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POST-ACCIDENT ANALYSIS OF VAPOUR CLOUD EXPLOSIONS IN FUEL STORAGE AREAS

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A Vapour cloud explosion which occurred in a large fuel storage area close to the harbour of Naples (Italy) was analysed by different methods. Useful 'experimental data' were obtained by the post-accident damage analysis (minimum overpressure experienced by different items) and by the seismograms recorded at different stations at the time of explosion (explosion duration and intensity).

The analysis of the seismic data allowed a first estimate of the amount of vaporized fuel. A more accurate estimate was obtained by modelling the rate of evaporation of the liquid fuel and the vapour cloud dispersion in the surrounding atmosphere. The dispersion calculation furnished the input data for the CFD gas explosion simulator AutoReagas and constituted the basis for a sensitivity analysis of the results to the amount of fuel involved in the explosion.

The results obtained with the different methods above were critically discussed and compared to the results obtained with the Multi-Energy method.

Keywords: VCE; CFD simulation; fuel storage area; post-accident analysis; seismic effects of explosion; heavy gas dispersion.

INTRODUCTION

Vapour cloud explosions (VCEs) have to be considered as a major hazard in industrial plants where large amounts of flammable materials are stored or processed[1]. In fact, many VCEs which occurred in the last two decades in fuel storage areas caused almost total destruction of the plant.

The damage analyses for VCEs are generally performed by adopting simplified calculation procedures such as the TNT-equivalency (TNT) and the Multi-Energy (ME) methods[2]. Recently, Computational Fluid Dynamics (CFD) codes have also been considered for this purpose. The CFD approach should allow a higher accuracy for the design of chemical plants, for the identification of the needs of protective systems, and for post-accident analysis. However, the performance of the CFD codes specifically developed for VCE simulation in congested environments is affected by the different combustion models and turbulence closure models adopted. Moreover, few modelling constants for the computation of turbulence and for the description of the complex interaction between flame front and turbulent flow field are introduced. These constants must be adjusted on the basis of experimental data and according to the results of properly designed analyses of sensitivity[3,4].

The CFD code AutoReagas was used in the present work for the simulation of a VCE, which occurred on 21 December 1985 in a fuel storage area in Naples (Italy). Since the case history of the accident has been presented in detail elsewhere[5,6], only the main aspects will be reported here, while particular emphasis will be placed on the procedure adopted for VCE analysis and simulation.

THE CASE HISTORY

On 21 December 1985, a VCE occurred in a fuel storage area located in the vicinity of Naples (Italy). The affected area (Figure 1) covered about 49,000 m^2 and contained 37 tanks used for the storage of gasoline, diesel fuel and fuel oil, with a total capacity of about 100,000 m^3. Two buildings, a loading unit and two rail tanks were also present. The whole area was highly confined by walls, buildings and by an embankment, with a mean height of about 8 m.

The accident originated from a spill of gasoline that occurred during a filling operation from a ship berthed in the harbour of Naples. Gasoline overflowed through the floating roof of tank no. 17 (Figure 1) for about 1.5 h, and the total amount of spilled fuel was estimated to be about 700 tons. The resulting pool covered the catch basin of the tank and the adjacent pumping area, which were connected through a drain duct. The formation of a large homogeneous vapour cloud was favoured by the relatively high ambient temperature (8°C), by the low wind speed (2 $m\,s^{-1}$) and by a long delay prior to the ignition. The latter occurred in the proximity of pumping station no. 2. The strong VCE and the following fire, which lasted over one week, destroyed all the buildings and the equipment within the area. The associated blast wave caused 5 casualties within the area, whereas minor effects were observed up to 5 km away.

A damage analysis was carried out after the accident[5,6]. The overpressures estimated by this analysis are reported in Table 1 for some significant locations inside the storage area and compared with the results of the CFD and ME analyses, discussed later. Particularly, the minimum overpressure

Table 1. Observed damages and peak overpressures (P_{max}) estimated by damage analysis and calculated by CFD simulation.

	Damage analysis		CFD analysis				
			Homogenous cloud				
		Estimated	Height 4 m	Height 6 m	Height 8 m	Non Homog. Cloud	ME analysis Cloud height
Observation point	Observed damage	P_{max}, kPa	P_{max}, kPa	P_{max}, kPa	P_{max}, kPa	P_{max}, kPa	P_{max}, kPa
Main building	Partial demolition	5.0	1.4	4.7	5.5	2.5	62
Guar–rail motorway	Damaged	7.0	6.0	24.7	9.8	5.1	60
Lubricant storage building	Damaged roof	11.0	4.2	5.1	9.3	3.4	63
Support of gravity tanks	Damaged	11.0	2.0	6.7	10.8	8.4	73
Rail tanks	Damaged	48.0	3.3	18.5	60.0	11.1	65
Tank 3	Destroyed	>4.1	2.6	4.3	16.5	9.5	77
Tank 4	Destroyed	>38.0	8.1	20.7	51.5	5.9	69
Tank 17	Destroyed	–	10.3	14.7	28.0	13.2	–
Tank 20	Destroyed	>1.9	2.8	4.3	4.7	2.6	76
Tank 101	Deformed	>1.8	1.4	2.5	3.5	2.6	75
Ignition point	–	–	24.6	32.8	60.0	6.5	–
Glass (up to 1 km)	Destroyed	3	–	–	–	–	4
Window frames (up to 500 m)	Destroyed	<10	–	–	–	–	9
Shed roof (600 m)	Destroyed	<10	–	–	–	–	8

required for tank failure is reported for some characteristic tanks.

THE SEISMIC WAVE

When a VCE occurs, a small part of the released energy is transferred to the soil in the form of a seismic wave while another part is transmitted through the atmosphere as a blast wave. If the released energy is large enough, both waves can be recorded by seismographs located at different distances from the explosion, and useful information can be derived from these records about the explosion duration and energy.

In the case history under examination, the seismic wave was clearly observed up to about 100 km from the explosion epicentre. Figure 2 shows the waves recorded at seismic stations located 9 km, 29 km and 82 km respectively away from the storage area.

The soil wave travels at a much higher velocity (of the order of $5 \times 10^3\,\mathrm{km\,s^{-1}}$) than the air blast wave (which travels at the speed of sound) and hence it was recorded earlier. However, the seismic wave usually undergoes strong reflection and distortion phenomena so that the resulting signal is much more disturbed than the corresponding air record.

The signal recorded at the nearest station (curve (d) of Figure 2) was too much distorted to obtain useful information, whereas the one recorded 82 km away (curve (a) of Figure 2) showed only a small disturbance. On the contrary, useful information could be obtained from the seismic data recorded at the station located 29 km from the explosion site (curves (b) and (c) of Figure 2).

The air blast wave record gives an explosion duration of about 4 s. Furthermore, the Richter magnitude, M, of an earthquake equivalent to the explosion can be measured

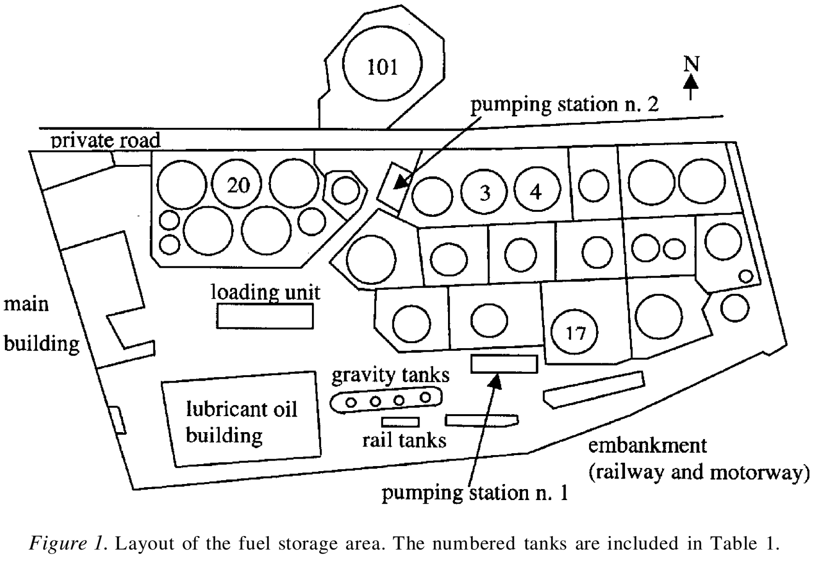


Figure 1. Layout of the fuel storage area. The numbered tanks are included in Table 1.

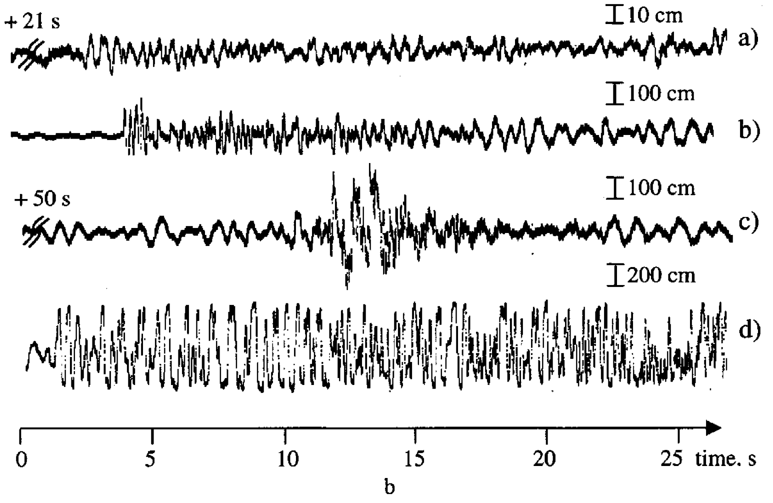


Figure 2. Seismic signals recorded at different distances from the explosion epicentre: (a) 82 km — soil blast wave; (b) 29 km — soil blast wave; (c) 29 km — air blast wave; (d) 9 km — soil blast wave.

from the seismogram, according to the following equation[7]:

$$M = \log_{10} a + c_1 \log_{10} \Lambda + c_2 \quad (1)$$

where a is the maximum amplitude of the signal, Λ is the distance of the seismograph from the explosion site, and c_1 and c_2 are constants which depend on the local position of the seismic station. By using equation (1), a value of $M = 3.54$ (Richter scale) is obtained.

The seismic energy E_S can be estimated by means of equation (2), obtained from the analysis of artificial (underground or surface) explosions of trinitrotoluene (TNT)[8]:

$$\log_{10} E_S = 4.78 + 2.57 m_{exp} \quad (2)$$

where m_{exp} is the explosion magnitude, which is related to M by the simple equation:

$$m_{exp} = 0.56M + 2.5 \quad (3)$$

Equations (2) and (3) yield an explosion magnitude $m_{exp} = 4.48$ and a seismic energy $E_S = 1.97 \times 10^3$ MJ.

The seismic behaviour of an atmospheric explosion located near the earth surface is similar to a shallow earthquake[8]. Indeed, only a small fraction of the total energy is transferred into seismic energy, because the largest fraction is converted into thermal energy and air blast energy. The seismic coupling factor α, i.e. the ratio of seismic to total energy, may vary considerably from case to case and strongly depends on soil characteristics.

According to Bath[7], the value $\alpha = 0.1$ can be assumed for shallow underground explosions if the source is located within 10 to 40 km from the measuring point. In the case under study, this value has been confirmed by independent evaluation performed on the basis of soil composition in the area of the explosion[6,9]. Hence, a total explosion energy of about 2.0×10^4 MJ can be calculated, which corresponds to 4.2 tons of TNT.

The amount of flammable vapour involved in an explosion of known energy can be evaluated through an explosion efficiency or yield factor, η. When using the TNT-equivalence method, values in the range 0.05–0.1 are usually adopted, whereas larger values are only considered when safe and conservative estimates are needed (for instance, separation distances between nuclear power plants and transport routes)[10-15]. This gives an exploded mass of 4.2–8.4 tons (heat of combustion of gasoline vapour = 46.4 MJ kg^{-1}).

These values do not disagree with the ME method, which uses a larger value of η (typically 0.2) but also assumes that the explosion strength is essentially determined by the fraction of vapour constrained in the congested parts of the flammable cloud[2,10].

THE CALCULATION OF THE VAPOUR MASS

The calculation of the vapour mass involved in the explosion is crucial in order to assess the consequences of such accidents. In the previous section, a first estimate was obtained from the seismic data recorded at various stations. A more accurate value can be obtained by computing the evaporation rate of gasoline during the fuel spilling.

The evaporation rate per unit area, R, can be evaluated by considering two contributions deriving, respectively, from the pool and from the liquid falling along the tank surface. According to Opschoor[16], the general relationship holds:

$$R = \frac{kWP_t}{R_g T} \ln\left(1 + \frac{P^\circ - P_\infty}{P_t - P_\infty}\right) \quad (4)$$

where R_g is the ideal gas constant, W is the vapour molecular weight, T is the liquid temperature, P_t is the ambient pressure, P° is the gasoline vapour pressure at the liquid temperature, P_∞ is the partial pressure of the evaporated liquid far from the liquid surface, and k is the mass transfer coefficient.

As far as the pool evaporation term is concerned, the mass transfer coefficient can be computed as[16]:

$$k = 0.002 \times v^{0.78} L_p^{-0.11} \quad (5)$$

where v is the wind velocity at the height of 10 m from ground and L_p is the pool size. On the basis of the post-accident analysis[6], the value $L_p = 60$ m was assumed since the pool covered the entire catch basin of the tank no.17 and the adjacent pumping area. Application of equation (5) yields for k the value 2.2×10^{-3} m s^{-1}.

A larger value is expected for the mass transfer coefficient related to the evaporation from the tank surface, because of the more favourable flow condition. The value $k = 5 \times 10^{-3}$ m s^{-1} was obtained for the 'winter-type' gasoline considered here ($W = 68$ g mol^{-1}), by applying the Chilton-Colburn analogy to a liquid film evaporating on a vertical cylinder[17].

Finally, by using equation (4) with $P_\infty << P^\circ$ ($P^\circ(8°C) = 77$ kPa) and $P_\infty << P_t$, one obtains for the overall evaporation rates the values of 20 kg s^{-1} and 5 kg s^{-1} respectively from the pool and from the tank wall. If the spill lasted for about 1.5 hours, the values above correspond to a total evaporated mass of about 135 tons.

This value is more than one order of magnitude larger than that estimated from the seismic energy. Actually, the flammable vapour cloud is usually constituted by a small fraction of the total vaporized liquid, due to the atmospheric dilution. Thus, in order to assess with a higher accuracy the size of the flammable vapour cloud, a gas dispersion analysis should be carried out, as discussed in the next section.

VAPOUR CLOUD DISPERSION ANALYSIS

The flammable portion of the vapour cloud generated by the gasoline evaporation was calculated by performing a cloud dispersion analysis. The software HEGADAS, developed by SHELL Research (HGSYSTEM)[18] and specifically devoted to heavy gas dispersion calculations, was used for this purpose. All details about the model features are reported in the literature[19].

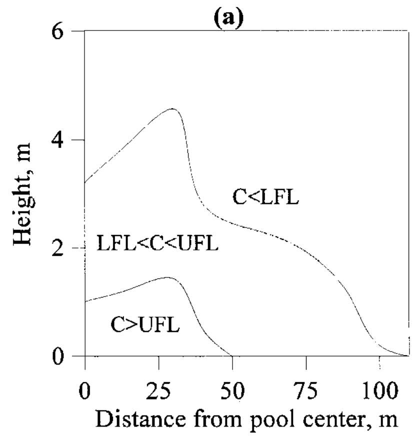
An evaporating pool of gasoline with an evaporation rate of 25 kg s^{-1} was considered as the source of the vapour cloud, according to the results of the previous section. In fact, the HEGADAS code does not allow the specification of two distinct evaporation sources, which would be necessary to describe the case under examination. Thus, it does not allow the specification of a distributed vapour source along the vertical axis, that would correspond to the evaporation term from the tank shell. This probably leads to underestimating the cloud height.

A steady-state calculation was carried out because of the long evaporation time prior to the ignition. The input data adopted for the simulation are reported in Table 2.

The average surface roughness z_r accounts for the presence of several obstacles such as dykes, tanks, buildings and pipes, which hinder the vapour cloud spreading. The adopted value ($z_r = 1$ m) is suggested in the reference manual[18] in the case of industrial sites, and approximately corresponds to 1/10 of the height of a typical obstacle (i.e., the fuel tanks). However, the sensitivity of HEGADAS with respect to z_r appeared to be very small. In fact, when decreasing z_r to 0.5 m the amount and the volume of flammable vapour changed by only 2.5% and 7%, respectively.

The influence of real obstacles on the gas dispersion process would be better accounted for by means of a CFD dispersion code. At present, three-dimensional heavy gas dispersion models have been proposed in the literature[20] but their application to congested environments calculations is still under investigation, mainly due to the lack of experimental validation[21].

Figure 3 shows the results of the dispersion calculation, in terms of cloud width and height along the downwind direction. The portion of cloud characterized by a fuel concentration (C) between the Lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL) is reported.



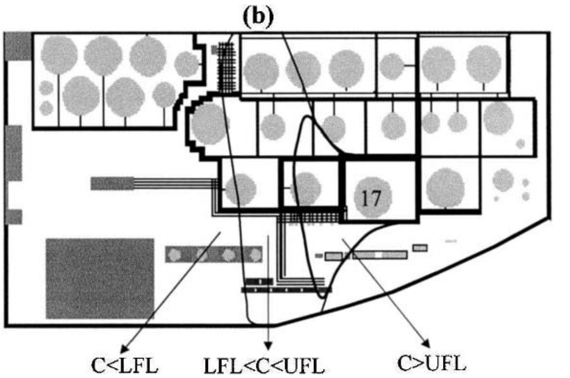


Figure 3. (a) Centre line vapour cloud height along the downwind direction. (b) Vapour cloud footprint on the fuel storage area as reproduced by CFD, 1 m above the ground.

With the values listed in Table 2, a total volume of about 45,000 m^3 and a total amount of 4 tons of flammable vapour were calculated, in good agreement with the fuel amount as estimated by the seismic analysis previously reported. These results were used as input data for the VCE numerical simulation performed by the CFD code AutoReagas.

CFD SIMULATION BY AUTOREAGAS

The VCE was simulated by means of the AutoReagas CFD code[22], specifically developed by TNO-PML (NL) and by Century Dynamics Ltd (UK) in order to obtain reliable predictions of the pressure field generated by the VCE.

Table 2. Input data for the steady state heavy gas dispersion calculation.

Air temperature, °C	8
Ground temperature, °C	10
Relative humidity, %	70
Wind velocity, m s^{-1}	2
Surface roughness, m	1
Pasquill stability class	D
Spill flow rate, m^3 h^{-1}	750
Pool length, m	60

AutoReagas uses the k-ε model[23] to describe the turbulent flow field and the turbulent burning velocity, S_t, to characterize the mixture reactivity[24].

The relationship between S_t and the volume based combustion rate (to be included in the mass conservation equation) introduces a dimensionless constant, C_t, which is the main modelling parameter. According to the results of a sensitivity analysis[4,5], the value $C_t = 100$ has been used in the present work.

The storage site was reproduced by AutoReagas by using a computational domain of $115 \times 63 \times 11$ planes along the x, y and z axes, respectively (Figure 4). The z axis (vertical axis) was extended up to 25 m to account for the upward expansion of the burned gases, which is horizontally hindered by the confinement. Within the volume where the combustion reaction takes place, a computational cubic cell (side: 2 m) was considered, whereas a graded grid was used in the far-field, where only the air blast effect must be accounted for.

Pipelines, equipment, catch basin walls and all other objects smaller than the computational cell size were treated with a sub-grid formulation. This introduces as parameters the fraction F_k of the turbulent energy which is lost by drag (to be included as a source term in the k-ε model), a characteristic turbulent length scale L_T and a drag coefficient C_D for any object[25].

The adopted values ($F_k = 0.5$, C_D ranging from 1 to 2, $L_T = 20\%$ of the cross flow dimension) were chosen according to the suggestions of a wide literature[3–5,25–28].

A pure butane vapour cloud was used for the CFD simulations, because butane represented the main component of the vapours generated by the winter-type gasoline involved in the explosion.

Following the results of the dispersion analysis reported in the previous section, a 300 m wide, 120 m long, stratified vapour cloud was considered. AutoReagas does not allow the specification of a continuous concentration profile within the cloud. Therefore, the stratification was obtained by specifying three regions with concentrations of 7% (rich mixture just above the gasoline pool), 3.1% (stoichiometric) and 2.5% v/v, respectively. Cloud ignition was assumed at pumping station no. 2, according to the collected testimonies[5,6].

Table 1 reports the results in terms of computed maximum overpressures (P_{max}) at specific locations inside the storage area. The computed overpressures which resulted were significantly lower than the corresponding values estimated by the damage analysis. CFD codes have been mainly validated against experimental data obtained at stoichiometric fuel concentration, so that only rather inaccurate predictions can be made for the flame speeds in the presence of local mixing in confined environments.

Thus, numerical simulations were also performed by considering homogeneous stoichiometric clouds. Three different heights of 4 m, 6 m and 8 m were assumed, corresponding to fuel amounts ranging from 4 to 8 tons, also according to the analysis of the seismic data. Results in terms of maximum overpressures are reported in Table 1.

By increasing the fuel amount available for combustion, the maximum generated overpressure is also increased for all locations considered inside the area. In particular, the results obtained with the 8 m height cloud configuration showed the best agreement with the overpressures estimated by the damage analysis. This result seems to confirm that the cloud height calculated by the dispersion analysis is underestimated, probably due to the presence of obstacles, which could not be included in the dispersion model.

Application of the ME method to predict the peak overpressures for the 8 m cloud was also performed by using the GAME[29] correlations, developed by TNO (NL) on the basis of MERGE and E-MERGE experimental data set[30].

The maximum source overpressure inside the vapour cloud was predicted to be 82 kPa, which corresponds to an explosion strength F between 6 and 7. As shown in Table 1, the ME method overestimated all the explosion overpressures observed within (or immediately close to) the vapour cloud, whereas, according to the aims of the method, a rather good prediction of the overpressures was observed at distances larger than 500 m from the explosion centre.

The explosion duration computed by CFD was about 3–4 seconds, i.e., a value very similar to the total duration of the air blast wave recorded at the seismic observatory located 29 km apart the explosion site. This value strongly disagrees with the corresponding ME results. In fact, for the observed values of F ($6 < F < 7$), which are consistent with the observed damages, the explosion duration at the ignition source should be of the order of 0.1 s.

Thus, it can be argued that those small-scale explosions simulated by the ME approach (which occur in very short times, involving very small volumes) are averaged by AutoReagas at a time-scale consistent with the dimensions of the adopted computational cell.

CONCLUSIONS

Vapour cloud explosions are very complex phenomena, whose destructive potential depends on the flammable mass involved, on the cloud dispersion and on the reactivity of the gaseous mixture. A consistent explanation of the incident can be obtained with appropriate use of different modelling approaches.

The CFD codes, such as the AutoReagas code employed here, can give a more accurate simulation of the VCEs, as compared with empirical correlation. However, the results depend to some extent on the adopted computational strategy, which is defined mainly by the grid dimensions, by the sub-grid description of the congested areas, and by the values of a few input parameters.

Among those parameters, the concentration, size and location of the vapour cloud play an important role. Accurate modelling of the fuel evaporation and of the dispersion phenomena leading to the vapour cloud formation could yield those data. In this field, marked improvements are expected by 3-D models, which are able to account for the effect of partially confined environments.

Moreover, further investigations are required in order to develop adequate models for flame front propagation through non-homogeneous fuel-air mixtures to be included within CFD codes specifically devoted to VCE simulation.

NOMENCLATURE

a	amplitude of the seismic signal, mm
C	concentration, % v/v
c_1, c_2	seismographic constants in equation (1)
C_D	drag coefficient

C_t dimensionless turbulent constant in equation (7)
E_S seismic energy, MJ
F explosion strength (ME method)
F_k fraction of turbulent kinetic energy loss by drag
k mass transfer coefficient, m s^{-1}
LFL Lower Flammability Limit, % v/v
L_p pool size, m
L_T turbulent length scale, m
M earthquake Richter magnitude
m_{exp} explosion magnitude
P_∞ partial pressure of the evaporated liquid far from the pool surface, kPa
P° vapour pressure, kPa
P_{max} maximum overpressure, kPa
P_t ambient pressure, kPa
R specific evaporation rate, kg s^{-1} m^{-2}
R_g ideal gas constant, J K^{-1} mol^{-1}
S_t turbulent flame speed, m s^{-1}
T temperature, K
UFL Upper Flammability Limit, % v/v
v Wind velocity, m s^{-1}
W molecular weight, g mol^{-1}
z_r average surface roughness, m
α seismic coupling factor
η explosion efficiency or explosion yield factor
Λ distance of the seismograph from the explosion site (km)

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