicated in the text.

5.3 Verification of MIM v1.2 Software Tool

The MIM v1.2 software has been verified against independent spreadsheet calculations, which have been presented in detail in an internal HSE report. Examples taken from this verification are presented in Appendix 1.

5.4 Example Application

Consider an explosion in which it has been assessed that a 0.1m diameter rod-shaped steel missile of mass 10kg could be produced and projected as far as a large mild steel vessel containing a hazardous substance. It is a requirement of the risk assessment to determine whether the vessel would be perforated, leading to domino effects. The velocity of the missile has been calculated as 200m/s and it is required to know whether the vessel would be penetrated by the missile.

Using the HPSC (1975) model (Equation 1)

$$MV^2 = 3 \times 10^9 \, D^3 \left(\frac{T}{D}\right)^{1.41}$$

where M = 10kg
V = 200 ms^{-1}
D = 0.1m

rearranging to find thickness, T:

Contents

$$T = \left(\frac{MV^2D^{1.41}}{3\ x\ 10^9\ D^3}\right)^{(1/1.41)}$$

$$= 0.024m$$

Therefore, the mild steel vessel would not be penetrated by the missile provided that it was more than 24mm thick.

MIM facilitates such calculations for a range of missile masses, and can also be used to calculate the penetration velocity required for a specified target thickness.

5.5 Possible Further Development

The literature search for material on industrial missile impacts could be extended. Bulson (1989)[24] and Bulson (1992)[28] are significant works that were unavailable at the time of this research, and it is possible that further models or validation data are included in this material. An area of possible development is a study on the effects of the contents of a vessel on the perforation energy. There is some data available for filled pipework under impact but no consistent model is available. No studies have considered the contents or the thermodynamic environment of a pressure vessel during impact.

The assumptions of the models used in MIM v1.2 are a significant simplification of what may be expected in reality. For example, missiles do deform on impact, and targets are likely to be discrete structures with specific weak points. To model these more complex situations adequately, a finite difference or finite element model would be required.

Contents

6.0 REFERENCES

Models of Industrial Missile Impact

1. Cox, B.G. and Saville, G. (eds.), '*High Pressure Safety Code*', High Pressure Technology Association, 1975, reprinted 1985.

2. Shaaban, A.A., 'Method for Computing Target-Missile Performance', in *Impact, Fragmentation and Blast (Vessels, Pipes, Tubes and Equipment)*, San Antonio, Texas, USA, 1984, p101-124.

3. Baker, W.E., 'Impact Effects of Industrial Missiles', in *Impact, Fragmentation and Blast (Vessels, Pipes, Tubes and Equipment)*, San Antonio, Texas, USA, 1984, p125-139.

4. Miyamoto, H., 'Integrity Assessment of Nuclear Containment Vessel Steels due to Missile Impact Load', *Nuclear Engineering Design*, **81**, September 1984, p277-283.

5. Barr, P., '*Guidelines for the Design and Assessment of Concrete Structures Subjected to Impact*', SRD R439 Issue 3, UKAEA, 1990.

6. Steel Construction Institute, '*Analysis of Projectiles*', HSE Offshore Technology Information, OTI 92 603, HMSO, London, 1992

7. Houweling, J. and Trense, R.W., 'Consequences of the Rupture of Vessels', in Methods for the Calculation of the Physical Effects of the Escape of Dangerous Material (Yellow Book), TNO, Netherlands, 1979, Chapter 9.

8. Recht, R.F., 'Containing Ballistic Fragments', in *Engineering Solids Under Pressure*, (ed. Pugh, H.), Institute of Mechanical Engineers, 1971, p50-60.

9. Ma Xaioqing and Stronge, W.J., 'Spherical Missile Impact and Perforation of Filled Steel Tubes', *International Journal of Impact Engineering*, **3**, No.1, 1985, p1-16.

Data Sources on Industrial Missiles

10. Corran, R.S., Ruiz, C. and Shadbolt, P. J., 'On the Design of Containment Shields', *Computers and Structures*, **16**, No. 1-4, 1983, p563-572.

11. '*Disintegration of an Ethylene Oxide Distillation Column at B. P. Chemicals, Antwerp, July 1987*', Incident Report, January 1988.

12. Holden, P.L., '*Assessment of Missile Hazards: review of Incident Experience Relevant to Major Hazard Plant*', report for HSE by SRD, 1986.

13. Reeves, A.B. and Holden, P.L., 'Analysis of Missile Hazards', *Institute of Chemical Engineers*, Symposium Series **93**, 1985, p205-222.

14. Closner, J.J. and Wesson, H.R., 'Safety and Reliability in the Storage of Refrigerated Liquefied Gases', *Structural Safety and Reliability: Proceedings of ICOSSAR the 4th International Conference on Structural Safety and Reliability*, Kobe, Japan, 1985, p645-651.

15. Rotz, J.V., 'Low Velocity Impact Tests on Reinforced Concrete Panels', *Proceedings of the Conference on Structural Engineering in Nuclear Facilities*, Raleigh, North Carolina, USA, 1984, p186-205.

16. Tam, V. and Simmonds, S., 'Modelling of Missile Energy from Gas Explosions Offshore', *The Management and Engineering of Fire Safety and Loss Prevention - Onshore and Offshore*, 3rd International Conference, Aberdeen, February 1991.

17. Zhong, H.Z. and Ruiz, C., 'Assessment of Damage Resulting from Missile Impact on a Spherical Shell', *International Journal of Impact Engineering*, **9**, No. 2, 1990, p223-236.

18. Nickell, R., Rashid, Y.R. and Kurkchubasche, I. R., 'Low Velocity Impact of Missiles on Reinforced Concrete Structures', *Journal of Pressure Vessel Technology, Transactions of ASME*, **113**, No. 2, May 1991, p127-139.

<u>**Rejected or Inadequately Described Missile Impact Models**</u>

19. Clancey, V.J., 'Diagnostic Features of Explosion Damage', *Sixth International Meeting of Forensic Sciences*, Edinburgh, September, 1972.

20. Moodie, K., 'Missile Effects Resulting from a Sudden Loss of Containment', *IBC Conference*, October 1988.

21. Yu, T.X. and Stronge, W.J., 'Large Deflections of a Rigid-Plastic Beam-on-Foundation from Impact', *International Journal of Impact Engineering*, **9**, No. 1, 1990, p115-126.

22. HSE, '*Canvey - an investigation of potential hazards from operations in the Canvey Island/Thurrock area*', HMSO, London, 1978.

23. Baker, W.E., Kulesz, J.J., Ricker, R. E. , Bessey, R. L. and Westine, P. S. '*Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and gas Storage Vessels*', NASA Report No: NASA-CR-134906, rept 02-4130, November 1975.

<u>**References Unavailable and hence not reviewed**</u>

24. Bulson, P.S. (ed.), 'Structures Under Shock and Impact', Proceedings of the First International Conference on Structures Under Shock and Impact, Cambridge, Massachusetts, USA, July 1989, Elsevier , 1989.

25. Barbagelata, A. and Vardanega, C., 'Contribution to the Formulation of Realistic Design Rules for Equipment Subject to Impact Loading', in 'Structures Under Shock

Contents

and Impact II', Proceedings of the Second International Conference on Structures Under Shock and Impact, Portsmouth, UK, June 1992, Computational Mechanics Publishers, Southampton, 1992.

26. Broadhouse, B. J., 'DYNA3D Analysis of Cone Crack Formation due to Heavy Dropped Loads On Reinforced Concrete Floors', in 'Structures Under Shock and Impact II', Proceedings of the Second International Conference on Structures Under Shock and Impact, Portsmouth, UK, June 1992, Computational Mechanics Publishers, Southampton, 1992.

27. Brown, M., Jacobs, M. and Mihsein, M., 'Impact and Perforation of Mild Steel Pipes by Low Velocity Missiles', in 'Structures Under Shock and Impact II', Proceedings of the Second International Conference on Structures Under Shock and Impact, Portsmouth, UK, June 1992, Computational Mechanics Publishers, Southampton, 1992.

28. Bulson, P. S., (ed.), 'Structures Under Shock and Impact II', Proceedings of the Second International Conference on Structures Under Shock and Impact, Portsmouth, UK, June 1992, Computational Mechanics Publishers, Southampton, 1992.

Software Quality Assurance Standard

29. Institution of Electrical Engineers, 'Software Quality Assurance Model Procedures', London, 1990.

Contents

APPENDIX

Verification Calculations for MIM v1.2 Models

Contents

A1. INTRODUCTION

The MIM model has been developed from the references reviewed in Section 3.3.1. Extensive verification has been undertaken for a range of velocities and material types and thicknesses. Full details have been given in the HSE internal report, but this Appendix gives selected examples.

The models used are given in Equations 1-5 in Section 3.3.1. The examples have been divided into those for a specified velocity and those for a specified thickness. The former examples use only Equations 1-4, and are presented in Section A2, while the latter examples use all five equations, and are presented in Section A3. The results presented are by no means exhaustive, but merely give an indication of the way in which they vary with the different variable input parameters.

A2. Impact on a target at a specified velocity

Method Miyamoto (1984) Equation 2
Blunt stainless steel fragments into hard pressure vessel steel

Mass of Missile / kg	Velocity / ms-1	Missile Diameter / m	Penetration / m	Penetration / mm
0.37	105	0.045	1.76E-03	1.8
0.92	10	0.061	1.04E-04	0.1
0.69	14	0.055	1.48E-04	0.1
10	30	0.134	9.97E-04	1.0
50	40	0.230	2.50E-03	2.5
100	50.9	0.290	4.34E-03	4.3
500	53.6	0.495	7.96E-03	8.0
1000	57.3	0.624	1.10E-02	11.0
2250	65.2	0.818	1.71E-02	17.1
5000	85.6	1.067	3.20E-02	32.0

Published validity ranges	
3-50	25-170

Method Barr (1984) Equation 4
Blunt steel fragments into a concrete target

Mass of Missile / kg	Velocity / ms-1	Target Material	Missile Perimeter / m	Penetration / m	Penetration / mm
0.37	105	Concrete Fcy=15Mpa	0.145	4.81E-02	48.1
0.92	10	Concrete Fcy=15Mpa	0.145	1.30E-02	13.0
0.69	14	Concrete Fcy=15Mpa	0.145	1.45E-02	14.5
10	30	Concrete Fcy=15Mpa	0.421	5.74E-02	57.4
50	40	Concrete Fcy=15Mpa	0.723	1.22E-01	121.5
100	50.9	Concrete Fcy=15Mpa	0.934	1.81E-01	181.2
500	53.6	Concrete Fcy=15Mpa	1.597	3.22E-01	322.1
1000	57.3	Concrete Fcy=15Mpa	2.012	4.27E-01	426.6
2250	65.2	Concrete Fcy=15Mpa	2.637	6.16E-01	615.8
5000	85.6	Concrete Fcy=15Mpa	3.442	9.86E-01	985.6
0.37	105	Concrete Fcy=22Mpa	0.145	4.17E-02	41.7
0.92	10	Concrete Fcy=22Mpa	0.145	1.13E-02	11.3
0.69	14	Concrete Fcy=22Mpa	0.145	1.26E-02	12.6
10	30	Concrete Fcy=22Mpa	0.421	4.97E-02	49.7
50	40	Concrete Fcy=22Mpa	0.723	1.05E-01	105.3
100	50.9	Concrete Fcy=22Mpa	0.934	1.57E-01	156.9
500	53.6	Concrete Fcy=22Mpa	1.597	2.79E-01	279.0
1000	57.3	Concrete Fcy=22Mpa	2.012	3.70E-01	369.6
2250	65.2	Concrete Fcy=22Mpa	2.637	5.33E-01	533.5
5000	85.6	Concrete Fcy=22Mpa	3.442	8.54E-01	853.7
0.37	105	Concrete Fcy=40Mpa	0.145	3.33E-02	33.3
0.92	10	Concrete Fcy=40Mpa	0.145	9.01E-03	9.0
0.69	14	Concrete Fcy=40Mpa	0.145	1.00E-02	10.0
10	30	Concrete Fcy=40Mpa	0.421	3.97E-02	39.7
50	40	Concrete Fcy=40Mpa	0.723	8.41E-02	84.1
100	50.9	Concrete Fcy=40Mpa	0.934	1.25E-01	125.4
500	53.6	Concrete Fcy=40Mpa	1.597	2.23E-01	223.0
1000	57.3	Concrete Fcy=40Mpa	2.012	2.95E-01	295.3
2250	65.2	Concrete Fcy=40Mpa	2.637	4.26E-01	426.3
5000	85.6	Concrete Fcy=40Mpa	3.442	6.82E-01	682.3

Published validity ranges	
0.2 - 1000	45-300

Contents

Method: Miyamoto (1984) Equation 3

Critical perforation velocity for sharp steel fragments passing through hard Pressure Vessel Steel Plate

Mass of Missile / kg	Plate Thickness / m	Nose Angle of Missile / Degrees	Velocity / m s-1
0.37	0.001	20	4.2
0.92	0.001	20	2.7
0.69	0.001	20	3.1
10	0.001	20	0.8
50	0.001	20	0.4
100	0.001	20	0.3
500	0.001	20	0.1
1000	0.001	20	0.1
2250	0.001	20	0.1
5000	0.001	20	0.0
0.37	0.01	20	132.3
0.92	0.01	20	83.9
0.69	0.01	20	96.8
10	0.01	20	25.4
50	0.01	20	11.4
100	0.01	20	8.0
500	0.01	20	3.6
1000	0.01	20	2.5
2250	0.01	20	1.7
5000	0.01	20	1.1
0.37	0.1	20	4182.3
0.92	0.1	20	2652.3
0.69	0.1	20	3062.6
10	0.1	20	804.5
50	0.1	20	359.8
100	0.1	20	254.4
500	0.1	20	113.8
1000	0.1	20	80.4
2250	0.1	20	53.6
5000	0.1	20	36.0
Published validity ranges			
3 - 50	0.007 - 0.038	0.066 - 0.16	

Method SCI Equation 5

Spherical steel fragments perforating pipework

Mass of Missile / kg	Missile Diameter / m	Pipe Diameter / m	ipe Thickne / m	Critical Velocity / ms-1
0.37	0.045	0.15	7.00E-03	301.0
0.92	0.061	0.15	7.00E-03	250.9
0.69	0.055	0.15	7.00E-03	265.7
10	0.134	0.15	7.00E-03	155.7
50	0.230	0.15	7.00E-03	112.8
100	0.290	0.15	7.00E-03	98.2
500	0.495	0.15	7.00E-03	71.2
1000	0.624	0.15	7.00E-03	62.0
2250	0.818	0.15	7.00E-03	52.7
5000	1.067	0.15	7.00E-03	44.9
Published validity ranges				
4 - 50	0.025 - 0.170	0.15	7 - 18	

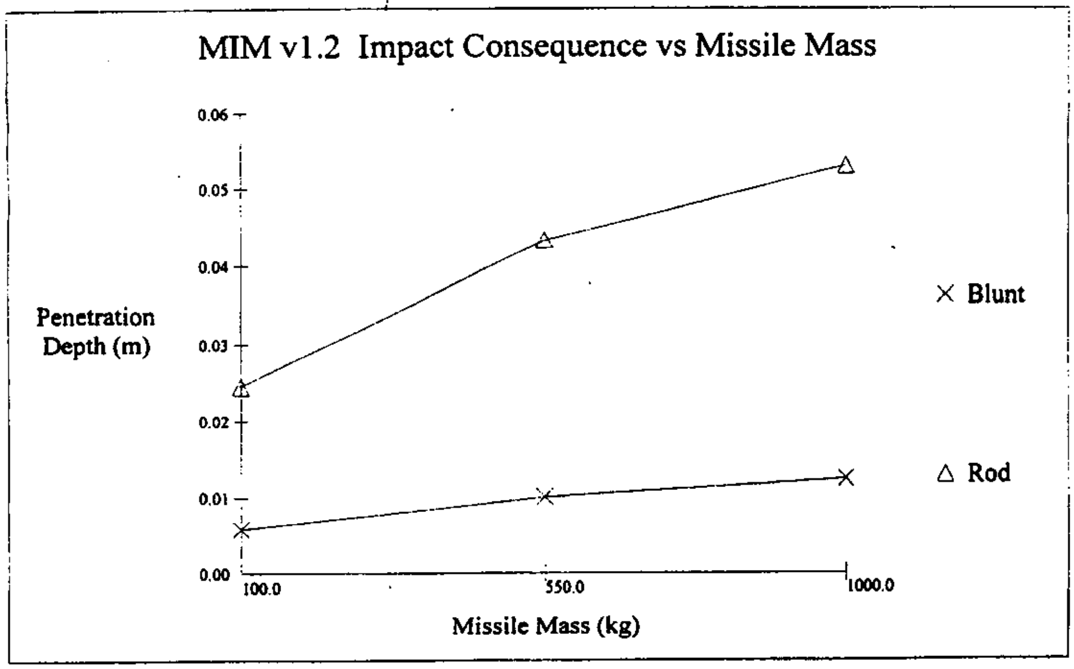

Figure A1 Verification Results for MIM v1.2

Target Material:	**Mild steel**
Missile Velocity (m/s):	**53**
Equation:	**1**

Contents

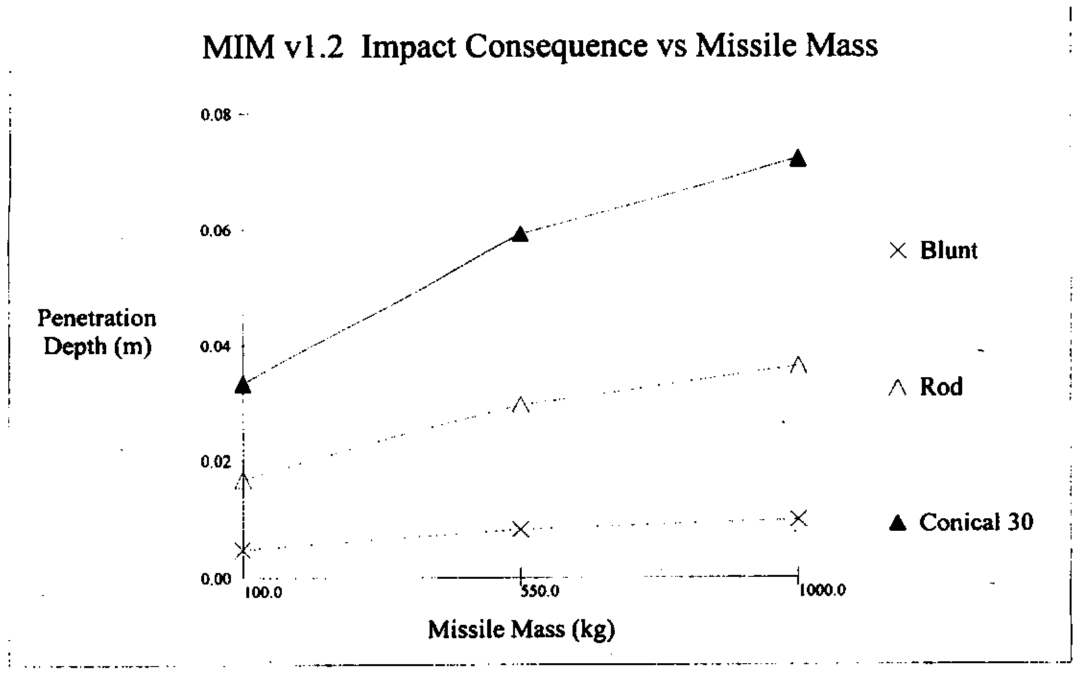

Figure A2 Verification Results for MIM v1.2

Target Material:	**Hardened steel**
Missile Velocity (m/s):	**53.0**
Equation:	**2**

Contents

A3 Impact on a target of specified thickness

Method HPSC (1975) Equation 1
Perforation velocities for rod shaped steel fragments into a mild steel target

Mass of Missile / kg	Target Thickness / m	Target Material	Rod Diameter / m	Velocity / ms-1
0.37	0.001	Mild Steel	0.008	14.9
0.92	0.001	Mild Steel	0.012	13.2
0.69	0.001	Mild Steel	0.010	13.0
10	0.001	Mild Steel	0.018	5.5
50	0.001	Mild Steel	0.038	4.4
100	0.001	Mild Steel	0.075	5.4
500	0.001	Mild Steel	0.137	3.9
1000	0.001	Mild Steel	0.168	3.2
2250	0.001	Mild Steel	0.212	2.6
5000	0.001	Mild Steel	0.306	2.3
0.37	0.003	Mild Steel	0.008	32.3
0.92	0.003	Mild Steel	0.012	28.6
0.69	0.003	Mild Steel	0.010	28.2
10	0.003	Mild Steel	0.018	11.8
50	0.003	Mild Steel	0.038	9.6
100	0.003	Mild Steel	0.075	11.6
500	0.003	Mild Steel	0.137	8.4
1000	0.003	Mild Steel	0.168	7.0
2250	0.003	Mild Steel	0.212	5.6
5000	0.003	Mild Steel	0.306	5.0
0.37	0.01	Mild Steel	0.008	75.4
0.92	0.01	Mild Steel	0.012	66.9
0.69	0.01	Mild Steel	0.010	65.9
10	0.01	Mild Steel	0.018	27.6
50	0.01	Mild Steel	0.038	22.4
100	0.01	Mild Steel	0.075	27.2
500	0.01	Mild Steel	0.137	19.6
1000	0.01	Mild Steel	0.168	16.3
2250	0.01	Mild Steel	0.212	13.1
5000	0.01	Mild Steel	0.306	11.8
0.37	0.1	Mild Steel	0.008	382.3
0.92	0.1	Mild Steel	0.012	339.1
0.69	0.1	Mild Steel	0.010	334.3
10	0.1	Mild Steel	0.018	140.1
50	0.1	Mild Steel	0.038	113.5
100	0.1	Mild Steel	0.075	137.8
500	0.1	Mild Steel	0.137	99.5
1000	0.1	Mild Steel	0.168	82.7
2250	0.1	Mild Steel	0.212	66.4
5000	0.1	Mild Steel	0.306	59.6

Published validity ranges

None	None

Contents

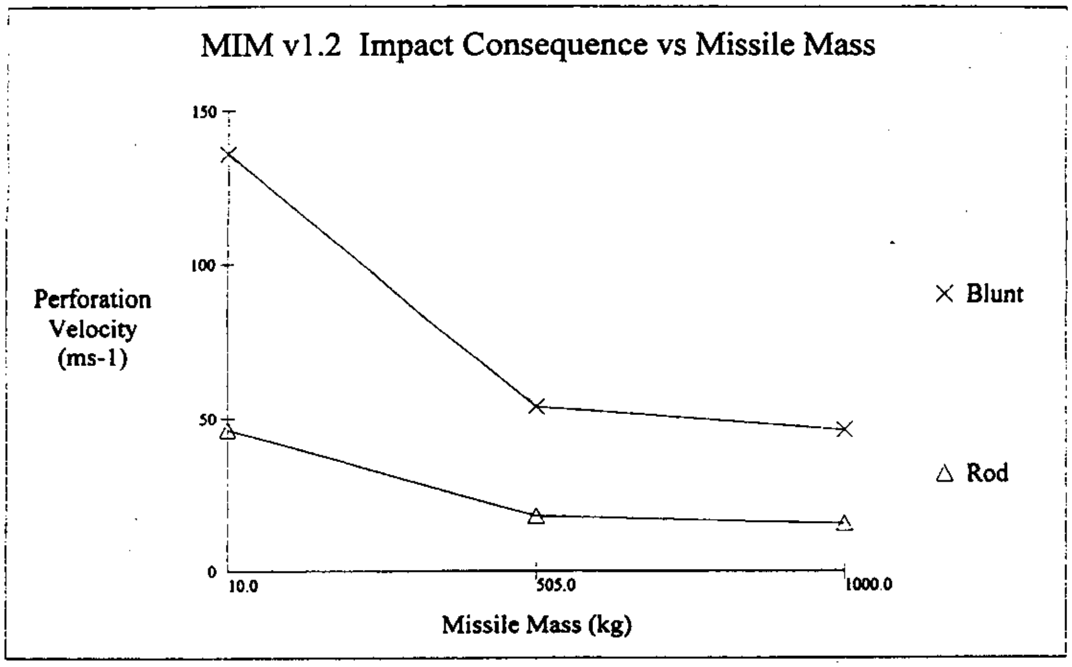

Figure A3 Verification Results for MIM v1.2

Target Material:	**Mild steel**
Target Thickness (m):	**0.01**
Equation:	**1**

Contents

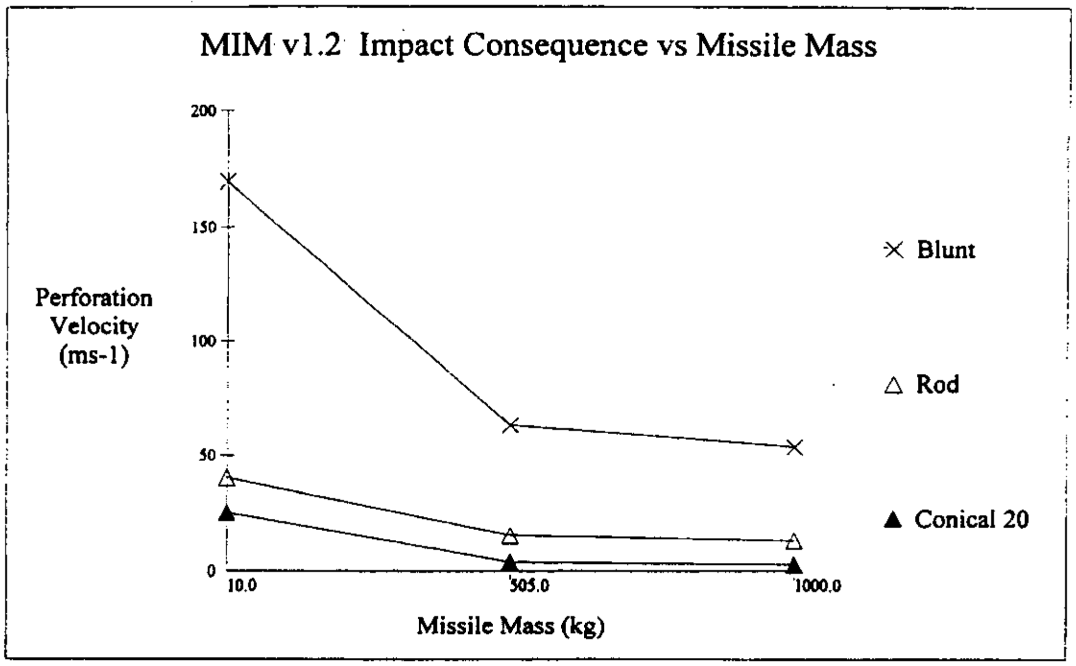

Figure A4 Verification Results for MIM v1.2

Target Material:	**Hardened steel**
Target Thickness (m):	**0.01**
Equation:	**3**

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