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EXAMPLES OF THE SUCCESSFUL APPLICATION OF A SIMPLE MODEL FOR THE ATMOSPHERIC DISPERSION OF DENSE, COLD VAPOURS TO THE ACCIDENTAL RELEASE OF ANHYDROUS AMMONIA FROM PRESSURISED CONTAINERS

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Examples of the successful application of a simple model for the atmospheric dispersion of dense, cold vapours to the accidental release of anhydrous ammonia from pressurised containers

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SUMMARY

A brief review of an earlier publication, which contains a description of a simple model for the atmospheric dispersion of heavy cold vapours, is given. The predictions of the model are compared with accounts of six accidents in which quantities of anhydrous ammonia in excess of ten tonnes escaped into the atmosphere from pressurised containers or pipelines. It is demonstrated that some of these accidents provide evidence that the escaping ammonia becomes part of a mixture which is denser than air and that a simple liquid column analogy may successfully be used to predict the rate of growth of the radius of the mixture with time, at least during the early stages of its development. It is also shown that another prediction of the model, that the heating of the cloud by the ground does not in general cause it to become buoyant, is also explicitly verified by the accounts of two of the accidental releases. The simplified assumptions made in the model are critically examined and it is shown that some progress can be made towards resolving uncertainties. It is argued that the choice of mechanisms for the rate of entrainment of air, and the associated scaling problems, are the greatest remaining uncertainties which must be tackled experimentally before a 'complete' model of heavy, cold vapour dispersion can be developed.

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CONTENTS

1. INTRODUCTION

In a recent paper,[1] a model for the atmospheric dispersion of 'puff' releases of dense, cold vapours has been described and has been applied to the sudden failure of vessels containing anhydrous ammonia under pressure. Reference (1) was used to predict the characteristic features of the ammonia-air mixtures formed as a consequence of such a failure, using a model in which three important physical phenomena – gravitational slumping, heating of the cloud by the ground and entrainment of air – were clearly described by simple mathematical equations. It was argued that three particular predictions are so insensitive to details of the modelling that they will remain, even when the existing formidable difficulties in describing a model of dense vapour dispersion have been overcome and a 'complete' and detailed scheme has been developed. These predictions are as follows.

1.1 Important predictions of Reference (1)

1.1.1 Denser than air mixtures (P1)

If ammonia is **rapidly** released from a pressurised vessel, a denser-than-air mixture of ammonia and air is formed. This is because the following sequence occurs; 'flashing' of the ammonia as the pressure in the vessel is relieved; vigorous bulk boiling causing fine fragmentation of the part of the ammonia that does not flash into vapour; the rapid turbulent entrainment of air; evaporation of the liquid droplets and cooling of the air; the consequent formation of a dense ammonia-air mixture. This phenomenon is explained in more detail by Haddock and Williams[2] and is also reviewed in Reference (1).

1.1.2 Rate of growth of radius (P2)

If it is arbitrarily assumed that enough air is entrained to evaporate all of the liquid droplets, and that the mixture of ammonia and air so formed is initially in a cylinder the height of which equals the radius, then the subsequent rate of growth of radius with time is well described by using a liquid column analogy. This describes the phenomenon known as **gravitational slumping.** In particular, the equation, first chosen by Van Ulden[3] for modelling the spread of Freon – 12 vapour clouds, is adequate, i.e.

$$\frac{dR}{dt} = c\sqrt{(\rho - \rho_a)\frac{gh}{\rho}} \quad \ldots (1)$$

where R is the radius, t is the time, ρ is the density of the mixture, ρ_a is the density of the air, h is the height of the cylinder, g is the acceleration due to gravity and c is a constant, taken to be unity. The rate of growth of the radius predicted by Equation (1), changes very little even if it is coupled with plausible prescriptions for the heating of the cloud by the ground or for the entrainment of air during and after gravitational slumping. The question of when this prediction ceases to be valid is addressed in Section 2.6.

1.1.3 Ground hugging (P3)

Unless the atmosphere is very still (i.e. almost no wind and little convective turbulence) the heating of the cloud by the ground does not cause it to become buoyant. That is, as it blows downwind it continues to hug the ground and plume rise does not take place.

In addition to the definite predictions P1, P2 and P3, several uncertainties were identified in Reference (1).

1.2 Uncertainties in the model

1.2.1 Large vapour clouds (U1)

There are no existing experimentally tested schemes for calculating the rate of entrainment of air into large, dense vapour clouds.

1.2.2 Scaling (U2)

Related to U1 is the problem of scaling. Can a model that may be found suitable for predicting the consequences of experimental releases in the range 0·1-1 Te, reasonably be expected to scale through three orders of magnitude, or more, in order to predict the consequences of the sudden failure of a large pressurised storage tank, possibly containing upwards of 1,000 Te?

1.2.3 Semi-pressurised tanks (U3)

Some of the largest existing pressurised storage tanks are kept semi-refrigerated, 0°C being a typical temperature (so that the pressure does not exceed about 50 psig, rather than the 90 psig of a tank at 15°C). In that case, the stored energy density is reduced and, should a rapid release occur, it is conceivable that the 'vigour' of the subsequent bulk boiling process might not be sufficient to produce the finely fragmented liquid droplets of ammonia necessary to ensure that the bulk of the contents of the vessel become and remain airborne. There are no experimental data, however, on the critical temperature below which this is true (see Section 2.5).

1.3 Examples of accidental release

In this note, reports of six accidental releases of ammonia are surveyed. It is shown that all of the predictions P1-P3 are surprisingly well verified by the facts that can be deduced from the reports – surprisingly that is, in view of the simplicity of the model and the difficulties in accurately defining a source for the atmospheric dispersion model. It is also shown that some progress can be made towards reducing the uncertainties U2 and U3 (but not U1). The six accidents are as follows.

1.3.1 The Houston tanker crash[4] (A1)

At about mid-day on 11 May 1976 a road tanker carrying 19 Te of anhydrous ammonia crashed through a barrier on an elevated section of motorway near Houston, Texas. The pressurised tank burst on falling to the roadway below, and the contents were rapidly released.

1.3.2 Spontaneous failure of a storage vessel,[5] Potchefstroom, South Africa (A2)

On 13 July 1973, a tank containing some 30 Te of anhydrous ammonia failed catastrophically while being filled from a tank car containing another 8 Te. It appears that most if not all of the contents escaped at once.

1.3.3 Train derailment and collision, Crete, Nebraska[6] (A3)

On 18 February 1969, a train derailment and collision caused the complete fracture of a rail tank car and the release of about 76 Te of ammonia.

1.3.4 Train derailment, Pensacola, Florida[7] (A4)

On 9 November 1977, a train derailment caused the tank head on a rail car to be punctured, so that 50% of the contents (some 40 Te) quickly vapourized.

1.3.5 Pipeline leaks, mid-America pipeline system[8] (A5)

On 6 December 1973, at Conway, Kansas, a pressurised ammonia pipeline ruptured and about 230 Te escaped into the atmosphere over a period of about half an hour (A5(a)). On 13 August 1974, the same pipeline failed again at Hutchinson, Kansas, and about 350 Te of ammonia escaped to the atmosphere over a period of about an hour (A5(b)).

Table 1 contains a summary of some of the relevant characteristics of the releases described above.

2. VALIDATION OF THE MODEL

It is notoriously difficult to extract information from eye-witness accounts of accidental releases, but these remain the only source of data with which comparisons can be made for releases in excess of 1 Te.

2.1 Verification of denser-than-air mixtures

Some of the work in this section has already been reported by Griffiths.[10] The contention is that, if ammonia escapes rapidly from pressurised containment the resulting vapour is denser than air.

The six accidents listed above have provided abundant evidence for the presence of heavy mixtures of ammonia and air, as is summarized in Table 2.

A1 – A professional photographer was in a building to the north of the site of the **Houston tanker crash** and began to take photographs after about a minute. The earliest of these photographs clearly shows a liquid-like tongue running away from the site of the crash (this photograph may be found in Reference (1)). The photograph shows that the total breadth of the plume was about six hundred metres.

A series of three photographs,[4] taken from above four days later, show the area of grass burnt by the ammonia cloud around the motorway intersection where the crash took place. This extended for some 200 m in the average upwind direction and some 400-600 m across the wind. There is one particularly interesting feature of these photographs (which are to appear in a forthcoming SRD publication on the modelling of the dispersion of heavy vapours). This is that the boundary of the burnt grass area was very sharp, particularly in the upwind and crosswind directions. This is to be expected of a gravity driven 'puff'. Experiments carried out in the laboratory[11] show that the denser fluid runs along the ground with a sharply defined leading edge. For a 'puff' that is both slumping and moving downwind, the trailing edge should reach a maximum distance upwind, come to a momentary halt and then retreat as the gravity driven velocity of the edge of the puff falls below the mean velocity of the centre of the puff. The Houston tanker crash, therefore, provides excellent evidence for the existence of a slumping vapour cloud.

A2 – Eye-witness accounts of the accident at **Potchefstroom** speak of an 'immediate resulting gas cloud' which was 'about 150 m in diameter and nearly 20 m in depth'.

In prediction 2 of Section 1.1 the assumption was made that enough air should be mixed into the escaping ammonia vapour-liquid droplet mixture to evaporate all of the droplets. For the escape of a complete tankful at 20°C this requires an air to ammonia mass-ratio of 20 : 1. If the visible cylinder at Potchefstroom contained all of the ammonia vapour*, this ratio is of the right order of magnitude. Subsequently, the puff moved slowly towards a nearby housing estate and became some 300 m in width at about 450 m downwind from the tank. The plume did not rise from the ground (people were killed 200 m downwind of the tank); moreover, dead or dying people, eighteen in all, were found on all sides of the failed vessel. Here, therefore, the ammonia behaved in a fashion that was at least non-buoyant.

A3 – Eye-witness accounts of the consequences of the train derailment and collision at **Crete, Nebraska,** speak of a vapour cloud which 'extended **westward** beyond the Big Blue River'. A map in the report[6] shows that this was at least 500 m. The cloud also extended for 'several blocks **north** and **south** of the railroad'. The north-south dimension of the cloud was, therefore, several hundred metres. One of those killed by the ammonia cloud was outside a house just over 100 m **northeast** of the fractured tank car. This is another example consistent with a dense ammonia-air mixture spreading in all directions.

A4 – The most remarkable feature of the **Pensacola** train derailment[7] was that the resulting cloud was picked up by the radar of the nearby Pensacola airport (directly upwind). After five minutes it was already 'about a mile across' and it travelled nine miles across land and water before fading. It did not become buoyant. The obvious candidate for a mechanism capable of producing such a broad cloud in five minutes is gravity driven slumping.

**During a recent visit to the USA, one of the author's colleagues, Dr R. F. Griffiths spoke with officials of the US National Transportation and Safety Board. In the aftermath of the Houston Tanker Crash there was some evidence that the vapour cloud detectable by smell was somewhat larger than the visible vapour cloud. There are scant data on the extent of this separation, however.*

A5 – On the whole, there is little to be gleaned from the report on the two **MAPCO pipeline failures**,[8] except that each accident is illustrated by photographs which show the visible cloud hugging the ground as it travelled downwind, so displaying non-buoyant behaviour.

2.2 Validation of numerical predictions of growth of radii

The evidence for the existence of dense ammonia-air mixtures is conclusive; what of the contention that Equation (1) may be used to predict their radii? Table 3 shows some of the consequences of the reported accidents together with the calculated predictions. The continuous releases from the MAPCO pipeline (A5) are excluded from this comparison since the model, as so far developed, applies to puff releases only. The specific prediction made in Reference (1) is that the spread of the cloud ought to be roughly independent of detailed assumptions about the rate of entrainment of air or the rate of heating of the cloud by the ground.

For two of the accidents, that at Houston (A1) and at Pensacola (A5), there are observations of cloud breadth at a known (or approximately known) time. As can be seen from Table 3, Equation (1) may be used to predict radii that agree with those observed to within a factor of $\sqrt{2}$. The constant c is uncertain to this extent – Van Ulden[3] shows that $c = 1$ is constant with his Freon-12 experiment while theoretical derivations of Equation (1), based on Bernouilli's Theorem, lead to the conclusion that $c = \sqrt{2}$ is possible.[12] In addition, the position of the upwind edges of the burnt grass area at Houston is consistent with that expected for a slumping cloud in the prevailing conditions of low windspeed.

As for the Potchefstroom accident, (A2) inspection of Table 3 shows that the cloud appears to have become broad enough to indicate that gravitational slumping forces were at work but that the simple model probably gives too large an estimate of the observed breadth. One possible reason for this is that the vessel was on a site among several other industrial installations and that the cloud moved towards a town. The buildings would cause turbulence in addition to that already present in the atmosphere and would perhaps mix and dilute the slumping cloud more effectively than predicted by the simple model (which assumes that the surrounding terrain is flat), thus terminating slumping relatively quickly. This explanation is consistent with the observed larger breadth of cloud at Pensacola, where the ammonia-air mixture began to travel over the sea, which qualifies as an extremely smooth surface (see Section 2.6 for a more detailed explanation). At Houston the only large body in the vicinity of the crash was the motorway intersection itself, which is an open structure; the intersection is within an urban area. It must be stressed, however, that there is no model known to the author with which it is possible to predict the effects of buildings on the atmospheric dispersion of heavy vapours.

In the remaining accident, at Crete (A3), the cloud rapidly became at least half-a-kilometre in radius, which corresponds to a few minutes of slumping. More detailed comparison with the model is not possible, since there is no information given about the time this took. Such scanty details as are available do not contradict the model.

On balance, then, the simple slumping model appears successfully to predict the rate of growth of an ammonia-air 'puff' spreading over a smooth surface, and prediction P2 made in the introduction stands up reasonably to comparison with observation.

2.3 Height of cloud

As has been explained, the initial height of the source cylinder for the atmospheric dispersion model is arbitrarily set equal to its radius. This is not a critical assumption since the cylinder rapidly collapses under gravity and, after a few seconds, the height does not much depend on the starting value (but this may not be true of more sophisticated models). Sooner or later slumping must stop and the height of the cloud must begin to increase. Subsequent predictions of the height as a function of time depend on the assumptions made about the rate of entrainment of air; this dependence, as has been shown, is not so crucial for the growth of the radius. The account of the Pensacola accident, however, states that after a few minutes or so the height of the cloud was 'about 125 feet', i.e. about 40 metres, when it was about a mile in diameter. In order to make a prediction with the simple model it is necessary to use not only Equation (1), but also assumptions about the rate of entrainment of air, as is explained in Reference (1). The model then predicts that the height of the cloud should be 40 m when the diameter is about 1300 m. Since there is great uncertainty about what the rate of entrainment of air into a heavy vapour should be, this agreement (to much better than a factor of two) is encouraging.

2.4 Prediction that the ammonia vapour cloud does not become buoyant

As has been explained, the ammonia is expected to entrain some ten or so times its own mass of air as it rapidly escapes from a pressurised vessel. The resulting ammonia-air mixture is cold, because liquid ammonia droplets have been evaporated, and so is denser than is the surrounding atmosphere. If the mixture is heated to the ambient temperature it becomes buoyant and could rise. Since the puff passes over a surface that is warmer than itself, there is a heating effect that could make it buoyant. On the other hand, air is also being entrained as a result of the action of ambient atmospheric turbulence. If the mixture was not also being heated, its density would always exceed or equal that of the atmosphere as it was being diluted. In Reference (1) it was shown, by numerical example, that (except, perhaps, when the ground is much hotter than the air above it, in unstable weather conditions, or when there is virtually no wind) the dilution effect is much the more powerful and the mixture never becomes buoyant. This is the basis for prediction P3, made in the introduction. Even if the mixture does become less dense than air it still may not rise, see Reference (1).

The prediction has been dramatically verified by the radar observations of the Pensacola accident (A4). The cloud was seen to travel for four miles over water and for five miles over land; it did not rise*. Similarly, the account of the MAPCO pipeline rupture at Conway (A5(a))[9] states that 'the foglike vapour was visible for $\frac{1}{2}$ mile from the leak, and invisible, but very irritating to the eyes, nose and throat for the next $3\frac{1}{2}$ miles from the leak. Beyond that point, NH_3 odours were readily detectable for 4 miles ...'. In other words, people at ground level felt the effects of the release for a distance of eight miles; there was no evidence that the plume ever became buoyant. Admittedly the MAPCO release was a continuous one, whereas the model of Reference (1) is for puff releases. In this particular respect, however, the prediction ought to apply equally to both continuous and puff releases.

2.5 Semi-refrigerated vessels

One of the uncertainties identified in Section 1.2, was whether the failure of a semi-refrigerated storage tank, at a temperature of e.g. 0°C, would result in the bulk of its contents becoming airborne. The Crete accident is of some relevance here, since the atmospheric temperature at the time of the release was only −15°C and the corresponding pressure inside that tank only 20 psig (see Table 1). In spite of this a large, slumping vapour cloud was formed which does not seem to have been any smaller than that expected following the failure of a fully pressurised tank. The uncertainties in the description of the consequences of the release are so great, however, that this point cannot be taken as having been proved conclusively. Nonetheless, it appears that caution is advisable as there is no evidence here to support the contention that the total mass of ammonia becoming airborne from a semi-refrigerated tank is smaller than that from a fully pressurised tank at, e.g. 90 psig. Equivalently, it is not safe to assume that the consequences of the sudden failure of a pressurised tank kept at a relatively low temperature will be less severe than those due to the failure of a fully pressurised vessel.

2.6 Scaling

The predictions of the rate of growth of the radius, obtained by using Equation (1), have been shown to be in reasonable agreement with the observed consequences of a 19 Te release (Houston), and a 40 Te release (Pensacola); they are also consistent with what was observed to happen after the complete rupture of a tank car containing 76 Te (Crete). The slumping formula has also been shown to be in agreement with the observed growth in radius of the 1 Te Freon-12 puff released by Van Ulden.[3] Recently, a series of puff releases of Refrigerant-12 air mixtures with masses between 50 and 250 kg have been completed at Porton and Equation (1) has successfully been used as an element of a model which has been developed for comparison with the experimental results.[13] The prediction that the rate of growth of radius is adequately described by Equation (1), at least until such time as the density effects are overcome by the action of turbulence within the surrounding atmosphere, appears to be a good one for puffs with masses varying over three orders of magnitude. This particular aspect of the scaling problem appears to have been satisfactorily resolved, therefore.

During Dr Griffiths' recent visit to NTSB, already mentioned in a previous footnote, this point was specifically raised with and verified by the authors of Reference (7).

2.7 The entrainment of air

Some qualitative observations about the relative strengths of density driven effects and atmospheric mixing may be made by comparing typical density induced velocities, which from Equation (1) are proportional to $(gh\,\Delta\rho/\rho)^{\frac{1}{2}}$, with a typical velocity fluctuation characteristic of the atmospheric turbulence. This can be either the friction velocity u_* or, in highly unstable weather conditions, the convective scaling velocity w_*.[15] The square of the ratio of these numbers $(gh\,\Delta\rho/\rho u_*^2)$ is the Richardson number. This criterion for determining which of the atmospheric turbulence or density effects dominate, i.e. $(gh\,\Delta\rho/\rho)^{\frac{1}{2}}\ \alpha\ u_*$, implies that the transition radius R_T obeys the equation

$$R_T \,\alpha\, \frac{1}{u_*}\left(\frac{gV\Delta\rho}{\pi\rho}\right)^{\frac{1}{2}} \quad \ldots (2)$$

where the assumption is made that the volume $V = \pi R^2$ remains roughly constant until this transition has been achieved.

A frequently used formula containing u_* is the logarithmic wind profile.[16]

$$u_* = \frac{k u(z)}{\ln\left(\frac{z}{z_o}\right)} \quad \ldots (3)$$

in which $u(z)$ is the windspeed at a height z, k is Von Karman's constant ($k \sim 0{\cdot}4$) and z_o is the meteorological roughness length; z_o is a function of the dimensions and spacing of geometrical obstacles on the site. Equation (3) is only valid for heights exceeding those of the obstacles; z_o varies from 1 m over cities, forests and low mountains, to a few centimetres over steppes and large, flat plains and down to as little as 1 mm over the sea.[17] Corresponding values of u^* for a windspeed $u(z)$ of 5 ms^{-1} with $z = 10$ m are 0·87, 0·38 and 0·22 ms^{-1} respectively so that, for a release of a given mass of gas, a factor of four variation in the predicted value of R_T is plausible from site to site.

Further complications arise when it is not appropriate to use u_* in Equation (2). One example has already been mentioned – when the atmosphere is very unstable, the convective scaling velocity w_* is more appropriate. If a release occurs among buildings, and the height of the cloud does not exceed those of the buildings, then account must be taken of the fact that the turbulence generated in building wakes is on average more 'vigorous' than that characterised by u_*, which is itself dependent on the value of z_o for the countryside upwind of the buildings. There are no general rules, however, for determining an average velocity with which to replace u_* in Equation (2) except to say that it ought to be somewhat larger.

The above considerations, then, lead to the conclusion that there should be a hierarchy of sites varying from the built-up, through flat countryside and down to the smoothest of all surfaces, the sea, and that a factor of four increase in the radius attained by the slumping cloud before gravitational effects have spent their energy, is plausible. This prediction appears to be nicely verified by the observations that at Potchefstroom the gravitational slumping appeared to terminate when the cloud was some 300-400 metres in diameter whereas, for a release of the same size at Pensacola gravitational slumping rapidly produced a cloud about 1500 m in diameter, after which the breadth increased relatively slowly. Roughly speaking, these sites respectively correspond to a built-up or partially built-up one and one surrounded by sea.

Qualitative arguments such as are presented in the foregoing are an aid to the understanding of the physical processes at work during the gravitational slumping phase. The problem of how properly to quantify the rate of entrainment of air into a dense cloud remains unresolved, however. For example, if there should be a really large release leading to the blanketing of an area of many square kilometres by a flat cloud with a high bulk Richardson number, it is conceivable that the turbulence within the air above the cloud can be as it were 'drained away' so that its effective vigour is much reduced. If so, u_* in Equation (2) should be replaced by something smaller and R_T should increase. This aspect of the scaling uncertainty (U2 and U1) cannot be resolved except by large scale experiments such as those, in which 5-10 Te of Freon-12 will be released as puffs, for which a feasibility study is now under way at Porton.[14]

3. CONCLUSION

The simple model for the dispersion of 'heavy' vapour clouds, developed in Reference (1), has been subject to much more detailed comparison with available reports of large scale accidental releases of ammonia than was undertaken in that reference.

The three predictions (P1-P3) outlined in Section 1.1 are borne out by the accounts of the accidents. Deviations from these predictions appear to be qualitatively explicable in terms of site characteristics such as the meteorological roughness length.

Some progress has been made towards resolving some of the uncertainties identified in Reference (1) and outlined in Section 1.3. The question of whether the consequences of a rapid release from a tank pressurised at a relatively low temperature (less than 0°C) are as severe as those for the same tank pressurised at a relatively high temperature (e.g. 20°C) has been examined in the light of the Crete accident (A3) and it appears that such a mitigation does not occur. The contention that, in the early stages of the cloud's dispersion, Equation (1) is an adequate predictor of the rate of growth of the radius, has been reasonably well verified for releases ranging over at least three orders of magnitude in mass.

It has been concluded that the greatest deficiency remaining in the understanding of the atmospheric dispersion of cold, heavy vapours is the prescription for the entrainment of air and that large scale experiments with controlled releases containing at least several tonnes of dense vapour are needed.

Finally, the simple model of Reference (1) is well able to predict some of the features of large scale releases of cold, heavy vapours. There is much merit in developing such simple models, based on well established physical principles, which can be used to make predictions without undue numerical complications. Nonetheless, the model is continually being reviewed as more and more data become available. Work is in hand to examine the sensitivity of the model to more sophisticated assumptions about entrainment of air at the top and edges of the slumping cloud. The model is being extended to take account of other than 'puff' releases – the evaporation of LNG from spreading pools accidentally spilled onto water, for example. Work is also to be undertaken to examine the possibility that the initial, rapid entrainment of air leading to the 'source cylinder' can be described by models which take into account the effect of the stored pressure energy of the ammonia.[18]

4. ACKNOWLEDGEMENT

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TABLE 1

Description of the various accidents referred to in this paper

Time and date	Place	Quantity of NH_3 available for release	Duration of release	Nature of release	Pressure	Atmospheric temperature	Description of weather conditions
11.15 May 11, 1976	Houston, tanker crash	19 Te	Virtually instantaneous	Pressurised vessel broke in two as road tanker fell to the ground	139 psig*	27°C	Light, variable winds with slight drift to the East
16.15 July 13, 1973	Potchefstroom, spontaneous failure	38 Te	Instantaneous	Spontaneous failure (brittle fracture) of dished end of horizontal bullet type tank	90 psig (measured)	19°C	The air was still at the time of the incident. Within a few minutes a 'slight' breeze developed from NW
06.30 February 18, 1969	Crete, train derailment and collision	76 Te	Instantaneous	Tank car completely fractured by collision	20 psig*	−15°C	No wind, temperature inversion
18.06 November 9, 1977	Pensacola, train derailment	~ 40 Te	50 percent of tank contents 'quickly vapourized'	3 inch wide by 38 inch long tear in the leading tank head near '10 o' clock position'	109 psig*	20°C	Overcast with broken clouds and a light rain. Wind from SW 'at 3-5 mph'
04.30 December 6, 1973	Conway, pipe leak	~ 230 Te	30 minutes or more	Rupture of overpressurised pipe-line	1200 psig or more°	− 6°C	Wind from NW at 5 to 10 mph Clear Sky
13.00 August 13, 1974	Hutchinson, pipe leak	~ 350 Te	60 minutes or more	Rupture of overpressurised pipe-line	1450 psig°	Not given	4 mph wind from SE

* Vapour pressures calculated using the Cragoe, Mayers, and Taylor equation as described in Reference (9), assuming that the temperature of the ammonia equals that of the atmosphere.

° Pressures recorded on MAPCO gauges.

TABLE 2

Summary of evidence for the existence of 'heavy' vapour clouds

	Accident	Existence of photographic or other recorded, evidence at time of incident	Evidence post-incident	Eyewitness accounts
A1	Houston, tanker crash	Photographs taken 1-6 minutes after the accident, showing liquid-like tongue of vapour stretching for several hundred metres	Photographs taken from above showing burnt grass extending for several hundred metres in every direction from the site of the crash	None giving more information than the photographic evidence
A2	Potchefstroom, spontaneous failure	NONE	Dead people found to East, South, South West and North of the tank	Immediate resulting gas cloud was 150 m in diameter and 20 m in depth. It moved towards a nearby housing estate without rising
A3	Crete, train derailment and collision	NONE	Dead found in a wide angle stretching from NW to NE	A cloud was formed which blanketed the area, extending West, North and South.
A4	Pensacola, train derailment	Cloud tracked on radar for many miles. Already a mile across after five minutes only. Did not lift off the ground	None in report	None to improve on radar scan evidence
A5 (a)	Conway, pipe leak	Photograph of visible vapour cloud hugging ground – non-buoyant rather than dense	NONE	Foglike vapour visible for $\frac{1}{2}$ mile. Irritating to eyes, nose and throat for $3\frac{1}{2}$ miles
A5 (b)	Hutchinson, pipe leak	Photograph of visible vapour cloud hugging ground – non-buoyant rather than dense	NONE	NONE

TABLE 3

Observed and calculated slumping dimensions

Incident	Quantity released Te	Observed consequences	Predicted consequences using Equation (1)	Comments
A1 – Houston Tanker crash	19	i After about one minute, the observed breadth of the cloud was 400-600 m.	The simple model predicts that this breadth would be attained in between one and two minutes (400 m after 50 seconds)	Good agreement (better than a factor $\sqrt{2}$ not expected)
		ii Maximum upwind distance measured by observing burnt grass was ~ 200 m	This is possible for a 20 Te puff of ammonia if its initial velocity is about 1·2 ms^{-1}	Since the 20 Te ammonia puff is mixed with 10 to 20 times that much air, its initial velocity must equal the windspeed at the time of the release. The wind traces given in Reference (4) show that windspeeds were low and that 1·2 ms^{-1} was possible. Good agreement.
A2 – Potchefstroom incident	38	i The immediate resulting gas cloud was 150 m in diameter and 20 m high	This diameter predicted within the first few seconds of slumping	Reasonable agreement
		ii Within a few minutes the visible cloud reached some 300 m in width and about 450 m downwind of the tank	These dimensions consistent with predictions for diameter after one minute only. After a few minutes it should be 1000 m	Reasonable evidence for gravitational slumping but model seems to over-estimate the diameter of the visible cloud; see Section 2.6.
A3 – Crete train crash	76	The vapour cloud extended westward for at least 450 metres, and north and south for several hundred metres ('several blocks')	A cloud containing 76 Te of ammonia should attain these dimensions after a few minutes	The scanty evidence does not contradict the model, but lack of evidence on time scales hinders comparison with theory
A4 – Pensacola train derailment	40	The radar at the airport picked up the cloud after a few minutes or so at which time it was about a mile (1500 m) in diameter.	Diameter at 4-7 minutes predicted to be 1000-1400 m	Good agreement with theory