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Statistical analysis of accidents on the Middle Asia-Centre gas pipelines

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Abstract

A statistical analysis of accidental rupture of pipelines and an evaluation of the possibility of obtaining a given value for certain hazardous parameters is presented. The analysis uses the database of accidents which occurred during the period 1980–1990 for the Middle Asia-Centre pipeline. The analysis takes into account those parameters which determine the energy potential of the accident and approximate formulas linking energy potential to the quantification of the resulting hazards are derived.

Keywords: Statistical analysis; Pipeline; Accident

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1. Introduction

For historical reasons, industrial development and urban growth in the Russian Federation took place mainly in the European part of the former Soviet Union. Because the major oil and gas fields are situated in the Volga basin and Easter regions, the gas pipelines are directed from East to West with forks into large industrial centres. This network passes through densely populated areas. Also, it should be noted that the major part of the gas pipelines have been in use for a long time: 36% – more than 20 yr, and 30% – from 15 to 20 yr [1]. Therefore, the development of methods for evaluating the probability of accidents relevant to the rupture of gas pipelines and the consequent possible hazards assessment is of importance.

The aim of the present work is a statistical analysis of accidental rupture of pipelines and the evaluation of the possibility to attain a given value of certain of the parameters describing the subsequent hazards. The analysis uses the data base of accidents which occurred during the period 1980–1990 for the Middle Asia-Centre

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pipeline. An approach is developed which permits the prediction of the change of risk level with altered operating conditions. In distinction to the present approach, previous studies were based on the investigation of the physical–chemical processes occurring during the break-up of the pipeline [2, 3].

While the main conclusions are derived for the pipeline mentioned above, for which a database was available, but they have more general meaning and would be useful in hazard assessment in many other situations.

2. Problem formulation and choice of parameters

The basis of the analysis presented in this paper is a database prepared as a result of regular observations of the pipeline operated by the Company “GasProm”. The pipeline Middle Asia-Centre is one of the largest networks in the Former SU. Operating pressure between compressor stations is about 40 atm, and pipe diameter varies from 500 to 1040 mm.

Statistical analysis of database is performed by two interrelated methods.

(1) *The determination of conditional probability W.* In this method the probability of the occurrence of an event is defined as the number of ways in which that event can occur divided by the number of all possible results of observations. For example, the probability of a crack with a given size is

$$W = \frac{\text{Number of accidents with a crack of given length}}{\text{Total number of accidents}} \times 100\%.$$

(2) *The determination of functional dependence* between the parameters which are responsible for the intensity of an accident and the parameters describing the resulting hazards. An example is the internal pipeline pressure and consequent range of distances over which fragments are hurled.

Two main limitations which are typical for existing databases should be taken into account. The first one is an incomplete accident description (usual unknowns are the kind of soil, the depth of pipeline beneath the surface and so on). The second restriction is the lack of exact information about the consequent hazards (range of flying fragments, thermal radiation area, etc.).

The parameters of pipeline accidents can be subdivided into two groups. The parameters of the first group are responsible for energy potential of the accident. These are the pumping pressure P, pipe diameter D, length of a crack L. It will be shown later (Section 4) that the most frequent lengths of a crack are about 20–40 m. This value is an order higher than the pipe diameter and of the order of distances over which the effects of the accident are felt, so that cylindrical symmetry can be accepted. Thus one may rearrange these parameters into the relation $E = PD^2$ which is the energy potential per unit length of the pipeline. Reasonably, the length of a crack is not included in this parameter because the L-value is unknown before the rupture. To take into account external conditions, corrections such as those required for underlying depth h and soil type k should be used. Therefore, the energy potential takes a general form:

$$E = PD^2 f(h) g(k),$$

where $f(h)$ and $g(k)$ are the functions associated with pipeline depth and type of soil.

The second group of parameters are conditioned by the factors determining the hazards from the accident. These factors are: crater formation in the ground in which the pipe is buried, shock wave, ignition of escaped gas and fire, and flying fragments.

Thus, the parameters describing this second group are consequent crater size, shock wave parameters, fire area, and range of fragments. Unfortunately, no shock wave parameters exist in the database so this parameter is not considered in the present work.

3. Total number of accidents

The database of accidents on Middle Asia-Centre (former USSR) pipelines used in this work contains descriptions of 142 events. All accidents took place between 1980–1990 excluding 1982 for which no information is available. The annual distribution of the events per year is presented in Fig. 1 and Table 1. Also presented is the number of events accompanied by fire. It follows from Table 1 that the mean number of accidents per year is 14, of which nine were accompanied by fire. The mean percentage of the total number of accidents with fire is 64%. The deviation from the mean percentage is presented in the last column of the Table 1. Only in 1990 the deviation from the mean value exceeded 15%.

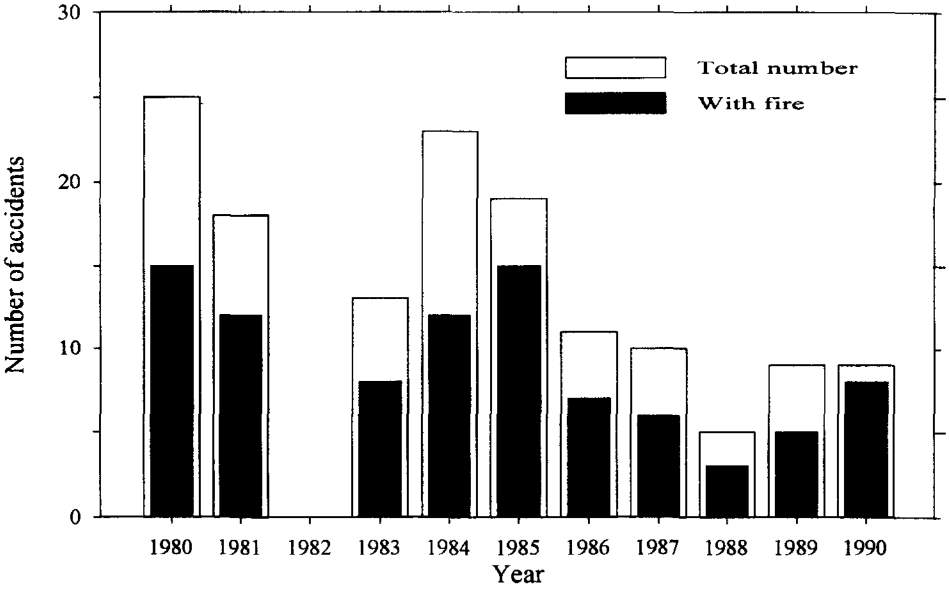

Fig. 1. The distribution of total number of accidents per year.

Table 1
Total number of accidents

Year	Number of accidents	Fire	Percentage [%]	Deviation from mean [%]
1980	25	15	60	−4.08
1981	18	12	66.67	2.59
1983	13	8	61.54	−2.54
1984	23	12	52.17	−11.91
1985	19	15	78.95	14.87
1986	11	7	63.64	−0.44
1987	10	6	60	−4.08
1988	5	3	60	−4.08
1989	9	5	55.56	−8.52
1990	9	8	88.89	24.81
Mean	14.2	9.1	64.08	

4. Length of a crack

The length of a crack is defined by pipe characteristics (type of material, manufacture date, operating conditions, the presence and quality of welded seams etc.) and working pressure. The length of a crack is the main parameter which fixes the limits of the crater size and therefore the area of complete destruction. A cumulative frequency polygon for the distribution of all accidents according to the size of crack is given in Fig. 2. By graphical interpolation we read from Fig. 2 that the 50% fracture is about 30 m, i.e., half the accidents occur with a crack longer than 30 m. Similarly, 90% ruptures have a crack longer than 5 m, and only of 1.5% accidents have a crack about 140 m long.

The distribution of the number of accidents with a given crack length is given in Fig. 3. The range of crack lengths was divided into 5 m lengths and the number of events for every length was calculated. Three histograms represent different initial pressure domains, namely: below 40 atm, 40–55 atm (which are the internal operating conditions of the pipeline), and above 55 atm. The last histogram in Fig. 3 shows the total number of accidents with a given crack length which is a sum of three previous graphs. It can be clearly seen that the most frequent lengths of a crack are about 20–40 m. No conclusions can be drawn either for the ranges at $P > 55$ atm, or at $P < 40$ atm due to the low number of events. These events influence the final histogram of total distribution only very slightly. As can be shown, all the histograms follow closely a logarithmic normal distribution.

5. Effect of flying fragments

In accordance with human hazardous criteria [4], fatality occurs (with 98% probability) if the mass of a fragment is larger than 4.5 kg and its velocity more than 7 m/s. In the case of pipeline rupture, as a rule, only a few heavy-mass fragments are formed. The mass of these fragments usually exceeds the above limit. So the

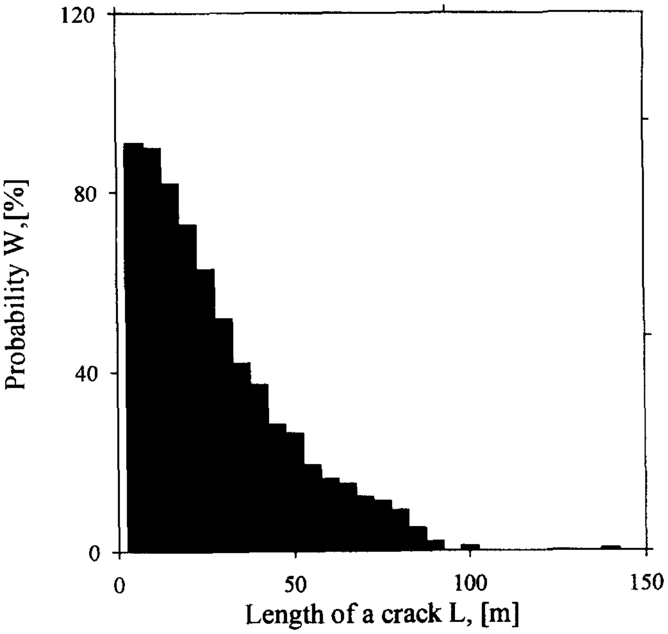

Fig. 2. The probability of a crack of a given length.

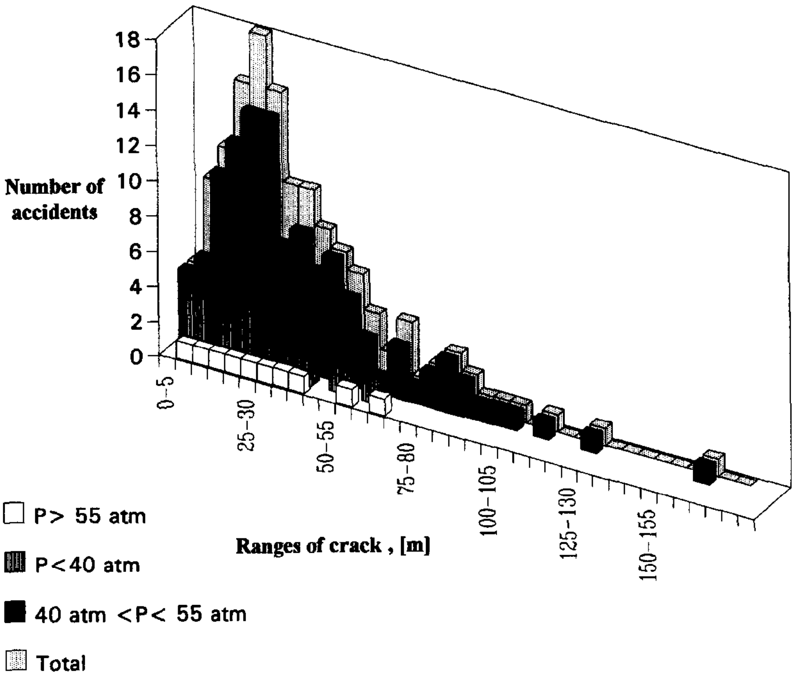

Fig. 3. The number of accidents with given crack length.

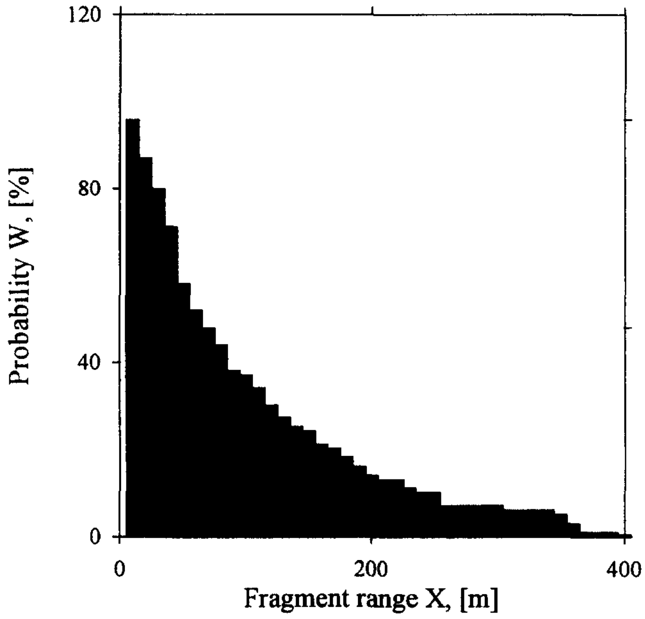

Fig. 4. The probability of fragment range.

main parameter which determines the hazard of flying fragments is their range (flying distance). A cumulative frequency polygon for the distribution of all accidents according to the range of fragments distances is given in Fig. 4. The probability was calculated from formula

$$W = \frac{\text{Number of accidents with a given fragment range}}{\text{Total number of accidents}} \times 100\% .$$

It is clearly seen that in half the cases the fragment's range is within 60 m and only in 5% of cases do the fragments travel 340 m or more.

Effect of fragments can be studied by linking the energy parameter $E = PD^2$ and maximal fragments flight range X. The parameters of underlying depth and kind of soil are not included here. This is because the functions $f(h)$ and $g(k)$ cannot be defined from the existing data due to an insufficient number of events for every type of soil. Indeed, the majority of accidents took place in a loamy soil. The number of events in loamy soil and for 1 m underlying depth is eight elements. This number is insufficient to provide a qualitative analysis. So, we will use data independent of soil type allowing that functions $f(h)$ and $g(k)$ can produce only systematic error. PD^2-values were found for all events listed in the database. To make the analysis more convenient the range of E was subdivided into intervals of 10 (atm m^2). A trivial solution of zero distance at $E = 0$ was also added. The values of fragment distances for every E-interval and calculation scheme is presented in the Appendix. Mean values of X corresponding to every E-interval are presented in Fig. 5.

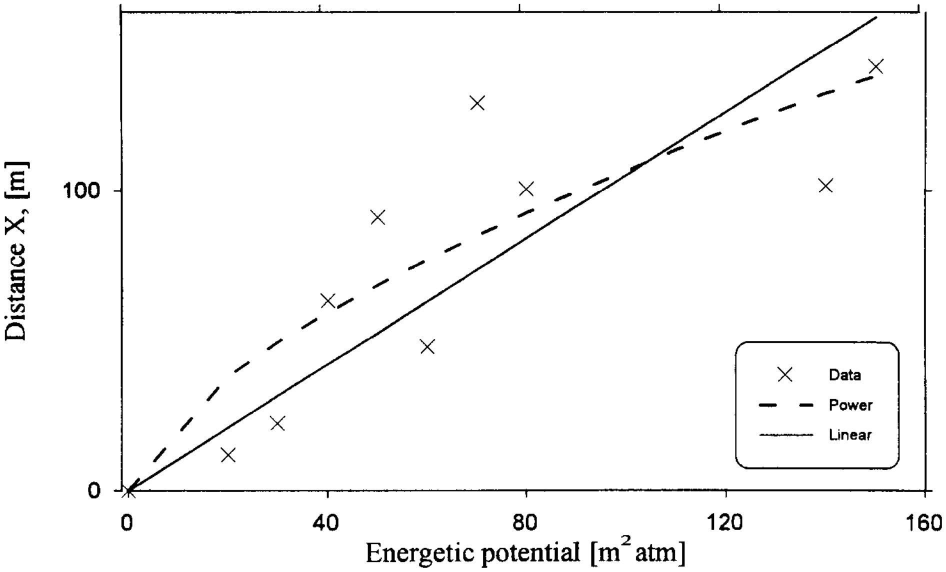

Fig. 5. Regression analysis for maximal travel of fragment.

As the dependence of $X(E)$ is unknown in advance we attempt an approximation using both linear (1) and power (2) functions

$$X = aE, \tag{1}$$

$$X = aE^b. \tag{2}$$

Here a and b are constants which can be found empirically. Function (2) can be presented in linear form using logarithmic coordinates:

$$\ln(X) = \ln(a) + b\ln(E) = a' + b\ln(E). \tag{2'}$$

Linear regressions of dependent values X_k (or $\ln(X_k)$) on independent values E_k (or $\ln(E_k)$) were performed using the linear regression utility from QUATRO-PRO standard statistical package. As a result of regressions the coefficients of (1) and (2′) dependencies were determined and summarised in Table 2, where v^2-value is a criterion of 'goodness of fit' for a curve (see Appendix). The curve leading to the smallest v^2-value can be considered as the best approximation approach. This judgement is valid only if a correct hypothesis is proposed. The essence of the parameter is the test of linearity of the regression curve by comparing variance within sets and variance about the regression line. It follows from Table 2 that in the case under consideration the power dependence is preferable. Fig. 5 presents the regression curves obtained.

Thus, we can conclude that the range of fragments from pipeline break-up can be calculated from the formula

$$X = 5.56E^{0.64} = 5.56[PD^2]^{0.64},$$

where we have P in [atm], D in [m], X in [m].

Table 2
Regression coefficients

Formula	a	b	v^2
$X = aE$	1.054	—	1.79
$X = aE^b$	5.559	0.642	1.65

Dependencies of this type can be used for pipeline engineering and design. For example, by increasing tube diameter and pumping pressure twice, one should take into account that the dangerous fragment range increases up to 3.8 times.

6. Crater formation

Crater sizes define the dimensions of the area of possible full destruction. This is particularly important when the pipeline is situated in the vicinity of a construction such as railway tracks, and so on. Due to the cylindrical symmetry of an accident one can assume a correlation between the length of a crack L and the length of a pit L_{P}. On the basis of the data, this correlation can be written with high accuracy as follows:

$$L_{\mathrm{P}} = 1.02L,$$

i.e., the length of a crack is very close to the length of a crater.

The width and depth of a pit are dependent on the energy of the released gas and the underlying depth of pipeline, h. The energy of the released gas is characterised by the energy potential per unit length multiplied by the length of a crack, $E_n = PD^2L$. The topography of dependence $V(E_n, h)$ (V is the volume of a crater) is presented in Fig. 6. Commencing with a volume 300 m^3, lines of equal volumes based on the database available are drawn after each 400 m^3. The dense circle-like curves in the

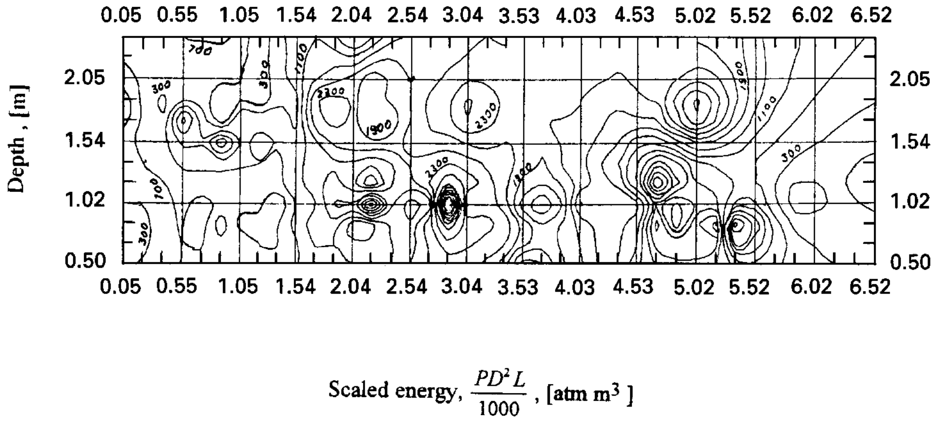

Fig. 6. Topography of crater sizes.

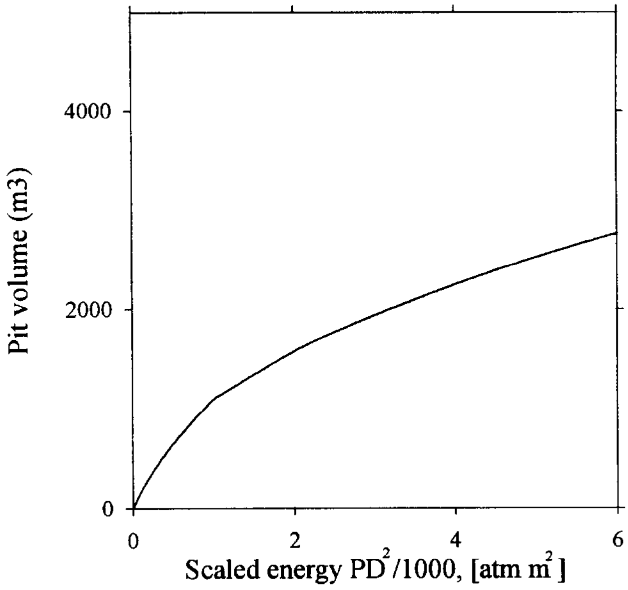

Fig. 7. Approximated dependence of crater volume on scaled energy.

figure correspond to the accidents with maximal crater volumes. One can see that within a zone $0.7 < h < 1.5$ m the majority of events with elevated V-values do not depend upon the energy potential. This feature of the curves can be explained by the fact that with low-depth pipelines (ground based), the main part of the energy is responsible for blast wave formation. On the contrary, at high depth the energy is insufficient to excavate the soil from a crater.

A standard designed value for the depth of the pipelines is $h = 1$ m, so most accidents took place at this underlying depth. Taking the depth $h = 1$ m as a reference point we analysed the dependence of the crater volume excavated vs. accident energy potential. The best estimate for $V(E_n)$, for $h = 1$ m, is presented in Fig. 7. The curve can be approximated by the equation

$$V = 1106\left(\frac{PD^2L}{1000}\right)^{0.511},$$

where we have P in [atm], D, L in [m]. In spite of the length of a crack L not being available before the accident one can use the formula for a first assessment of maximal crater size taking into account the most probable range of L, 20–40 m, found above (see Section 4).

7. Thermal radiation

The ignition of released gas can result in a fire. Two kinds of fire hazards should be analysed: the fire from neighbouring flammable substances (forest, grass, buildings and so on), and direct thermal radiation from burning gas jet or plume. In distinction to the case of fragments (Section 5) the type of dependence between fire area and initial parameters can be determined theoretically in advance. Indeed, according to [5] the 50% hazard radius R from jet fire causing wood ignition and subsequent secondary sources of fire can be determined from empirical formula

$$R = 1.9 + 0.4G^{0.47}. \tag{3}$$

Here G is the rate of outflow which is proportional to the internal pressure P and the square of the characteristic size of orifice D_j, so that $G \sim PD_j^2$.

Assuming that the secondary sources of fire determine the boundary of the fire area, we propose a similar equation for the characteristic radius of fire:

$$R_f \sim A' + B'G^k$$

where A', B', and k are the constants which should be determined. Hence, because the area of fire $S \sim R_f^2$,

$$S \sim (A')^2 + 2A'B'G^k + (B')^2G^{2k};$$

or introducing new constants,

$$S \sim A + BG^k + CG^{2k}.$$

Noting that $G \sim PD_j^2$ we have the following dependencies for fire area in the case of pipeline rupture:

(1) at complete destruction of the cross section of the pipe $D_j = D$ and

$$S \sim A + B_1P^kD^{2k} + C_1P^{2k}D^{4k}; \tag{4'}$$

(2) at partial (crack-like) destruction of the pipeline it is reasonable to take $D_j^2 \sim DL$, so the area of fire becomes a function of the product PDL:

$$S \sim A + B_2(PDL)^k + C_2(PDL)^{2k}. \tag{4''}$$

The most frequent events according to the database are the crack-like destructions of the pipeline. Thus, we found a theoretically predicted form of dependence of fire area S upon main parameter PDL (4″) and further try to find the unknown constants A, B_2, C_2, and k.

The range of PDL parameters was divided into six intervals of 500 [atm m^2] collecting together all events within each interval. The mean values of fire area for each interval of PDL is plotted in Fig. 8. The dependence of fire area on the PDL parameter presented in Fig. 8 can be approximated by a linear function

$$S_l = 18\,500 + 10.1PDL \tag{5}$$

or power function

$$S_p = 1350(PDL)^{0.45} \tag{6}$$

with approximately the same accuracy, so the validation using v^2-parameter is not required here. Therefore we can use the linear combination (with equal weights) of

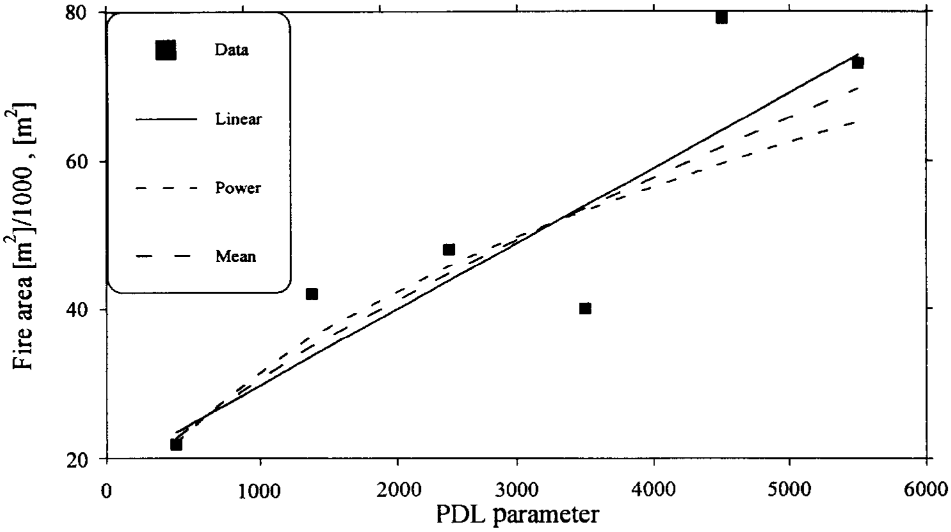

Fig. 8. Determination of fire area.

Eqs. (5) and (6):

$$S = (S_l + S_p)/2 = 9250 + 5PDL + 670(PDL)^{0.45}, \tag{7}$$

here we have S in [m^2], P in [atm], D, L in [m], which is the most probable for fire area obtained as a result of statistical analysis. The form of Eq. (7) is very close to the predicted one (4″) with $A = 9520$, $B_2 = 670$, and $C_2 = 5$. Moreover the constant k gives a surprising good agreement with the index in Eq. (3) and equals approximately 0.45.

8. Discussion and conclusions

Any details of failures of major hazard plants and pipelines are useful in assisting the analysis of such accidents required for risk assessment. The analysis above aggregates the data available and provides quite simple relationships to describe a range of outcomes.

The authors used in full all the database available. Certainly, there is inevitably limitations on the data, a degree of averaging and simplification of what are often complex features of pipeline releases. However, sufficient data to accurately model the outcomes of an accident are frequently unavailable after a pipeline failure. To our mind this does not undermine the value of the data presented, however the limitations of the relationships are obvious and should be recognised.

In principle, the relationships obtained could be expanded to include new parameters describing such phenomena as behaviour of cracks (depending on non-uniformities of the mechanical properties of pipelines and interactions between cracks); accelerations given to different shapes and masses of fragments and aerodynamics effects; the time history of the accidents (which is important for the area of any consequent fires); types of soil; and many others. The collection of additional information is required to provide a more detailed consideration and requires the more accurate, detailed and knowledgeable treatment of accident consequences.

From statistical analysis of the database of the accidents occurring on the pipeline Middle Asia-Centre, the following conclusions can be drawn:

The main combinations of the parameters were identified allowing the determination of hazardous levels of an accident. These parameters responsible for the energy potential of a pipeline accident are usually known in advance. The approximate formula linking energy potential to the quantification of the resulting hazards were found.

Approximately 64% of accidents were accompanied by fire. On average 14 accidents took place per year.

The most probable length of a crack in the pipeline varies in length from 20 to 45 m.

In half the cases the range of flying fragments did not exceed 60 m, although a marginal possibility exist (~ 5%) to find a fragment up to 350 m away from the rupture. A correlation formula was derived which linked the energy potential of the accident and the consequent range of fragments.

The length of a crater caused by pipeline rupture is linearly proportional to the length of the crack by a factor of 1.02. A certain underlying depth exists (0.7–1.5 m) at which the maximal sizes of crater are most probable.

The most part of the conclusions, to our mind, are of general importance, although the statistical analysis presented above was performed on the basis of data from only *one* of the largest pipeline networks. The main general groups of parameters and forms of dependencies could be applied to risk analysis on any other pipeline. Comparison with similar analysis for other pipelines of the same type would be highly useful.

Acknowledgements

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Appendix

Regression analysis for fragment range

Number – i	1	2	3	4	5	6	7	8	9	10
Intervals of energy potential E_i [atm m^2]	20	30	40	50	60	70	80	110	140	150
Ranges of fragment scattering X_k^i [m]	12	9.5	35	150	5.6	190	102	200	19	130
		10	40	18	75	250	78		185	20
		36	75	235	40	30	20			57
		35	40	60	30	110	349			360
			55	80	80	400	45			
			10	75	40	47	12			
			55	105	8	190	164			
			150	50	25	9.2	30			
			140	1.5	22	300	220			
			35	37	110	180	40			
				32	120	230	27.5			
				13		150	119			
				50		90				
				40		85				
				170		40				
				48		250				
				50		10				
				150		175				
				16.5		120				
				100		135				
				250		60				
				25		45				
				50		50				
				25		15				
				350		70				
				40		360				
				80		220				
				40		150				
				30		10				
				350		60				
				110		35				
						75				