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Journal of Hazardous Materials A77 (2000) 1–9

Journal of Hazardous Materials

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Flixborough revisited — an explosion simulation approach

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Received 15 June 1998; received in revised form 29 February 2000; accepted 1 March 2000

Abstract

A literature study of explosion estimation reports from the Flixborough accident was performed and commented. The results from this survey were compared to the results obtained from explosion simulations. The simulations were done with a computer model of the Flixborough plant using the EXSIM software simulation tool. The comparison showed that explosion magnitude estimates in the literature based on visual inspection are much lower than the simulated results, while the estimates based on calculations to a large degree conform with the simulations. The simulations also showed that the exact location of the ignition source does not seem to be significant for the magnitude of the explosion. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Process safety; CFD; Gas explosions; Accident; EXSIM

1. Introduction

The Flixborough accident has been thoroughly documented elsewhere [1–4], only a brief summary is given here. On June 1, 1974, there was an uncontrolled leakage of about 30 tons [1] of cyclohexane at the Nypro (UK) plant at Flixborough, UK. A few minutes after the leakage started, the explosive cloud was ignited. A violent explosion occurred, causing the death of 28 men and severe damage to the buildings on the site. A plan of the plant is shown in Fig. 1.

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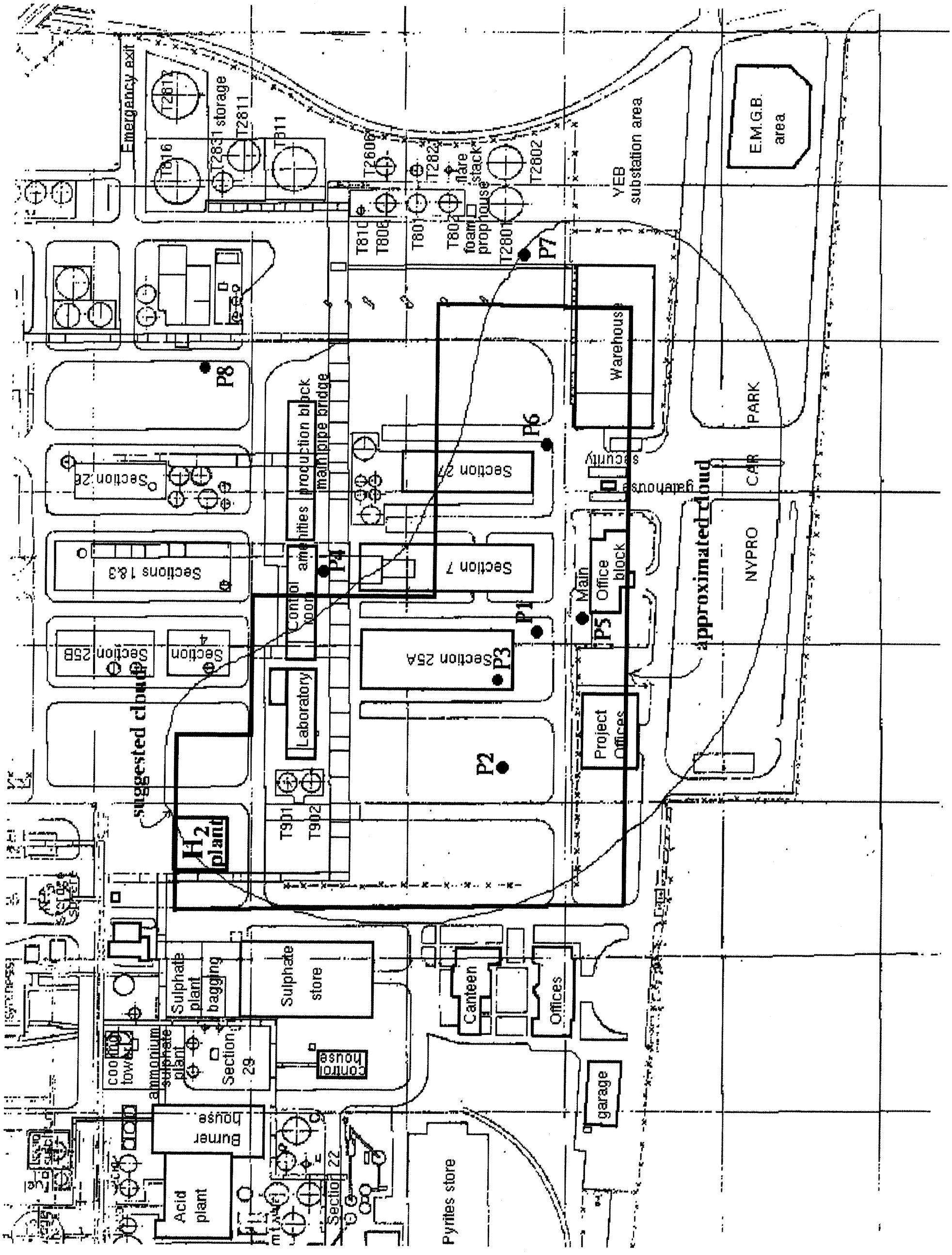
PII: S0304-3894(00)00197-7


Emergency exit
T2812
T2831 storage
T2811
T811
T816
T2606
T2822
flare stack
T2802
T810
T808
T801
T802
foam propohouse
T2801
P7
VEB substation area
E.M.G.B. area
P8
production block
main pipe bridge
utilities
amenities
Section 26
Section 27
P6
Warehouse
security
gatehouse
PARK
CAR
NYPRO
approximated cloud
Sections 1&3
P4
Section 7
Control room
P1
Main
Office block
P5
Section 25B
Section 4
Section 25A
P3
Laboratory
suggested cloud
P2
Project Offices
T901
T902
H2 plant
Sulphate plant bagging
Sulphate store
Canteen
Offices
cooling tower
ammonium sulphate plant
Section 29
control house
garage
Burner house
Acid plant
Section 22
Pyrites store

In the last 10 to 15 years, comprehensive computational fluid dynamics (CFD) models for gas explosion analyses have been developed. These models take account of the real geometric layout of complex process plants. The reviews of Hjertager [5] and Hjertager and Solberg [6] give the status of these models. Most of these models are now in a state where they have been validated against large scale data from explosions in realistic geometries. Also, the uncertainties between predictions and experimental data have been quantified. This means that the models may now be used to analyse consequences of actual accidents. Previously, the authors have analysed the Piper Alpha accident from the statistical load estimation viewpoint using the EXSIM CFD code [7,8].

The present paper will review the previous analyses of the Flixborough accident and apply the EXSIM CFD computer model for analysing the accident.

2. Literature review

Several authors have estimated the maximum overpressure in the exploding gas cloud [1,3,4]. The estimates are either based on observation of the damage or calculations of the energy release in the explosion.

2.1. Estimation of ignition point and gas cloud volume and location

Sadee et al. [1] have made an estimation of the explosive cyclohexane–air mixture to be a total volume of about 400 000 m^3, shaped like a banana or boomerang in its footprint, containing 30 tons of cyclohexane at a concentration of 2% per volume. The authors also pointed out that a likely source of ignition was the reformer furnace of the nearby hydrogen plant. Gugan [3] stated 36 tons as a likely cyclohexane mass. Marshall [4] also stated the hydrogen plant as a probable point of ignition. Generally, there seems to be an agreement with respect to the general conditions of the leakage and the location of ignition in most reports of the Flixborough accident.

2.2. Estimation of explosion pressure

2.2.1. Sadee et al., 1976

The site survey performed by Sadee et al. [1] describes 11 selected structures that substained damage. The maximum explosion pressures are visually estimated at nine of these locations and compared to an ‘‘equivalent’’ TNT explosion.

Where the damage was particularly severe, i.e. at the apparent explosion centre and at the caprolactam control building, Sadee et al. [1] made no estimation of the explosion pressure. The caprolactam building was simply described as being demolished. Further from the explosion centre, several structures and their damage were thoroughly docu-

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Fig. 1. Plan of Flixborough plant. Assumed gas cloud reconstructed from Sadee et al. [1]. Pressure monitoring points P1...P8 are described in Table 1 in the text.

mented. The authors estimated overpressures in the range 70–15 kPa (0.70–0.15 bar) at corresponding approximate distances of 100–300 m.

2.2.2. Gugan, 1979

Gugan [3] describes the damage done on the reactors R2525 (here called P2) and R2526 (here called P3) and concludes that the net crushing pressure on the skirts of these vessels must have been in excess of 760 kPa (7.6 bar). The skirts were provided with several apertures for ventilation and access, and a rise in the outside pressure would quickly be followed be a rise in the inside pressure, thus reducing the net load on the skirts. Depending on the assumption of the pressure rising rate, Gugan estimates a free atmospheric pressure in the range 1039–1518 kPa (10.4–15.2 bar), the latter mentioned first.

A parked road tanker (here called P7) was estimated to have been exposed to an explosion pressure in the range 340–1000 kPa (3.4–10 bar) [3,9].

A drain cover (here called P6) of cast iron sustained damage from a pressure in excess of 1000 kPa (10 bar).

Based on the energy release in the exploding cyclohexane–air mixture and the pressure rising rate, Gugan argues that the pressure in the centre of the flammable cloud probably was of the order of 2500 kPa (25 bar) and maybe as high as 4400 kPa (44 bar).

2.2.3. Roberts and Pritchard, 1982

Scattered over the site was a large number of lamp posts. Roberts and Pritchard [10] carried out an examination of the deformation of 17 of these lamp posts. The deformation of such hollow cylinders can be calculated for force per unit length for a given duration. Alternatively; given the deformation, one can calculate force per unit length for a given period, i.e. the impulse, these lamp posts were subjected to.

Some lamp posts were knocked down by the explosion pulse, thus the impulse must have been greater than their internal resistance. One of the lamp posts sustained a large deflection, but from the deformed shape, it was possible to calculate an assumed impulse. This lamp post is here denoted as P8.

Roberts and Pritchard estimated the total impulse on this lamp post to be $I = 3.7$ kPa s. With an estimated value for the duration of the positive phase of the impulse of $t_d = 200$ ms, the ‘‘dynamic pressure’’ was calculated to be $P_d = I/t_d = 3.7/0.2 = 18.5$ kPa (0.185 bar). The air velocity was found by the equation $P_d = 1/2\,\rho U^2$ with $\rho = 1.2$ kg/m^3; thus: $U = \sqrt{2P_d/\rho} = \sqrt{2 \cdot 18.5 \cdot 10^3/1.2} = 176\,\mathrm{m/s}$.

2.2.4. Marshall, 1987

The remains of the Nypro plant were also inspected by Marshall [4]. His classification is based on visual inspection.

Marshall concluded that the main office building (here called P5) had been subjected to an overpressure in excess of 70 kPa (0.7 bar). He further estimates a reasonable overpressure for the oleum plant control building to be 50 kPa (0.5 bar). For the caprolactam plant control building (here called P4), Marshall suggested a best estimate of overpressure to be about 100 kPa (1 bar).

2.2.5. Comments to results found in the literature

It is interesting to note that the two authors basing their estimates on visual inspection (Sadee, Marshall) to a large degree conform in the assumed pressure values, i.e. on the low side of 1 bar. Gugan, on the other hand, bases his estimates on calculations that produce explosion pressures of magnitude 10 bar. Roberts and Pritchard have also based their estimates of the explosion impulse on calculations.

According to Bjerketvedt et al. [11], Gugan's estimates of the pressure in the center of the explosion (25–44 bar) are only likely if there had been a detonation. It is uncertain whether Gugan's calculations are applicable to detonations.

3. Computer implementation

3.1. Plant layout and gas cloud

The geometry of the Flixborough plant was reconstructed in the computer for this article on the basis of drawings and photos provided by the Health and Safety Executive [12] supplemented with details from The Inquiry report [2] and Gugan [3]. A visualization of the computer model is shown in Fig. 2. The final computer model held 3500–4000 obstructions. The gas was cyclohexane, as in the real case.

The computer model implemented a 400 000 m^3 stoichiometric vaporised cloud of cyclohexane and air, with equal height and an approximated banana-shaped footprint as described by Sadee et al. [1]. The approximation to the prescribed cloud was done with three rectangular parallelepipedes combined to one large cloud. The ignition point was taken to be somewhere inside the H_2 plant.

The Flixborough simulation cases were built up of approximately 180 000 control volumes. The grid was exponential, with the smallest control volumes being cubes with sidelengths of about 1.5 m. The total calculation domain was approximately $300 \cdot 300 \cdot$

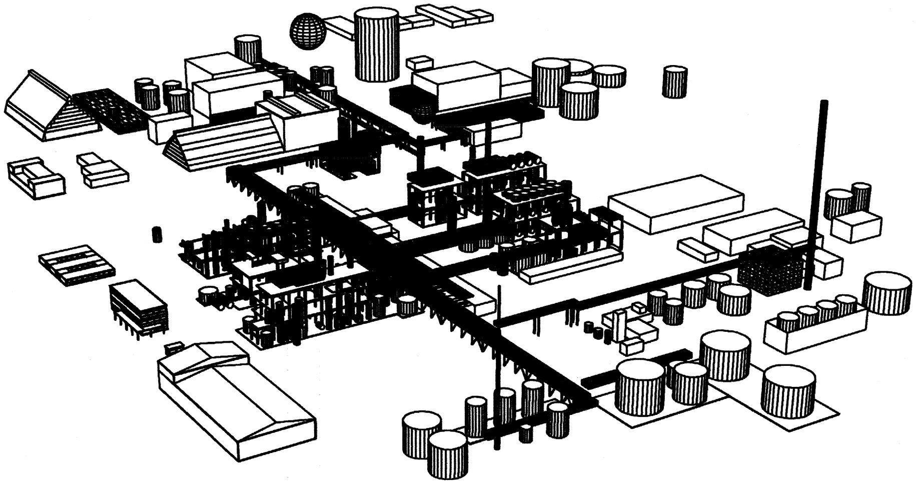

Fig. 2. Visualization of the EXSIM computer model implementation of the Flixborough plant.

Table 1
Description of pressure monitoring points

Pressure monitoring point	Reference to literature[a]	Description
P1	S1	Apparent explosion centre
P2	G12	Freestanding reactor 5 from sec. 25 A
P3	G13	Reactor 6, sec. 25 A
P4	S3/M3	Control building, south side
P5	M2	NW corner of main office building
P6	G16	Cast steel drain cover
P7	G15	Parked road tanker
P8	R15	Lamp post

[a] S = Sadee et. al [1], G = Gugan [3], M = Marshall [4], R = Roberts and Prithcard [10].

100 m, the smallest value being the height, and the smallest control volumes located in the most congested areas within the flammable cloud.

One hundred simulations were performed with randomly varied location of the ignition source within the H_2 plant. The simulator software used in this work was the EXSIM code [13–16].

3.2. Pressure monitoring points

The pressure monitoring points in the simulation were chosen so that comparison with the visual or calculated pressure levels in literature could be done. The eight chosen pressure monitoring points are described in Table 1.

4. Simulation results

The pressure values in Table 2 are shown as mean maximum overpressure over 1 ms and explosion impulse for 100 different simulations, all of them with their ignition point located on the ground floor of the H_2 plant.

Table 2
Maximum explosion overpressure over 1 ms and explosion impulse. Mean values from 100 different simulations with ignition point located at the ground floor of the H_2 plant

Pressure monitoring point	Distance from ‘‘explosion centre’’[a] [m]	Maximum explosion overpressure [kPa (bar)]	Explosion impulse [kPas]
P1	0	1360 (13.6)	27.3
P2	55	1290 (12.9)	26.0
P3	30	1650 (16.5)	27.6
P4	90	400 (4.0)	14.1
P5	20	1310 (13.1)	26.1
P6	70	1400 (14.0)	25.4
P7	150	220 (2.2)	7.9
P8	170	100 (1.0)	6.7

[a] As denoted by Sadee et al. [1].

A collocation of previous estimated values from the literature and simulated results is shown in Table 3.

4.1. Discussion

The concurrence of results from Gugan's estimations [3] and the simulated results (P2, P3, P6, P7) is striking. The values are very similar. Gugan has investigated the Flixborough case thoroughly and done a great number of calculations to quantify the magnitude of the explosion. It seems that his estimations and further mathematical treatment based on data from the observed damage to a large degree confirm the simulation results.

The explosion pressure estimations of Sadee et al. [1] and Marshall [4] are much lower than the values from the simulations. The reason might be that their values are based on visual inspection, not calculations. The collapse of buildings such as the control room and main office block has resulted in their conclusion of an explosion pressure of magnitude 1 bar, while the simulations show that the actual pressure might be 4.0 bar (P4) and 13.1 bar (P5). This may indicate that an assumption of explosion pressure estimation based on visual inspection alone can lead to large assessment errors. There is little evidence of the possible maximum explosion pressure when the structure is demolished.

4.2. Effect of ignition point location

With respect to a change in assumed ignition point location, the results show little variation around the mean values for the eight pressure monitoring points described in the previous section. The mean value, $\bar{x}$, standard deviation, s, and coefficient of variance, $V = s/\bar{x}$, of the 100 simulations with randomly varied ignition point location inside the ground floor of the H_2 plant are shown in Table 4. As can be seen, at these distances from the ignition point, the exact location of the source is not significant. Other parameters, such as turbulence generation due to congested areas, will override the importance of the initial ignition effects.

Table 3
Results from literature compared to simulated results

Pressure monitoring point	Literature[a] estimated explosion overpressure [kPa (bar)]	Simulated explosion overpressure [kPa (bar)]
P1	–	1360 (13.6)
P2	1039–1518 (10.4–15.2)^{G}	1290 (12.9)
P3	1039–1518 (10.4–15.2)^{G}	1650 (16.5)
P4	100 (1.0)^{M}/70 (0.7)^{S}	400 (4.0)
P5	$>$ 70 (0.7)^{M}	1310 (13.1)
P6	$>$ 1000 ($>$ 10.0)^{G}	1400 (14.0)
P7	340–1000 (3.4–10.0)^{G}	220 (2.2)
P8	3.7 kPas (impulse)^{R}	6.7 kPas (impulse)

[a] S = Sadee et. al [1], G = Gugan [3], M = Marshall [4], R = Roberts and Prithcard [10].

Table 4
Mean, standard deviation and coefficient of variation for 100 simulations of explosion pressure and impulse at Flixborough. Pressure in bar, impulse in kPas

Pressure monitoring point	Approximate distance from explosion centre [m]	Explosion overpressure [bar]			Explosion impulse [kPas]		
		$\bar{x}$	s	V	$\bar{x}$	s	V
P1	0	13.6	0.18	0.0135	27.3	0.30	0.0111
P2	55	12.9	0.25	0.0195	26.0	0.06	0.0024
P3	30	16.5	0.36	0.0218	27.6	0.14	0.0050
P4	90	4.0	0.01	0.0016	14.1	0.33	0.0237
P5	20	13.1	0.33	0.0249	26.1	0.23	0.0088
P6	70	14.0	0.24	0.0172	25.4	0.64	0.0254
P7	150	2.2	0.22	0.1021	7.9	0.81	0.1027
P8	170	1.0	0.19	0.1865	6.7	1.60	0.2374

A natural effect is the increasing coefficient of variance in both explosion pressure and impulse as the distance from the explosion centre (and also from the ignition point) increases. A little more noteworthy is the observation that the coefficient of variance is of the same order for both pressure and impulse. Taking the integrating aspect of the impulse under consideration, we would expect less variance from the impulse than the pressure.

5. Conclusions

A literature study and explosion simulations of the Flixborough accident have been performed. Viewpoints stated in the literature very much conform in the assumption of the initial conditions just before the explosion, but the estimates of the actual explosion pressure vary with the authors' approach to the problem. Authors relying on visual inspections of the damage have lower estimates of maximum explosion pressure than authors who have performed calculations.

The simulations of the accident show that the maximum explosion pressure at Flixborough may have been of magnitude 15 bar. They also show that the exact location of the ignition point source within the H_2 plant is insignificant.

The simulated results agree mostly with estimates in the literature based on calculations, as opposed to visual inspection.

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