The Assessment of Impact on Nuclear Power Plant Structures in the United Kingdom

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INTRODUCTION

The results of impact research carried out over more than a decade in the United Kingdom and elsewhere are now being put together in the form of guidelines documents. These are for use in safety assessment investigations for operational nuclear plant and in the design of barriers in new Nuclear Power stations. UK studies are the outcome of a co-ordinated research programme undertaken by the CEGB, UKAEA and National Nuclear Corporation.

A considerable amount of research has been undertaken in the UK and throughout the world into the effects of impact. This has been, to a very large extent, experimental in nature in order to improve understanding of the consequences of impact and to assemble a data base of results. In addition, because of the difficulties of predicting the characteristics of the impactor in certain events, experimental studies have also been undertaken in order to give guidance on the size and velocity of missiles. Where possible, experiments have been conducted at different scales so that confidence in extrapolation to plant-size conditions from research study sizes may be assured.

Computer codes are in use for assessment purposes but their validation for specific applications has also involved experimental studies. We are not at a stage when we can give general support to the use of computer methods although this continues to be a principal objective behind much of the UK research programme. However, recognising the limitations in our knowledge of material properties under strain-rate affected conditions, in the mathematical modelling of properties, even where these are known, and, perhaps as importantly as any other factor, in our ability to define the conditions in any postulated event with precision, we have largely directed our research towards empirical methods. By their very nature, being based on available data, these have limitations as well, but they have the advantage over computer analyses of being relatively simple and quick to use. In any case, until a computer code is able to reproduce the conditions of the impact event up to and including the representation of failure of the target, empirical methods will have their place in the assessment route.

A significant strength of computer modelling is the ability to define the geometry of target and missile, whereas empirical methods tend to account for such aspects in a very restricted manner. Many of the earlier tests used circular-section missiles and flat targets and it has been a major feature of recent work in the UK that, at least as far as the missiles were concerned, the geometry be varied from the most simple, axisymmetric, solid and flat nosed missile shape previously used. Concrete targets have been varied in terms of reinforcement distribution and a small amount of work has been carried out with prestressed targets but all have been flat. Concrete targets include walls, floors and roofs and the class has been extended to cover steel clad walls and blockwork. Steel targets have been either flat panels or pipes. Clearly, any guidance for steel targets is limited in scope and its application has tended to be stretched to cover structures much different in geometry from those for which test data is available. It follows that there continues to be a question mark over the effect of target shape for different levels of damage.

There are three documents now available to designers and assessors from the partner organisations and one other is in the course of preparation. Those available are (1) procedures for the characterisation of missiles, (2) guidelines for the design and assessment of concrete structures subjected to impact and (3) pipewhip guidelines. The last of these will not be dealt with in this paper. The document in preparation deals with assessment of perforation damage to steel structures subjected to airborne missile impact. The second-mentioned document has been made publicly available by the UKAEA and it can be anticipated that we will endeavour to do the same with the others.

GUIDELINES FOR MISSILE CHARACTERISATION

We are here concerned with failure of nuclear power station plant leading to the generation of free flying missiles. Such failures are of low probability but are nevertheless addressed in the hazard assessments which are a routine part of both the design and the preparation of safety cases for nuclear power stations. All pressure vessel materials are covered by the guidelines, except reinforced concrete, but care has to be exercised if the methods are considered for other applications. For example, the description of pressure vessel failure does not apply to aluminium or certain cryogenic steels.

Missiles are generated when, through mechanical failure, a store of controlled energy (typically potential energy of compression of a gas in a pressure vessel, elastic strain energy in a loaded component or kinetic energy in a rotating machine) is converted into the unintended translational energy carried by some fragment or object. Alternatively the missile may be 'fed' by external agencies as with jet impact.

Missiles generated as a result of the failure of pressurised or rotating components or as a result of wind action are covered by the UK guidelines. They do not include lengths of whipping pipe, which are covered separately. In this paper, only missiles resulting from the disruptive failure of pressurised components are discussed.

The general requirements for each step in the assessment are as follows:

a) Establish whether the guidance covers the particular vessel contents. (Any issue of the procedure document is limited by the extent of experimental data available.)

b) Where called for, determine an appropriate failure frequency and failure mode for the component.

c) Determine the missile velocity and kinetic energy.

d) Consider hazard mitigation. (This has several features which are, in certain respects, peculiar to the missile source. Retention, missile trajectory or range and missile attitude are amongst the considerations required.)

Missile Type and Vessel Contents

Missiles are characterised on the basis of experimentally obtained relationships (Baum, 1987). The data is presently available for only two types of vessel contents: vessels containing high pressure gas and vessels containing a liquid at a temperature such that rupture initiates flash evaporation. Even for these vessels it is not possible to cover all types of missile because of an absence of experimental data. The absence of experimental data prevents the characterisation of vessels containing a liquid where flash evaporation does not occur and the absence of sufficient data those which are pressurised with gas but where a large proportion of the volume is occupied by loose particulate material.

The current guidelines for cylindrical vessel missiles deal with end-caps, rockets, which are the other portion of the vessel producing an end cap missile, whole vessel, arising from an axial split, single large fragment, single small fragment and fragments from disintegration. Spherical vessel missiles are limited to hemispherical fragment and fragments from disintegration. Our interest is primarily in cylindrical vessels and pipes (which are not covered by the guidelines) and it is for those that research continues.

Failure Frequency

If it is necessary to include an assessment of failure frequency, the event giving rise to missiles must be identified as random or non-random (such as common mode / common cause failures and knock-on failures). Examples of non-random failure are of a non-seismically qualified pressure vessel in a severe earthquake or by blast or missiles from an adjacent failed vessel. In these cases it may be necessary to assume a probability of failure equal to unity following the initiating event. With regard to random failures, the potential failure frequencies of pressurised components are clearly influenced by the standard of design and manufacture, by the operating conditions and by the provision of inspection / maintenance procedures. It is possible to use statistical studies of historical failures of pressure vessels but the operational regimes of those vessels must be equivalent, in at least a qualitative sense, to that of the plant being assessed, for the failure rate to be meaningful.

Failure Mode

The failure mode of a pressurised component is important in determining the characteristics of any missile generated. The nature of the fracture determines the fracture path and hence the missile geometry. The likelihood of three types of fracture, namely brittle, ductile / brittle and ductile, must be considered and the guidelines follow Baum's (1987) approach.

The nil ductility temperature of the material of the pressurised component is compared with the operating temperature. If the operating temperature is sufficiently low that the material toughness is low and it may therefore fail by cleavage, brittle rupture can occur. In respect of brittle fracture, it should be borne in mind that the number of fragments is subject to certain constraints:

a) the total of the missiles make up the surface of the vessel

b) there will be a distribution of fragment sizes, with some larger pieces

c) missiles below a certain minimum size will not cause significant damage.

The guidelines give some possible, approximate methods for indicating the potential number of missiles arising from brittle fracture. It should be noted that as well as a large number of relatively small fragments, large fragments are also usually found. As an example, Brown and Smith (1944) reported that brittle rupture of a 11.7 m diameter sphere generated 20 fragments.

If the operating temperature of the pressure vessel is above the nil ductility temperature, the most likely mode of failure is ductile fracture.

As pointed out by Baum (1987): "There are, at present, no well established criteria for predetermining the course of a ductile fracture and both regular and irregular missiles have to be considered. Ductile failures generally generate a small number of large missiles." See, for example, a discussion on the topic of 'Design of chemical and nuclear installations against impacts from plant generated missiles' (Chicken, 1980).

Missile Velocities

Ideally, given sufficient experimental data and a good understanding of the physical processes involved, missile velocities would be determined on the basis of statistical correlations. At present, however, missile velocities, which are an upper bound to the available experimental data, are derived from graphically presented relationships. These were presented by Baum (1987) with the exception that for a single small fragment missile from an ideal gas filled vessel the correlation has since been amended (see Figure 1). The graphs present both data and the recommended, upper limit velocities. This gives scope to the user to make a less conservative assessment if he is able to justify the results. Where there is a large body of data covering a wide range of parameters, the upper limit velocities are typically twice the mean value. In those cases where data is sparce, the upper limit velocity may, for conservatism, be increased by 50% to give it comparable statistical significance.

To determine the upper limit velocity of a missile, one of two parameters is required, F, the dimensionless initial acceleration of the missile, or E, the available expansion energy of the vessel contents. In addition, the velocity of sound in the high pressure gas, a_o, is required for vessel contents -1a. The external pressure is generally assumed small relative to the internal pressure, P_o, but in cases where this does not apply, F should be based on $P_o - P_e$, rather than on P_o.

$$F = \frac{P_o AR}{Ma_o^2} \qquad (1)$$

$$a_o = \sqrt{\frac{\gamma P_o}{\rho_o}} \qquad (2)$$

where γ is the isentropic expansion coefficient.

For an approximately perfect gas, Baum (1984a) shows :

$$E = \frac{P_o \phi_o k}{\gamma - 1} \qquad (3)$$

$$\text{where } k = \left[1 - \left(\frac{P_e}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right] + (\gamma - 1)\frac{P_e}{P_o}\left[1 - \left(\frac{P_e}{P_o}\right)^{\frac{-1}{\gamma}}\right] \qquad (4)$$

Where the pressure, P_o, is sufficiently high that intermolecular forces and finite molecular size influence the behaviour of the gas or where the initial temperature and pressure ratio, P_o/P_e, are such that towards the end of the expansion condensation will occur, the ideal gas approximation is no longer valid and E must be evaluated using the Mollier chart for the gas in question. Note that P_e is the external pressure and not necessarily equal to one atmosphere (0.1MPa).

The combination of pressure and temperature at which non-ideal gas behaviour becomes important can be determined from a generalised compressibility chart (Perry and Chilton, 1973 or Bannister et al, 1978). The behaviour can be regarded as ideal if $1.05 \geq \bar{P}/\bar{\rho}K_u\bar{T} \geq 0.95$ where $\bar{P} = P_o/P_c$, $\bar{\rho} = \rho_o/\rho_c$ and $\bar{T} = T_o/t_c$ are the pressure, density and temperature normalised with respect to conditions at the critical point. K_u is the Universal Gas Constant (8.314 J/K/mol).

When E is required for a liquid which flashes on rupture, it must be evaluated from the Mollier chart for the particular fluid (that is, an enthalpy-entropy chart) or from a temperature-entropy chart.

For an ideal gas-filled vessel end-cap missile, the recommended velocity follows a simple analysis by Moore (1967) which assumes the full rupture pressure acts on the missile during its motion from its initial position for a distance equal to the diameter of the opening generated by its removal from the vessel.

For an ideal gas-filled vessel rocket missile, F is calculated with A = the area of the open end of the vessel.

We have only two data points for a single large fragment missile. Otherwise, the data for end cap missiles are the basis for the recommended upper limit velocity.

Examples of the derivation of some of the missile characteristics based on the above approach are given in the Appendix.

Hazard Mitigation

The UK guidelines follow Baum (1987) with regard to assessing missile range and that, in turn, is based on Baker (1984). The information will not be repeated here. Baum (1987) also describes the approach for discounting pressure vessel missile hazard on the basis of available energy which is included in the UK Guidelines.

ASSESSMENT OF CONCRETE STRUCTURES

The UK guidelines (Barr, 1988) deal only with flat plate targets. Where the amount of curvature in the impact-affected area is small, the approximation to a flat slab is justified. However, the effect of curvature is to be investigated in due course. Two broad classifications of missile are considered, "soft" for those significantly deformed as a result of the impact and "hard" for those insignificantly deformed. In the case of the former, a force-time history may be used to calculate the target response. A typical example of a soft missile is a crashing military fighter aircraft. With hard missiles, the impact force is controlled by the strength of the concrete in the impact zone. The boundary between the two classifications (that is, "semi-hard"), which may affect the assessment of damage arising from some of the pressure vessel missiles considered above, is not yet completely specified by UK tests.

The guidelines cover damage levels identified as perforation, penetration, spalling and scabbing together with a mode which involves through thickness cracking. All damage levels are considered for hard missile impacts but only penetration for pipe missiles (semi-hard) and only perforation for soft missiles.

Hard Missile Impact - Perforation

The perforation mode of damage is associated with the missile passing completely through the target. Following Barr et al (1983) and Gittus (1982), we have recommended a correlation of data based on a CEA/EDF formula (Berriaud et al, 1978), modified to include the influence of reinforcement quantity and accounting for non-circular section missiles by means of an equivalent diameter given by the perimeter divided by π :

$$V_c = 1.3\rho^{1/6} f_{cy}^{1/2} \left[\frac{pe^2}{\pi M} \right]^{2/3} (r + 0.3)^{1/2} \qquad (5)$$

Limits of applicability for the variables are given in Fullard and Barr (1987). The quantity r represents the amount of reinforcement expressed as a percentage each way in each face (Barr et al, 1983). Wicks et al (1987), considering low velocity tests, concluded that impact surface reinforcement did not contribute very much towards the perforation velocity. More recently, reinterpretation of that test data suggested that for those cases where the reinforcement levels are different in the two faces, r should be taken as one third the each way value on the front face plus two thirds the each way value on the rear face. Wicks et al (1987) noted an improvement in the perforation resistance if the reinforcement level is achieved with smaller diameter, closer meshed reinforcement but we are not ready to quantify this for guidelines purposes yet.

It will be seen that target width and boundary conditions are not accounted for. In fact much information derives from tests where the span to thickness ratio, w/e was in the region of 8 but with a wide range of boundary conditions. The problems in resolving the issue can be seen from the following appraisals of low velocity tests, all involving perforation at speeds well below the range for which the prediction is found to hold (45 m/s). Tests using targets with rear face-only reinforcement, reported by Wicks et al (1987), included two span to thickness ratios. These suggest that a multiplier to a value of V_c, derived using the two thirds r term, $(0.6 + 0.068\, w/e)$ is appropriate for $5 < w/e < 7.6$. In another series (Sinclair et al, 1987), for $w/e = 5$, a multiplier of 0.65 could be asserted from the results. However, in the latter case it was assumed that r was equal to the full value of reinforcement in the rear face. Even if the same reinforcement expression is used in both cases for the same span, the comparison of measured perforation velocity with predicted velocity would be different. The final complicating factor is that the boundary conditions were different in the two cases.

The UK guidelines for hard missile perforation deal with steel plated walls, adding an amount to the r term equal to the fractional cross section of the plate, for rear face plating. Front face plate contribution is small and is associated with shear plugging. However, the guidelines advise that steel plates added to blockwork barriers have the effect of making the composite barrier indistinguishable from a plated concrete target. The guidelines report that tests on unplated concrete blockwork targets (f_{cy} = 22 MPa, mortar 7 MPa) indicate they are perforated with 60% of the energy required for monolithic concrete slabs of the same strength and thickness.

Nose shape effects are not included in the above perforation formula. The limited data indicates that, for target thickness to missile diameter ratios of 1 or less, a hemispherically nosed missile needs a velocity at least 30% greater than a flat nosed missile, while sharp nosed missiles (cone or chisel) need velocities at least 10% greater.

If impact direction is non-perpendicular, work done with short missiles and equal missile diameter and target thickness indicates that it is conservatives to use the line of sight thickness in the perforation formula. Impact resistance increased as a result of missile rotation as it passed through the target but nose shape effects increased the perforation energy compared with flat nosed missiles by less than 10%.

Hard Missile Impact - Sub-perforation

For both penetration and scabbing assessments, the UK guidelines specify the use of the NDRC(79) formula as recommended by Gittus (1982). No guidance is given for spalling. Experimental evidence suggests that the extent of spalling in a prototype structure cannot be assessed from scale model testing. The guidelines discuss a cracking mode of damage which is observed as the development of a full through thickness crack. For velocities above 30 m/s, the scabbing velocity is approximately the same as the cracking velocity. On the other hand, Sinclair et al (1987) indicated that cracking damage could be produced for high mass, low velocity impacts at velocities well below the predicted scabbing velocity. As a consequence, on-going research in the UK is seeking to produce a suitable assessment procedure for low velocity impacts.

Semi-Hard Missile Impact

Recent experiments with hemispherically ended shell-type missiles have shown that the structural collapse of the missile only influences the perforation velocity for shell thickness to diameter ratios less than 0.05 and that values less than 0.025 are required before enhancement to the perforation velocity exceeds 20%.

In the case of pipe missiles striking open-end on, the Gittus (1982) recommendation of the NDRC(79) formula for penetration is followed.

Apart from this limited information we are unable to provide guidance for semi-hard missile assessment. It can be noted that progress is being made in this area with regard to validating computer codes.

Soft Missile Impact - Perforation

The guidelines cover impact by a crashing military aircraft and involve the determination of an average dynamic force, F_{av}. The assessment of perforation by a soft missile is also done on the basis of a comparison of the average force applied by the missile with the dynamic punching strength, F_p of the concrete slab. F_{av} is defined as 90% of the total impulse delivered divided by the time to deliver that portion of the total impulse. The dynamic punching strength is given by:

$$F_p = 8170\,(R\,f_{cu})^{1/3}\,T\,\pi(D + 2.5T) \qquad (6)$$

The method is accurate when the duration of loading is greater than the time for the slab to reach its peak deflection response. Otherwise, equation (6) provides a conservative estimate of the punching strength. The data on which the expression is based involved slabs with aggregate size to slab depth (A_g/T) of between 5% and 7% and the expression may become non-conservative for smaller values. With the following parameter ranges:

$$0.07 < T < 0.9 \text{ m},$$

$$0.66 < D/T < 1.3 \text{ m},$$

$0.22 < R < 1.26$ %ew,
$25 \times 10^6 < f_{cu} < 63 \times 10^6$ Pa
and $0.05 < A_g/T < 0.07$,
an accuracy of $\pm 20\%$ has been obtained.

CONCLUSIONS

It is clear that for missile characterisation, more work is required to generate data on long vessels or pipes where the reservoir affects the acceleration of missiles, and also on other vessel contents such as flashing fluids, non-flashing fluids and vessels containing particulates. The fact that upper bound methods are used is a conservatism that is only partly off-set by providing details of the data base to allow the user scope for justifying lower missile velocities. It is considered that improvements to the correlations of existing data could be made and these could be more statistically meaningful where there is sufficient data.

Assessment of impact is based on best fits to available test data. However, boundary effects, concrete reinforcement selection and missile geometry are not yet addressed as completely as needed. In addition, guidance to the assessment of low velocity damage needs to be made available.

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NOMENCLATURE

(Note that certain symbols are defined only within the text.)

A	Breach area	m^2
a_o	Velocity of sound in high pressure gas	m/s
D	Diameter of missile	m
E	Maximum expansion work available from vessel contents	J
e	Concrete target thickness	m
F	Dimensionless initial missile acceleration (eqn (1))	
f_{cu}	Concrete cube strength	Pa
f_{cy}	Concrete cylinder strength	Pa
h	Vessel wall thickness	m
k	See equation (3)	
M	Missile mass or Unfragmented missile mass	kg
M_v	Total mass of vessel	kg
P_e	Pressure of atmosphere external to vessel	Pa
P_o	Vessel rupture pressure	Pa
p	Missile cross section perimeter	m
R	Vessel radius or Average rear face reinforcement level	m %ew
T	Depth from impact face to rear face reinforcement	m
V	Peak missile velocity	m/s
V_c	Concrete perforation velocity	m/s
w	Target span	m
γ	Isentropic expansion coefficient	
ϕ_o	Volume of vessel contents	m^3
ρ	Density of concrete	kg/m^3
ρ_o	Density of vessel contents	kg/m^3

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Appendix: Examples of Missiles Generated by the Rupture of a Cylindrical Pressure Vessel

Vessel details

Material = steel (density, $\rho_f = 7850 \text{kg/m}^3$)
Radius, R = 1 m
Vessel length, L = 6 m
Vessel volume, ϕ_o = 18.85 m^3
Wall thickness, h = 0.01 m
Operating pressure, P_o = 2.0 MPa
External pressure, P_e = 0.1 MPa

The vessel is assumed to contain air at ambient temperature (that is, the isentropic expansion coefficient, $\gamma = 1.4$ and the velocity of sound in the undisturbed gas, $a_o = 345$ m/s).

The problem

The nature of missile production is uncertain and the possibilities are to be examined for three different missile types using the upper limit velocities of Baum (1987).

The total energy available to do work on the fragments, E , is derived from equations (3) and (4):

$$E = \frac{P_o \phi_o k}{\gamma - 1}$$

$$\text{where } k = \left[1 - \left(\frac{P_e}{P_o}\right)^{\frac{\gamma-1}{\gamma}}\right] + (\gamma - 1)\frac{P_e}{P_o}\left[1 - \left(\frac{P_e}{P_o}\right)^{\frac{-1}{\gamma}}\right]$$

$$\text{Then } k = \left[1 - \left(\frac{0.1}{2.0}\right)^{\frac{1.4-1}{1.4}}\right] + (1.4 - 1)\frac{0.1}{2.0}\left[1 - \left(\frac{0.1}{2.0}\right)^{\frac{-1}{1.4}}\right]$$
$$= 0.4256$$

$$\text{Then } E = \frac{2 \times 10^6 \times 18.85}{(1.4 - 1)} \times 0.4256$$
$$= 40.1 MJ$$

End cap missile, 1-1a

End cap mass, M = 377 kg. F is given by equation (1):

$$F = \frac{P_o A R}{M a_o^2} = \frac{P_o \pi R^3}{M a_o^2} = \frac{2 \times 10^6 \times \pi \times 1^3}{377 \times 345^2} = 0.14$$

End cap velocity is given by:

$$V = 2 F^{0.5} a_0 = 2 \times 0.14^{0.5} \times 345 = 258 \text{ m/s}$$

$$\text{Kinetic energy} = \frac{1}{2} M V^2 = \frac{1}{2} \times 377 \times 258^2 = 12.55 \text{ MJ}$$

Rocket missile, 2-1a

The missile is assumed to be the whole vessel minus one end cap.

Rocket missile mass, M = 3395 kg.

F is given by equation (1):

$$F = \frac{P_oAR}{Ma_o^2} = \frac{P_o\pi R^3}{Ma_o^2} = \frac{2 \times 10^6 \times \pi \times 1^3}{3395 \times 345^2} = 0.0155$$

Rocket velocity is given by:

$$V = 2.18\,[F(\frac{L}{R})^{0.5}]^{2/3}\,a_0 = 2.18\,[0.0155\,(\frac{6}{1})^{0.5}]^{2/3} \times 345$$
$$= 85 \text{ m/s}$$

$$\text{Kinetic energy} = \frac{1}{2}MV^2 = \frac{1}{2} \times 3395 \times 85^2 = 12.26 \text{ MJ}$$

Whole vessel missile, 3-1a

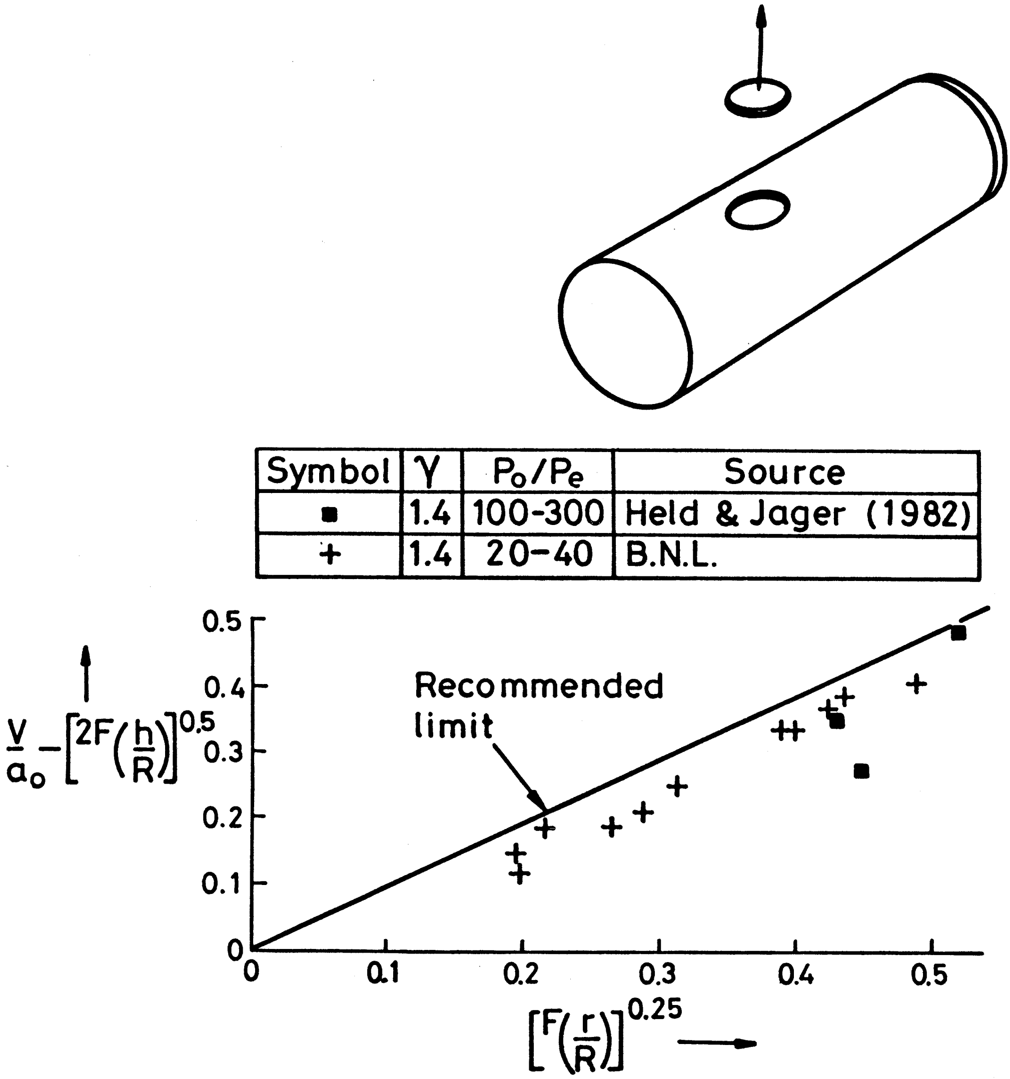
The missile is assumed to be the whole vessel with an axial split.

Vessel mass, M = 3772 kg.

Vessel velocity is given by:

$$V = 0.17\,(2\,E/M)^{0.5} = 0.17\,(2 \times \frac{40.1 \times 10^6}{3772})^{0.5} = 24.8 \text{ m/s}$$

$$\text{Kinetic energy} = \frac{1}{2}MV^2 = \frac{1}{2} \times 3772 \times 24.8^2 = 1.16 \text{ MJ}$$



Symbol	γ	P_o/P_e	Source
■	1.4	100-300	Held & Jager (1982)
+	1.4	20-40	B.N.L.

Recommended upper velocity

$$\frac{V}{a} = \left[\frac{2Fh}{R}\right]^{0.5} + 0.96 \left[\frac{Fr}{R}\right]^{0.25}$$

Where h is the wall thickness

FIG.1. A Single Small Fragment Ejected from a Cylindrical Vessel. Ideal Gas.