THEORY

VULN MODEL

DATE: December 2023

The VULN model converts the results of consequence models of hazardous effects into probabilities of levels of concern to the user. Typically these may be probabilities of death but they may also relate to financial damage or potential for escalation.

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1	July 2004	First draft created for SAFETI 6.5	D. Worthington		
2	Nov 2009	Updated with modelling extensions for Phast 6.6	D. Worthington		
3	March 2010	Final version for 6.6 release	D. Worthington	Yongfu Xu	
4	May 2013	Added a discrete impulse method for Phast 3D project	D. Worthington		
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ABSTRACT

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1 INTRODUCTION

1.1 The VULN Model

The current implementation of the VULN model converts radiation and explosion modelling results into probability of concern.

Radiation vulnerability is modelled as a relatively simple look up method.

For explosions it contains a number of methods to support different purposes. Each method is based on published literature, starting with the Purple Book approach[i]. In principle the model can be used in conjunction with any explosion model and its first implementation is to enable Multi-Energy, Baker Strehlow Tang and Vessel burst model results to be used in a Phast Risk QRA.

1.2 Background

People are vulnerable to explosions in a number of ways; causes of death include building collapse, impact by flying debris generated within buildings, impact by flying debris from objects starting away from the building, translation impact, burns and primary lung damage. There has been considerable research into understanding these mechanisms, much of which is oriented towards the subject of warfare.

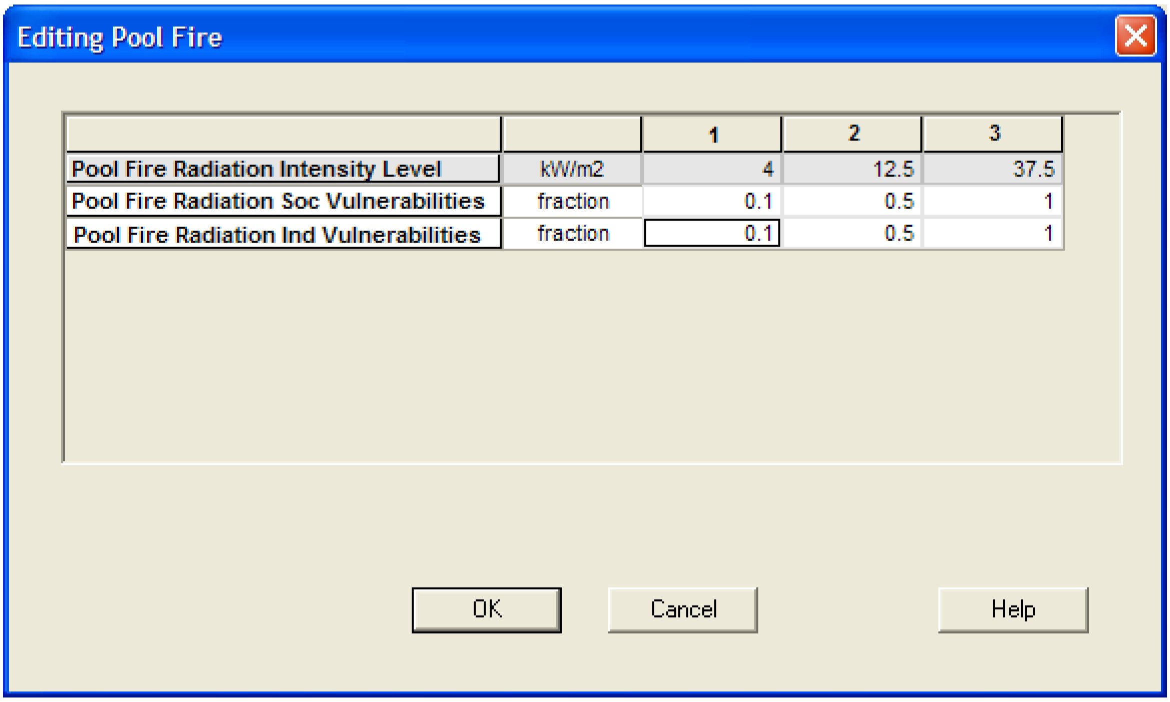
There has also been work oriented towards the needs of safety management in the process industry and the Green Book[ii] and the HSE sponsored works[iii] [iv] [v] provide a discussion of the possible ways people and buildings can be harmed by explosions. This subject is of considerable complexity and is not duplicated here.

We are particularly interested in being able to calculate probability of death from information about the strength of the explosion for application in hazard analysis and QRA studies. Fortunately there are publications that explain how to do this in practice; the Purple Book, and those from the CIA[vi] CCPS[vii] and the API[viii]. These methods relate probability of death to the overpressure and/or impulse information from the explosion calculations and we use the term ‘vulnerability’ to refer to such methods.

2. RADIATION VULNERABILITY

2.1 Radiation Intensity Method

The inputs to this method are radiation intensity and exposure time. The vulnerabilities are provided in tabular form and vulnerability must increase with radiation intensity. There is also an input defining the exposure time necessary to cause this level of harm and this time is common to all intensity levels.



When the model calculates vulnerability it uses the observed radiation level and exposure time to look up the vulnerability according to the table. There is no interpolation so the model behaves as a step function. For instance radiation levels in the range 4kW>= Intensity <12.5kW will have a vulnerability of 0.1 according to the tabular input. Below the lowest intensity level in the table the vulnerability is zero. Below the required exposure time the vulnerability is zero.

3. EXPLOSION VULNERABILITY

3.1 Purple Book Method (Discrete Overpressure)

The Purple Book method is based on overpressure levels alone.

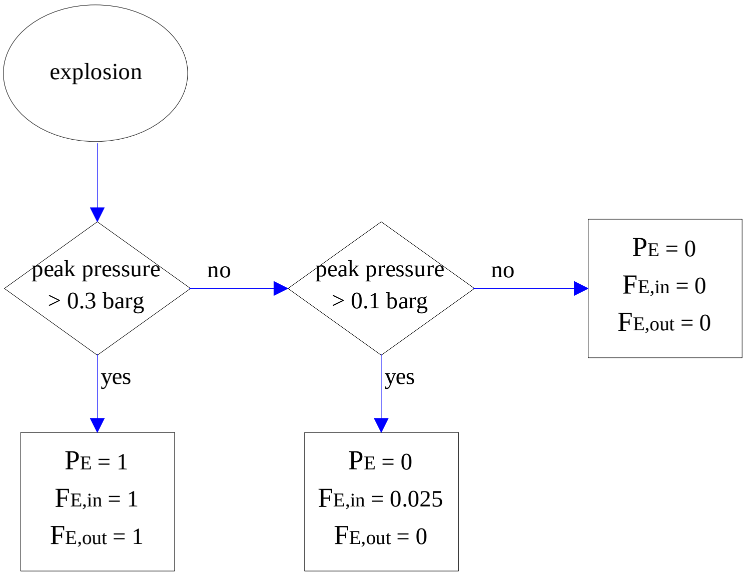


Figure 1 - ***Figure 3.2 from the Purple Book - Calculation of the probability of death, P_E, and the respective fractions of the population dying indoors and outdoors, $F_{E,in}$ and $F_{E,out}$ from exposure to a blast/explosion.***

So there are two key and discrete overpressure levels that define vulnerability, 0.1 and 0.3barg. So using the model we define 2 vulnerability levels;

Indoor Population

Level	Indoor Vulnerability	P_0/barg
1	1	0.3
2	0.025	0.1

Outdoor Population

Level	Outdoor Vulnerability	P_0/barg
1	1	0.3
2	0	0.1

3.2 CIA Method (Log-interpolated Overpressure)

In this method there are a family of lines that define vulnerability according to the type of building. As with the Purple Book the method is based on overpressure alone but the use of lines present the vulnerability (conditional probability of death) as continuous functions rather than discrete levels.

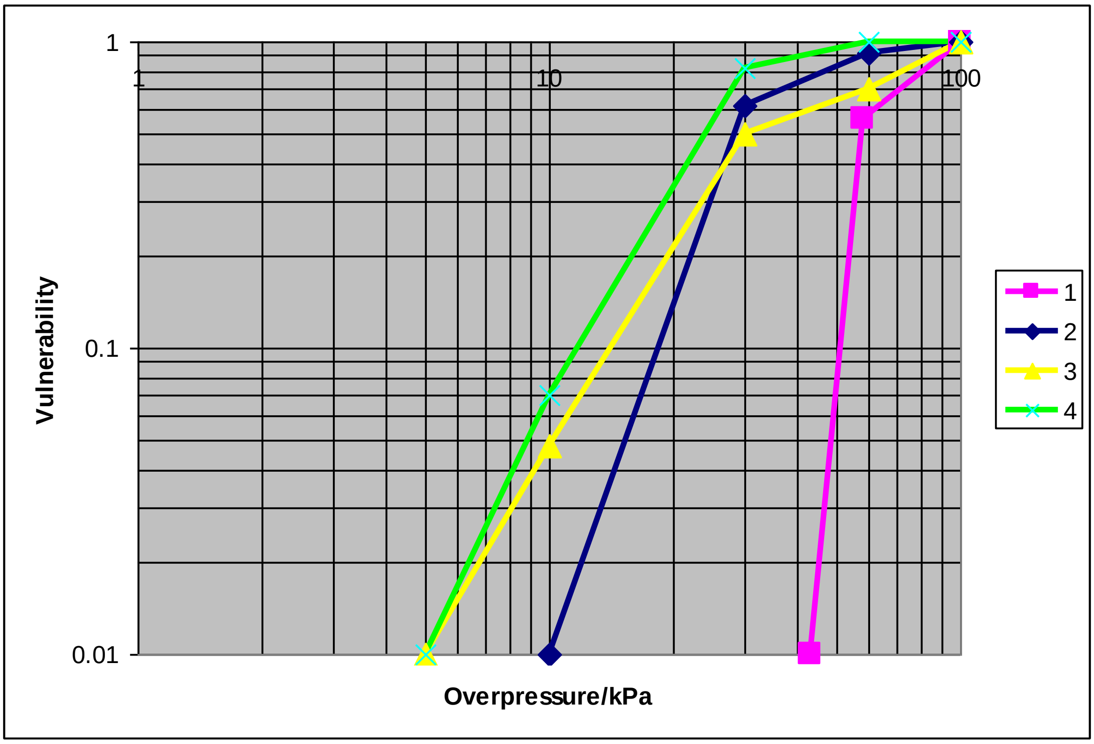


Figure 3 – Vulnerability for the 4 Different Building Types

The data points used in the model are listed below;

Building Type 1 Hardened structure building: special construction, no windows

Point	P_0/kPa	Indoor Vulnerability
1	43	0.01
2	58	0.56
3	100	1

Building Type 2 Typical office block: four storey, concrete frame and roof, brick block wall panels

Point	P_0/kPa	Indoor Vulnerability
1	10	0.01
2	30	0.62
3	60	0.92
4	100	1

Building Type 3 Typical domestic building: two-storey, brick walls, timber floors

Point	P_0/kPa	Indoor Vulnerability
1	5	0.01

2	10	0.048
3	30	0.5
4	60	0.7
5	100	1

Building Type 4 ‘Portacabin’ type timber construction, single storey

Point	P_0/kPa	Indoor Vulnerability
1	5	0.01
2	10	0.07
3	30	0.82
4	60	1
5	100	1

Using these data points the model interpolates on a log basis to calculate a vulnerability for a given input overpressure level.

3.3 Linear Interpolation Method (Linear-interpolated Overpressure)

This method is the same as the CIA method but instead performs the interpolation for both vulnerability and overpressure on a linear basis.

3.4 Pressure and Impulse Method

The previous methods use overpressure criteria only, however, both overpressure and impulse are influential in determining the response of a building to a blast wave. Vulnerability can be expressed as a function of both these inputs and the normal form of the relationship is typically a family of curves tending towards an L shape;

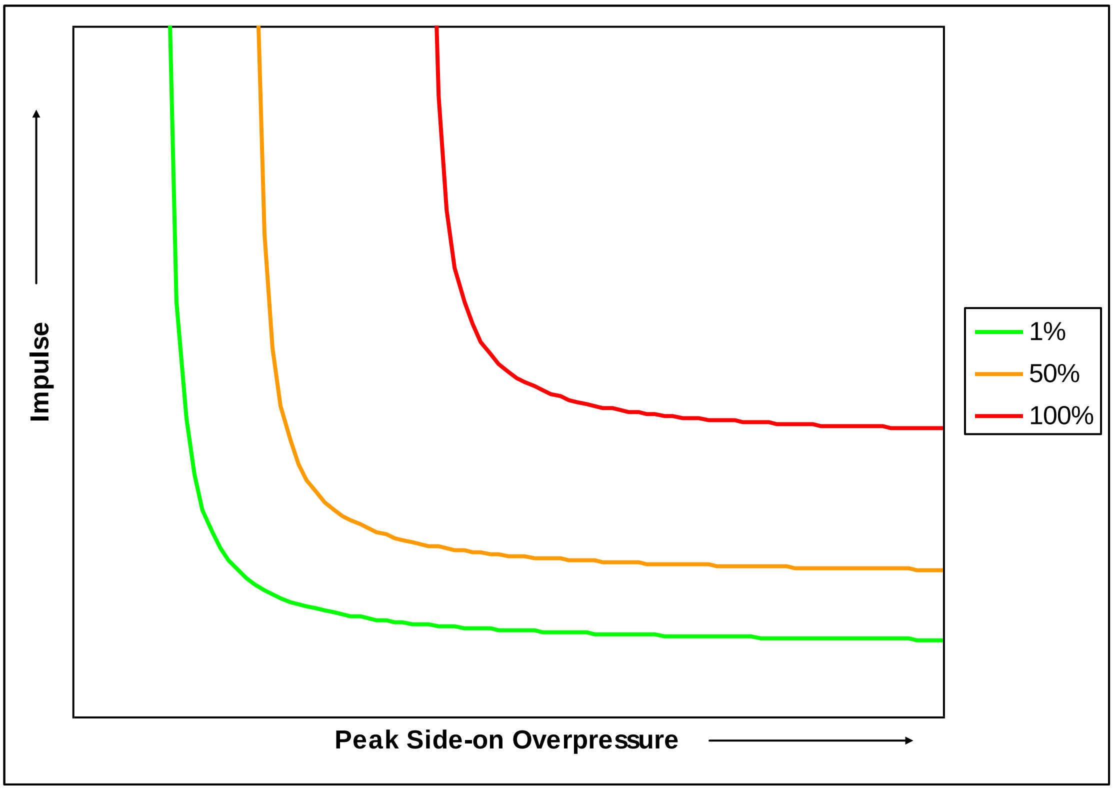


Figure 4 – Impulse Pressure example showing 1%, 50% and 100% vulnerability

Examples of such curves may be found in the Green Book, the CCPS Book and the Atkins reports where pressure and impulse are shown on log-log plots.

The user may want to use curves derived for a particular building type from these publications (brick-built house for instance) or derive curves specifically for a particular building in consultation with a structural engineer.

To apply the overpressure and impulse relationship in this model we take advantage of the common shape of these curves to define the vulnerability relationship;

$$I_i = I_{0,i} + \left(\frac{P - P_{0,i}}{A_i} \right)^{-E_i} \quad (1)$$

Where

I_i	Impulse for a given vulnerability level, i and overpressure level P
$I_{0,i}$	Threshold level of impulse for vulnerability level i
P	Overpressure level
$P_{0,i}$	Threshold level of overpressure for vulnerability level i
A_i	Constant to scale curve shape for vulnerability level i
E_i	Exponent to scale curve shape for vulnerability level i

The model may then obtain a vulnerability value by stepping in discrete levels according to user choice. There is no interpolation with this method.

3.5 Probit Method

Probit methods have been applied to explosion damage. For instance the Green Book[ii] uses some probit functions to define building damage levels based on overpressure and impulse (Annex IV). A straightforward probit relation based on overpressure alone was presented by Hurst et al of the HSE in 1989[ix]. To provide the DNV model with support for the probit type of method we provide the user with the ability to define A, B and N constants (on an SI basis) and the usual probit functions are used to calculate probability of death. The default constants are based on the HSE paper;

=

$$\mathrm{Pr} = 1.47 + 1.35 \ln(P / psig) \quad (2)$$

Which converts when using SI units for pressure (Nm^{-2}) to (using factor 6894.7572 Nm^{-2} per psi)

$$\mathrm{Pr} = -10.462 + 1.35 \ln(P / Nm^{-2}) \quad (3)$$

3.6 Discrete Impulse Method

The Pressure and Impulse method can be used for this purpose but for efficiency this method is provided to calculate lethality based on Impulse only. It works in a very similar way to the discrete pressure method only using impulse values instead.

3.7 Limits

The vulnerability is always in the range 0 to 1 inclusive.

For overpressures below the lowest values in the tables the vulnerability is assumed to be zero. For overpressures above the highest values in the table the maximum vulnerability is held without further increase.

3.8 Minimum Probability of Death

A parameter is provided to Vuln such that if a calculated probability of death is less than this parameter value then the level of harm is set to zero. This is of particular use in combination with the probit method but also applies to the other explosion vulnerability methods.

4. DISCUSSION

A comparison of all the 'Overpressure only' methods reveals apparently quite similar behaviour as shown in Figure 5 but this is quite misleading given the logarithmic axes. For instance at the higher pressure levels all the methods give a lethality of 1 over 1 bar except the probit method which give just over 0.5. Choice of method unfortunately appears to introduce yet another uncertainty in the QRA.

Specific building response on the other hand may be modelled using the Pressure-Impulse method and this allows the QRA to match the expected behaviour of a given building.

When applying these vulnerability relationships to risk calculations it is also possible to take into account the effect of reflection and dynamic effects. This model assumes that this additional calculation is made outside the vulnerability model. Phast Risk assumes that the vulnerability is based on 'side-on' overpressures and that reflection will increase the equivalent 'side-on' pressure to be compared with the defined curves.

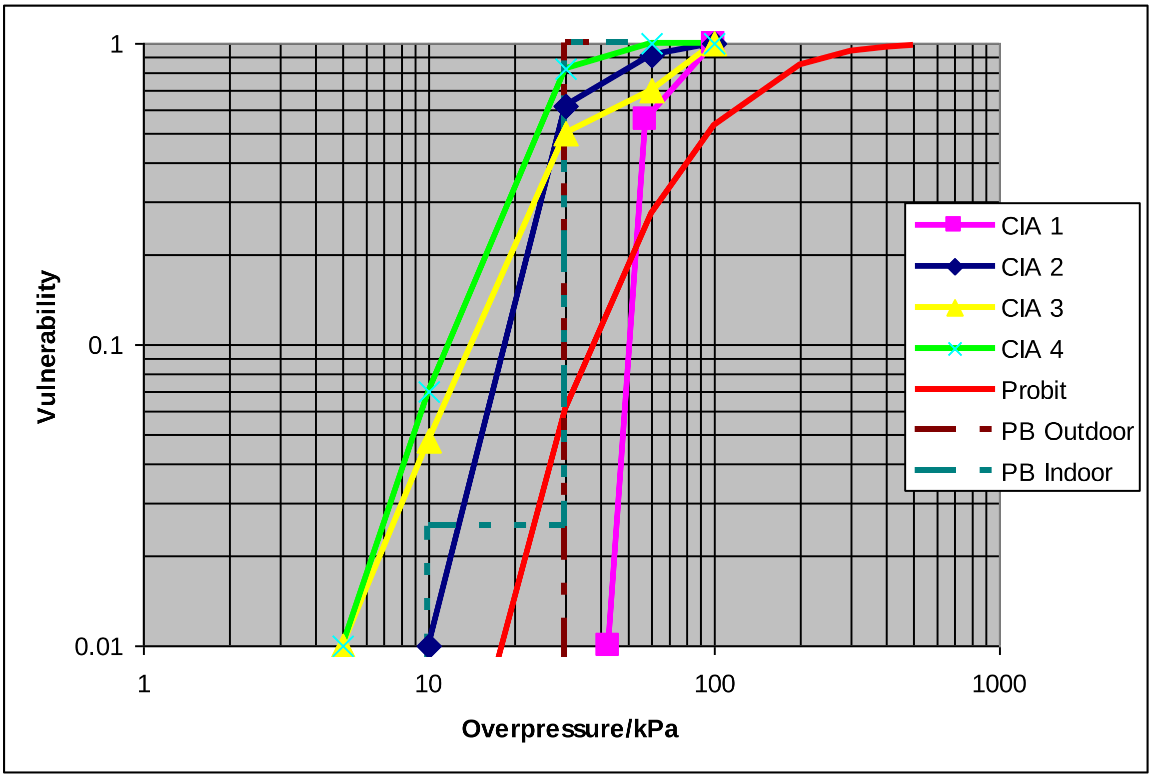


Figure 5 – CIA, Probit and Purple Book methods Compared

5. CONCLUSIONS AND RECOMMENDATIONS

The Purple Book and CIA methods provide a straightforward way to calculate vulnerability.

The overpressure/impulse method is less convenient for the user but offers the possibility of matching the QRA predictions to specific building designs and failure responses.

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